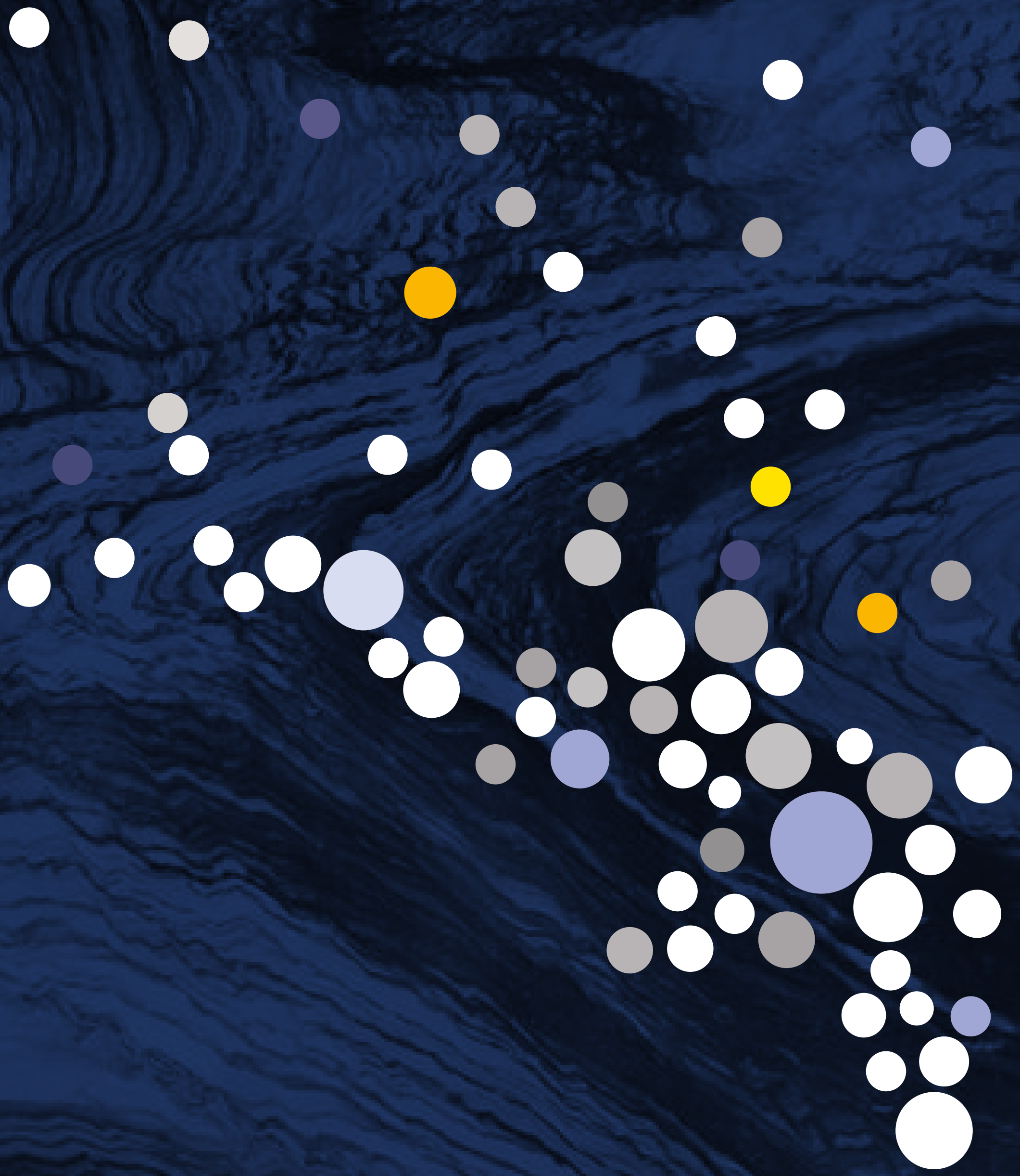
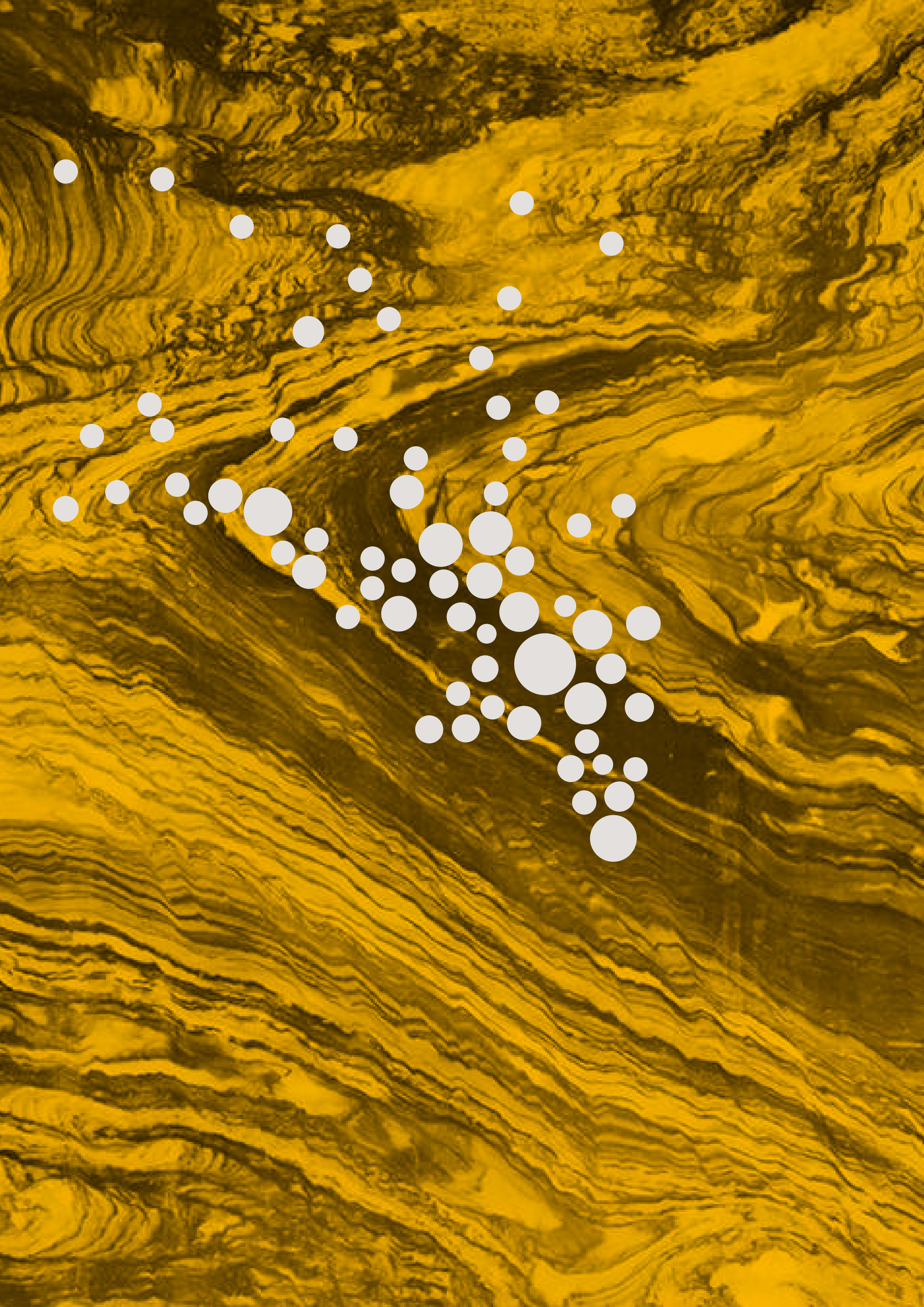


SOUTH AUSTRALIA

NUCLEAR FUEL CYCLE ROYAL COMMISSION REPORT

MAY 2016



NUCLEAR FUEL CYCLE ROYAL COMMISSION REPORT

Rear Admiral the Honourable Kevin Scarce AC CSC RAN (Rtd) – Commissioner

May 2016

NUCLEAR
FUEL CYCLE
ROYAL
COMMISSION

ISBN 978-0-9945776-4-1 (hardback)
978-0-9945776-0-3 (online resource)
978-0-9945776-1-0 (paperback)

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6 May 2016

His Excellency the Honourable Hieu Van Le AO
Governor of South Australia
Government House
ADELAIDE SA 5000

Your Excellency

On 19 March 2015 you issued to me a Commission to inquire into and report on the potential to participate in four areas of activity in South Australia that comprise the nuclear fuel cycle.

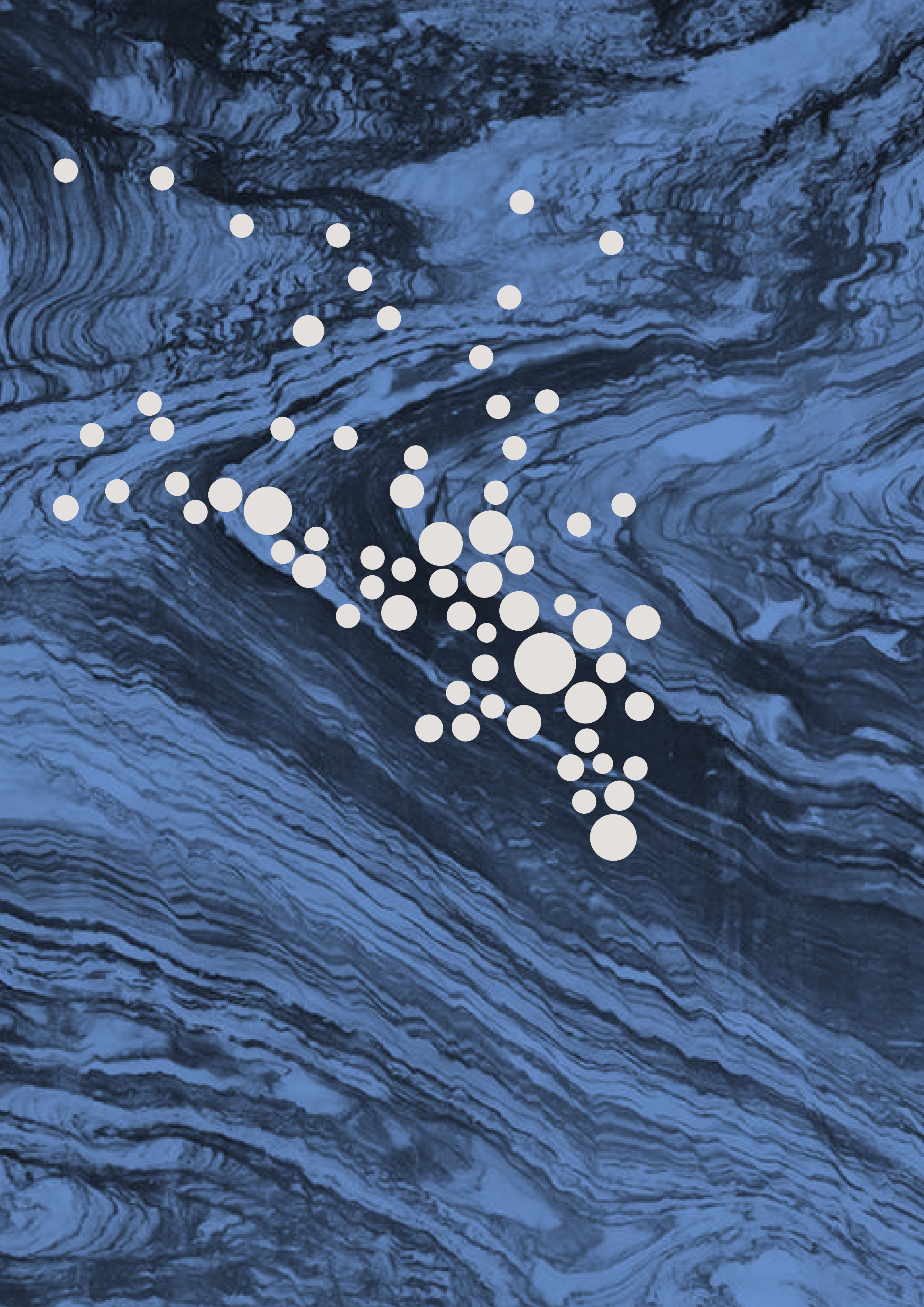
I hereby present you with my Report pursuant to the Commission addressing the Terms of Reference.

Yours sincerely

KScarce

Kevin J Scarce AC CSC
Royal Commissioner
Nuclear Fuel Cycle Royal Commission

investigating opportunities and risks for south australia



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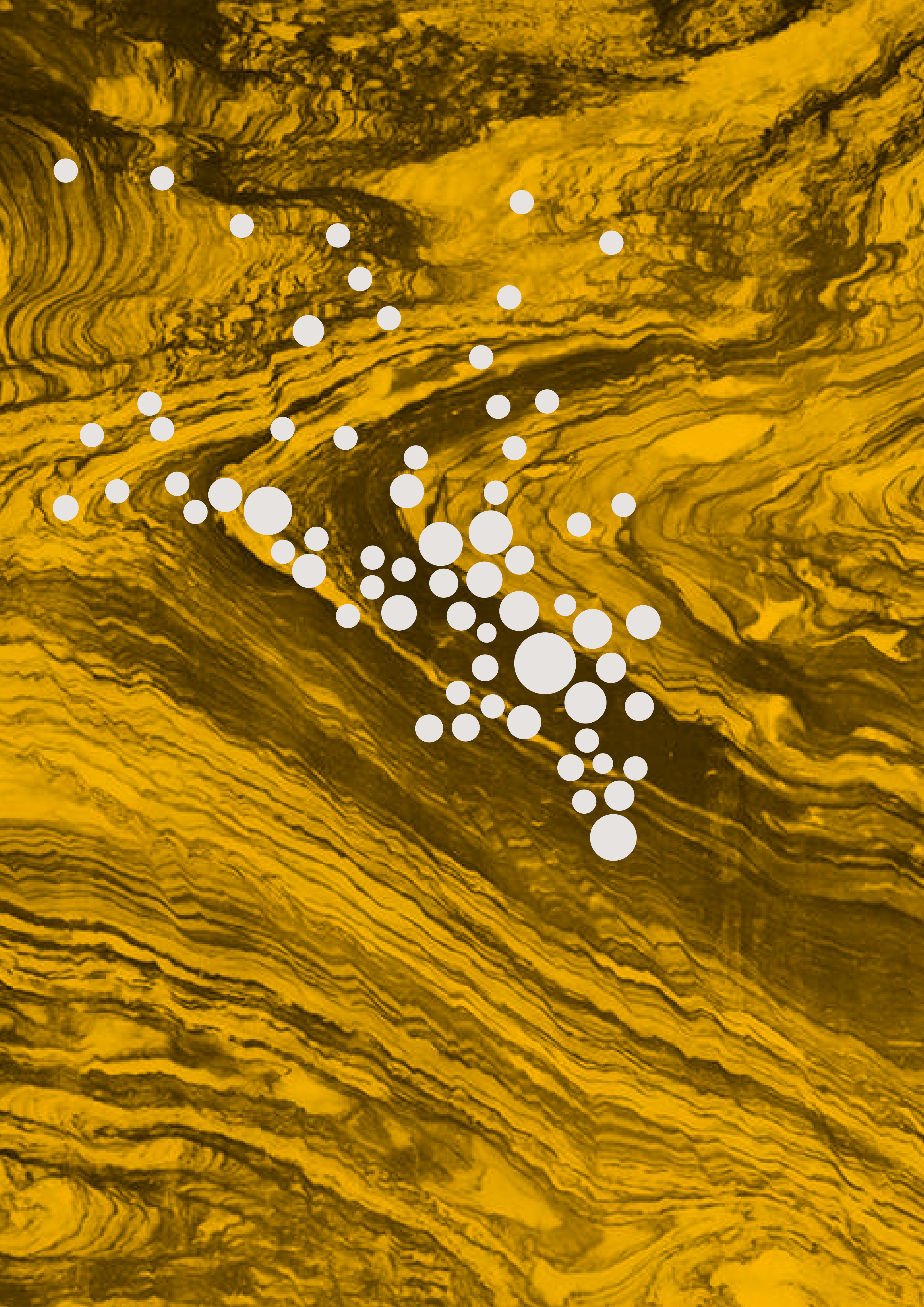


PREFACE

The Nuclear Fuel Cycle Royal Commission was established by the South Australian Government on 19 March 2015 to undertake an independent and comprehensive investigation into the potential for increasing South Australia's participation in the nuclear fuel cycle, specifically in four areas of activity:

- expanded exploration, extraction and milling of minerals containing radioactive materials
- the further processing of minerals and the processing and manufacture of materials containing radioactive and nuclear substances
- the use of nuclear fuels for electricity generation
- the establishment of facilities for the storage and disposal of radioactive and nuclear waste.

In each of these areas, the Commission was required to examine and report by 6 May 2016 on the feasibility, viability, risks and opportunities associated with a potential expansion of the nuclear fuel cycle from the perspectives of the environment, the economy and the community, including regional, remote and Aboriginal communities.

The Commission committed to conducting an independent, evidence-based process that was open and transparent. From the outset, its focus was on understanding facts and not accepting perceptions.

The Commission's process was independent of government, industry and lobby groups. It was conducted by a dedicated group supported by external expertise engaged by the Commission.

At the outset, the Commission produced Issues Papers inviting submissions on the associated risks and opportunities of each of the activities in the cycle.

In response to the Issues Papers, the Commission received as evidence more than 250 submissions from a wide range of individuals and organisations in the private, public and not-for profit sectors.

In its public sessions conducted from September 2015, the Commission heard oral evidence from 132 expert witnesses from Australia and overseas, which was streamed live on the internet.

It also conducted its own research, in Australia and overseas. As part of considering the commercial viability and economic impacts of potential nuclear activities specific to South Australia, the Commission engaged organisations with the expertise and experience to undertake detailed assessments.

Internationally, the Commission held meetings and site inspections at nuclear fuel cycle facilities and with experts in Asia, Canada, Europe, the United Arab Emirates, United Kingdom, and United States of America.

The major elements of this evidence were drawn together in the Commission's Tentative Findings, which were published on 15 February 2016, with an invitation for responses to better inform this report. About 170 responses that directly addressed the contents of the Tentative Findings were received.

In conducting an open and transparent process, and to encourage participation in its activities as the inquiry proceeded, the Commission engaged widely with the South Australian community, including five rounds of community information sessions in regional, remote and Aboriginal communities.

The Commission's approach has produced a large volume of information, which supports the reasoning and findings in this report. The submissions, public session videos and transcripts, financial assessment reports and Tentative Findings responses are published on the Commission's website, www.nuclearrc.sa.gov.au

This report represents both an end and a beginning: the culmination of the Commission's work, but the start of consideration by South Australians as to whether they want to increase the state's participation in the nuclear fuel cycle.

SUMMARY

South Australia can safely increase its participation in nuclear activities. Such participation brings social, environmental, safety and financial risks. The state is already managing some of these risks, and the remainder are manageable.

Some new nuclear fuel cycle activities (see Figure S.1) are viable. One in particular, the disposal of international used fuel and intermediate level waste, could provide significant and enduring economic benefits to the South Australian community.

Viability analysis undertaken for the Commission determined that a waste disposal facility could generate more than $100 billion income in excess of expenditure (including a $32 billion reserve fund for facility closure and ongoing monitoring) over the 120-year life of the project (or $51 billion discounted at 4 per cent). Given the significance of the potential revenue and the extended project timeframes, the Commission has found that were such a project to proceed, it must be owned and controlled by the state government, and that the wealth generated should be preserved and equitably shared for current and future generations of South Australians. This presents an opportunity that should be pursued.

Social consent is fundamental to undertaking any new nuclear project. Social consent requires sufficient public support in South Australia to proceed with legislating, planning and implementing a project. Local community consent is required to host a facility. In the event that this involves regional, remote and Aboriginal communities, consent processes must account for their particular values and concerns.

Political bipartisanship and stable government policy are also essential. This is particularly important given the long-term operation of facilities and the need for certainty for potential client nations.

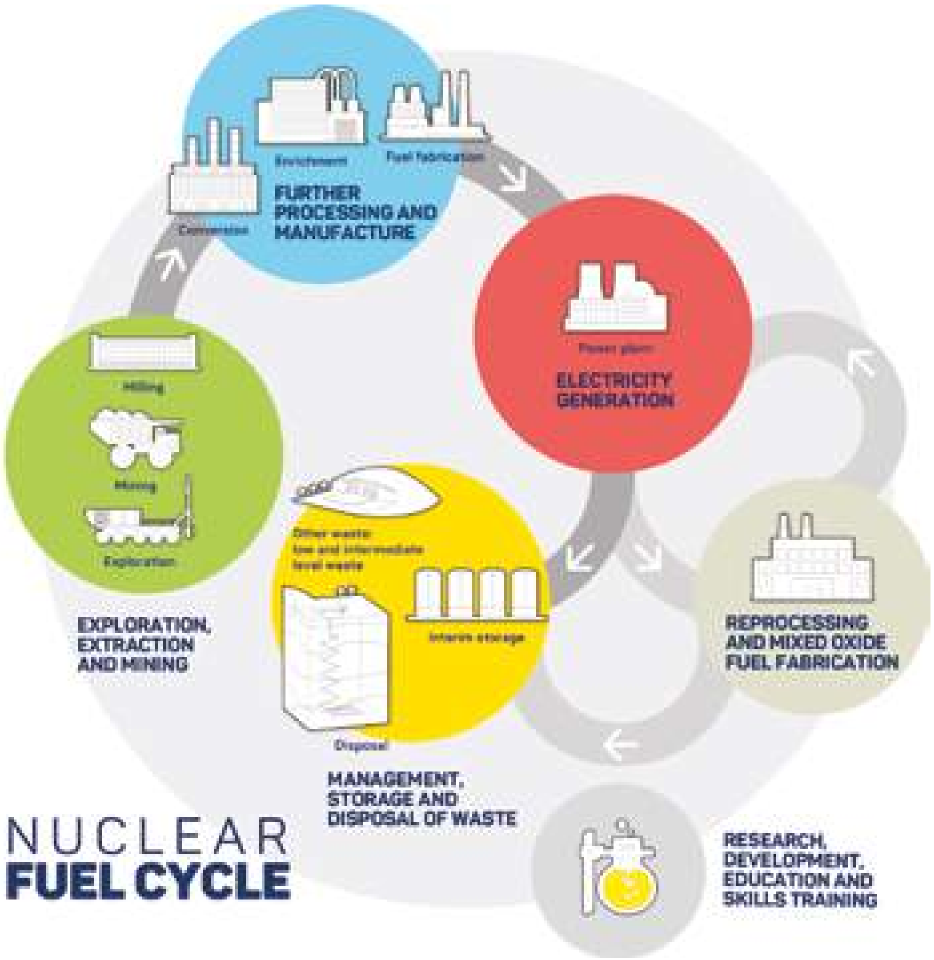


Figure S.1: The nuclear fuel cycle

EXPLORATION AND MINING OF RADIOACTIVE ORES

The Commission found that the administrative and regulatory processes that manage current exploration and mining operations are sufficient to support a safe expansion of activity. However, the existing regulatory approvals processes for new uranium mines are unnecessarily duplicative at the state and federal levels. The Commission therefore recommends that the South Australian Government **pursue the simplification of state and federal mining approval requirements for radioactive ores, to deliver a single assessment and approvals process.**

There is good geological reason to believe new commercial deposits of uranium could be found in South Australia, but the challenge is that vast areas in the state remain unexplored. There are a number of barriers to industry investment in further exploration while commodity prices are relatively low.

Expanded uranium exploration and mining would provide additional benefits to the state. To realise this potential, the Commission recommends that the state government **further enhance the integration and public availability of pre-competitive geophysical data in South Australia.** It should **undertake further geophysical surveys in priority areas, where mineral prospectivity is high and available data is limited.** It should also **commit to increased, long-term and counter-cyclical investment in programs such as the Plan for Accelerating Exploration (PACE) to encourage and support industry investment in the exploration of greenfield locations.**

While lessons learned from legacy sites in Port Pirie and Radium Hill are now incorporated in contemporary regulatory standards for new operations, the Commission recommends that for future developments the South Australian Government **ensure the full costs of decommissioning and remediation with respect to radioactive ore mining projects are secured in advance from miners through associated guarantees**.

FURTHER PROCESSING AND MANUFACTURE FROM RADIOACTIVE ORES

The Commission found the most significant environmental and safety risks associated with further processing of uranium for use in nuclear reactors are posed by chemicals rather than radioactivity. Many of these materials are already used and safely managed in Australia. Some risks would require new regulatory frameworks.

South Australia is technically capable of providing these services; however, there are significant barriers to entering these commercial markets. Further, these markets are currently over-supplied. The Commission considers that the provision of these services would not, either singularly or in combination, be commercially viable in the next decade.

There could be a potential competitive advantage if further processing services were linked with a guarantee to take back used fuel for permanent disposal. This concept of fuel leasing could in turn provide additional employment and technology-transfer opportunities. The Commission recommends that the South Australian Government **remove at the state level, and pursue removal of at the federal level, existing prohibitions on the licensing of further processing activities, to enable commercial development of multilateral facilities as part of nuclear fuel leasing arrangements.**

In relation to the production of medical isotopes, there are potential opportunities to expand existing facilities in the state. The Commission recommends that the South Australian Government **promote and actively support commercialisation strategies for the increased and more efficient use of the cyclotron at the South Australian Health and Medical Research Institute (SAHMRI).**

ELECTRICITY GENERATION FROM NUCLEAR FUELS

The Commission looked closely at reactor safety and the major accidents associated with nuclear power plants. While acknowledging the severe consequences of such accidents, the Commission has found sufficient evidence of safe operation and improvements such that nuclear power should not be discounted as an energy option on the basis of safety.

Taking into account the South Australian energy market characteristics and the cost of building and operating a range of nuclear power plants, the Commission has found it would not be commercially viable to develop a nuclear power plant in South Australia beyond 2030 under current market rules.

However, there will in coming decades be a need to significantly reduce carbon emissions and as a result to decarbonise Australia's electricity sector. Nuclear power, as a low-carbon energy source comparable with other renewable technologies, may be required as part of a lower-carbon electricity system. While the development of other low-carbon technologies will influence whether nuclear power would be required to meet Australia's future energy needs, it would not be able to play a role unless action is taken now to plan for its potential implementation. The Commission recommends that the South Australian Government **pursue removal at the federal level of existing prohibitions on nuclear power generation to allow it to contribute to a low-carbon electricity system, if required.**

In developing Australia's future electricity system there is a need to analyse the elements and operation of that system as a whole, and not any single element in isolation. This will be significant in determining the role that nuclear and any other technologies should play. The Commission recommends that the South Australian Government **promote and collaborate on the development of a comprehensive national energy policy that enables all technologies, including nuclear, to contribute to a reliable, low-carbon electricity network at the lowest possible system cost.**

Given the prospect that new reactor designs, and in particular smaller reactors, might be viably integrated in the Australian electricity network, the Commission recommends that the South Australian Government also **collaborate with the Australian Government to commission expert monitoring and reporting on the commercialisation of new nuclear reactor designs that may offer economic value for nuclear power generation.**

MANAGEMENT, STORAGE AND DISPOSAL OF RADIOACTIVE WASTE

There are large inventories of used nuclear fuel and intermediate level waste in safe but temporary storage around the world. Used nuclear fuel, a solid ceramic in metal cladding, generates heat, is highly radioactive and hazardous. The level of hazard reduces over time with radiation levels decreasing rapidly during the first 30 to 50 years of storage, with the most radioactive elements decaying within the first 500 years. However, the less radioactive but longer-lived elements of used nuclear fuel require containment and isolation for at least 100 000 years. The most serious accident involving used nuclear fuel involves potential exposure to radiation. Used fuel in storage or disposal cannot cause an explosion similar to that associated with a severe accident at a nuclear reactor.

There is international consensus that deep geological disposal is the best available approach to long-term disposal of used fuel. The Commission has found that there are now advanced programs in a number of countries that have developed systems and technologies to isolate and contain used nuclear fuel in a geological disposal facility for up to one million years. The most advanced of these will commence operation in the 2020s.

The safety of deep geological disposal is assured through the combined operation of geology and engineered barriers, and a detailed understanding of the radiological risks associated with used nuclear fuel. The evolution of geological conditions during the past hundreds of millions of years is well understood, and therefore future behaviour over hundreds of thousands of years can be predicted with confidence following detailed study. Engineered barriers are designed and constructed to complement the surrounding geology, and thereby provide a passively safe system of isolation and containment. The predicted future interactions between the used fuel, the engineered barriers and the surrounding geology are complex, but can be modelled and tested with a high degree of precision. The Commission has therefore found that South Australia has the necessary attributes and capabilities to develop a world-class waste disposal facility, and to do so safely.

To determine its viability, the Commission deliberately took a cautious and conservative approach to assessing used fuel inventories and potential global interest in international used fuel disposal. Based on those inputs, the Commission determined that a waste disposal facility could generate $51 billion during its operation (discounted at the rate of 4 per cent). Further analysis indicated that by accumulating all operating profits in a State Wealth Fund, and annually reinvesting half the interest generated, a fund of $445 billion could be generated over 70 years (in current dollar terms).

There is a range of complex and important steps that would need to be taken to progress such a proposal. The Commission has therefore recommended that the South Australian Government **pursue the opportunity to establish used nuclear fuel and intermediate level waste storage and disposal facilities in South Australia consistent with the process and principles outlined in Chapter 10 of this report.** This includes suggested immediate steps, and those that may arise in the future. The immediate steps are for the government to:

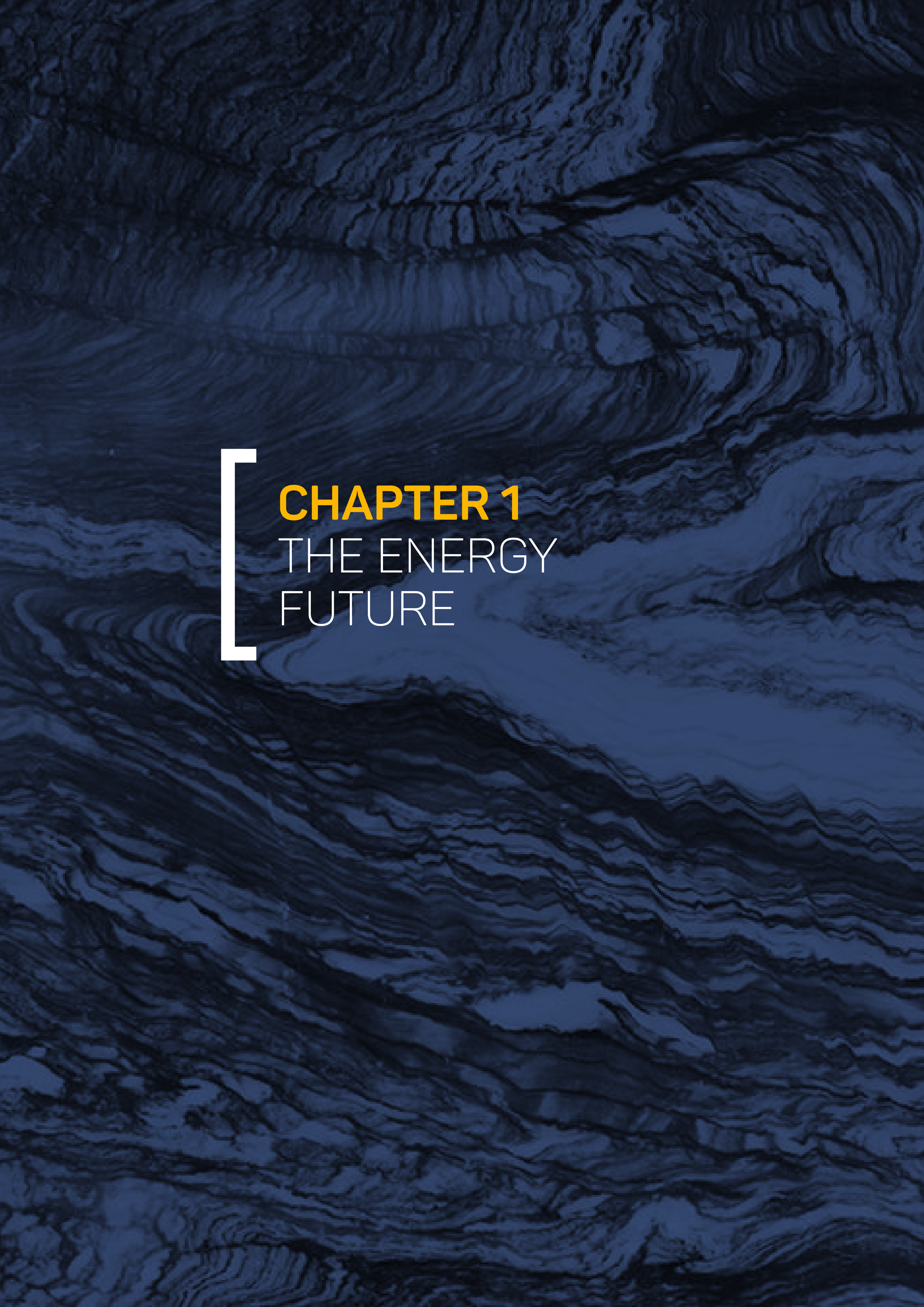
a. make public the Commission's report in full

b. define a concept, in broad terms, for the storage and disposal of international used fuel and intermediate level waste in South Australia, on which the views of the South Australian community be sought

c. establish a dedicated agency to undertake community engagement to assess whether there is social consent to proceed

d. in addition, task that agency to:
   - i. prepare a draft framework for the further development of the concept, including initial siting criteria
   - ii. seek the support and cooperation of the Australian Government
   - iii. determine whether and on what basis potential client nations would be willing to commit to participate.

The immediate next steps should be undertaken free from any debate about whether expenditure of public money in pursuing this opportunity is contrary to law. The government may quite properly want to seek further information or greater detail on matters considered by the Commission. It may also seek information in anticipation of a community request. Therefore, the Commission recommends that the South Australian Government **remove the legislative constraint in section 13 of the *Nuclear Waste Storage Facility (Prohibition) Act 2000* that would preclude an orderly, detailed and thorough analysis and discussion of the opportunity to establish such facilities in South Australia.**



CHAPTER 1

THE ENERGY FUTURE

CHAPTER 1: THE ENERGY FUTURE

1. The energy sector in Australia is undergoing transformation. This transformation needs to be guided by stable medium- to long-term government policies to encourage investment. Such policies should be based on evidence, not opinion or emotion.

There can be no doubt that the energy sector in Australia and elsewhere is changing dramatically. Although the major trends of this transformation are increasingly apparent, the extent and pace of change are not.[1] The trends include a decentralisation of electricity generation, the retirement of ageing coal plants, the development of new generation technologies, a focus on and preference for low-carbon energy sources, and changes in networks and the way in which the costs of these networks will be met.[2]

It remains unclear which energy options Australia will embrace.[3] The CSIRO's comprehensive Future Grid Forum Research Program, in analysis undertaken in 2013 and 2015, indicates that any of a range of possible scenarios for Australia's future electricity system remains plausible.[4] Any claim that there is certainty about future outcomes should be treated with caution.

The evidence suggests that the pace of changes to the energy sector will depend upon government policy, and will not be driven by technology and cost alone.[5] The transition pathway to low-carbon sources will be influenced by their relative costs and policy choices such as the incentives provided for new capacity to be installed.[6] The changes in transmission and distribution networks will be influenced by the extent of decentralised generation, ongoing reliance on networks to provide reliability of supply, and a desire for decentralised generators to sell surplus electricity.[7] It will also be influenced by the development of new pricing models to equitably fund networks among their users. All these matters will also be influenced by consumer behaviour in adopting new technologies for generation, storage and demand management.

Energy transformation will require substantial capital investment in both generation and networks.[8] Investment in generation has been affected by uncertainty about future policy,[9] recently demonstrated by the effect on investment from changes in 2012 to legislated subsidies in favour of renewables.[10] This is not to express a view about the desirability of those changes but to illustrate that investment is highly sensitive to policy uncertainty.

Given the complexity of the issues and cost of transformation, planning must be based on evidence.[11] That evidence should focus on a combination of cost, reliability and carbon intensity. This is discussed in greater detail in Chapter 4 Electricity generation. It is critical that long-term decision making should not rely solely on what is presently popular.

2. The opportunities for future South Australian participation in the global markets for uranium ore and other nuclear fuel cycle services are highly dependent on the policies and decisions of all nations to address climate change.

The Paris Agreement negotiated at the 2015 United Nations (UN) Climate Change Conference agrees to overall global reductions aimed at limiting any rise of the global average temperature to well below 2 degrees Celsius (°C) above pre-industrial levels. The Paris Agreement allows signatories to develop their own measures for reducing emissions and does not identify mechanisms for determining a country's share of reductions.[12]

This flexibility makes medium and long-term predictions about the actions needed to be taken to transition to low-carbon systems challenging. While the goal and general trends are known, neither the pace of change nor the transition pathway for any country can be identified with certainty.[13]

This is significant to the development of future energy generation technology, including nuclear energy and the industries that supply it.[14] The suitability of nuclear power for any country depends on the other power generation options available, as well as its political, economic and social circumstances. Many countries have already pursued nuclear power, some have committed to pursuing it, some are considering it, and others have decided against it or decided to abandon it.[15]

For this reason considerable caution must be exercised in making predictions about the future growth of nuclear power. There are firm global commitments to growth in installed nuclear capacity from current levels of about 380 gigawatts (GWe) to about 450 GWe by 2030.[16] However, firm predictions beyond 2030 are much more problematic.

Estimates by the International Energy Agency (IEA) based on emissions targets consistent with the Paris Agreement's 'well below 2 °C' target, show very substantial growth in nuclear generation.[17] That scenario is possible, as are scenarios with little or no growth. Ambitious projections of long-term nuclear industry growth have a history of not being realised. It is for that reason the Commission has not relied on such projections in its reasoning.

3. Significant additional global action will be required to achieve the 'well below 2 °C' target. The slower the abatement action taken now, the greater the action that will need to be taken later, and the greater its costs and impact on the economy.

Before the Paris conference, countries informed the UN of their stated intentions to reduce carbon emissions.[18] The intended nationally determined contributions reflected a range of commitments to reduce emissions of greenhouse gases, the most significant of which is carbon dioxide.[19]

Even if implemeted, modelling suggests that these commitments will only limit the increase in global temperature to about 2.7 °C.[20] That central estimate is within a fairly wide range of an increase up to 4 °C. Even assuming countries meet their commitments, the 'well below 2 °C' target will require significant further action.[21]

If one takes the approach of a total carbon budget reflecting the total permissible emissions into the atmosphere, it can be seen that the slower the abatement actions taken now, the faster the need for abatement in the future.[22] Modelling of emissions mitigation schemes to reduce global warming demonstrates that delaying emissions reductions from 2020 to 2032 would require more than a doubling of reduction rates to meet the same target.[23]

Moreover, analysis suggests that the speed of abatement will affect its ultimate cost.[24] Delayed abatement will, in the interim, increase risks of temperature increase, entrench a more emissions-intensive economy and defer cost reductions in low-emissions technology.[25] This will lead to higher eventual costs of abatement. Further, costs have been projected to increase at a rate disproportionate to the delay.[26]

4. It will be necessary to significantly transform Australia's energy sector to both reduce emissions and support pathways to decarbonise other economic sectors such as transport.

Australia has many options in reducing emissions from electricity generation. They include measures to improve efficiency and new technologies that manage demand.[27]

Given that electricity generation in Australia accounts for about one-third of national carbon emissions,[28] there is a need to transform the electricity generation sector to meet future carbon emission targets.

There is a widely held view, although it is not current policy in Australia, that to achieve the 'well below 2 °C' target it will be necessary to have an energy sector with zero net emissions by 2050.[29] Modelling suggests that it is unlikely that Australia could fully decarbonise its electricity sector by 2050 by relying on renewables alone. Combined cycle gas turbines will be required for system stability in the absence of other dispatchable generation. The importance of this timeframe is that such a transition is necessary to facilitate transformations in other sectors. For example, to switch fuel from carbon-intensive energy sources in industry and transport it is necessary to support a transition from carbon-based fuels to either electric- or hydrogen-fuelled vehicles, which is now incentivised in some countries.[30]

5. Nuclear power is presently, and will remain in the foreseeable future, a low-carbon energy generation technology.

Some energy generation technologies, particularly those that burn fossil fuels, generate substantial carbon emissions during their operation, while others such as solar photovoltaic (PV), concentrated solar thermal, wind and nuclear do not.[31] However, all energy generation technologies create emissions over their life cycle. These emissions are generated during plant construction (including in the extraction, manufacture and use of building materials such as steel, concrete and silicon), operation, maintenance and decommissioning.[32]

A large number of studies of life cycle emissions from electricity generation have been undertaken over several decades, with divergent results.

The National Renewable Energy Laboratory (NREL), the primary laboratory for renewable energy and energy efficiency research and development in the United States, undertook a peer-reviewed analysis and harmonisation of all earlier studies on carbon emissions from various electricity generation technologies. The significance of the harmonisation was that the assumptions and parameters of the various studies were assessed, allowing for their direct comparison.[33] The output of the analysis has been adopted by the Intergovernmental Panel on Climate Change (IPCC).

As shown in Figure 1.1, the median estimates under the NREL analysis ranked the emissions of nuclear (12 grams carbon dioxide equivalent per kilowatt hour (gCO_2-e/kWh) within the range of solar PV (18–50 gCO_2-e/kWh, depending on technology choice) and wind (12 gCO_2-e/kWh).

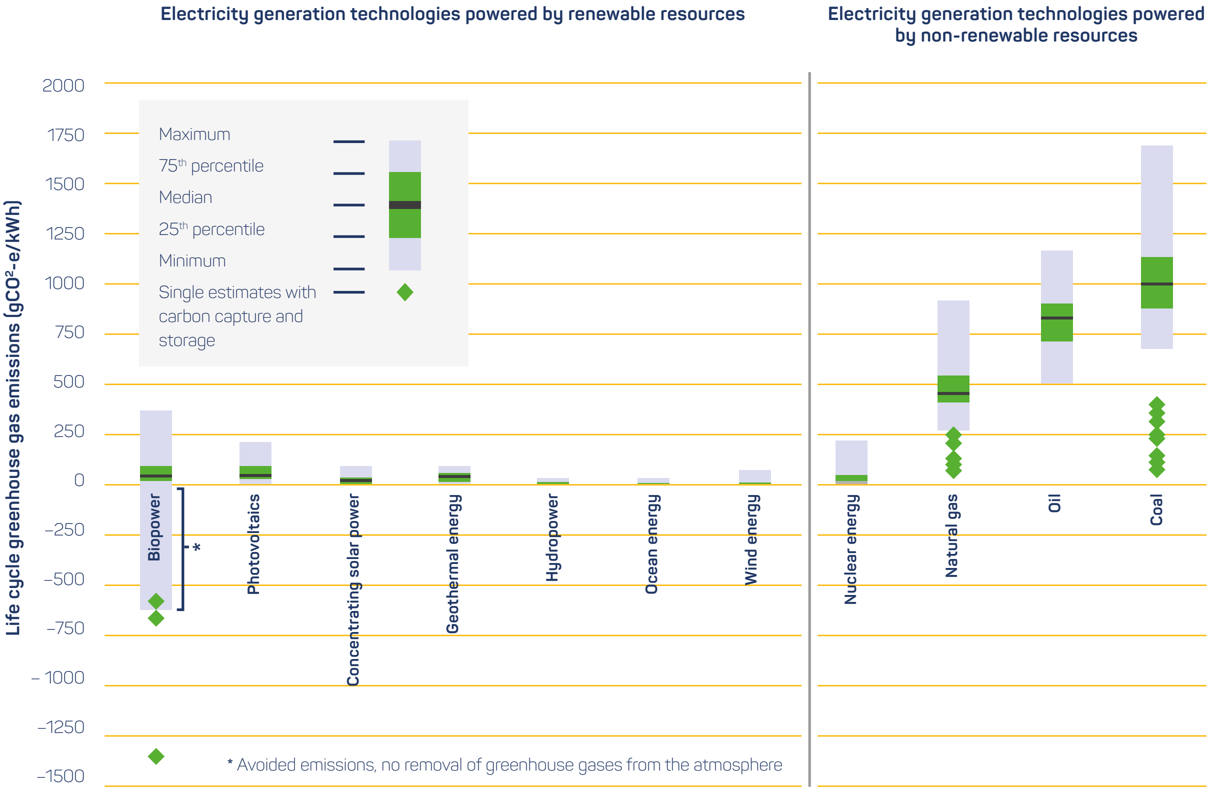


Figure 1.1: Life cycle greenhouse gas emissions for electricity generation technologies

Data sourced from National Renewable Energy Laboratory, 'Life cycle assessment harmonization results and findings', NREL.gov, last modified 21 July 2014, www.nrel.gov/analysis/sustain_lca_results.html

Note: gCO_2-e/kWh=grams carbon dioxide equivalent per kilowatt hour

That nuclear has emissions in the range of solar PV, wind, concentrated solar thermal and other renewables is supported by other significant contemporary studies.[34] In each case, those technologies are substantially less carbon-intensive than gas and significantly less again than coal. Across earlier studies the estimated emissions range for nuclear has varied considerably.[35] This variation arises from different methods for performing harmonisation over a large range of studies—some may be less complicated to perform, but result in less precision.[36] The NREL study is significant because of its comprehensive and detailed analysis.

The breakdown of carbon emissions for nuclear energy has been estimated to be approximately one-third for activities and services associated with manufacturing nuclear fuel, one-third for construction and decommissioning, and one-third for operation, storage and disposal of waste.[37] The life cycle carbon emissions for nuclear power have decreased marginally in recent years. This is due to increased energy efficiency, particularly the shift to centrifuge enrichment techniques from the more energy-intensive gaseous diffusion, and the higher proportion of low-carbon electricity used in nuclear conversion, enrichment and fuel fabrication.[38]

Nuclear will continue to be a low-carbon option for the foreseeable future. Studies have shown that even a substantial decline of ore grades to levels far lower than those currently mined in Canada or Australia (from either uranium-specific or polymetallic deposits) would have a minor effect on carbon emissions from nuclear power.[39] In any event, if uranium demand were to increase there is significant potential for the discovery of new deposits with economic grades. Were that to occur, the emissions intensity of mining uranium would not increase.[40]

6. In Australia, nuclear power cannot contribute to emissions reductions before 2030 because of the long lead time to make new capacity operational. It could contribute after that time, which may be important if more rapid action is required to be taken to reach a net zero emissions target from energy generation by 2050.

Following a lengthy period in which new reactors were not constructed in Europe and the United States, recent experience in those countries indicates that new nuclear capacity has taken substantially longer to construct than planned.[41] Construction of new reactors has at best, in countries outside Europe and the United States, been completed in about six years.[42] The fastest development of a new global nuclear program is in the United Arab Emirates; it took 10 years from the initial policy decision in 2008 to the planned start of operations in 2017. This program had the advantage of replicating nuclear plant designs already constructed and licensed in their country of origin.

When construction times are combined with the time it would take to develop a regulatory structure and implement policy,[43] the earliest likely date at which nuclear power could come into operation in Australia would be from 2030.[44] The Commission does not accept views that a nuclear power capability would take longer on the basis that a decade-long period of decision making and planning would be required.[45] Those timeframes reflect a business-as-usual approach and do not account for a targeted focus on achieving an outcome to address a recognised need.

In the event that fast and rapid action is required by Australia after 2030, nuclear power might play a useful role. This becomes particularly significant if the nation makes only modest progress in reducing emissions before 2030 and is required to commit to eliminating carbon emissions from electricity generation by 2050. In pursuing a policy of rapid decarbonisation, nuclear power might be a useful and significant contributor.

7. It would be wise to plan now for a contingency in which external pressure is applied to Australia to more rapidly decarbonise. Action taken now to settle policy for the delivery and operation of nuclear power would enable it to potentially contribute to reducing carbon emissions.

Australia's current emissions reduction targets, and any further contributions, both national and international, were the subject of discussion before the UN 2015 Climate Change Conference. In the period leading up to the first progress review of the Paris Agreement in 2020, Australia's future commitments could again be the subject of discussion. That will occur in the context of other countries forming views about their fair share of abatement and the respective contribution of other nations to achieving the overall goal.

In that time, Australia may come under pressure to decarbonise more rapidly than it had planned. It is apparent from the Paris Agreement, with its associated national commitments, that the politics of climate change abatement remain fluid.

Australia's current commitments require it to reduce emissions to five per cent below 2000 levels by 2020, giving a target of 530 megatonnes carbon dioxide equivalent ($MtCO_2$-e).[46] Australia's emissions are projected to be 656 $MtCO_2$-e in 2019–20, requiring a further reduction of 126 $MtCO_2$-e to meet the target.[47] Firm commitments to further reductions have not yet been made.

Previous policy measures aimed at addressing carbon emissions have proven politically contentious. This has led to limited discussion and consideration of potential policy options. As scientific evidence on the impact of climate change mounts, perhaps it is time for a change in approach to facilitate a scientifically led debate. Long-term policy options need to be considered now if the nation is to avoid the disproportionate consequences of attempting to quickly reduce carbon emissions from electricity generation.

The Australian Government will formally review its current and future carbon abatement commitments in 2017.[48] This would be an ideal time for scientific rather than politically led discussions about future options.

The scope of the review has not been defined. In view of what is said elsewhere in this report, it will be important for such a review to contemplate not only Australia's current and short-term commitments, but also to prepare a strategy to meet longer-term goals, with sufficient flexibility to accommodate future developments.

8. While it is not clear whether nuclear power would be the best choice for Australia beyond 2030, it would be prudent for it not to be precluded as an option.

Australia should position itself to be able to take advantage of all the potential options in the event of a requirement for rapid emissions reduction.[49] It would be wise to facilitate a technology neutral policy for Australia's future electricity generation mix.

To make a range of technologies available, action is required now.

In the case of nuclear power, those actions include the:

- amendment of existing legislation
- setting of key policies that would send relevant signals for private sector investment
- development of an electricity market structure
- development of a new regulatory framework that addresses key principles of non-proliferation, safety and security in the use of nuclear energy.[50]

If such preparatory steps are deferred, nuclear power would continue to be precluded as an option—meaning that it would always be an option over the horizon.

Making nuclear power available as an option does not mean it would be the best choice for Australia in 2030. Other developments may well lessen the need for it. However, that should not be assumed. The present considerable optimism about the future cost of renewable generation and storage does not ensure certainty about these outcomes.[51] Nor should the development of nuclear be regarded as static. As nuclear projects are implemented in other countries, and as new systems are developed, particularly small modular reactors, the costs of nuclear may demonstrate that it should be part of a low-cost, low-carbon energy system in Australia.

NOTES

1 Transcripts: Baldwin, p. 1586–1587; Swift & Falcon, pp. 49–52, 62; Graham, p. 410; Skarbek, pp. 36–37. Submissions: Australian Industry Group, pp. 2–5.

2 Transcripts: Makhijani, pp. 428–429; Swift, pp. 140–141.

3 Transcript: Makhijani, pp. 428–429. Submission: Australian Industry Group, pp. 2–5.

4 CSIRO, *Change and choice: The future grid forum's analysis of Australia's potential electricity pathways to 2050*, 2013; *CSIRO, Electricity network transformation roadmap: Future grid forum: 2015 refresh – Technical report*, 2015, p. 100.

5 Transcript: Diesendorf, pp. 67–72.

6 Transcripts: Constable & Cook, pp. 463–464; Garnaut, p. 21. ClimateWorks Australia, *Pathways to deep decarbonisation in 2050*, ClimateWorks Australia, 2014, p. 5.

7 Transcript: Makhijani, pp. 428–429.

8 ClimateWorks Australia, *Pathways to deep decarbonisation in 2050*, ClimateWorks Australia, 2014, p. 5.

9 Transcript: Garnaut, pp. 16–17. Submission: Australian Industry Group, p. 4.

10 Transcript: Garnaut, p. 15–17.

11 Submission: Energy Policy Institute of Australia, pp. 3–4.

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Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website:www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

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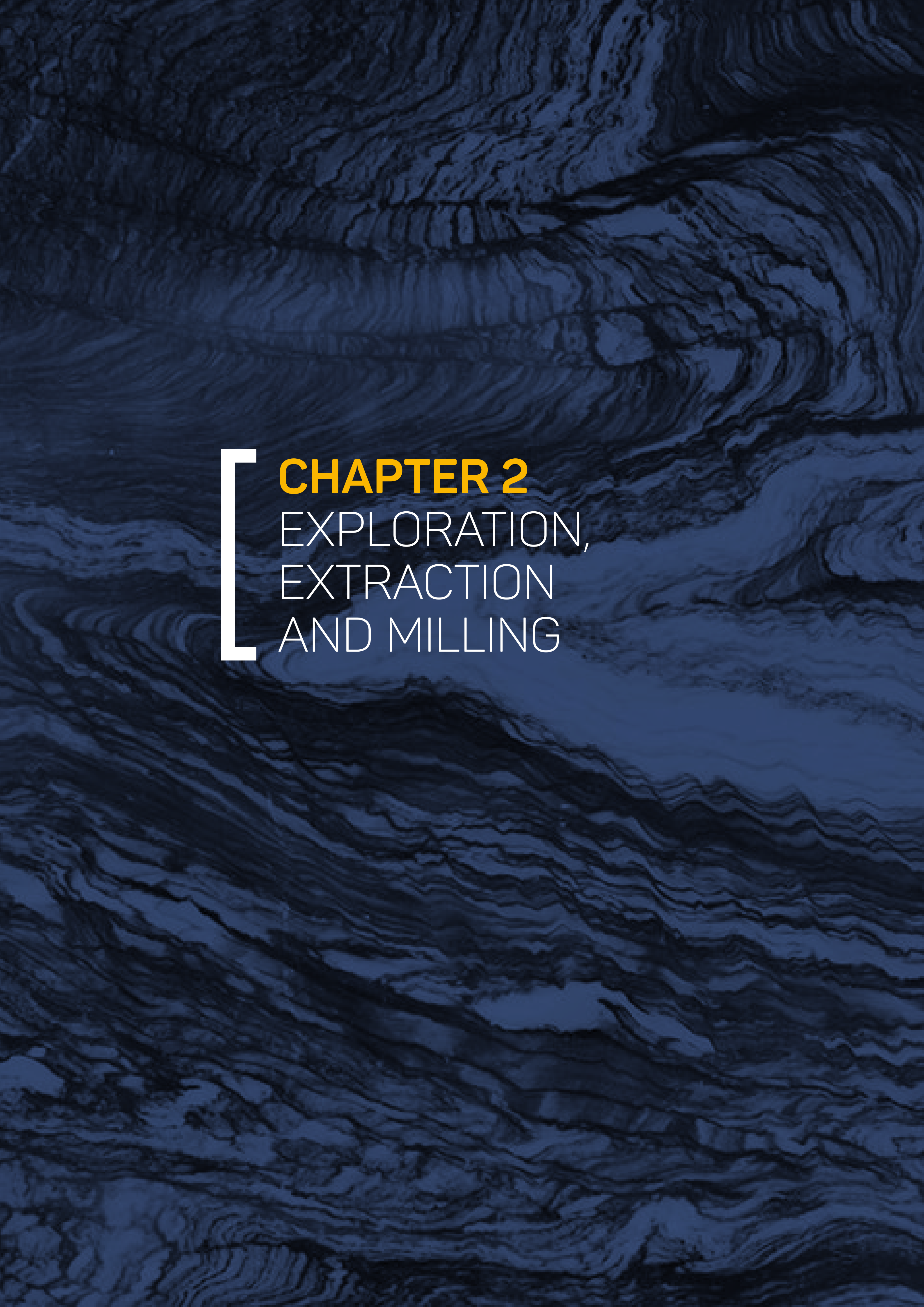

CHAPTER 2

EXPLORATION, EXTRACTION AND MILLING

CHAPTER 2: EXPLORATION, EXTRACTION AND MILLING

The activity under consideration is the expansion of the current level of exploration, extraction and milling of minerals containing radioactive materials in South Australia.

WHAT ARE THE RISKS?

9. Exploration activities for all minerals are most commonly undertaken by remote geophysical reconnaissance and low-density soil/ rock geochemical methods, which pose low environmental risks. Where drilling occurs, the existing administrative and regulatory processes, if properly applied, are sufficient to manage the environmental and other risks.

Most modern exploration methods cause little environmental disturbance, as they involve geophysical data collection, surface sampling and stream sediment analysis.[1]

In the case of uranium, the exploration process is similar to that for any other mineral commodity. Geophysical surveys are used to detect characteristics associated with uranium mineralisation, including anomalies in measured radioactivity, magnetism, gravity and electrical conductivity. They are first performed from the air to identify sites of interest, which are then surveyed on the ground.[2] Surface features of the site, such as soil, stream sediment and geology, are sampled and analysed to obtain further information about the underlying geology and potential mineralisation.[3]

Depending on the results of the geophysical surveys and surface exploration, physical investigation of the underlying geology is undertaken. This involves borehole drilling into the ground to obtain a sample of rock material.[4] Technical analysis of the sample provides information about gamma radiation, groundwater and other physical characteristics, and chemical analysis is undertaken to quantify the geochemistry.[5]

These characteristics can then be used to model the framework of the underlying geology and identify further targets for exploration.[6]

More significant environmental impacts associated with mineral exploration may arise from the use of borehole drilling, which can directly affect surface water, groundwater, soil, flora and fauna.[7] When a site is selected for exploration drilling, it is cleared of vegetation. Depending on the density of that vegetation and the topography of the area, this can be done with minimal impact, although drilling areas may require heavy machinery to excavate sumps, as well as to clear tracks and drill pads.[8] Drilling activity may cause other impacts that require monitoring and management, including light, dust, vibration and noise.[9]

Exploration for minerals in South Australia is undertaken in accordance with licences issued by the state government. A program for environment protection and rehabilitation (PEPR) approved by the Department of State Development (DSD) is also required before activities commence.[11] A PEPR provides details about the mineral commodity targeted by an exploration company and the proposed exploration program, including landowner and native title holder engagement strategies and environmental management measures. The PEPR approach requires companies to take account of environmental risks before, during and after exploration.[12]

When exploration programs finish, a company is required to return the sites to their natural, pre-exploration state, as far as possible[13], for example, by 'ripping' tracks, which loosens compacted topsoil to promote regeneration of the native vegetation.[10] If exploration activities are likely to cause a significant environmental disturbance or are to occur in sensitive environmental areas, for example, national parks, there are provisions for the state government to require financial bonds.[14]

Once DSD is satisfied with the PEPR, a tenement area will be granted for a specified term of up to five years.[15] A radiation management plan (RMP), prepared in accordance with guidelines issued by the South Australian Environment Protection Authority (EPA), is also required to ensure adequate radiation protection of workers, the public and the environment.[16] The EPA is South Australia's independent environmental regulator.

In South Australia, uranium exploration has a history of compliance with environmental protection measures, although there have been instances where this has not occurred. For example, in 2008, Marathon Resources was found to have inappropriately disposed of wastes at sites where it had undertaken exploratory drilling. The regulator required the company to undertake rectification works, which were appropriately completed and independently verified.[17]

10. Mining and milling activities for all minerals pose risks to human health and the environment, which need to be managed. If expanded, uranium mining and milling activities in South Australia would create similar risks to those arising from current uranium mining activities.

The methods used in Australia to mine uranium are underground, in-situ leaching (ISL), also known as in-situ recovery, and open-cut.[18] There are other extraction methods, such as acid heap leaching, not currently used commercially in Australia.[19]

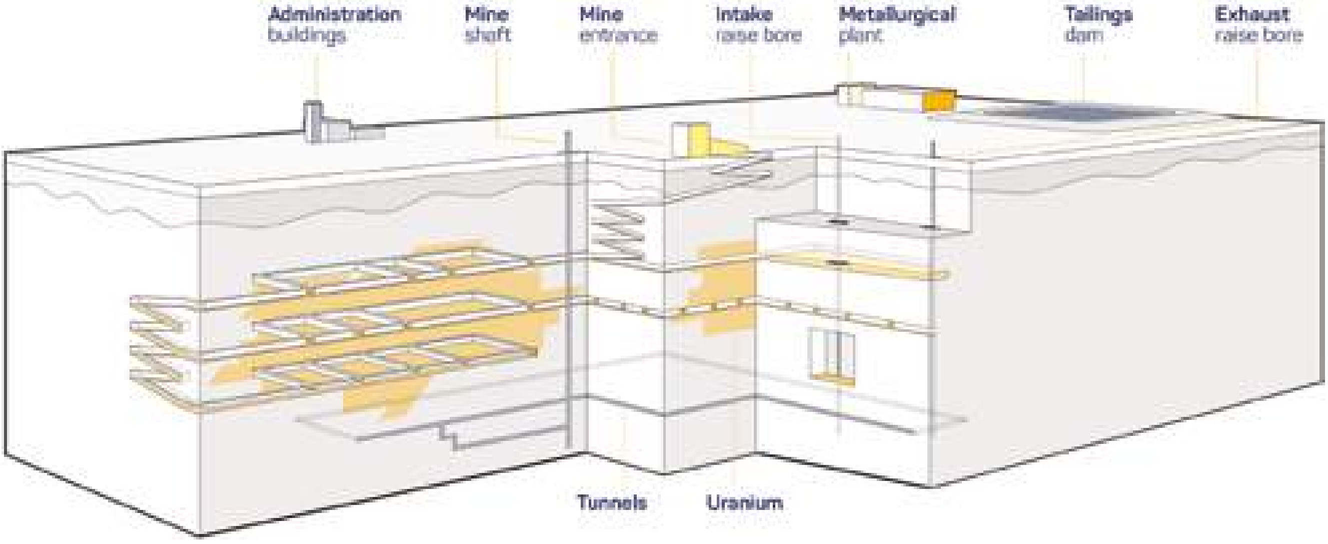

Figure 2.1: A cross-section of an underground mine

Olympic Dam in South Australia, which is owned and operated by BHP Billiton, is an underground mine that uses a sub-level open stope method (see Figure 2.1). This method is complex and requires extensive infrastructure.[20] In addition to the mine (see Figure 2.2), the operations at Olympic Dam include tailings storage dams, waste rock storage areas, product storage areas, an ore processing plant, administrative and residential buildings, and infrastructure to facilitate transport and the supply of utilities.

Operations at underground mines pose risks to workers, the environment and, potentially, members of the public.[21] If appropriate risk management strategies are not implemented, mining operations might result in underground collapse, rock fall, dust and noise pollution, and exposure to radiation and other radioactive particulates, causing harm to workers and the public, or environmental contamination.[22] Prevention and mitigation measures are used to reduce the risks of underground mining activities in accordance with regulatory requirements.[23] This would continue to be the case if underground operations using the present mining method were to be expanded.

Some of the environmental impacts identified in current and former mines elsewhere in Australia are more challenging than in the arid conditions of South Australia. The geochemical composition of a uranium ore body, in particular the presence of sulphides, increases the potential for uranium to migrate through the environment. That migration is assisted by water in areas of wetter climatic conditions.[24] As a result, strategies for managing the environmental impacts of uranium mining activities need to consider not only the nature of the extraction method, but also local climatic and geochemical conditions.

MINE WASTES

Uranium mining requires a radioactive waste management plan (RWMP) that is approved by the EPA and updated as requested by the operator or the regulator. A RWMP outlines how a proponent will manage risks to the environment resulting from mining processes, including the production and management of radioactive wastes.[25]

Mine wastes, known as tailings, comprise solid and liquid chemical wastes generated through milling and leaching processes. They often include fine suspended particles of rock mixed with acids and other chemicals. In the context of uranium mining, tailings generally contain radioactive elements, including radium and radon.[26] However, inadequate containment at tailings dams is a more significant hazard than the radioactivity level.[27]

A loss of containment has the potential to result in tailings breaching the dam containments and seeping into underlying geology and aquifers. If breaches occur, the tailings can render groundwater unsafe for use by humans and fauna. For these reasons, tailings dams and facilities are engineered and reinforced to avoid seepage or structural collapse. Tailings dam engineering plans must be reviewed by DSD before approval is given to start mining activities.[28] Mining companies are required to monitor and report annually on the integrity of their tailings dams and their retention

Figure 2.2: Underground mining at the Olympic Dam mine

Image courtesy of BHP Billiton

performance. In its most recent environmental protection and management program report, BHP Billiton stated there had been no recent embankment failures and that the groundwater beneath the tailings storage facility had not reached a level where it interacts with vegetation, indicating that any potential seepage was being managed.[29]

Other general and mine-related wastes, both liquid and solid, are generated during mining activities and, once the mine has closed, are retained on the mine site.[30] If these wastes interact with surface or groundwater, they can produce leachate, which can infiltrate and contaminate the underlying groundwater.[31] Leachate can contain contaminants, including radionuclides, heavy metals and acids, which can render the groundwater unusable. Waste and tailings facilities must be suitably lined with clay or geotextile fabrics to prevent their interaction with the surrounding environment.[32] At the end of mining operations, tailings dams are required to be capped to ensure that wastes are contained and risks to the environment are managed.

GENERATION OF DUST AND HANDLING OF ORES

Underground and open-cut mining poses a risk to workers through exposure to radioactive dust particulates and radon gas[33], particularly due to the use of explosives, heavy machinery and processing equipment, and other ground disturbances.[34] There is a known association between exposure to these sources and historical experience of lung cancers in workers in uranium mines, where those mines operated with limited or no protective measures for workers.[35]

In modern uranium mining operations, such as those at Olympic Dam, the EPA-approved RMPs contain measures to protect the health of workers. A key control is to minimise direct handling of materials containing uranium. This is achieved through the use of machinery and automation, for example, in uranium oxide packing facilities. Other controls include dust suppression by wetting dry surfaces, ventilation to remove radon gas, real-time air quality monitoring, and filtration systems, including in the cabins of trucks used underground. For workers, measures include wearing personal protective equipment, cleaning uniforms and showering.[36]

The radiation exposure of employees is monitored and doses are compiled in reports to the EPA, which are publicly available.[37] Data on radiation doses to uranium mine workers in Australia is collated by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) in the Australian National Radiation Dose Register (ANRDR).[38] As set out in Chapter 7: Radiation risks, the data shows that the exposure of workers is significantly lower than the regulated limit.

In a submission to the Commission, it was asserted that the RMP at Olympic Dam had not been updated between 1998 and 2013.[39] The implication was that protection measures in mining operations had not been effectively regulated by the regulator or managed by the operator. The evidence is that at all times there was an effective RMP at Olympic Dam that had been approved by the EPA, the regulator. During the period in question, the EPA had not needed to amend the plan and the measures in the plan were implemented, as evidenced by the EPA's regular inspection of the mine's radiation safety measures.[40] Therefore, the criticism made is not a basis for suggesting that radiation protection could not be effectively managed at Olympic Dam or elsewhere in the future.

IMPACTS ON FAUNA

Tailings fluids are acidified and contain other harmful chemicals. In an arid environment, the water held in tailings dams can attract native fauna. When fauna access tailings dams, the result can be illness or death. Significant numbers of birds and mammals have perished in the past in tailings facilities at Olympic Dam.[41] BHP Billiton has since implemented measures to minimise the interaction between the fauna and tailings dam water, including fencing and light and noise-deterrent systems, which have reduced but not eliminated the risks.[42] Netting of the dams has also been proposed.[43]

RISKS TO WATER SOURCES

Water is required during mining operations for minerals processing, dust suppression and equipment washing. As mines tend to be located in remote areas, away from major pipeline infrastructure, water is a critical resource. It can be sourced from the surface, including lakes and rivers, or from aquifers. In so doing, there is the potential for over-extraction of groundwater. As well as depleting water resources, this could cause soils and remnant water to become saline.

The water requirements at Olympic Dam are substantial, with operations using an average of 37 megalitres of groundwater a day.[44] Water is primarily supplied to operations from Wellfields A and B, which draw from the Great Artesian Basin, and are located 120 kilometres (km) and 200 km respectively north-east of operations.[45]

The quantity of water used is limited by BHP Billiton's operating licence, which is issued by the South Australian Department of Environment, Water and Natural Resources. A monitoring program is incorporated in the licence to track water use. The quantities of water extracted are recorded and are publicly available in annual reports. Current extraction is within the regulated limits.[46]

Concerns have been expressed in the past that water consumption at Olympic Dam was having a negative effect on the environmentally sensitive Mound Springs, where water from the Great Artesian Basin reaches the surface.[47] However, ongoing monitoring has not identified any changes in the springs beyond those predicted when Olympic Dam was established and those stated in the 1997 environmental impact statement. This is demonstrated by measurements of the rate of flow and monitoring of flora communities.[48]

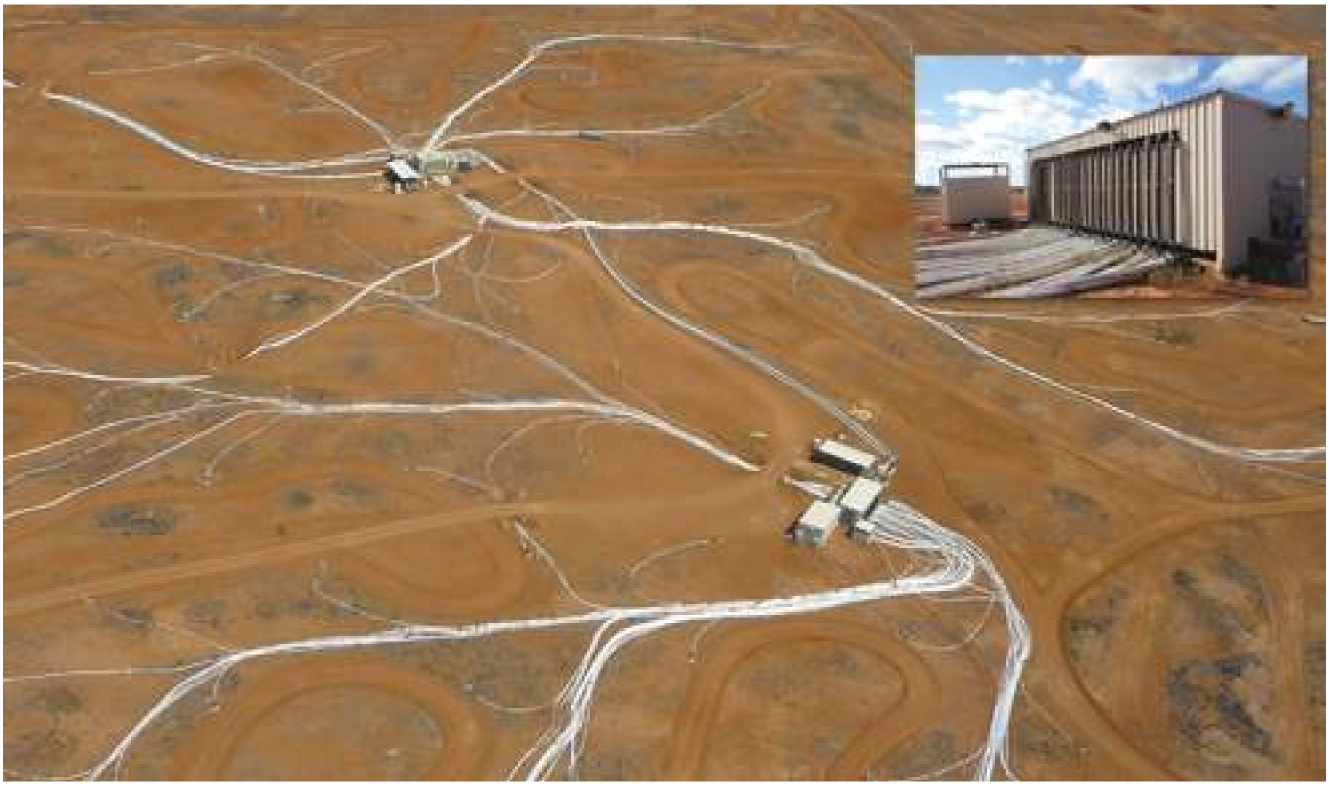

Figure 2.3: The Four Mile ISL wellfield, with inset showing pipework linking into a well-house

Image courtesy of Heathgate Resources

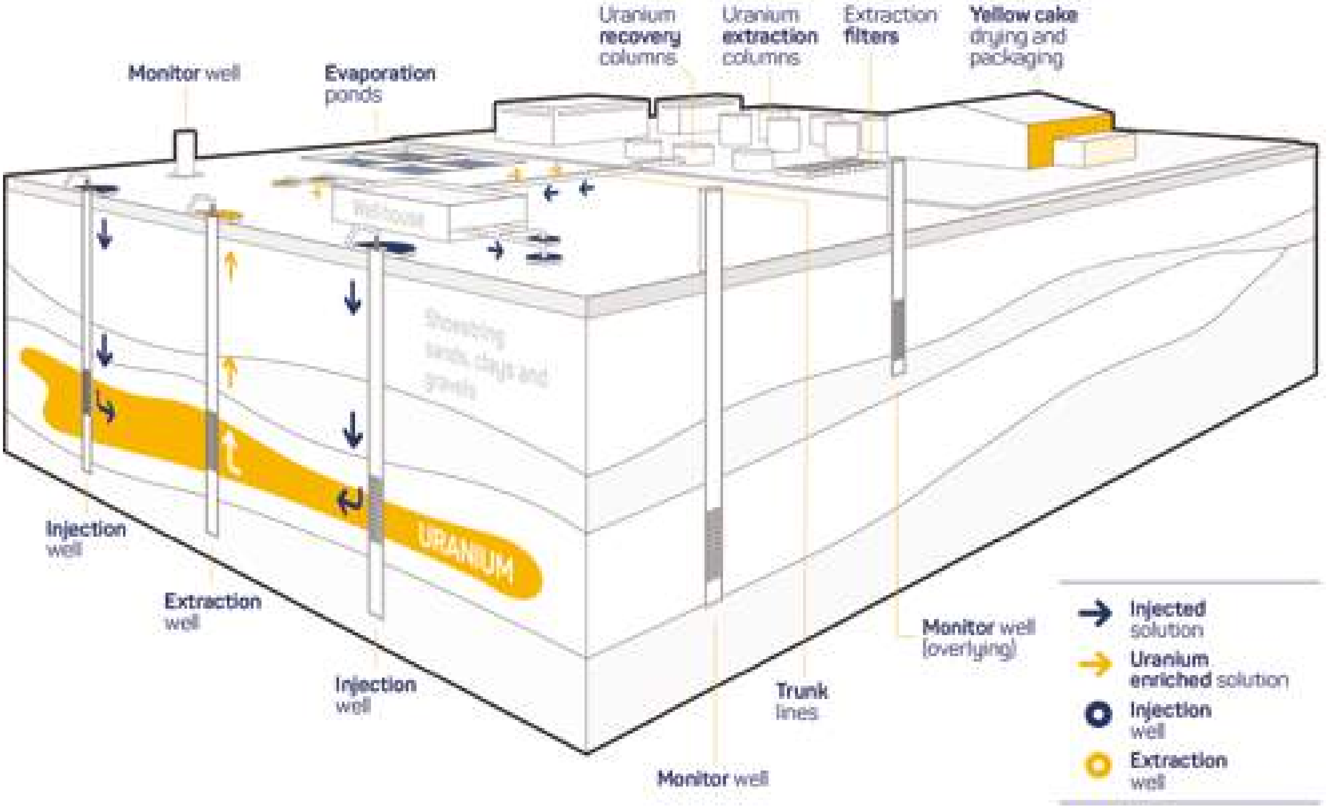

Figure 2.4: A cross-section of an in-situ leach uranium mine

11. In-situ leach (ISL) mining in South Australia is conducted in aquifers, which, because of their natural salinity and radon content, have no human or stock use. As in underground mining, the risks of ISL mining are managed by operators under the supervision of regulatory authorities.

ISL mining recovers uranium from permeable sandstone deposits by continuously recirculating a leaching solution through mineralised ore zones, mobilising the uranium and then recovering and concentrating the uranium at surface facilities.[49]

The type of leaching solution used—whether acidic or alkaline—depends on the composition of the geology and environmental considerations. The South Australian ISL mines—Beverley, Beverley North and Four Mile—use dilute sulphuric acid and hydrogen peroxide to extract the uranium from the host rock.[50]

ISL mines require both extraction and monitoring wells, as well as a system to transport the solution containing uranium to a processing plant. Unlike underground or open-cut mining, the uranium is extracted with minimal ground disturbance. This is indicated in Figure 2.3, which shows the wellfields at Four Mile and the above-ground pipework, which ultimately leads to the associated processing plant. When mining operations conclude, it is possible to remove all above-ground facilities and remediate the site as close as possible to its form before mining.

ISL mining produces a range of potential environmental risks that are specific to this particular form of extraction. These are discussed below. In South Australia, ISL activities are presently undertaken in aquifers that have no human or stock use because of their high natural salinity and radon content (a natural breakdown product of uranium).[51]

POTENTIAL CONTAMINATION OF NON-TARGET AQUIFERS

ISL mining requires the injection and extraction of a leaching solution at pressure into the underlying target aquifer (see Figure 2.4).[52] It is necessary to manage the potential for the migration of leaching solutions to areas outside the designated extraction zone, such as underlying or overlying aquifers. As part of this, the movement of fluids within a target aquifer is modelled to enable the planning of the rates and location of injection and extraction.

The risk of migration is managed through constant monitoring and modelling of underground movements of leaching fluids.[53] This is done through a ring of nearby monitor wells, which are installed beyond the mining zone.[54] Water samples are taken regularly from these wells to allow for the early detection of any unplanned migration of mining fluids.[55]

In leaching the uranium, some solution is removed from the extraction circuit to ensure that the target aquifer does not become over-pressurised, as this could cause the solution to migrate. The removed fluid, known as the 'bleed', is stored as liquid waste awaiting disposal.

SOLID AND LIQUID WASTES

ISL mining produces both solid and liquid wastes. The liquid wastes include the bleed solution and other solutions resulting from the recovery of uranium at the processing plant. They are saline, moderately acidic and contain some unrecovered uranium. These liquid wastes are held in evaporation ponds to reduce their volume before disposal into a designated aquifer, in accordance with the approved RWMP.[56]

The long-term impact of the injection and disposal of fluids into an aquifer is presently understood to be mitigated by the process of natural attenuation, which neutralises contaminants in groundwater over time without the need for further intervention.[57] The process takes place due to chemical interactions between the groundwater and underlying geology.[58]

ISL miners in South Australia plan to remediate post-extraction groundwater at their operations through natural attenuation.[59] Where this occurs, the mechanisms and rate at which the remediation will occur should be supported by laboratory tests and modelling.[60]

Heathgate Resources, the operator of the Beverley and Beverley North mines, is planning to undertake a trial program of remediation by natural attenuation.[61] The trial would require demonstration before the post-extraction stage in line with EPA approvals and, should natural attenuation not be demonstrated to be occurring, the company would be required to undertake alternative measures to remediate the affected aquifers.[62] At the Beverley and Four Mile mines, there is evidence to suggest that natural attenuation will take place over the long term in accordance with the modelling to date.[63]

ISL mines also produce solid low level radioactive wastes, such as used equipment from processing and laboratory activities. However, these wastes are produced in smaller quantities at ISL operations than at underground mines. The wastes are managed in purpose-built repositories that are regulated by the EPA and operated in accordance with ARPANSA requirements.[64]

RISKS FROM RADIOACTIVE MATERIALS

Heathgate Resources has an EPA-approved RMP, which identifies the potential pathways through which workers could be exposed to radiation as radon decay products, radioactive dust, gamma radiation and surface contamination.[65] Radiation protection measures include the use of personal protective equipment and hygiene practices.[66]

Further, operational areas are monitored for the presence of radioactive materials and workers are required to wear thermoluminescent dosimeter badges, which measure their external exposure to gamma radiation.[67] Mine operators calculate annual doses to workers and include this information in an annual report to the EPA.[68] The data is also provided to ARPANSA for inclusion in the ANRDR.[69]

12. The lessons that have emerged from the state-owned uranium mine at Radium Hill, which closed in 1961, and the associated treatment plant at Port Pirie have been incorporated into current regulatory frameworks.

The Radium Hill mine was operated by the South Australian Government from 1954 until November 1961. Uranium ore was extracted and transported by rail to the Rare Earths Treatment Plant at Port Pirie, also operated by the state government. At the treatment plant, the ore concentrate was processed into uranium oxide concentrate through an acid leach and ion exchange process. The treatment plant ceased uranium processing activities in 1962, although the site was subsequently used for other commercial activities. The state government continues to manage the sites of those facilities.

The activities on those sites were not planned, operated, regulated or decommissioned in accordance with current practice, nor would they have been permitted under the current regulatory framework. Typical of the conduct of mining activities in that era, operations were primarily focused on orderly production and without any evident contemplation of environmental impacts.[70] Risks to the health of workers were considered, although radiological risks were not prioritised.[71]

The lack of environmental consideration is demonstrated by numerous characteristics of each site. In the case of Radium Hill, crushed waste rock containing traces of radioactive ore was used to construct roads and other infrastructure.[72] Closure of the site simply involved the removal and sale of plant.[73] The tailings dam, which was not an engineered

Figure 2.5: From left, the Radium Hill tailings dam in 1964; in 1980 before rehabilitation; and in 2015

Images on left courtesy of the Department of State Development

structure but was built using uncompacted tailings, was not capped when the mine closed. As a result the wind dispersed tailings into the surrounding landscape.[74]

In the 1980s the government capped the tailings dam at Radium Hill; however, this was only a short-term solution to the problem of dispersion. Figure 2.5 shows that subsequent erosion is occurring and the tailings are being exposed, although to a lesser extent than before they were capped.[75] In future, it will be necessary to increase the capping thickness and reduce the angle of the dam walls to stem erosion.[76]

At the Port Pirie treatment plant, the tailings dams were built on tidal mud flats, a sensitive marine environment, and are uncapped. Although mitigated by levees, the risk remains for further dispersion of radioactive materials and metallic elements during flooding caused by king tides.[77]

The failure to consider the environment in the planning, operating and decommissioning of these facilities has resulted in ongoing management challenges. Although subsequent assessments of both sites show they do not pose a serious radiological risk to the health of visitors to the sites[78], the state government is required to continue to monitor and manage potential environmental contamination. Environmental reports in relation to both sites identify the need for longer-term management plans, although these are yet to be completed.[79]

These experiences have fed into today's regulatory frameworks for mines, which are directed towards protecting the environment using management and preventative measures.

The current regulatory regime requires:

- the environmental consequences of mining activities to be addressed in the establishment and operation of mines and associated facilities. The licensing process for new mines requires comprehensive environmental impact statements, involving associated investigation and testing to ensure the risks are properly characterised and can be appropriately managed[80]
- the remediation of mine sites as part of their planned closure, to minimise ongoing risks to the environment. To avoid environmental legacy issues and associated costs, the PEPR must be approved by regulators before the mine starts operating and is regularly updated during the life of the mine[81]

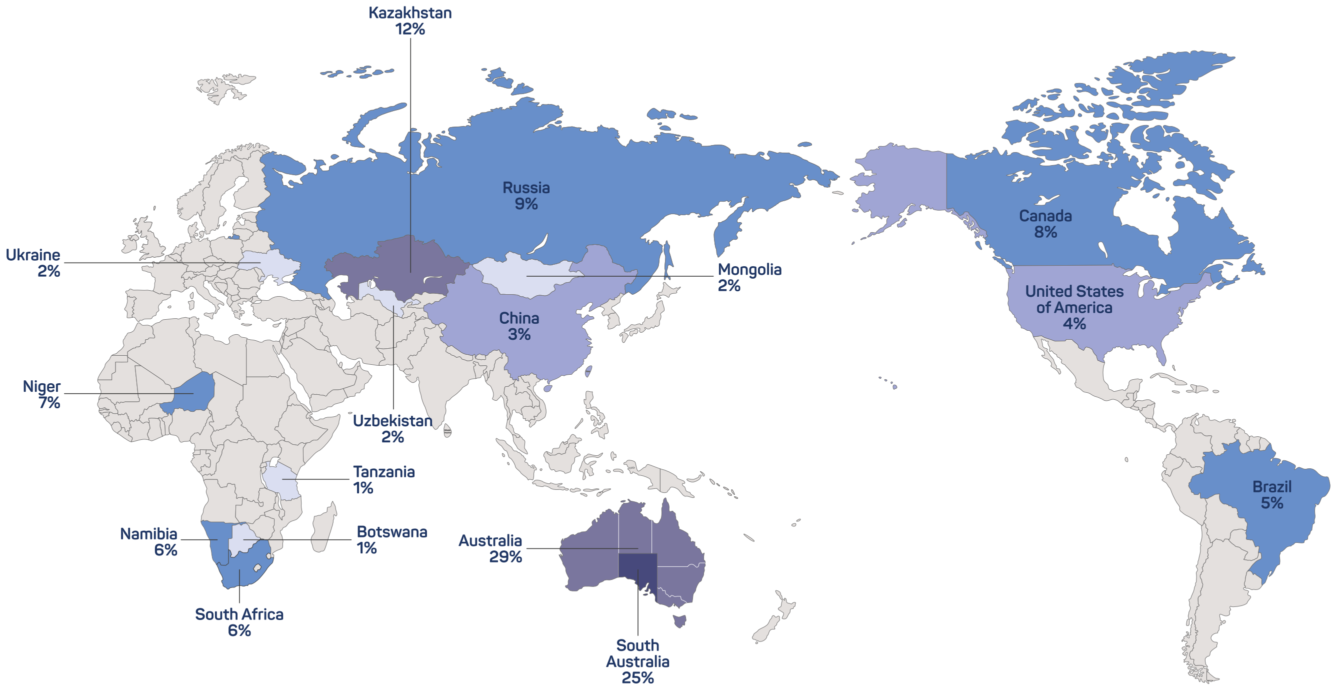

Figure 2.6: Economically viable global uranium resources

Data supplied by the Department of State Development

- the physical separation of mines and mineral processing facilities from sensitive environments.[82] Current planning and environmental regulation requires both DSD and the EPA to assess proposed mining and mineral processing operations. Proposals are also released for public consultation. These processes would not permit current similar developments in environmentally sensitive areas or near large population centres[83]
- an independent regulator to monitor and enforce compliance with regulatory requirements, which are in accordance with internationally accepted standards.[84] As South Australia's independent environmental regulator, the EPA is responsible for protecting people and the environment from harm associated with radioactive substances and setting standards relating to other environmental impacts, such as site contamination and waste. An EPA-approved licence, requiring compliance with national radiation safety measures and enforceable penalties in the event of a breach, is a prerequisite for radioactive mineral extraction and processing.[85]

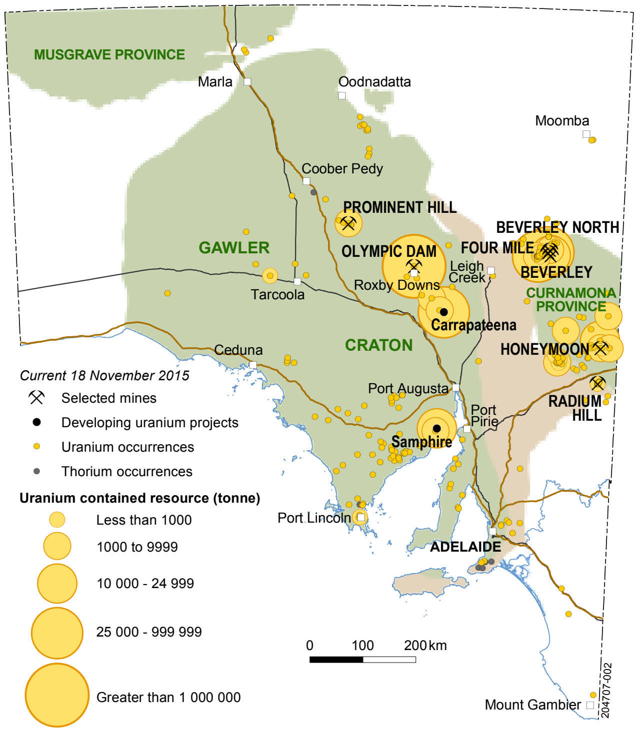

Figure 2.7: Uranium mines and mineral resources in South Australia

Map supplied by the Department of State Development

13. Generally, the risk of post-closure impacts from exploration and mining is addressed by a regulator holding a financial security or bond. The amount of the bond reflects the estimated cost of remediation and is usually adjusted over the mine's operational life.

The South Australian Government seeks financial assurances in the form of bonds or bank guarantees from mining companies and, in some cases, exploration companies to cover the costs of environmental remediation should the company not be able to do so adequately.[86] DSD calculates the value of the assurance based on its assessment of the greatest amount of environmental disturbance that could occur, and, depending on its level of confidence in the assessment, may include a contingency.[87] DSD engages quantity surveyors to assist in accurately estimating the cost of remediating each aspect of the project, and it may review the estimate if operations change significantly.[88]

The bond system was not standard practice when Olympic Dam, the state's largest mining project, was established [89], thereby making it an exception. BHP Billiton has made an internal financial provision to address estimated remediation and closure costs for the mine.[90] Any future expansion of Olympic Dam would come under a new indenture that would take account of the bond requirement; however, this would not be implemented until a decision was made to proceed with the expansion.[91]

ARE THE ACTIVITIES FEASIBLE?

14. Given the detailed knowledge of uranium deposits in South Australia, the similarity of geological characteristics in the north of the state, and what is known about the development of mineral systems, there are good reasons for concluding that new commercial uranium deposits can be found in the state.

South Australia has approximately 25 per cent of the world's known uranium resources, or about 80 per cent of Australia's uranium resources (see Figure 2.6).[92]

There are a range of well understood primary and secondary uranium deposits in South Australia. Figure 2.7 shows the identified deposits and their relative size.

Olympic Dam is the largest known uranium deposit in the world.[93] It is a primary uranium deposit associated with copper, iron oxide, gold, silver and rare earth elements, and is hosted in the 1.5 billion-year-old Hiltaba Suite Granite.[94] Other primary deposits have been located in South Australia, most recently at Carrapateena.[95]

Primary uranium deposits are known to have formed through hydrothermal systems or the movement of magmatic fluids from deep within Earth's crust. These fluids moved under pressure through the underlying geology, transporting uranium and other minerals, and consolidated closer to the surface.[96] Experience from discoveries of deposits in other mineral systems has shown that where one primary mineral deposit is discovered, other deposits of the same mineral composition are likely to exist. The process of formation also can indicate the size of related deposits. A large primary deposit may be associated with numerous smaller deposits. This inference can be shown as a Zipf curve.[97] Figure 2.8 plots on a Zipf curve South Australia's primary uranium deposits. Based on these, there is likely to be a range of undiscovered significant uranium deposits.

The potential for primary uranium deposits suggests there are likely to be many secondary deposits, which are formed within ancient river systems (paleochannels). The uranium-enriched fluids that are derived from the erosion of a primary deposit are transported by groundwater, where they eventually accumulate due to a change in water or rock chemistry. Those deposits are localised and generally contain small quantities of uranium.[98] The uranium in the Frome Embayment at Beverley is a secondary deposit hosted within sandstone as a series of uranium roll-fronts, derived through the weathering of the exposed uranium-enriched rocks of the northern Flinders Ranges.[99]

15. Despite reliable estimates that further commercial deposits of uranium exist in South Australia, there are numerous barriers to the successful exploration for those deposits. These barriers are shared with exploration projects for other minerals.

Exploration for uranium is similar to other minerals and is conducted only when a number of conditions are satisfied. An exploration company will carefully assess these conditions before seeking an exploration licence.

A market for a mineral commodity must exist or be reasonably likely to exist, although opportunities for uranium in particular can be difficult to assess given the prevalence of long-term contracts in that market.[100] Access to investment is also required before exploration activities start.[101] Once an ore body is identified, an exploration company will quantify that deposit, including its mineral characterisation, location and economic potential.[102] Specific aspects, such as recovery costs, are also generally quantified in the business case for exploring for a particular deposit.

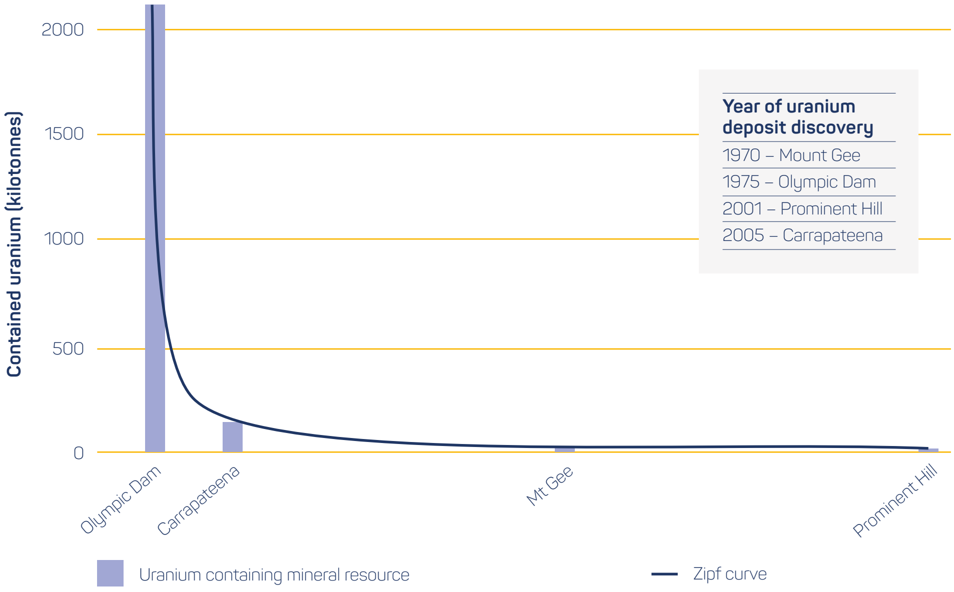

Figure 2.8: Known uranium deposits containing mineral resources and reserves in South Australia

Data supplied by the Department of State Development

Consistent with other minerals, the successful development of a uranium deposit requires access to supporting infrastructure, such as roads, railways, airfields and ports, and services, including electricity, water and gas.[103]

In South Australia, minerals explorers are required by their licence conditions to report their exploration expenditure to DSD. That information shows that uranium exploration expenditure has decreased significantly in the past decade from a high of $118 million (m) in 2007/08 to $2.3m in 2014/15 a 98 per cent reduction — see Figure 2.9. There has been a decrease in expenditure of about 77 per cent since 2012/13.[104]

EXTENT AND THICKNESS OF COVER

In significant parts of South Australia, crystalline rock-bearing minerals underlie a deep layer of sedimentary cover (see Figure 2.10).[105] Depending on the depth of that cover, the geochemistry of uranium and other minerals is obscured and cannot be properly detected through remote-sensing techniques. In some cases, the only way to accurately understand the underlying geology is by drilling, which only provides data for a small area. This poses a technical challenge to identifying the locations of mineral-bearing rock and, if discovered, to economically extracting the ore.[106]

That challenge is recognised by government, industry and academic institutions, with a range of strategies being developed to support an increase in exploration. A prominent national strategy is UNCOVER, which seeks to promote more collaboration and information sharing to address a common set of key issues associated with extensive cover.[107] UNCOVER has led to the development of further policies, including the National Mineral Exploration Strategy, by the state and federal governments and the Industry Roadmap by the exploration industry.[108] Although these policies indicate there is broad agreement as to what could be done to overcome this barrier to exploration, and initiatives such as South Australia's Plan for Accelerating Exploration (PACE) are consistent with the identified priorities[109], the full benefits of the implementation of UNCOVER are yet to be realised.[110]

COST OF DRILLING ACTIVITIES

Exploration drilling programs are expensive: about $500 /metre using diamond drilling methods.[111] If the target mineralisation were hosted in crystalline basement geology (see Figure 2.10) overlain by barren sedimentary rock, the cost to drill down to the uranium-bearing minerals would be significant.[112]

The Adelaide-based Deep Exploration Technologies Cooperative Research Centre (DET CRC) is conducting research into lowering the cost of exploration drilling and acquiring data.[113] This has led to the development of the Coiled Tubing Drilling Rig for mineral exploration, complemented by the Lab-At-Rig® continuous geochemical

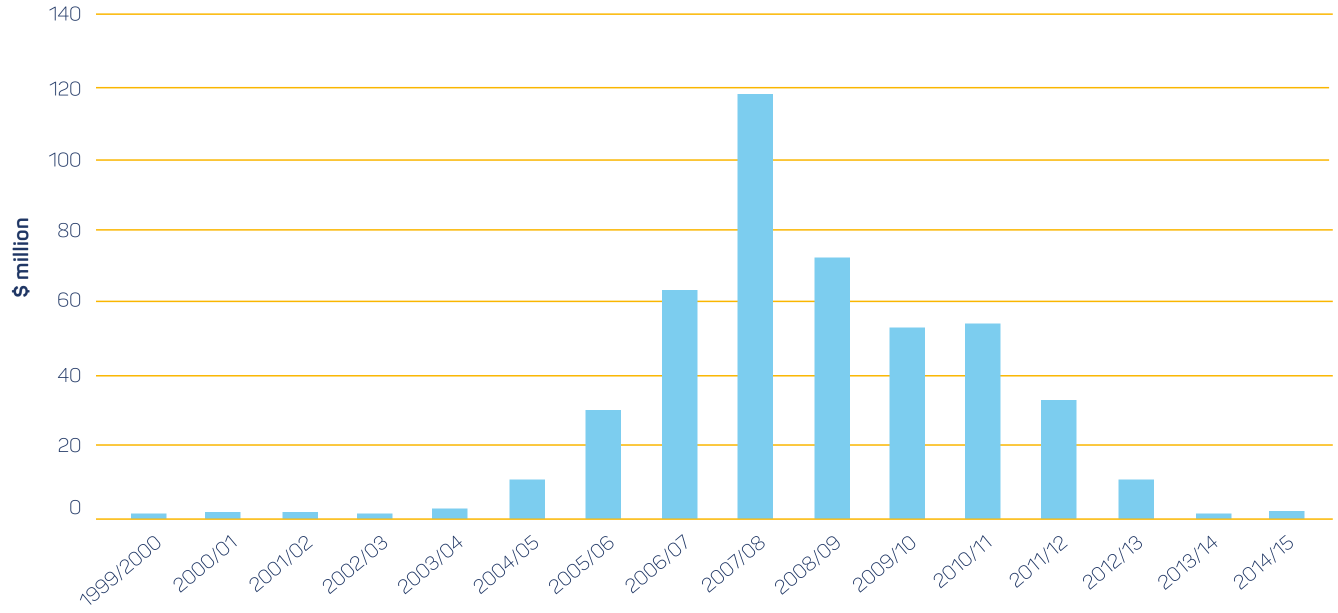

Figure 2.9: South Australian uranium exploration, 1999/2000 to 2014/15

Data supplied by the Department of State Development

testing attachment.[114] These innovations are designed to facilitate better characterisation of the geophysics and geochemistry of the geology being drilled, assisting geologists to tailor drilling strategies for greater efficiency.

LOW PROBABILITY OF SUCCESS IN DRILLING AT GREENFIELD LOCATIONS

Exploration companies target regions of known mineral potential (brownfield exploration) to increase the likelihood of discovering an economic mineral deposit (see Figure 2.11).[115]

There is greater risk associated with exploration in greenfield locations, which have not been surveyed before.[116] When combined with the high cost of exploration, this lower probability of success makes greenfield exploration less attractive. To offset risk, greenfield exploration requires technical skill and knowledge of the target mineralisation. This involves interpretation of high-resolution geoscientific data and experience in locating mineral deposits.

In addition to the expense associated with drilling, these issues have led to a paucity of drilling data across large areas of South Australia.[117] An example is the Pandurra Formation (extending from Whyalla towards Coober Pedy in central South Australia), which is considered prospective for uranium. It is estimated that only 27 holes penetrating the basement geology have been drilled within a 40 000 square kilometre area.[118]

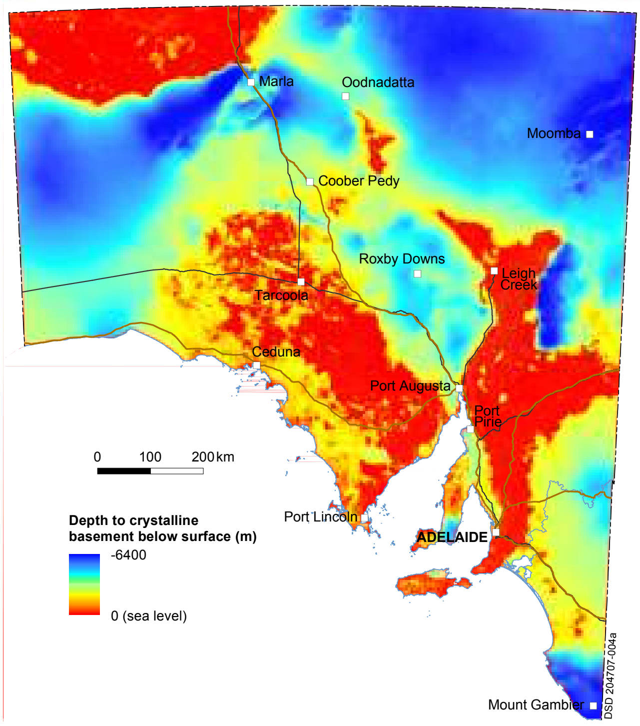

Figure 2.10: Depth to crystalline basement in South Australia

Map supplied by the Department of State Development

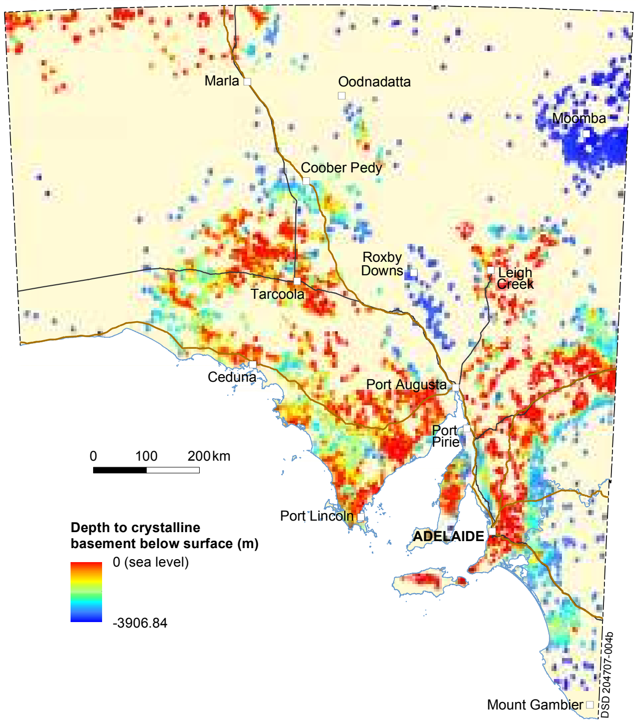

Figure 2.11: Drill core locations and measured depth to crystalline basement in South Australia

Map supplied by the Department of State Development

Figure 2.11 shows the drilling locations in South Australia and demonstrates that large parts of the state are under-explored, with no drilling or only shallow drilling.

LACK OF WIDESPREAD APPLICATION OF NEW SENSING TECHNOLOGY

Geophysical surveying of South Australia has been conducted on a wide scale by the South Australian Government and other research organisations, including the collection of magnetic, radiometric and gravity data.[119] This data provides a general characterisation of the state's surface geology (to a depth of about 30 cm) and, to a lesser extent, the underlying geological structures.[120] Exploration companies and research organisations conduct geophysical surveys on a finer scale directly on the Earth's surface using methods such as 'magnetotellurics', a technique that measures electrical and magnetic fields to understand geophysical structures.[121]

The larger the range of the geophysical survey, the larger the resolution, so a detailed survey is required to identify subtle geological features. Geophysical surveying on a detailed scale is not used often, as it is costly to commission.[122] This has led to gaps in the high-resolution geoscientific data sets available for some parts of the state.

THE NEED TO ENHANCE THE STATE'S HIGH-RESOLUTION GEOSCIENTIFIC DATASET

Extensive geoscientific data has been collected throughout the state, which can assist in identifying areas with mineral potential. The data is consolidated in the South Australian Resource Information Geoserver, a public electronic database administered by the state government, which comprises data contributed by past exploration companies, research organisations and its own surveys. Despite there being gaps in the overall coverage of the state, this comprehensive dataset is high quality and is internationally well-regarded.

However, there is potential to further enhance the utility of this dataset to explorers. In practice, each geophysical technique is employed independently and provides information about a specific geophysical aspect, whereas the characteristics of many aspects are relevant to a commercial decision to investigate an area's mineral potential.[123]

To that end, combining the different aspects of the dataset into a single comprehensive framework would further enhance the system and its potential to deliver benefits.[124] Although this would present challenges[125], ongoing technological developments associated with the collection of geophysical data, including cheaper instrumentation and higher data storage and processing capacity[126], make integration more feasible. Given that the South Australian Government already maintains a substantial central repository for geoscientific data obtained by other entities, it is logical that it would take a leading role in both integrating the data and making it accessible to the public.[127]

16. The South Australian Government's Plan for Accelerating Exploration (PACE) has led to increased investment in mining exploration. Counter-cyclical investment will leave South Australia better placed to take advantage of subsequent recoveries in the markets for minerals commodities.

PACE was devised to support increased exploration investment in greenfield drilling activities. Through the program, the state government offers a financial contribution to an explorer to assist in meeting the costs of drilling activities. In return, the explorer provides the geological samples collected during drilling to the government for consolidation in the Drill Core Reference Library, which promotes greater understanding of areas where little exploration has occurred in the past.[128]

This co-investment strategy has underpinned an additional $700m in private mineral exploration investment over 10 years and has increased South Australian mining revenue by $2400m.[129] It also contributed to the significant discoveries of the Carrapateena, Four Mile and Prominent Hill deposits.[130] Although optimistic economic circumstances and encouragement from other discoveries also impact significantly on increased exploration expenditure in South Australia, it is evident that PACE made a strong contribution in supporting that growth.[131] In November 2015, the South Australian Government invested a further $20m in a new two-year cycle of PACE, known as PACE Copper, which provides financial support for greenfield drilling activities.[132]

These outcomes show that the mineral exploration industry is better placed to take advantage of upward trends in the markets for their targeted commodities when they invest in projects during less favourable economic conditions. It is ideal for government to support that investment on a 'counter-cyclical' basis, that is, at a time when overall exploration expenditure is low.[133] Such a strategy could alleviate some of the challenges associated with developing viable mining operations that are discussed in this chapter, namely the significant length of time required to establish a mine. Therefore, it is necessary to consider the means by which support for greenfield drilling projects can be sustained over the longer term.

IN WHAT CIRCUMSTANCES ARE THE ACTIVITIES VIABLE?

17. Consistent with mineral exploration, there are significant barriers to the viability of new uranium mine developments in South Australia.

The average price of South Australian uranium (U_3O_8) during the past decade has been about $70 a kilogram (kg) (see Figure 2.12), although it recently increased.[134] The current price of about $80 per kg is considered too low by some companies to develop or operate a mine.[135]

Exploration for any new mineral deposit is high-risk and success is limited.[136] Globally, there have been fewer than 10 newly identified greenfield resources for uranium in the past decade.[137] There is also considerable risk in converting a deposit into a mine.[138] As well as investment hurdles, there can be technical difficulties with the mineralogy and dispersion of the ore in the deposit.[139] Deposits are often deep, requiring underground infrastructure to be built to access the deposit, increasing the time to extraction.[140] It can take up to 20 years from discovery to extraction for large-scale mines.[141]

Navigating state and federal government processes to obtain new uranium mine approvals in South Australia and other Australian jurisdictions can take a long time.[142] For example, it has taken Toro Energy more than 10 years to be in a position to develop the uranium deposit at Wiluna in Western Australia.[143] Proposals require long-term, detailed scientific and engineering investigation and analysis in the form of an environmental impact statement, which can take considerable time and expense to collate.[144] In some instances, the commodity market for uranium has decreased to the extent that a mine considered financially viable at the outset of the process is no longer viable by the time it is approved.[145]

Approvals for new mines are usually handled exclusively by the relevant state or territory government. However, because federal legislation (the *Environment Protection and Biodiversity Conservation Act 1999*) refers to uranium mining as a 'nuclear action'[146], there is a requirement for Australian Government approval before a licence is granted. Whether any added environmental benefit flows from this duplication in process has been questioned by numerous organisations.[147]

Federal and state governments have sought to address these issues through administrative arrangements that establish agreed criteria sufficient to meet the requirements of both levels of government. An 'assessments bilateral' has been agreed that specifies the requirements for assessing the environmental impacts of new mines, such

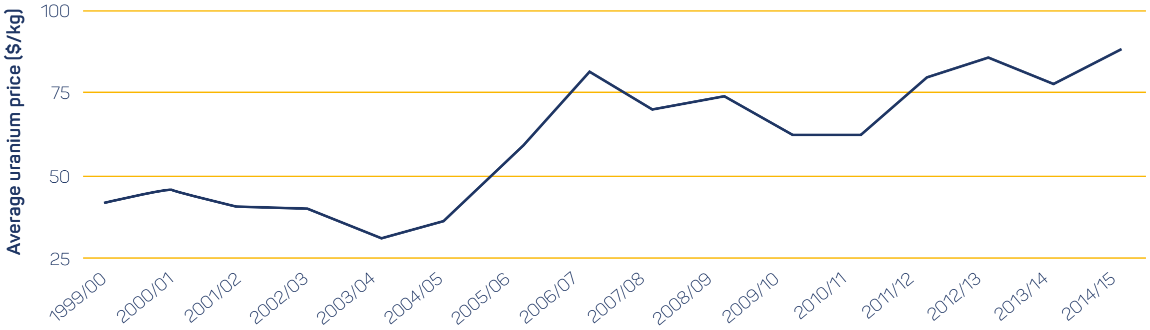

Figure 2.12: Average prices of South Australian uranium, 1999/2000 to 2014/2015

that proponents need to meet one set of criteria rather than two.[148] A bilateral arrangement relating to approvals, through which an approval by the state could be used as the basis for an Australian Government approval, is being negotiated between the federal and South Australian governments.[149]

Even if the administration of the processes could be coordinated, they remain separate, have different timeframes and may still require different information—despite their common purpose. These parallel processes can result in differing conditions being imposed on the same activity, or duplicated conditions, which effectively require the same studies to be undertaken twice to demonstrate compliance. This has increased the anticipated costs of, and timeframes required for, regulatory approval for new uranium mines.[150]

18. Increases in the uranium price will not occur until existing global inventories are used. Recent commercial decisions in Australia by those currently operating or developing uranium mines do not offer any clear indication of the position in the longer term.

The international uranium market is currently oversupplied with uranium.[151] This has changed the way in which suppliers and customers have traditionally transacted, as customers move to purchase uranium on the spot market rather than entering into long-term contracts.[152] It is unlikely that demand will increase, with a corresponding price rise, until at least 2018.[153] The potential for a future increase is contingent on several factors, including the extent to which Japan restarts its nuclear reactors following the Fukushima Daiichi nuclear accident and China's decisions as to its sources of uranium.[154]

Uranium is produced either alone or, as is the case at Olympic Dam, as a by-product during the recovery of other minerals.[155] The uranium price has minimal impact on the production of uranium at Olympic Dam, as the mine's principal source of revenue is copper, to which uranium production is tied.[156] BHP Billiton's decision in 2012 to postpone a planned expansion of Olympic Dam and investigate less capital-intensive designs was principally related to activity in the global copper market, not uranium.[157]

Mines using the ISL technique have been established at four locations in South Australia: Beverley, Beverley North, Four Mile and Honeymoon. Although these mines produce uranium exclusively, Four Mile is the only operation that is currently extracting uranium.[158] The Beverley wellfields are currently under care and maintenance. At Beverley North, the Pepegoona satellite plant is offline pending infrastructure modifications aimed at increasing future production.[159] Uranium recovered at Four Mile is pumped to the Pannikin satellite plant at Beverley North, before being transported to the Beverley plant for further processing.[160] Operations at the Honeymoon ISL mine were suspended in 2013 due to high production costs and ongoing difficulties in achieving design capacity.[161]

Outside South Australia, the Ranger mine in the Northern Territory has been operational since 1981, but in recent years has decreased its production of uranium, as it has shifted from direct ore extraction to processing stockpiled ore.[162] Production in 2014 was 1165 tonnes (t) uranium oxide concentrate (UOC) due to an incident at the mine in December 2013.[163] In 2015 it rose to 2005 t.[164] Plans to develop an underground mine on the Ranger Project Area have been suspended, with the owner citing the current operating environment and the end, in 2021, of its mining authority as reasons.[165] If a final investment decision is made to develop the Wiluna deposit in Western Australia, the mine is predicted to produce 695 t of uranium a year.[166] Mines at the Kintyre and Yeelirrie deposits, also in Western Australia, are planned, although final investment decisions are yet to be taken.[167]

19. In recent years, the annual output of South Australian uranium mines has been between 4000 and 5000 tonnes UOC. Increasing output beyond those levels would require the reinstatement of production at some mines, and to be substantially increased, would require investment in the development of new production capacity.

South Australian uranium production in 2014/15 was valued at about $346.5m (see Figure 2.13). Average production of UOC during the past decade was 4438 t per year, with an average annual value of about $321m.[168] Since 2012/13, production volumes have decreased by 17 per cent, with a corresponding decrease in royalties payable to the state government from $17.8m to $15.9m in 2014/15.[169]

In 2014/15, Olympic Dam produced 3144 t UOC and Four Mile produced 922 t.[170] Increasing the state's uranium output beyond current levels would require bringing the mines presently under care and maintenance back into production.

However, significant increases in production levels could only be achieved through substantial investment in new capacity. A new ISL mine could be established more quickly than an underground or open-cut mine, although as production levels from South Australian ISL mines indicate, its impact on overall production would not be as substantial.[171]

BHP Billiton is currently investigating the benefits of incorporating another uranium ore processing method, heap leaching, into its processing flow at Olympic Dam.

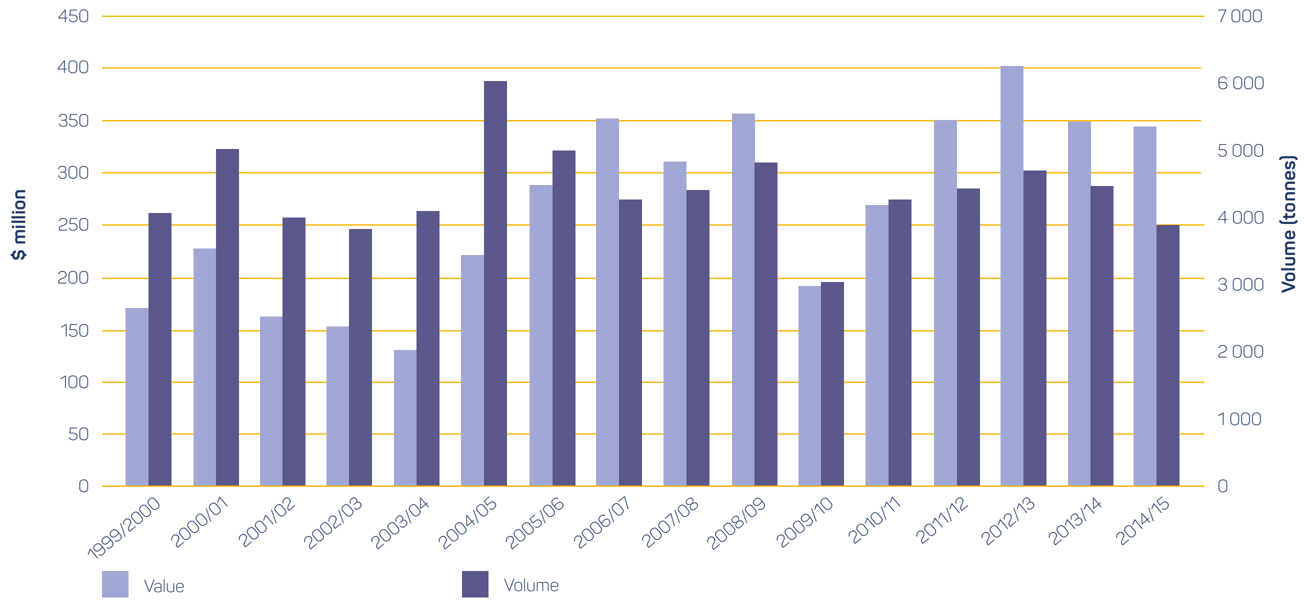

Figure 2.13: South Australian uranium production, 1999/2000 to 2014/15

Data supplied by the Department of State Development

This method involves treating the mined ore with an acid solution over about a year so that uranium and some copper may be extracted more efficiently during later stages of the process.[172] While uranium ore could be processed more efficiently if these trials prove successful, it is unclear whether this would have any impact on a decision to increase output.

20. Uranium production has produced benefits to the South Australian economy, and will continue to do so.

21. An expansion of uranium production would add value to the economy, but expectations should be tempered. Even were production to increase to meet very optimistic demand forecasts prompted by strong climate action policies, the value of production over the long term and associated royalties are relatively small in terms of the state's total revenues.

South Australian uranium production has, considering its aggregate value over the past 15 years, made a substantial economic contribution: see Figure 2.13. In 2014/15, South Australia's uranium exports met about 4.5 per cent of global demand.[173] This is the lowest level since 2010/11.[174]

It is difficult to predict long-term uranium demand given its dependence on a variety of factors, including the structure of global policy measures to reduce greenhouse gas emissions and the extent to which nuclear energy plays a part in those measures. However, should there be a significant increase in global demand for nuclear energy, the contribution that uranium production could potentially make to future prosperity in South Australia can be placed in some context.

The International Energy Agency (IEA), in anticipation of the 2015 United Nations Climate Change Conference in Paris, released forecasts on future electricity demand and the potential growth of low-carbon energy sources if action is taken to address greenhouse gas emissions and to limit global average temperature to 'well below 2 °C' above pre-industrial levels. The scenario developed by the IEA assumes that nuclear capacity will be expanded substantially by 2030, resulting in additional capacity of 274 gigawatt electrical (GWe).[175] It also estimated that installed capacity could be between 520 GWe and 837 GWe in 2040.[176]

If this scenario were to be realised, global demand for UOC would be expected to be about 130 kilotonnes (kt) in 2030 and about 170 kt in 2040.[177] If South Australia were to maintain its current share of the global uranium market, and assuming that production capacity could be expanded, its UOC production would increase to about 6100 t of uranium by 2030 and about 7700 t by 2040.[178]

If that expansion were to occur, and the UOC price were to increase and stabilise at about $128 per kg in 2030 and beyond, the total revenue from South Australia uranium sales would be about $770m in 2030 and about $980m in 2040.[179] At current rates, the South Australian Government would receive royalties of $40m in 2030 and $50m in 2040.[180] To place these values in context, the total mineral and petroleum royalty received in 2014 was $237.5m.[181]

Therefore, the increased royalties that would flow from greater uranium production, even at very optimistic levels, would not have a significant impact on South Australia's economy.

Other views have been expressed about the economic potential that increased uranium production might offer to the Australian economy, including what would occur if Australian producers were to capture a greater share of an expanding world market for uranium.[182] The economic benefits described would be significant if they were realised. However, it is important to place those projections in context. To realise the potential benefits would require both substantial investment to expand production capacity well beyond present levels by 2040, as well as substantial increases in installed nuclear capacity internationally.

The situation would be different if South Australia were to take further steps in processing uranium into fuel for nuclear reactors. The value that can be derived from those activities is higher than that associated with uranium exports. The potential viability of facilities undertaking those activities is addressed in Chapter 3: Further processing and manufacture.

22. Energy generation technologies that use thorium as a fuel component are not commercial and are not expected to be in the foreseeable future. Further, with the low price of uranium and its broad acceptance as the fuel source for the most dominant type of nuclear reactor, there is no commercial incentive to develop thorium as a fuel. Although South Australia possesses numerous thorium deposits, it does not have a competitive advantage in that resource as it does with uranium.

Thorium is common in the earth's crust (about three to five times more abundant than uranium) and is principally associated with monazite, a by-product of heavy mineral sands mining.[183] There is a mineral sands mine near Ceduna in South Australia. However, operations at that mine were suspended in February 2016 due to market conditions.[184]

The identified global thorium resource is estimated at about 6212 kt[185], of which Australia's total proven thorium reserve is approximately 595 kt.[186] Thorium is not currently mined in Australia.[187]

The long-term outlook for the thorium market will be tied to developing a technology that can consume thorium as a fuel in nuclear reactors.[188] No commercial nuclear fuels based on, or containing, thorium are currently available[189], although some prototype reactors exist, and organisations in Canada, China, India and Norway are undertaking research.[190] Despite research efforts aimed at developing thorium into a viable nuclear fuel, it is unlikely to be used in commercial nuclear activities in the foreseeable future.[191]

Even if thorium-bearing fuels were developed for commercial use, the quantity of thorium required in a fuel source would be much less than the quantity of uranium required to produce the same amount of energy.[192] This being so, there is unlikely to be significant increased demand for thorium and no appreciable increase in investment in extraction operations.

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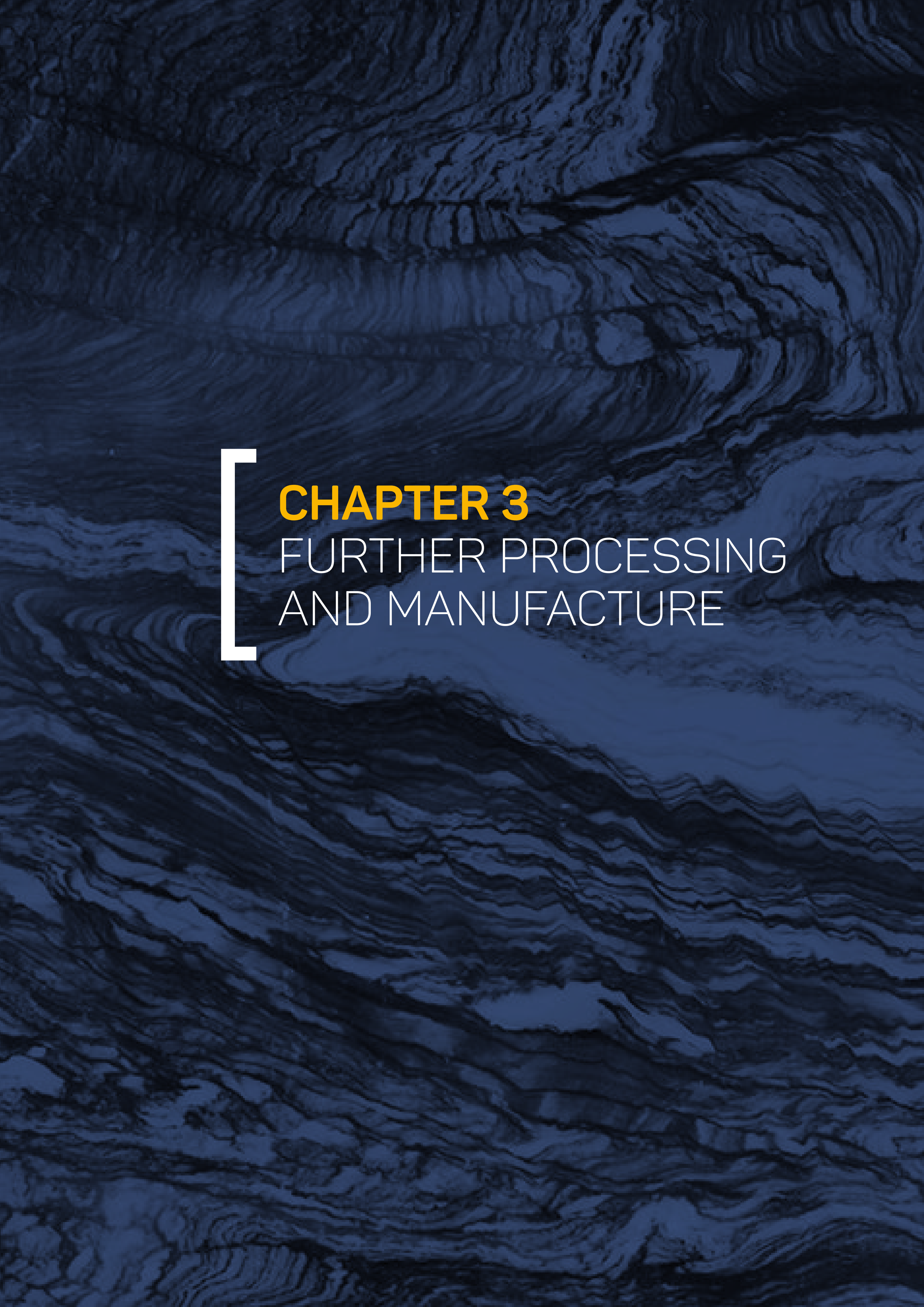

CHAPTER 3

FURTHER PROCESSING AND MANUFACTURE

CHAPTER 3: FURTHER PROCESSING AND MANUFACTURE

The activity under consideration is the further processing of minerals, and the processing and manufacturing of materials containing radioactive and nuclear substances (but not for, or from, military uses) including conversion, enrichment, fabrication or reprocessing in South Australia.

CONVERSION, ENRICHMENT AND FUEL FABRICATION

WHAT ARE THE RISKS?

23. For conversion, enrichment and fuel fabrication facilities, the most significant environmental and safety risks are posed by toxic, corrosive and potentially explosive chemicals, rather than the radioactivity of the materials.

Facilities undertaking conversion, enrichment and fuel fabrication activities use both chemical and physical processes to transform natural uranium into reactor fuel.

In conversion, enrichment and fuel fabrication facilities, the predominant risk to workers' health arises from handling uranium hexafluoride (UF_6)[1], a compound of uranium and fluorine. It is a toxic, volatile solid at ambient temperature, but is easily converted into a gas for enrichment. If it comes into contact with water or water vapour during any step of the process, UF_6 forms hydrofluoric acid (HF), a corrosive gas or aqueous liquid that is toxic by inhalation and skin contact.[2] It also forms uranyl fluoride (UO_2F_2), which is chemically toxic if inhaled or ingested.[3] The toxic effect of UF_6 exposure depends on its concentration, moisture level and the duration of contact. The chemical hazards of UF_6 are of greater concern than the radiation hazard due to the low radiotoxicity of uranium.[4]

Other chemical risks are posed by hydrogen (H_2), a potentially explosive gas, and fluorine (F_2), a reactive, corrosive gas that is toxic by inhalation or skin contact.[5] These risks are well understood and effectively managed and regulated in Australian industry.[6] Chemical safety control systems comprise: infrastructure that prevents releases, measures that mitigate consequences in the event that releases occur, and personal protective equipment for workers.[7]

The environmental risks associated with these processes stem mainly from the chemical nature of the compounds involved, not their radioactivity—the compounds have flammable, toxic, corrosive or reactive properties that can cause harm if not properly managed.[8] Many of these compounds are already used safely and managed responsibly in Australian chemical manufacturing processes and are subject to assessment under the National Industrial Chemicals Notification and Assessment Scheme (NICNAS).[9]

Greater environmental risks stem from the possible build-up, movement and chemical nature of uranium as a heavy metal, than from the release of lighter molecules, such as H_2, which are less likely to accumulate in soil or aquifers (although these still need to be assessed).[10] If released into the environment, UF_6 reacts with water vapour, resulting in insoluble uranium compounds that ultimately settle in soil and underwater sediments.[11] While uranium is not particularly mobile, it can become soluble in oxidising conditions over long periods.[12] The chemical nature of the potentially released compounds poses a higher risk than the radiological hazard, which is low.[13]

Facilities for these further processing activities have measures in place that mitigate the consequences of the potential accidental release of hazardous substances. These include:

- routine sampling and monitoring, both inside and outside site boundaries[14]
- highly engineered storage systems for UF_6 and other hazardous materials, such as specialised, leak proof steel containers[15]
- tail gas venturi scrubbers[16]
- training and supervision[17]
- emergency response planning and coordination with local authorities.[18]

Conversion, enrichment and fuel fabrication activities produce wastes that require management to ensure the safety of workers and to protect the environment. Conversion and enrichment processes create hazardous liquid wastes.[19] Fuel fabrication produces various industrial and combustible wastes, including dewatered waste sludge and uranium materials.[20] Conversion of uranium oxide (U_3O_8) into UF_6 results in a number of impurities, including vanadium, sodium, iron and molybdenum, becoming concentrated and separated.[21] Some of these elements can be captured and may have monetary value, particularly molybdenum[22]; others are benign and can be disposed of as landfill. Each of the waste streams is managed according to strict protocols within facility licences. Techniques exist to minimise the hazardous materials in the waste produced during further processing activities, such as filtering or scrubbing gaseous discharges, and recovering and reusing the chemicals in liquid discharges.[23]

The proliferation risks of those technologies, particularly those associated with enrichment, are addressed in Chapter 7: Radiation risks.

FURTHER PROCESSING OF URANIUM

Uranium oxide (U_3O_8) cannot be used as a fuel to generate electricity without further processing. The processes that transform U_3O_8 into fuel are conversion, enrichment and fuel fabrication.

Uranium **conversion** involves the chemical change of mined and milled U_3O_8 into a gas: uranium hexafluoride (UF_6). **Enrichment** follows conversion to increase the concentration of the uranium-235 (^{235}U) isotope from its natural level of 0.7 per cent to between 3 and 5 per cent. It is necessary to enrich uranium before it can be used in most types of nuclear reactor.

The final step in preparing uranium for use in a reactor is **fuel fabrication**. This process transforms uranium back into an oxide form (UO_2) and then into dense ceramic pellets, which are sealed into zirconium metal tubes. These are then arranged into fuel assemblies that can be loaded into a reactor core.

A more detailed explanation of these processes is contained in Appendix C: Further processing methods.

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24. The risk of significant releases of radioactive materials into the environment during normal operation at conversion, enrichment and fuel fabrication facilities is low because of the nature of those materials.

Conversion, enrichment and fuel fabrication processes produce radioactive wastes, which pose a low radiological risk because of the nature of those wastes.[24] The main wastes are listed below:

- Depleted uranium—the process of enriching uranium produces a large amount of depleted uranium (DU) hexafluoride.[25] Commonly referred to as 'tails'[26], DU is a by-product of the manufacturing process and requires secure storage.[27] Under some market conditions, the tails can be re-enriched, but the volumes of DU are large and enrichers have long-term programs to 'de-convert' DU tails to a stable oxide form, recycling the resultant fluorine.[28]
- Decay daughters of uranium—very small amounts of naturally occurring radioactive elements may accumulate in the chemical process circuits of uranium conversion (and de-conversion) facilities. These are the natural decay daughters of uranium.[29] The total amount of these wastes is negligible and generally below regulatory exemption limits.[30] If the wastes exceed these limits, they are retained as low-level waste (LLW) and disposed of accordingly.
- Contaminated liquid surfactants—further processing facilities use liquids to wash materials that can become contaminated with low levels of uranium compounds. These liquids can generally be concentrated and the uranium recycled into the process circuit. During this process, protective clothing and equipment can become contaminated and are also retained as LLW.
- Contaminated filters—further processing facilities have active filtering and scrubbing systems for their gaseous and liquid discharges. These systems produce contaminated filters, which are retained as LLW.[31]

The potential rupture of a containment vessel during the handling, transport, storage and waste disposal phases of processing can lead to contamination of the facility and effects on workers and the environment.[32] The extent of these risks depends on the radioactive substances, types and extent of radiation emitted, and their physical and chemical forms.[33] Radioactive releases after a serious accident at a facility are also possible. However, the radiological consequences would be limited due to the low radiotoxicity of the uranium compounds involved.[34]

The high temperature treatment (calcining) of uranium oxides and grinding operations on uranium fuel ceramics during fuel fabrication pose dust hazards.[35] If inhaled or ingested, low-level airborne radioactive materials present health risks to workers.[36] These risks are managed by the use of personal protective equipment, ventilation and air filtration systems, alarm systems and safe operating practices[37], as well as continuous monitoring of radiation doses at each facility to ensure exposure is as low as reasonably achievable.[38] Regulatory bodies also have a role in ensuring that safety measures are effective.[39]

Uranium enrichment and light water reactor fuel fabrication plants handle uranium that is isotopically enriched in uranium-235 (^{235}U). The risk of a 'criticality incident' (an uncontrolled fission chain reaction occurring for a short period releasing radioactivity, including neutrons, which are particularly harmful to health[40]) in such a facility is very low due to an industry-wide ^{235}U enrichment limit of 5 per cent. Below such a limit criticality is practically impossible outside a reactor environment.[41] A contained and controlled criticality is safely maintained in a nuclear reactor during an operational cycle.

In addition to the regimes that manage risks associated with chemicals discussed earlier, there are established administrative, engineered and regulatory controls that effectively manage the radiological risks of further processing activities, including the waste streams. Radiation dose limits and requirements for radiation protection are set in accordance with Australian and international standards as developed by the International Atomic Energy Agency (IAEA).[42]

If conversion, enrichment or fuel fabrication facilities were developed in South Australia, limits would apply to fix maximum safe levels of radiation exposure. In addition, the design and operation of manufacturing facilities for the purposes of radiation protection would need to be licensed by the South Australian Environment Protection Authority (EPA) under the *Radiation Protection and Control Act 1982* (SA).[43]

ARE THE ACTIVITIES FEASIBLE?

25. There is no technical impediment to providing conversion, enrichment or fuel fabrication services in Australia.

Conversion, enrichment and fuel fabrication are services provided on a commercial basis in an international market.[44]

While the technology required to develop and operate conversion, enrichment and fuel fabrication facilities is sophisticated, particularly in the case of the last two, its transfer to South Australia would be technically feasible.[45] Arrangements would need to be made to acquire such technology from experienced overseas operators or vendors. The security and non-proliferation obligations that would need to be addressed for enrichment technology also would need to be considered.[46] Accessing the skilled workforce required to construct and operate such facilities would be feasible, given Australia's existing trade base and competencies in advanced manufacturing industries.[47]

The development of facilities in Australia to provide these services is prohibited by legislation. The *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) prohibits the federal Minister for the Environment from approving the construction or operation of nuclear processing facilities, except for conversion facilities.[48] Those provisions were introduced as part the anti-nuclear platforms of parties that held the balance of power in the Senate at the time.[49]

In South Australia, both conversion and enrichment activities are prohibited by the Radiation Protection and Control Act. This prohibition may be removed by proclamation by the Governor, only if satisfied that arrangements are in place to control such operations.[50] For these activities to be feasible the EPBC Act would need to be amended and, in South Australia, an appropriate proclamation made.

In addition to the repeal of any prohibition, a regulatory structure would need to be developed to provide for the licensing and ongoing regulation of such facilities. This would provide prospective operators with certainty about the regulatory environment in which they would be operating.

IN WHAT CIRCUMSTANCES ARE THE ACTIVITIES VIABLE?

26. At present, the market for uranium conversion, enrichment and fuel fabrication services is oversupplied. The extent of the oversupply suggests current suppliers will be able to meet demand in the short to medium term.

The demand for conversion, enrichment and fuel fabrication services is directly related to the number of operating nuclear power plants. Demand for those services will at any point reflect the needs of power plants several years in the future.[51]

The reduction in the number of operational nuclear power plants, primarily as a result of shutdowns in Japan, has reduced demand for these services, significantly affected price and resulted in overcapacity.[52]

The precise amount of capacity oversupply is in contention.[53] While there is underutilised capacity in existing facilities, its extent is affected by secondary sources of supply[54], such as the transfer to civil use of excess military stockpiles or enriched uranium and the re-enrichment of depleted uranium.

The long-term prospect for further demand of processing activities is uncertain. Not only is it challenging to estimate the extent to which low carbon energy demand will be met by nuclear generation, but also the demand for conversion, enrichment and fuel fabrication services will depend on national policies on domestic self-sufficiency. For example, the conversion, enrichment and fuel fabrication needs of new Chinese reactors aim to be met domestically.[55]

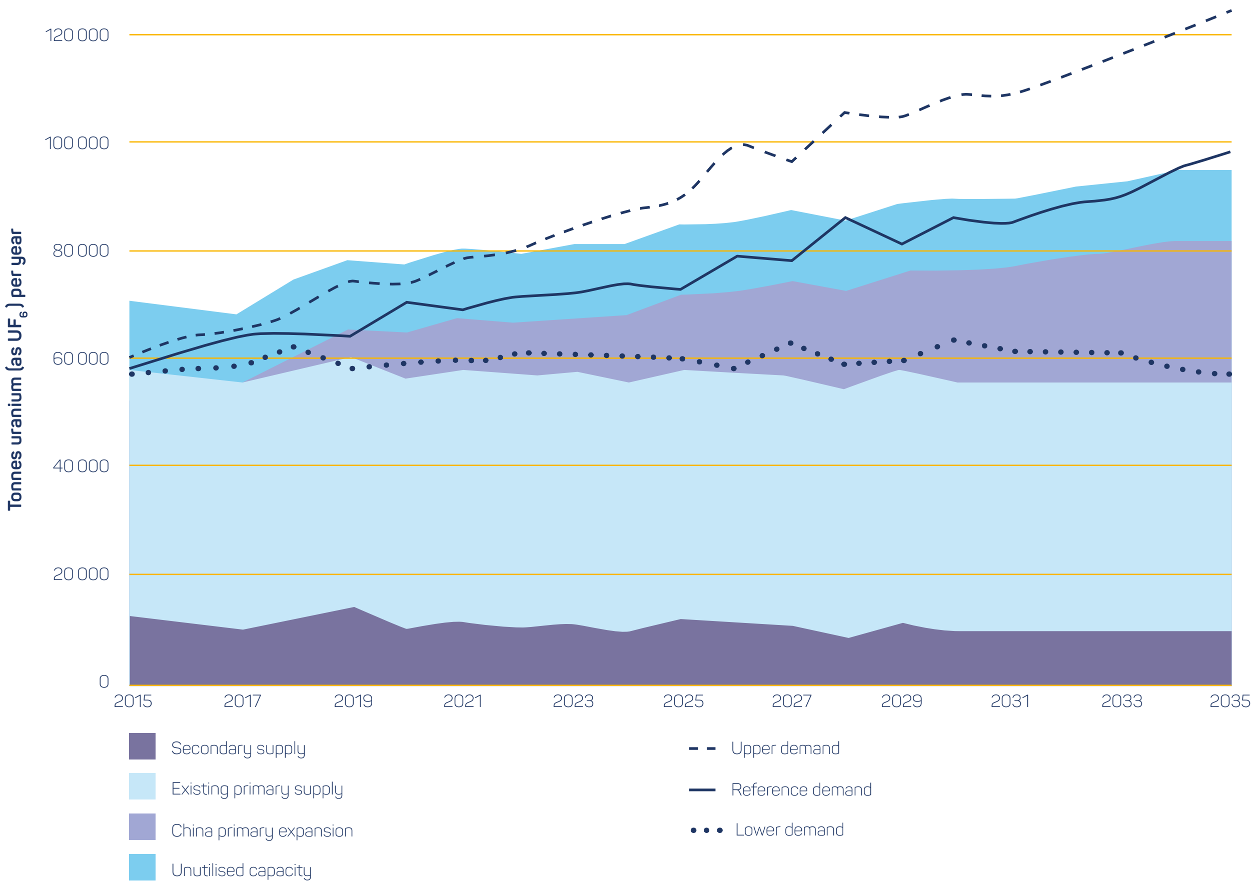

Figure 3.1: Current and projected global demand and supply for UF$_6$ conversion (tonnes uranium)

Data sourced from World Nuclear Association, *The nuclear fuel report: Global scenarios for demand and supply availability 2015-2035*, 17th edn, 2015, p. 117, fig. 6.3

CONVERSION

Conversion services are presently provided by a small number of major suppliers in Canada (Cameco Corporation), France (AREVA), Russia (ROSATOM) and the United States of America (ConverDyn).[56]

In 2015, the World Nuclear Association (WNA) estimated that production capacity in excess of demand was about 22 per cent, as shown in Figure 3.1. Secondary supplies are available from the waste streams of earlier enrichment, which contain uranium and can themselves be enriched. Other secondary sources include reprocessed uranium and inventories held by Russia and the US Department of Energy.[57] These supplies are estimated to be equivalent in quantity to overcapacity from primary sources.

The WNA estimates suggest that increased use of existing capacity would meet growth in demand to at least 2033.[58] This estimate is consistent with the International Energy Agency's view of the projected growth in nuclear power plants that would arise if the policy commitments made before the 2015 United Nations Climate Change Conference were implemented.[59]

ENRICHMENT

Enrichment services are currently provided by organisations in Germany, the UK and Netherlands (URENCO), France (AREVA), Russia (ROSATOM) and the USA (URENCO).[60] Other, smaller suppliers in China (China National Nuclear Corporation) and Japan (Japan Nuclear Fuel Limited) are mostly used to meet domestic demand.[61]

Demand is met primarily by enrichment plants, with secondary supplies sourced from the down-blending of highly enriched uranium released from military stockpiles, the re-enrichment of depleted uranium fuels, and the underfeeding of centrifuge plants. A combination of factors, including the 2011 Fukushima Daiichi accident, premature shutdown of power stations in Europe and the USA, and inventories held by traders, has led to an accumulation of primary enrichment capacity and enriched uranium inventories.[62]

The current level of oversupply in the enrichment market is approximately 18 to 25 per cent.[63] WNA demand forecasts in 2015 suggest that current enrichment capacity (measured in separative work units or SWU) could meet demand until 2025, as shown in Figure 3.2. Beyond this period, the WNA forecasts that prospective capacity in China would meet growth in demand.

FUEL FABRICATION

Fuel fabrication services are currently provided by companies across 16 nations in Asia (China, India, Japan, Kazakhstan, Korea), Eastern Europe (Romania, Russia), Western Europe (France, Germany, Spain, Sweden, United Kingdom), North America (Canada, USA) and South America (Argentina, Brazil). The main fabricators across these countries are typically reactor vendors and include AREVA, Westinghouse and Mitsubishi. The market includes a significant number of organisations that have developed fabrication capacity to meet local demand, such as the utilities company KEPCO in Korea and entities in India and Pakistan.[64] Fabricators that are also reactor vendors, which previously only produced fuel for their own reactor design, are increasingly producing fuel for competitors' reactor designs.[65]

Overcapacity for fuel fabrication services cannot be described in the same terms as conversion and enrichment. This is because fuel fabrication services do not produce a commodity, but a manufactured product. Suppliers compete by offering improved performance through improved fuel designs. Therefore, the existing overcapacity, estimated to be more than double current requirements, is not simply due to a fall in demand; it is also because multiple suppliers have the capacity to produce a diverse range of fabricated fuel designs suitable for a range of reactors.[66]

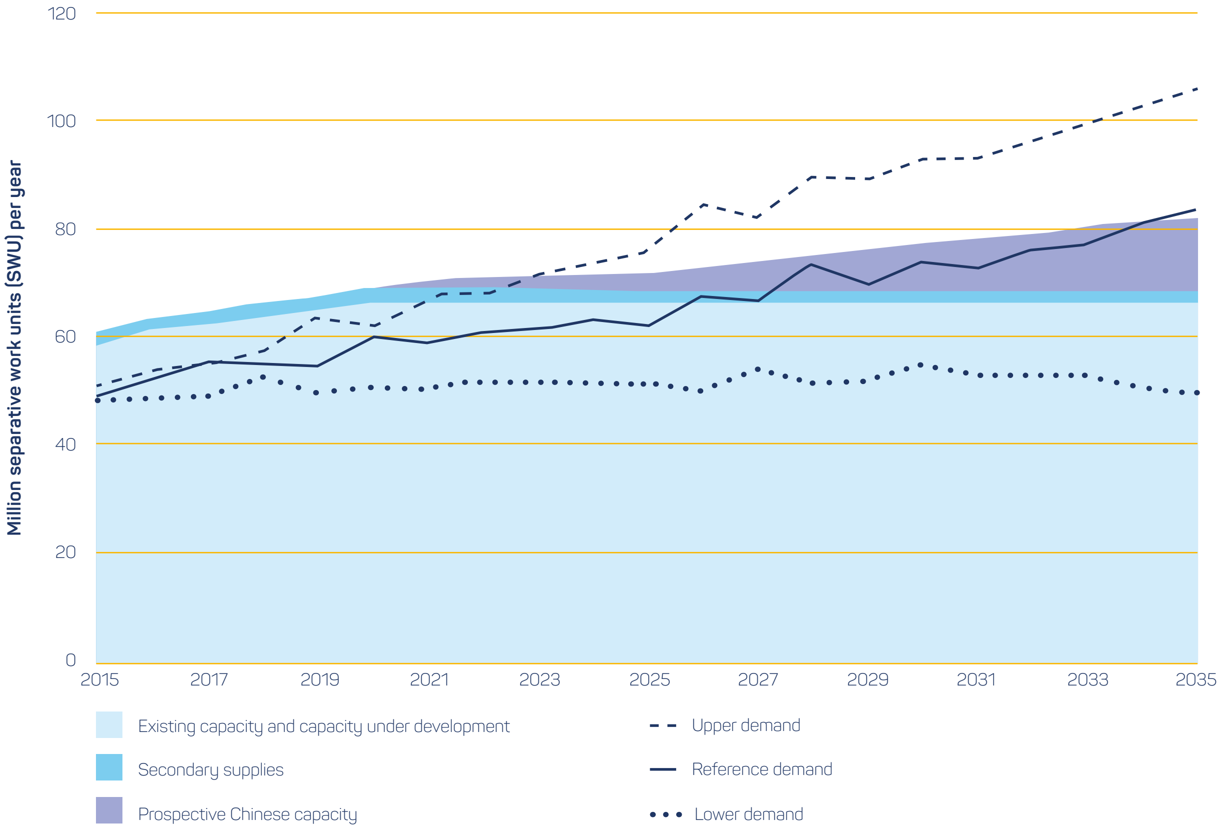

Figure 3.2: Current and projected global demand and supply for enrichment services

Data sourced from WNA, *The nuclear fuel report*, p. 136, fig. 7.5

27. An Australian operator seeking to supply conversion, enrichment or fuel fabrication services would face significant barriers to entry.

Because Australia does not produce nuclear energy, any facility to further process uranium would supply only international markets. This is significant because all facilities providing conversion, enrichment and fuel fabrication services are in countries that have a domestic nuclear energy industry. The largest and most dominant providers of each of those services are sustained by supply to substantial nuclear energy programs in their own countries in addition to meeting international requirements.[67]

The absence of a domestic nuclear energy market in Australia is but one challenge to the development of further processing services in South Australia.

The markets for these services are characterised by a small number of global service providers that operate specialised facilities.[68] Incumbents have significant advantages:

- Current commercial enrichment technologies are owned and controlled by two principal global suppliers, URENCO and TENEX. It would be necessary to reach licensing arrangements with one of them at a price which allowed the activity to be conducted profitably. Furthermore, the licensing of that technology in the case of URENCO and TENEX requires international legal agreements to be reached with the governments that own that technology. In the case of URENCO, an arrangement to establish one facility took more than five years to be reached.[69]
- Links between fuel fabrication technology and the technology of a reactor vendor mean that at present all fuel fabrication facilities are owned by reactor suppliers, with the sole exception being one fabricator closely cooperating with a vendor.
- The vertical integration of some suppliers that provide further processing services diminishes the capacity of an entrant to secure contracts for any one service.
- Production, particularly enrichment, can be expanded at existing facilities. A facility can be expanded by adding further cascades, avoiding the cost of establishing and licensing a new facility.
- Long-term contractual arrangements for the supply of most services are in place and privately negotiated. This is the case for many arrangements for further processing, and universal for the supply of fuel fabrication services.[70]

In addition to facing these challenges, new entrants would also face the challenge of acquiring skills and other capabilities, developing infrastructure, and licensing facilities and products. In the case of fuel fabrication, it would be necessary to undergo the expensive and time consuming process of obtaining safety certification of fuel designs from licensing authorities in customer countries.

An operator might seek to provide more specialised services than those directed at nuclear energy. For example, developing fuels for research reactors or target plates for medical isotope production would not face the same barriers. In those cases, an arrangement with a domestic operator to meet requirements such as security of supply might sufficiently alter the normal circumstances faced by a new participant to permit entry.

28. Financial assessments concerned with the potential viability of a new entrant point to, at best, marginal investment outcomes for further processing facilities based on proven technologies and a limited range of positive investment outcomes for facilities based on proprietary or unproven technology.

As further processing services are provided on a commercial basis, assessment of their viability is best undertaken by an investor with relevant knowledge and experience in that market. There can be no substitute for such analysis. However, because further processing activities are prohibited and cannot be licensed in Australia, no commercial operator is likely to undertake such an assessment.

To address viability, financial assessments of potential profitability of facilities established in Australia were undertaken for the Commission.[71]

Those assessments concluded that further processing facilities based on current and proven technologies were at best marginal investments and, in many cases, had negative returns.[72] Positive returns were indicated for facilities that used proprietary or unproven technologies, although significant investments would need to be made to demonstrate and commercialise those technologies. Those conclusions, and the analysis undertaken, are described in detail in Appendix D: Further processing—analysis of viability and economic impacts.

Those assessments proceeded on the basis that new facilities without any market advantage needed to compete with existing operators. That means the assessments do not answer whether a facility would be viable if established in partnership with an existing operator or if it had market power due to a unique, attractive offering.

The analysis:

- addressed the profitability of standalone conversion, enrichment and fuel fabrication facilities; the combination of conversion and enrichment; and a vertically integrated operation providing all three services
- addressed different technological or process options for each further processing service—both dry and wet conversion processes, gas centrifuge and laser enrichment, and, in the case of fuel fabrication, fuels for both light water and heavy water reactors
- undertook estimations based on facility capacities similar to those currently operating internationally
- developed life cycle cost estimates for developing each of the further processing facilities and its supporting infrastructure in South Australia
- assessed revenues based on prices that were the long-term average for the supply of conversion and enrichment services, and on published reports of agreements for fuel fabrication services.

The financial analysis found, as shown in figure 3.3, that:

a. There are some limited circumstances in which a standalone conversion facility in South Australia could be viable.

A conversion facility using a wet process is not viable in most future scenarios and marginal in some.[73] It would be viable if the price for conversion services were at or above the long-term average of A$21 per kilogram of uranium. A dry conversion facility is potentially viable under a wider range of prices than wet. However, dry conversion is used commercially in only one international facility.[74]

b. A centrifuge enrichment facility is not likely to be viable in South Australia as a standalone activity.

An enrichment facility using gas centrifuge technology would not be viable under a wide range of scenarios.[75] This is the case even if prices reverted to their long-term historical average of A$182 per SWU by 2030.

Despite substantial private investment, laser enrichment technology has not yet been demonstrated to be feasible on a commercial scale.[77] However, if it could be delivered

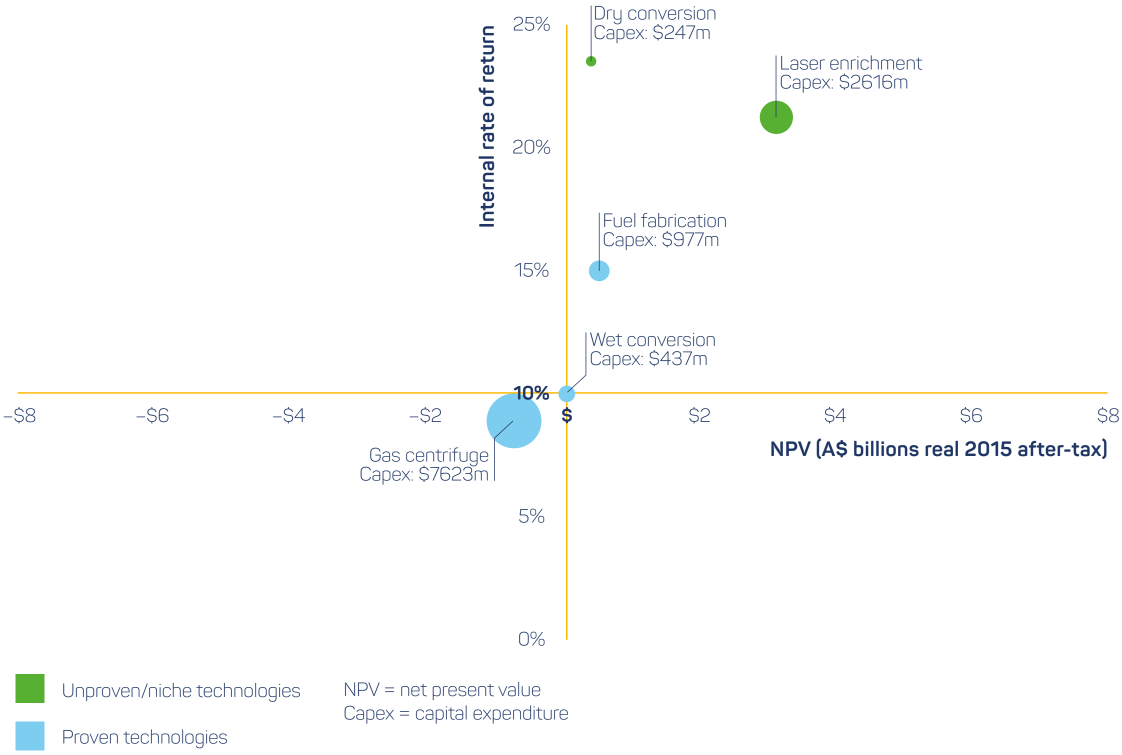

Figure 3.3: Commercial viability of standalone further processing facilities[76]

at approximately half the capital cost of gas centrifuge enrichment, as has been asserted in evidence to the Commission[78], it would have considerable value as a disruptive technology.

This would require substantial additional investment in research, development and the demonstration of commercially unproven technology. The Commission has not included these costs in its viability analysis.

c. Fuel fabrication facilities could be commercially viable, the more profitable being those concerned exclusively with fabricating fuel for light water reactors.

A fuel fabrication facility established in South Australia could generate a positive return on investment if such a facility could capture approximately 9 per cent of the market for fabricated light water reactor fuel[79]. Capturing this share would depend on South Australia establishing a unique selling proposition that it does not currently have.

29. Overall, given the barriers to entry, market oversupply, uncertainty around future growth and limited range of positive investment outcomes, there would be no opportunity for the commercial development of further processing capabilities in South Australia, assuming they were in competition with existing suppliers. The position could be different for an existing supplier seeking to expand its operations.

The analysis undertaken for the Commission suggests that even if prices for each of these services were to return to their long-term averages, bearing in mind the barriers to entry and at best the marginal viability of proven technologies, there is not likely to be any opportunity for further commercial processing activities in South Australia. That position would be different if:

a. substantial growth in the demand for services from nuclear power stations being developed in Asia could not be met by existing global or domestic capacity

b. demonstration of the feasibility of a technology (for example, laser enrichment) substantially reduced the cost of establishing a facility

c. an alternative competitive advantage was demonstrated relative to existing suppliers (for example, security of supply, non-proliferation and/or fuel leasing arrangements).

Although the first two of these scenarios are not presently probable, neither are they implausible. The third would depend on pursuing waste storage and disposal options addressed in this report and, if they were successful, would represent a realistic opportunity. Capitalising on the opportunity created by any of those circumstances would depend on reaching an agreement with the holder of the technology, either under licence or in partnership, to support a new facility in South Australia.

30. Proximity of uranium mining would not, by itself, present a competitive advantage for conducting processing activities. However, the concept of fuel leasing has the potential to alter that position.

It does not appear that transport costs of uranium oxide concentrate are such a significant component of the costs of conversion, enrichment and fuel fabrication services as to provide a competitive advantage. As such, close proximity to where uranium is mined does not itself justify the development of domestic conversion facilities. An Australian facility would benefit only from avoiding the cost of transporting UOC to a converter located elsewhere, presently in Europe or Canada. This cost advantage is estimated to be less than 3 per cent of the cost per kilogram of the UOC.[80] However, this potential advantage would be offset by the disadvantage that an Australian conversion or enrichment facility would experience in having to transport its output – a specialised activity – to fuel fabricators in the northern hemisphere. Whether there is any remaining advantage would require identifying specific customers, and assessing a range of other factors, which are too uncertain to be the subject of this analysis.

The Commission's financial analysis of further processing activities did not take account of the potential effect of a fuel leasing service. Such a proposal might affect the growth in demand for further processing services by providing a unique service that combines used fuel management and further processing. Such a service would be particularly valuable for customers with substantial used fuel management challenges. This would significantly alter the market share and price assumptions underlying the financial analysis. Fuel leasing is discussed in Chapter 5.

REPROCESSING

31. Reprocessing of used nuclear fuel has proven to be a risky technology to introduce, and its commercial viability has been undercut by the availability and low cost of uranium. Without nuclear power generation, a used fuel reprocessing facility would not be needed in South Australia, nor would it be commercially viable.

After several years of being used, nuclear fuel is discharged from the reactor core. At this point, there are two pathways for the fuel. The first, reprocessing, involves the separation of plutonium (Pu) from the irradiated uranium.[81] The other is to temporarily store, and later dispose of, the used fuel in a deep geological repository.

In the standard method of reprocessing, known as PUREX (plutonium and uranium recovery by extraction), the used fuel is cut up and dissolved in hot nitric acid and the plutonium and uranium are separated from fission products and heavy by-products.[82] Both are subsequently converted to oxide powders. Both the plutonium and uranium can be recycled and manufactured to produce uranium oxide or mixed oxide (MOX) fuels for use in a limited number of reactors.[83] A further description of aqueous reprocessing and other methods is given in Appendix C.

Reprocessing has been undertaken only in countries with nuclear power programs. The countries currently engaged in reprocessing are France, Japan, Russia, India and the UK.[84]

Reprocessing has proven to be highly expensive and technically complex. The cost of extracting and reprocessing the plutonium for use as nuclear fuel is greater than the cost of new uranium.[85] There is a sufficient global supply of uranium at low cost for existing and committed reactors.[86]

Regarding the technical complexity, two countries with highly sophisticated nuclear industries and considerable expertise, Japan and the UK, have faced significant difficulties in successfully developing commercial reprocessing facilities. Japan's Rokkasho reprocessing plant has been under construction for more than two decades. To 2013, the estimated start-up date had been postponed 20 times.[87] The facility is now expected to be operational in 2018.[88] In 2011, the Japan Atomic Energy Commission predicted that the construction and operating costs of the facility over 40 years would amount to about US$120 billion, approximately 10 times the cost of interim storage.[89] The UK's recent reprocessing plant, the Thermal Oxide Reprocessing Plant (THORP), faced a number of challenges in its operation[90] and never operated at its intended capacity. THORP will cease reprocessing by 2018 due to falling domestic customer demand and following the completion of existing international contracts.[91]

A number of responses to the Tentative Findings suggested a more favourable view of reprocessing should have been taken in light of future reactor developments.[92] The long-term prospects of those technologies are addressed in Chapter 4: Electricity generation, and in Appendix E: Nuclear energy — present and future. Those responses do not alter the view that a new reprocessing facility based on current technology would not be economically viable under current and likely future market conditions.[93] For these reasons, and without the development of domestic nuclear power generation, there would be no need to develop a reprocessing facility in South Australia. Given this finding, the environmental risks associated with the activity do not require further consideration. The proliferation risks associated with reprocessing and separated plutonium are addressed in Chapter 8: Non-proliferation and security.

NUCLEAR MEDICINE

32. The Australian Nuclear Science and Technology Organisation (ANSTO) already operates a research reactor and associated facilities for manufacturing molybdenum-99 in Sydney. Considering the cost of duplicating this infrastructure and the nature of the market, it would not be profitable or cost-effective for South Australia to engage in this activity.

The use of radioactive isotopes for imaging, diagnosis and the treatment of illness and disease, broadly known as nuclear medicine, plays an essential role in modern medical practice.[94] Radioisotopes are targeted at specific tissues to help detect and monitor health issues, or to deliver doses of radiation to selected areas to treat disease without damaging surrounding healthy tissue.

Radioisotopes for medical procedures are produced in either a reactor or cyclotron, depending on the type required. The majority of the most commonly used medical radioisotopes are produced in only a small number of research reactors around the world.[95] Because most isotopes decay swiftly after production, location of production and transportation are critical issues.[96]

Currently, the most commonly used radioisotope in diagnostic procedures is technetium-99m (^{99m}Tc), which is produced from the decay of its parent isotope, molybdenum-99 (^{99}Mo).[97] In Australia, this is produced exclusively in ANSTO's OPAL research reactor in Sydney.[98]

Figure 3.4: The cyclotron at the South Australian Health and Medical Research Institute

Image courtesy of SAHMRI

ANSTO is constructing a new nuclear medicine manufacturing plant, which will significantly expand its capacity to manufacture ^{99}Mo: it plans to triple production to meet increasing Australian and some international demand.[99] The radioisotope ^{99m}Tc can be produced using non-reactor technologies; however, unlike research reactors, they are unable to do so efficiently and in sufficient volumes to meet demand.[100] Noting that ^{99m}Tc has a short half-life (six hours), production must be close to where it is used.

South Australia imports ^{99}Mo for medical procedures from ANSTO.[101] At present, there is no demand in Australia for a second reactor for medical purposes.[102] There would be significant barriers to establishing a reactor in South Australia for this purpose, not least the expense and complexity of the required infrastructure.[103]

33. There are opportunities, complementary to ANSTO's activities, to make greater use and expand the capabilities of the cyclotron and laboratories concerned with the manufacture of radiopharmaceuticals at the South Australian Health and Medical Research Institute (SAHMRI).

South Australia's cyclotron, a particle accelerator, is located at the SAHMRI (see Figure 3.4). It produces a range of radioisotopes in relatively small volumes for medical applications within the state.[104] It is also used for research and development of new techniques and products in the field of nuclear medicine.[105] It has capacity for further utilisation.[106] Manufacturing radiopharmaceuticals using the cyclotron produces very small quantities of short-lived wastes, which are managed on site and regulated by the South Australian EPA. South Australia has significant expertise and skill in this field, within hospitals, universities and at the Molecular Imaging and Therapy Research Unit at SAHMRI.[107]

There is a range of opportunities to expand the cyclotron's current capabilities that could be realised with further investment.[108] These lie in the research and development of new techniques for manufacturing radioisotopes for medical applications, the skilling of Australian and overseas technicians, and research to develop new imaging techniques and therapies. They relate to[109]:

a. producing and handling positron emission tomography (PET) isotopes, by assessing the manufacture and diagnostic effectiveness of new or prospective positron emitters

b. undertaking new, commercially focused trials on promising radiopharmaceuticals of both diagnostic and therapeutic types

c. developing new micro-dosimetry tools and methods for verifying the effectiveness of therapeutic radiopharmaceuticals—this has commercial potential because it facilitates the licensing of new drugs that use radionuclides

d. examining how to commercially produce the alpha and beta emitting radionuclides that are emerging as components in new and promising therapeutic radiopharmaceuticals.

Expansion of the cyclotron's capabilities could be realised gradually. Incremental steps could include[110]:

a. installing a beam-splitting system with increased targets to facilitate further research and experimentation into prospective and novel areas of nuclear medicine, including tracers, proton therapy and targeted alpha therapy

b. developing a unique expertise and training capacity on an international scale in these novel areas of nuclear medicine, potentially within an on-site training centre

c. developing infrastructure to enable the commercial manufacture of iodine-123 (^{123}I) for use in specialised imaging and diagnosis. Following closure of the Australian cyclotron that supplied this isotope, it is currently imported from Canada.[111] As well as import replacement, there is scope to export to the Asia–Pacific market

d. developing a range of novel research and development programs using the enhanced cyclotron capabilities.

Investments in such infrastructure could enable South Australia to develop an internationally recognised centre of expertise in nuclear medicine research. Collaboration between the SAHMRI, South Australian universities, other research organisations and the private sector would be central to the successful development of such a centre. A plan would need to be developed to address the strategies required to realise such opportunities.

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84 Transcript: Von Hippel, p. 680–681.

85 ibid., p. 680.

86 Deutch & Moniz, 'The nuclear option', p. 78.

87 M Toki & M Pomper, 'Time to stop reprocessing in Japan', *Arms Control Today*, January/February 2013, p. 24.

88 Japan Nuclear Fuel Limited, *Corporate Profile*, 2015, p. 4.

89 International Panel on Fissile Materials, *Plutonium separation in nuclear*, p. 65.

90 Nuclear Decommissioning Authority, *Annual report and accounts: Financial year: April 2014 to March 2015*, 30 June 2015, p. 4.

91 Nuclear Decommissioning Authority, *Annual report*, p. 8; Sellafield Ltd, 'Spent fuel management: Magnox reprocessing – The plan', http://www.sellafieldsites.com/solution/spent-fuel-management/magnox-reprocessing/the-plan.

92 South Australian Nuclear Energy Systems, response to Nuclear Fuel Cycle Royal Commission Tentative Findings; Engineers Australia, p. 5; Edwards, pp. 2–3.

93 International Panel on Fissile Materials, *Plutonium separation in nuclear*, p. 124.

94 Transcript: Baccanti, p. 1611.

95 Transcript: Jenkinson, p. 1619.

96 Transcripts: Takhar & Bezak, p. 1590; Jenkinson, p. 1626. Submission: The Medical Association for the Prevention of War (Australia) (MAPW) & Public Health Association of Australia (PHAA), p. 17.

97 Transcript: Jenkinson, pp. 1616, 1627; Takhar and Bazak, p. 1596. Submission: MAPW & PHAA, pp. 17–18.

98 Transcripts: Jenkinson, p. 1618, Takhar and Bezak, p. 1596.

99 Transcript: Jenkinson, p. 1619. Submission: ANSTO, p. 10. ANSTO, *What is the ANSTO Nuclear Medicine Project*, 2016, http://www.ansto.gov.au/BusinessServices/ANMProject/AboutANM/index.htm.

100 Transcript: Jenkinson, pp. 1620–1621.

101 Transcript: Jenkinson, p. 1618. ANSTO, 19 March 2016, http://www.ansto.gov.au/BusinessServices/ANMProject/AboutANM/index.htm.

102 Transcript: Jenkinson, p. 1619.

103 ibid., p. 1621.

104 Transcript: Takhar & Bezak, pp. 1594–1595.

105 ibid., pp. 1591–1592.

106 ibid., pp. 1591, 1593.

107 P Takhar, letter to the Nuclear Fuel Cycle Royal Commission, 24 March 2016.

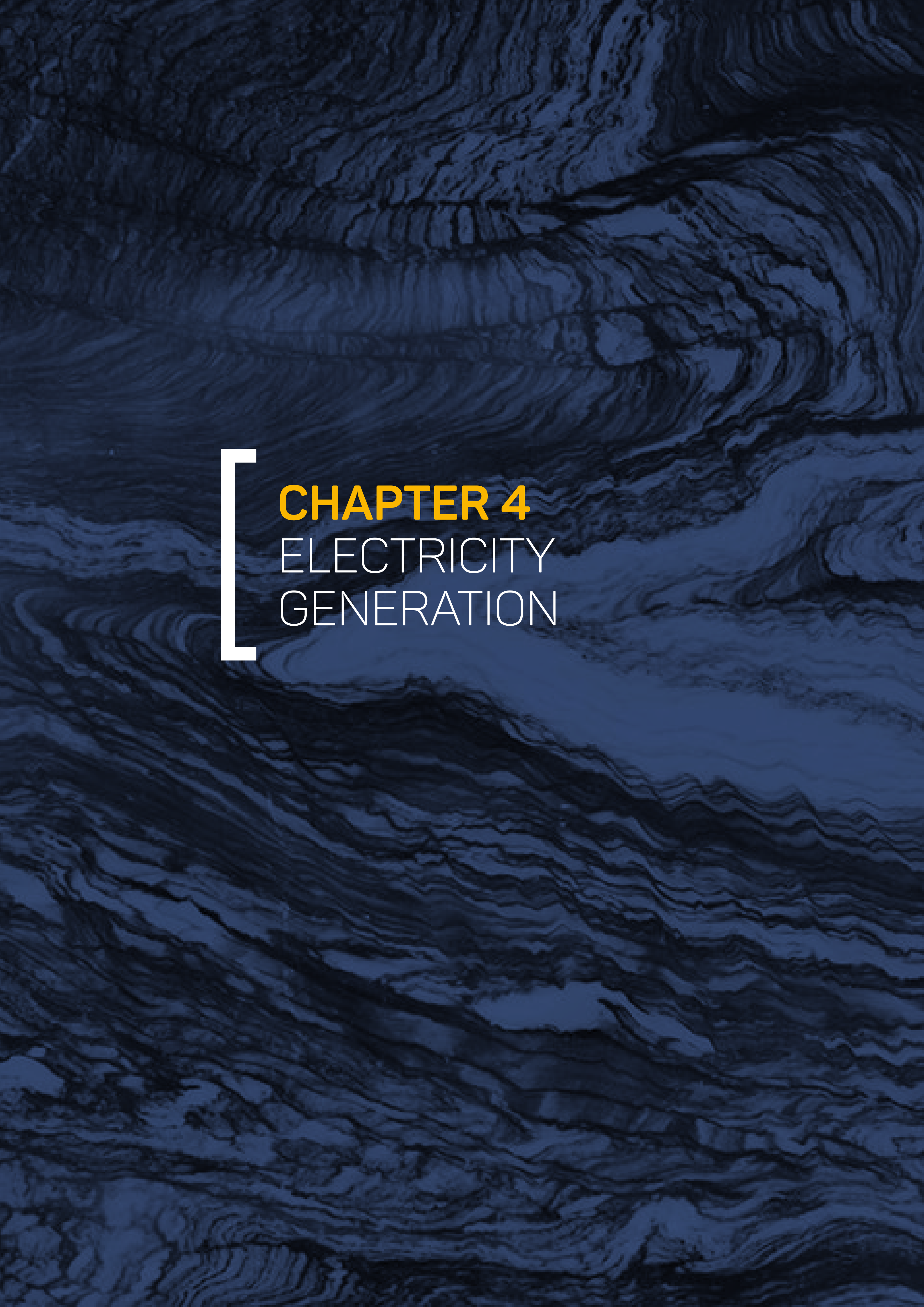
108 Transcript: Takhar & Bezak, p. 1590. Submission: MAPW & PHAA, p. 17.

109 Transcript: Takhar & Bezak, pp. 1589–1590, 1601–1602.

110 P Takhar, letter to the Nuclear Fuel Cycle Royal Commission, 24 March 2016.

111 Transcript: Jenkinson, p. 1622.

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website:www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions



CHAPTER 4
ELECTRICITY GENERATION

CHAPTER 4: ELECTRICITY GENERATION

The activity under consideration is the establishment and operation of facilities to generate electricity from nuclear fuels in South Australia.

WHAT ARE THE RISKS?

34. Nuclear power plants are very complex systems, capable of producing large amounts of energy. They are designed and operated by humans, who can make mistakes.

Nuclear power reactors are carefully engineered vessels that enable the heat energy produced from the fission of uranium nuclei to be captured, through boiling water and creating steam, and transferred to a steam turbine electricity generating system. The electric power output of new light water reactors being deployed today is up to 1600 megawatts electric (MWe).[1] Modern reactor designs are described further in Appendix E: Nuclear energy – present and future.

The risks associated with generating nuclear power are fundamentally related to the large amount of energy produced in the relatively small volume of a reactor core. Hazards that must be managed and controlled in a reactor include the rate of fission heat produced and, in certain circumstances associated with the failure of equipment or control systems, the potential release of radioactive materials.[2] During normal operation, excess heat in a reactor is removed by a coolant, which in most modern reactors is water. When a reactor is shut down, whether for routine reasons or due to an accident, the fission chain reaction immediately stops; however, thermal energy remains in the fuel and the radioactive decay of fission products produces new heat.[3] This can cause damage to, and even melting of, fuel material if the heat is not removed by a coolant.[4]

Fuel cooling in all scenarios is of paramount importance as coolant loss can quickly develop into a serious loss-of-coolant-accident (LOCA). Nuclear engineers and safety analysts focus extensively on ways to avoid fuel damage in all credible and simultaneous LOCA pathways, including coolant pipe breaks and loss of power to coolant pumps.

While reactor design plays a significant role in overall safety, human operation is equally important: human error in management, control, maintenance and accident response can have severe consequences. Human error and reactor design flaws have been shown to be critical contributing factors to operating inadequacies, equipment damage and technical failures that can lead to major accidents.[5] Modern reactor designs incorporate many safety mechanisms to protect against operator error, as discussed in Appendix E.

35. There have been three major accidents in nuclear power plants involving the release of radioactive material into the environment: Three Mile Island in 1979, Chernobyl in 1986 and Fukushima Daiichi in 2011. Each accident has been thoroughly and credibly investigated to determine both the causes and lessons to be learned.

The three major reactor accidents have been carefully analysed and better understood through root-cause investigations, resulting in numerous principles that could be applied to improve safety. Credible studies include those by the International Atomic Energy Agency (IAEA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the United States Nuclear Regulatory Commission (NRC).[6]

The broader health impacts are addressed in Chapter 7: Radiation risks.

THREE MILE ISLAND

In March 1979, one of the two Three Mile Island nuclear reactors in Pennsylvania, USA, suffered a serious loss of coolant. The combination of equipment failures and inadequate operator safety training and response led to a loss of water to remove heat from the reactor's core.[7] This caused the partial melting of fuel assemblies.[8] Primary water flow to the damaged core was eventually restored many hours later.[9] No deaths or injuries resulted. The vast majority of radiation released from the core was contained within the reactor containment building, with only insignificant amounts being released to the environment.[10] The reactor has remained out of operation since the accident.[11]

An initial inquiry[12] and subsequent analyses of the accident have led to many improvements in plant design and operation, as well as increased scrutiny and more stringent safety requirements from the regulator in the USA.[13]

CHERNOBYL

The Chernobyl reactor in Ukraine was a Russian RBMK design, unique to the former Soviet Union. Such a reactor used natural uranium for fuel, water as a coolant, and graphite as a moderator. This kind of reactor could be unstable in certain operating conditions. If an RBMK reactor lost its coolant its nuclear reaction proceeded faster, due to the greater moderating effects of graphite in the absence of water, rather than the reaction stopping itself as in the case of light water reactors. Also, RMBK reactors lack the level of containment that light water reactors have.

The accident at the Chernobyl reactor in April 1986 was due to this instability, combined with serious deficiencies in safety culture, operator experience and management capability.[14] Through bypassing safety systems during an unauthorised experimental test of the reactor control system, the core became unstable, leading to an increase rather than a decrease in fission heat production as the core temperature rose.[15] This induced two chemical explosions and a consequent fire that ultimately caused the death of two workers and the release of a significant amount of radioactive material into the environment over 10 days.[16]

FUKUSHIMA DAIICHI

In March 2011 the Great East Japan earthquake and tsunami triggered a nuclear accident at the Fukushima Daiichi nuclear power plant. The circumstances are explained in greater detail in Appendix F: The Fukushima Daiichi accident. In summary, the reactors at the Fukushima Daiichi plant were early-model boiling water reactors. Flooding caused a loss of both on-site and off-site electrical power and led to the loss of reactor core cooling capability in three reactors.[17] This ultimately resulted in a LOCA that caused fuel melting and fission product release.[18] The parallel generation of hydrogen gas resulted in chemical explosions, causing significant structural damage to plant buildings.[19] Thorough examinations of the incident identified various deficiencies including:

1. critical weaknesses in plant design and in emergency preparedness in the event of severe flooding.[20] These included an insufficiently high flood wall, emergency power supplies that were vulnerable to flooding, and a more limited form of primary containment compared to modern reactors
2. weaknesses in Japan's regulatory framework in both a lack of regulatory independence and multiple decision makers, which obscured lines of responsibility[21]
3. the absence of an appropriate safety culture within the reactor operator, the nuclear regulator and the government[22], resulting in a number of unchallenged assumptions[23], including that the plant was so safe that an accident of this magnitude was simply unthinkable, and that electrical power could never be lost at a plant for more than a short time
4. lower preparedness among plant operators for the conditions and stresses that could arise in the event of a severe accident.

Table 4.1: Environmental releases for specific radionuclides from the Three Mile Island, Chernobyl and Fukushima Daiichi accidents

Accident	Iodine-131 (PBq)	Caesium-137 (PBq)
Three Mile Island[a]	0.00055	–
Chernobyl[b]	1760	85
Fukushima Daiichi[c]	100–500	6–20

a. L Battist & HT Peterson Jr, 'Radiological consequences of the Three Mile Island accident', Office of the Standards Development, US Nuclear Regulatory Commission, Washington D.C., 1980, p. 264.
b. UNSCEAR, *Sources and effects of ionizing radiation*, vol. II, scientific annex D, 2008, p. 49.
c. UNSCEAR, *Sources, effects and risks of ionizing radiation*, vol. I, scientific annex A, 2013, p. 40.
Note: The becquerel (Bq) is the SI unit of radioactivity equal to one decay event per second. One petabecquerel (PBq) is equal to 10^{15} Bq.

RELEASES OF RADIATION

The major radioactive substances released into the environment during these accidents are summarised in Table 4.1. Two radionuclides, the short-lived iodine-131 (^{131}I), with a half-life of eight days, and the long-lived caesium-137 (^{137}Cs), with a half-life of 30 years, were particularly significant for the radiation doses they delivered to the environment. Strontium was also released, but the additional radioactivity associated with its release was negligible when compared with natural background levels.[24]

At Three Mile Island, although fission products were released from the damaged core into the containment vessel, only very small amounts of radioactive substances were released into the environment.[25] At Fukushima, considerable amounts of radioactive substances, predominantly caesium and iodine, were released into the environment.[26] The effective dose of radiation to the Japanese public was about 10–15 per cent of the comparable dose to the European populations affected by radiation from Chernobyl.[27]

36. The lessons learned from the design, siting and cultural factors that contributed to these accidents have been applied to new developments.

The three major nuclear accidents have shown that the numerous complex interdependencies at nuclear power plants need to be understood, monitored and controlled so that reactor cooling is maintained at all times. Many analyses of the accidents have advanced the industry's understanding of how accidents comprise a progression of events from an initiating incident.[28] This has helped to reduce the probability of LOCAs in modern reactors through improvements in physical engineering and design measures, sophisticated instrumentation, automated operational controls and interlocks, and strengthening safety cultures.[29] The establishment and subsequent updates of international nuclear safety reporting mechanisms through the Convention on Nuclear Safety (1994) have also fostered international cooperation and information sharing on lessons learned among nuclear power plant operators.[30]

In the year that followed the Fukushima accident, many countries cooperated in a comprehensive assessment of nuclear risk and safety (so-called 'stress tests') to review the design of nuclear power plants against site-specific extreme external hazards.[31] These tests have led to useful recommendations, including the installation of additional backup electrical power and cooling water sources.[32] To mitigate the potential release of radioactive materials, measures have been developed and implemented in many countries. These measures include improved emergency response planning, reactor operator training, human-factors engineering, and radiation protection strategies, including administering iodine tablets to potentially affected individuals.[33] Following the Fukushima accident, all of Japan's remaining nuclear reactors were shut down for a review of their safety. Reactors are permitted to restart only after these reviews and are subject to a new regulatory framework. The restarts are progressive and are proceeding slowly,[34] due primarily to community resistance. Three of 46 reactors have been restarted to date.

In September 2012, the IAEA Director General initiated an inquiry into the Fukushima Daiichi accident. The resultant report, *The Fukushima Daiichi accident: Report by the Director General*, and its associated technical volumes, released in 2015, identified a number of lessons for the global nuclear industry that built on those learned from the stress tests, previous nuclear accidents and other studies of the Fukushima accident.[35] Lessons presented in the report focused on:

1. the design of nuclear power plants and their safety systems
2. radiation containment
3. the need to properly prepare for multiple severe external hazards that simultaneously or in sequence affect operations at nuclear power plants
4. the need to strengthen regulatory oversight and assessment of plants
5. the need to create safety cultures in which stakeholders question basic assumptions and continually improve operational safety.[36]

While there can be no guarantee that severe accidents will not occur again, they are rare, given there have been 16 000 cumulative years of nuclear power plant operation in 33 countries. The risk of a nuclear accident should not of itself preclude the consideration of nuclear power as a future electricity generation option.[37]

If nuclear power were to be contemplated in South Australia, the responsible operator would be able to benefit from the accumulated safety knowledge of the global nuclear industry, including the lessons learned from prior accidents. As well, relevant local reactor safety expertise from the Australian Nuclear Science and Technology Organisation (ANSTO) and the Australian Radiation Protection and Nuclear Safety Authority (ARPANSA) is available.

IS THE ACTIVITY FEASIBLE?

37. Nuclear power is a mature, low-carbon electricity generation technology. Its deployment is characterised by large upfront capital costs and long periods of construction and operation. It offers high capacity and reliability, but does not efficiently follow the peaks and troughs of a highly variable demand profile.

The use of nuclear fission to commercially generate electricity was first achieved over 60 years ago.[38] Today the world's fleet of commercial nuclear power plants is predominantly made up of a small number of established water-cooled designs.[39]

Since the 1950s, reactor designs have continued to evolve to deliver increased efficiency and improved safety.[40] Large, modern designs incorporate independent safety systems that are both 'active', which include electrically powered pumps and valves, and 'passive', which take advantage of fundamental physical forces and mechanisms such as gravity and natural convection to maintain cooling to the reactor core.[41] 'Defence in depth' is another key safety feature of modern reactors; it ensures multiple barriers are in place to provide protection should a single barrier fail.[42]

Nuclear power plants are essentially baseload generators that run continuously. Their ability to operate flexibly to meet variations in demand depends on the reactor type and the refuelling cycle. The typical features of modern nuclear reactor designs are addressed in Appendix E.

In recent years, the complexity of some larger-capacity reactor designs and more stringent reliability and safety requirements have increased the difficulties of plant construction.[43] These have been key drivers of the cost and schedule overruns that have characterised recent construction programs[44], including several plants in Europe and the USA. Further, contemporary construction experience has declined given the lapse of time between current building programs and those undertaken decades ago.[45] Recent estimates of the cost of construction excluding finance (the overnight construction cost) in Europe and the USA range from A$9.25 billion for a Westinghouse AP1000 plant to A$14.8bn for an AREVA-designed EPR plant, with estimated construction schedules ranging from six to fifteen years, including cost and schedule over-runs.[46] The quoted contract price of the United Arab Emirates' current build program is slightly lower, at A$7.1bn for each of the four APR1400 reactors under construction. However, it is not known whether the vendor has been able to deliver the project within its contracted projection.[47]

Some evidence suggests that, for the current generation of large reactors, integrated construction programs involving multiple reactors of standardised design may have greater success in adhering to planned costs and achieving shorter build schedules.[48] The Commission's approach to estimating the capital construction cost of a nuclear power plant for the purpose of analysing its viability for Australia is explained in Finding 45 and in Appendix G: Nuclear power in South Australia—analysis of viability and economic impacts.

38. The technology to develop a nuclear power plant could be transferred readily from experienced commercial vendors. Careful consideration would need to be given to appropriate siting to ensure that water requirements for reactor operation could be met sustainably.

A number of commercial reactor vendors are capable of partnering with a South Australian entity for the construction and operation of a nuclear power plant. In nations new to nuclear power, partnerships for the development of a plant typically include arrangements to allow for knowledge transfer and local workforce training.[49] The lack of experience with nuclear power generation in South Australia would not preclude the development of a nuclear power plant at an appropriate site.[50]

The geophysical characteristics necessary for safe and efficient plant operation include low seismicity and ready access to adequate amounts of water for the current generation of large light water reactors.[51] While most parts of South Australia are geologically stable, sustainable access to water resources would need to be carefully assessed, given the reliance on water for cooling in most modern nuclear power plants.

In relation to the location for any potential large nuclear power plant in South Australia, a coastal site would be necessary to meet the significant water requirements for cooling using saltwater.[52] These requirements are addressed in detail in Appendix E.

Coastal siting might be a lesser consideration for future small modular reactor (SMR) designs, which have not yet been commercially developed.[53] Importantly, freshwater requirements for plant operation also need to be considered.[54]

39. If nuclear power were to be considered in South Australia, analysis should focus on a proven design that has been constructed with active and passive safety features. For commercial electricity generation in the foreseeable future this would include analysis of potential small modular reactors based on light water designs because of their suitability for integration in smaller markets, but not advanced fast reactors or other innovative reactor designs.

Any consideration of nuclear power in South Australia would need to focus on a reactor design with the following characteristics:

1. A proven design licensed by a reputable nuclear safety regulator. This would avoid project, technical and commercial risks and costs associated with construction of first-of-a-kind technology.[55] It also would increase confidence that the design would be able to be licensed in Australia, as it would need to comply with the relevant Australian licensing and regulatory framework. It may also reduce the level, and associated costs and timeframes, of the design assessment required.
2. A design previously constructed, ideally multiple times, would allow cost and schedule to be determined with greater certainty.[56] As nuclear power plant construction projects proceed overseas, reported construction costs should be monitored closely and independently verified.

3. A reactor design should be based on recent construction, with an experienced team and specialist workforce.[57]
4. The design should incorporate proven active and passive safety features for nuclear power plants (see Appendix E for a detailed explanation) that capture lessons learned from ongoing operations and fault scenarios.

Several proven designs incorporate the required and preferred design features identified above, and it is likely that more will become available in the next decade.[58] In particular, given the current maturity of the technology, it is likely that light water SMR designs will be available.[59] The smaller capacity of SMRs makes them attractive for integration in smaller electricity markets such as the National Electricity Market (NEM) in South Australia.[60] For this reason, it will be important to follow the development of such reactors.

Although there are no commercially operational examples of light water SMRs[61], several are in advanced stages of development and the early phase of licensing.[62] A study commissioned by the British government to address the potential availability of identified light water SMR designs confirmed the need for further detailed technical analysis. The study found SMRs would require A$1bn–2bn of development funding over five to seven years to be commercialised. Commercial deployment of a design would provide credible evidence of capability and cost.

In comparison, advanced fast reactors and other innovative reactor designs are unlikely to be feasible or viable in the foreseeable future (see Appendix E).[63] The development of such a first-of-a-kind project in South Australia would have high commercial and technical risk.[64] Although prototype and demonstration reactors are operating, there is no licensed, commercially proven design. Development to that point would require substantial capital investment.[65] Moreover, electricity generated from such reactors has not been demonstrated to be cost competitive with current light water reactor designs.[66]

The recent conclusion of the Generation IV International Forum (GIF)[67], which issued updated projections for fast reactor and innovative systems in January 2014[68], suggests the most advanced system will start a demonstration phase (which involves completing the detailed design of a prototype system and undertaking its licensing, construction and operation) in about 2021.[69] The demonstration phase is expected to last at least 10 years and each system demonstrated will require funding of several billion US dollars.[70] As a result, the earliest possible date for the commercial operation of fast reactor and other innovative reactor designs is 2031.[71] This timeframe is subject to significant project, technical and funding risk. It extends by six years a similar assessment undertaken by GIF in 2002.[72] This means that such designs could not realistically be ready for commercial deployment in South Australia or elsewhere before the late 2030s, and possibly later.[73]

40. The future viability of nuclear power, as for any generation source, can only be analysed as part of the electricity supply system in which it would be integrated.

The potential viability of a new nuclear power plant in South Australia cannot be determined by simply comparing its associated costs with those of other electricity generating technologies.[74] Commercial profitability would be determined by the more complex issues of how, when, and at what price the electricity produced by any new generating plant would be made available to customers.[75] This requires an understanding of the established market structure, its rules of operation and its likely evolution.[76]

South Australia is part of the NEM, which is one of the longest continuous electricity transmission systems in the world. The NEM supplies electricity to about 10 million customers across the Australian Capital Territory, New South Wales, Queensland, South Australia, Tasmania and Victoria.[77] The main network is a legacy system—designed in the 1980s—comprising more than 300 generators that supply electricity via the transmission network.[78] Six cross-border interconnectors connect the transmission networks of the participating regions, with the amount of electricity imported or exported at any given time limited by the capacity of the transmission line.[79] Figure 4.1 shows the physical generating and transmission assets in the South Australian subregion of the NEM. The coal-fired power plant located at Port Augusta has been omitted as it will cease operation in 2016.

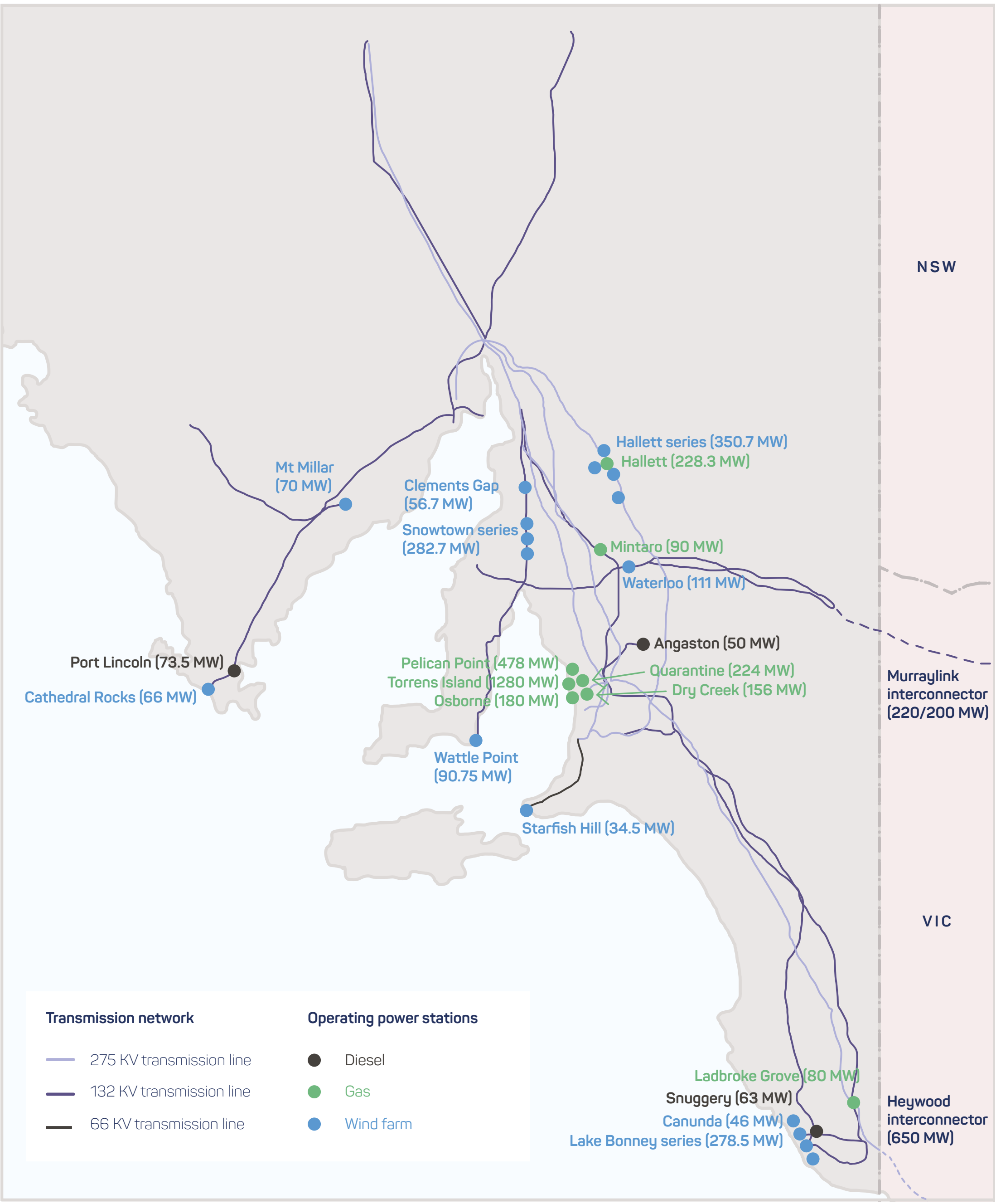


Figure 4.1: The South Australian region of the National Electricity Market (NEM), detailing power stations, transmission networks and interconnectors

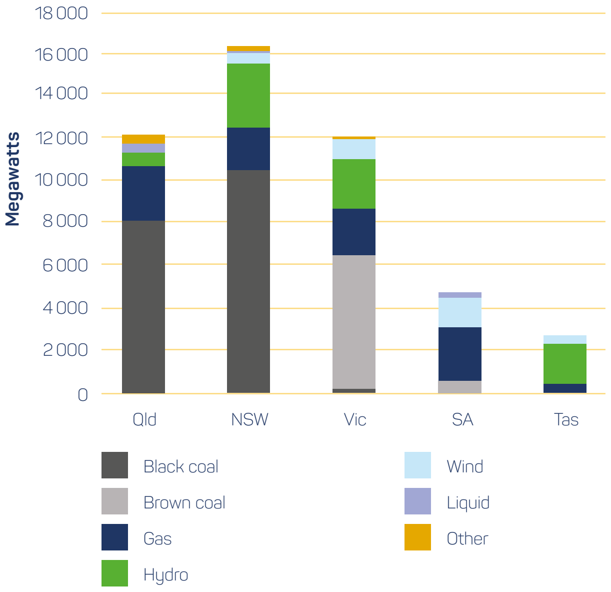


Figure 4.2: NEM generation capacity by region and fuel source, 2015

Data sourced from the Australian Energy Regulator (AER), *State of the energy market report*, 30 June 2015, p. 29

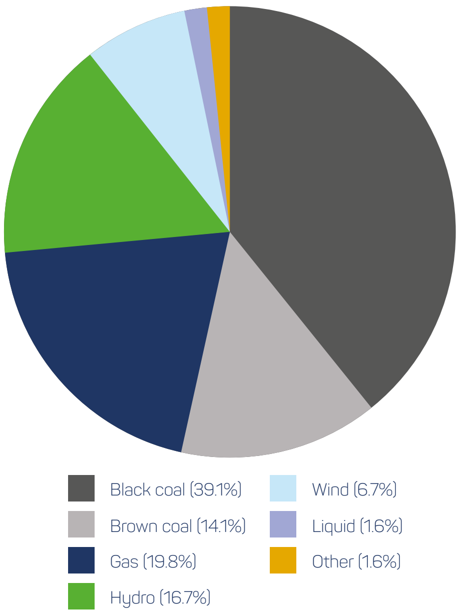


Figure 4.3: NEM generation capacity by fuel source, 2014/15

Data sourced from AER and Australian Energy Market Operator (AEMO)

41. The NEM is carbon-emissions intensive, does not require electricity generation sources to bear the full costs of their carbon emissions, and is subject to government interventions directed at lowering carbon emissions, which are not technology neutral and have not been demonstrated to achieve a low-carbon system with the lowest overall cost.

Black and brown coal-fired generators represented 53 per cent of installed generation capacity in the NEM in 2014/15 (see Figure 4.2 and Figure 4.3), but supplied 76 per cent of output.[80] This high share of coal-fired generation contributes more than one-third of national carbon emissions, and means the Australian electricity sector is one of the most carbon-intensive in the world (see Figure 4.4).[81]

The retirement of a significant percentage of that capacity is already planned over the next two decades.

There is currently no mechanism to impose the cost of emissions on generators, although this was enacted by carbon pricing from 1 July 2012 to 30 June 2014. During this time coal-fired generation output declined by 12 per cent, but it quickly recovered when carbon pricing was abolished. The Large-scale Renewable Energy Target (LRET) scheme, which was launched in 2001, aimed to decrease the carbon emissions intensity of the NEM by providing a financial incentive for renewable energy generation technologies to enter the market. The LRET is not a technology–neutral scheme: it offers incentives to develop a group of renewable technologies—most significantly wind and solar PV. Different policies are likely to have differing economic impacts and costs in reducing CO_2 emissions. They also have different effects in different NEM regions (see Box: South Australia's electricity price competitiveness to 2030 and beyond). A review of policies, their effectiveness and economic impacts will be released by the Climate Change Authority in 2016.[82]

42. While the NEM predominantly comprises ageing centralised generators, low average wholesale prices and relatively flat average demand forecasts present challenges to the viability of any new electricity generation infrastructure suited to baseload supply.

Approximately 58 per cent of coal-fired and 24 per cent of gas-fired generation in the NEM was first commissioned more than 30 years ago, as shown in Figure 4.5, although this does not account for capacity expansions and upgrades after commissioning. Consequently, a significant number of generators have fully amortised capital costs, allowing them to operate at low short-run marginal costs and therefore offer low wholesale prices for the energy they generate. Any new capacity would be more expensive because capital costs would need to be recovered. At some stage, as the existing generators require replacement, incentives for investment in new generation capacity may need to be contemplated.

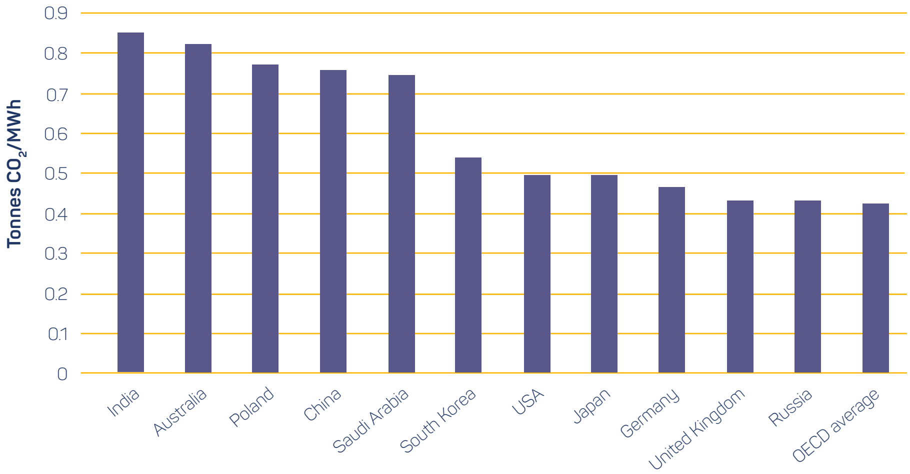


Figure 4.4: Electricity sector emissions for various OECD countries in 2011

Data sourced from A Stock, *Australia's electricity sector: Ageing, inefficient and unprepared*, Climate Council of Australia, 2014, p. 8

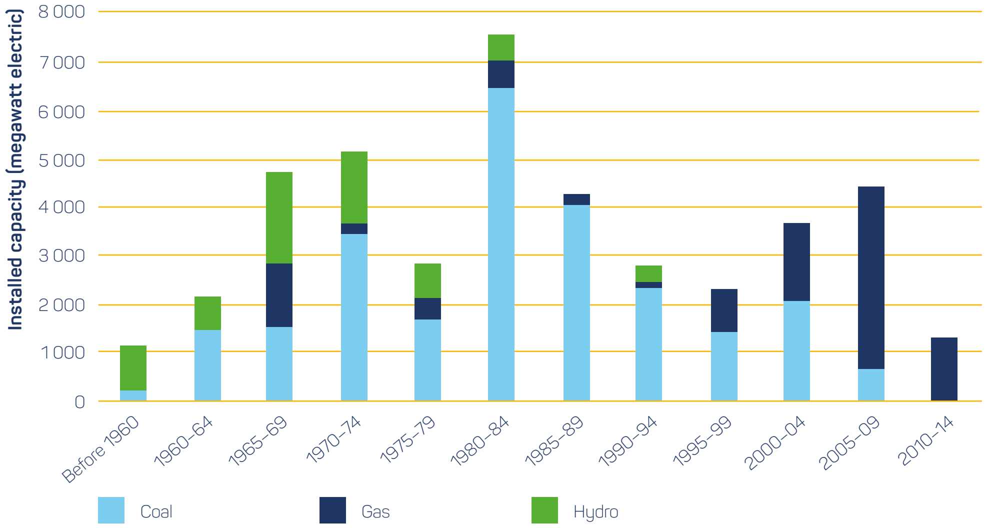


Figure 4.5: First commissioning date of operational baseload capacity in the NEM

Data sourced from the Chamber of Minerals and Energy of Western Australia, submission to the Nuclear Fuel Cycle Royal Commission, p. 22

A significant amount of generating capacity will be withdrawn from South Australia during the next few years due to the closure and mothballing of coal and gas-fired generators. This will place more reliance on importing electricity from Victoria through the interconnectors, unless generation capacity is replaced locally.[83]

Generators in the NEM sell electricity through a wholesale spot market. As an energy market, generators are paid based on the energy they supply, and the cheapest offers of electricity at any time are dispatched to meet demand.[84] Generators need to be able to offer their electricity at a sufficiently competitive price to ensure selection for dispatch and are only able to sell electricity at very high prices when demand exceeds available supply.[85]

As shown in Figure 4.6, electricity demand in the NEM has declined during the past five years due to several factors including high electricity prices, penetration of roof-top solar photovoltaics (PV), increased energy efficiency and the closure of aluminium smelting and manufacturing facilities, for example, automotive factory closures in Victoria

BASELOAD VERSUS PEAKING GENERATORS

Generation technologies differ in terms of their flexibility of operation and consequently their ability to take advantage of fluctuations in the market.

Baseload generators such as coal and nuclear are typically operated to maintain a constant level of generation, and are therefore most profitable when required to meet a steady and predictable level of demand.

Peaking generators such as gas are able to start up quickly compared with other generation technologies, and therefore have the flexibility to react to sharp increases in demand. Peaking generators can still be profitable even though they may only operate for several days a year. Because they are the only source of supply at such times, they are able to charge large wholesale prices, enabling them to meet their costs despite their infrequent operation.

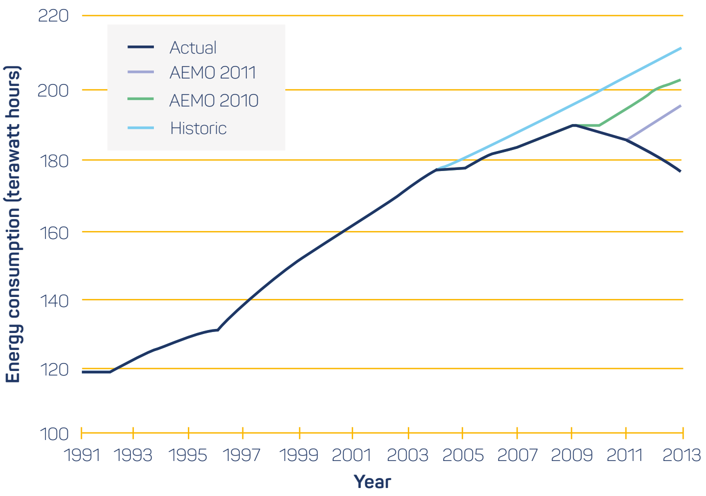


Figure 4.6: Energy consumption in the NEM—actual and predicted

and South Australia.[86] This decline, which was not predicted by the industry, has resulted in the temporary and permanent removal of some capacity from the NEM.[87]

The flat demand for electricity has negated the need for further generation investment in the near future, with the vast majority of new generation being LRET-incentivised wind energy.[88] However, the intermittent nature of wind generation can lead to it supplying a large amount of energy during low demand periods, resulting in low and even negative wholesale prices at these times. This presents a challenge for baseload generation technologies to compete financially.[89]

43. The following characteristics of the South Australian region of the NEM affect the viability of current or potential new baseload generators, such as a nuclear power plant:

a. The annual demand profile is characterised by peaks that substantially exceed average daily demand, which results in one-third of South Australia's generation mix being used less than 200 hours annually.

The South Australian region of the NEM is characterised by significant peaks in its demand profile on both short and long time scales. This is predicted to continue, with the maximum demand forecast to reach 2.2 times the average demand by 2024–25, easily the largest ratio of any region in the NEM, as shown in Figure 4.7 and discussed in Box: South Australia's electricity price competitiveness to 2030 and beyond.[90] This poses a significant challenge for the commercial viability of large-scale plant because although a large amount of capacity is needed to meet maximum demand, the amount of time this maximum capacity is used is limited.

b. The daily minimum demand for electricity has been falling as a result of increased penetration of solar PV. Yet solar PV has had little effect on peak demand requirements.

The minimum operational demand typically occurs in the middle of the day, and, given this coincides with the maximum operation of solar PV, has caused a steady decrease in operational minimum demand in South Australia during the past several years. By 2023–24, it is expected that solar PV will completely meet demand between 12:30 and 14:30 on particular minimum demand days.[91] Conversely, the uptake of solar PV has had little impact on operational maximum demand, particularly as peak demand typically occurs between 16:00 and 21:00 on hot summer days, when solar PV is past peak operation.[92]

c. Total demand is small, with low expected short- and medium-term growth, such that a very large generator would supply a large portion of demand.

As discussed, total demand in South Australia is relatively small compared with other regions in the NEM, with maximum demand between 2900 megawatts (MWe) and 3400 MWe.[93] Large-scale generators typically have capacity of about 1000 MWe, approximately one-third of current maximum demand in South Australia.

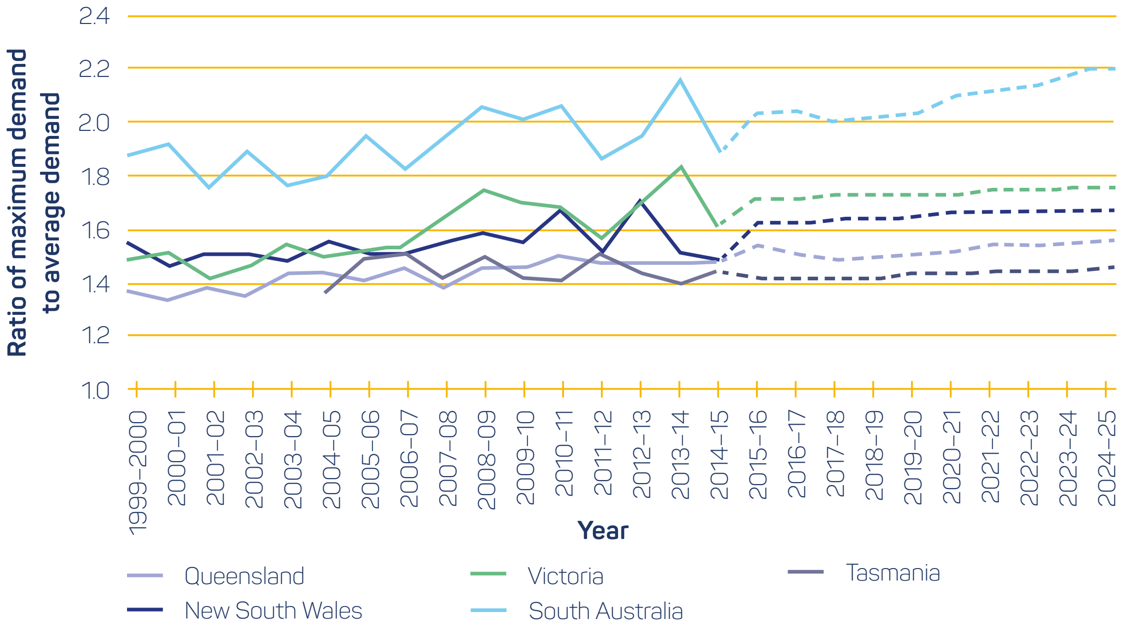


Figure 4.7: Ratio of maximum demand to average demand for each region in the NEM

Data sourced from AER, *State of the energy market report*, 30 June 2015, p. 26

d. There is substantial, and growing, intermittent generating capacity, which relies on interstate coal generation and peaking gas generation to continuously balance supply and demand.

In 2014/15, wind and solar PV made up 34 per cent and 7 per cent respectively of South Australia's total generation capacity. This high penetration of intermittent generation necessitates having a large amount of capacity that is ready to meet demand in periods of low wind and sunlight. Demand cannot always be met by local generation, requiring South Australia to import electricity from Victoria via the Heywood and Murraylink interconnectors.[94] This is typically sourced from coal-fired generation due to its low cost.[95]

e. The penetration of wind has altered the operational characteristics of existing gas and coal generation from baseload to load following.

Because wind farms typically have very low short-run marginal costs, they can place particularly low-cost bids in the NEM, which consequently sees all wind energy dispatched in South Australia when it is available.[96] As a result, fossil fuel plants that were historically operating as baseload generation are now operating as peaking generation, that is, periodically dispatched to meet peak demand rather than constantly supplying the minimum demand.

f. South Australia's relative isolation from the wider NEM due to limited transmission interconnection inhibits the import and export of electricity.

The import and export of electricity across state borders is limited by the physical constraints of the interconnectors—200/220 MWe for Murraylink and 460 MWe (currently being upgraded to 650 MWe) for Heywood.[97]

g. Relative to other regions of the NEM, South Australia has one of the highest average wholesale prices and some of the greatest price volatility.

South Australia has had either the highest or second-highest average annual electricity wholesale price in the NEM for each of the past nine financial years.[98] This has negatively affected the competitiveness of energy-intensive industries in the state. Additionally, South Australia has experienced significant price volatility (both highs and lows) in the past few years compared to other NEM regions. Price volatility in South Australia has been driven by coal and gas plant withdrawals, concentrated generator ownership (lack of competition), and limited capacity to import electricity via the interconnectors (see Box: South Australia's electricity price competitiveness to 2030 and beyond).[99]

SA’S ELECTRICITY PRICE COMPETITIVENESS TO 2030 AND BEYOND—POLICY IMPACTS

The Commission’s modelling considered the effect on wholesale electricity prices in a scenario where there was no nuclear, but increasing renewable generation to 2030 and beyond. This assessment was necessary to both form a baseline against which the introduction of nuclear generation could be contrasted and identify any supply shortfall that a nuclear generator could fill.

This analysis offers some insights into the policy effects of reducing carbon emissions to South Australia’s future electricity competitiveness relative to other regions of the NEM to 2030 and beyond.

Over recent years, the South Australian subregion of the NEM has had some of the highest average wholesale electricity prices in the nation. These prices make up part of the retail electricity price paid by businesses and households. The other parts are the cost of the transmission and distribution network, taxes, and subsidies paid to generators. Figure 4.8 compares South Australian wholesale prices with those of other NEM subregions since 2006/07.

The volatility in South Australia’s wholesale electricity prices (the extent to which prices range from highs to lows) relative to the other NEM states is shown in Figure 4.9. South Australia experiences a much higher frequency of both negative and very high regional reference prices relative to the other NEM states. The very low price events are attributable to significant electricity supply from intermittent renewables during periods of low demand, whereas the very high price events are attributable to a combination of factors, including on occasion the need to rely on open cycle gas turbines when there is little or no supply from intermittent renewables.

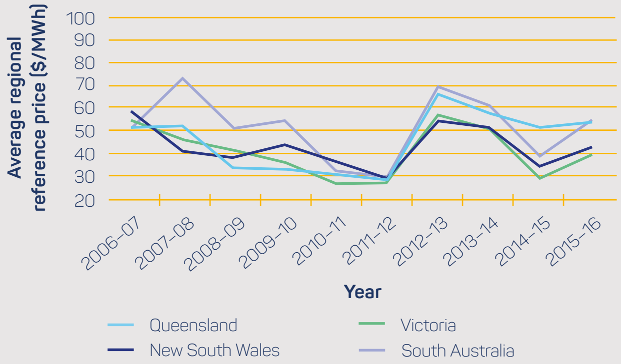


Figure 4.8: Annual average regional wholesale price across mainland NEM states from 2006/07 to 2014/15

Data sourced from Australian Energy Market Operator (AEMO), Average price tables

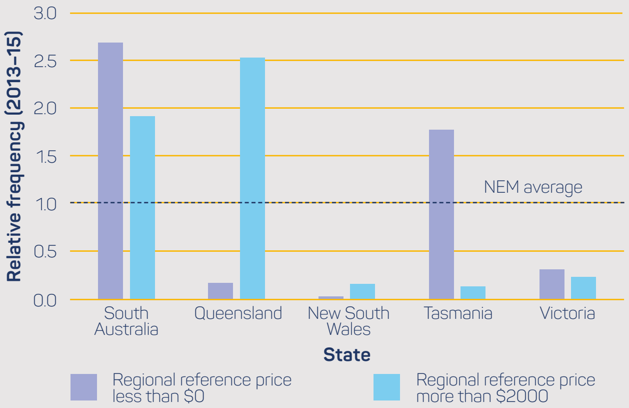


Figure 4.9: The frequency of negative and very high regional wholesale prices in NEM regions relative to the average, 2013–15

Data sourced from AEMO, Pricing event reports

The modelling undertaken for the Commission distinguished between two means of delivering low-carbon energy generation to meet abatement targets between 2017 and 2030:

1. continuing policies, such as the LRET scheme and emissions reduction fund, which is not technology neutral (a Current Policies scenario).
2. introducing market mechanisms, such as a carbon price, which is technology neutral (the New Carbon Price scenario).[1]

After 2030, the model assumed that a carbon price would apply. The scenarios and corresponding assumptions are explained in greater detail in Table G.2 and Figure G.2 in Appendix G: Nuclear power in South Australia—analysis of viability and economic impacts. The wholesale price was derived from the lowest-cost mix of technologies that was determined based on the current Australian estimates of the costs of renewables and storage shown in Figure G.3 of Appendix G. These assume subtantial cost reductions for both renewables and storage technologies.

Under both scenarios the average wholesale electricity price is higher in South Australia than it is now. However, the two policies had significantly different effects on electricity price competitiveness for South Australia.

SA'S ELECTRICITY PRICE COMPETITIVENESS TO 2030 AND BEYOND—POLICY IMPACTS (CONT'D)

Current policy mechanisms (not technology neutral)

A continuation of current policy interventions was shown to lead to continuing growth and relatively higher concentration of renewable generation in South Australia, compared to other regions (see Figure 4.10). The difference arises in the analysis as a result of better wind resources in South Australia; the presence of existing low-cost generation in some other regions, which diminishes the attractiveness of installing new capacity; and differences in state-based policies supporting new renewable capacity.

This policy has clear implications for wholesale price competitiveness in South Australia, as shown in Figure 4.11. In the period between 2017 and 2030, it leads to wholesale electricity prices in the state being 20 per cent higher than the NEM average. The comparatively higher price in the model arises from a combination of effects that includes the predicted high penetration of renewables in South Australia, the lack of diversity in the local generation mix to meet the balance of demand, and the lower shares of renewable generation in other regions of the mainland NEM.

Carbon price policy mechanism (technology neutral)

If a technology-neutral policy such as a carbon price were introduced to drive emissions reductions, there would be more uniform growth in the share of renewable generation across the mainland NEM states, as shown in Figure 4.10. This is because all generators must meet the full costs of their carbon emissions, including low-cost generators in other regions. Under this policy South Australia was still estimated to have the greatest share of renewable generation; however average wholesale prices in the state became similar to other regions as a carbon price leads to a rapid increase in renewable capacity from 2017, as shown in Figure 4.11.

Prices converge under both scenarios beyond 2030, as a carbon price is assumed to apply under both scenarios modelled.

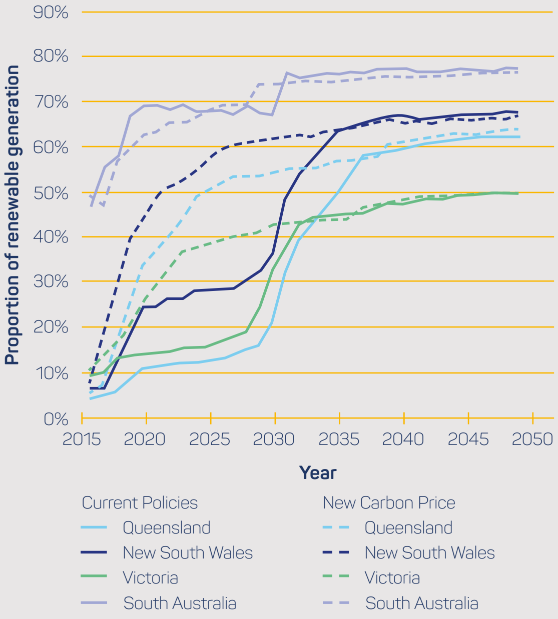


Figure 4.10: Renewable generation as a proportion of total generation by 2050 in the mainland NEM states under the Current Policies or New Carbon Price scenarios

Data sourced from Ernst & Young, *CGE modelling assessment*, underlying market model data

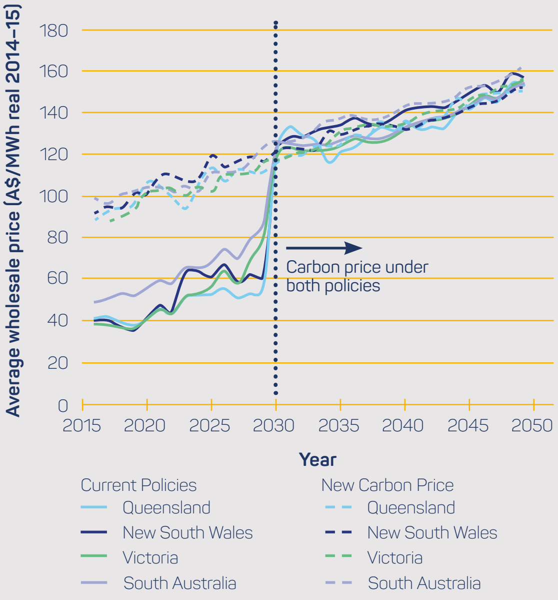


Figure 4.11: Annual average wholesale price of electricity to 2050 for all mainland NEM states under Current Policies and New Carbon Price scenarios

Source: Ernst & Young, *CGE modelling assessment*, underlying market model data

[1] Ernst & Young, *Computational general equilibrium modelling assessment*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2016, section 3.2, pp. 26-27.

IN WHAT CIRCUMSTANCES IS THE ACTIVITY VIABLE?

44. An assessment of the viability of establishing a nuclear power plant in the South Australian NEM would require a full systems investigation.

Whether any additional electricity generator, including a nuclear power plant, would be able to deliver a sufficient return on investment in the South Australian NEM depends on whether it would be dispatched to supply electricity at a price that generates profits. This would require a full systems analysis of:

- the costs of establishing and operating a new nuclear power plant in South Australia[100]
- the levels of future demand in the South Australian NEM at the time that such a plant might be operating, which in turn would require an analysis of the earliest reasonable date of operation[101]
- the costs and outputs of the generators that would be competing to meet that demand—both existing generators and those likely to be integrated into the grid over the same time—which would inform analysis of the wholesale prices with which a new nuclear power plant might need to compete[102]
- the impact of carbon abatement policy measures on the electricity market[103]
- wholesale prices in the South Australian subregion following the introduction of any new generating capacity.[104]

45. Based on analyses addressing these issues, it can be concluded that, on the present estimate of costs and under current market arrangements, nuclear power would not be commercially viable to supply baseload electricity to the South Australian subregion of the NEM from 2030 (being the earliest date for its possible introduction).

The Commission did not find that nuclear power is 'too expensive' to be viable or that it is 'yesterday's technology'. Rather, it found that a nuclear power plant of currently available size at current costs of construction would not be viable in the South Australian market under current market rules.[105] The outcome of this analysis is consistent with a wide range of realistic scenarios. It does not necessarily apply to other jurisdictions in Australia. In fact, some of the modelling suggests that nuclear might well be viable elsewhere, as the challenges facing baseload generation in South Australia are not shared with other regions of the NEM. This is explained in more detail below, and in Appendix G: Nuclear power in South Australia—analysis of viability and economic impacts.

CAPITAL COST OF NUCLEAR

The development of a nuclear power plant involves a substantial upfront capital investment before operating revenues are earned. The amount of this investment is therefore critical to an analysis of viability. To have confidence in its estimated costs, the Commission applied the following criteria:

1. The reactor technology had to have been successfully constructed and commissioned elsewhere at least twice by 2022.
2. All cost estimates were to be based on realised-cost benchmarks or, if they were not available, independently verified estimates.

In terms of attempting to establish the likely capital costs of a new nuclear power plant, the Commission assessed that the most reliable data is recent, realised benchmarks in project development and construction timeframes. In the case of new technologies that have not been constructed, such as SMRs, the Commission considered that it was necessary to take a conservative approach to projected costs until they could be demonstrated. It did not consider the costs of advanced reactors that are not commercially proven and hence have no reliable bases for estimating costs.

The estimate of total costs used by the Commission for construction of a large pressurised water reactor (PWR) is set out in Table 4.2. The estimate is derived from known costs of the Westinghouse AP1000 PWR (1125 MWe) based on available realised costs for the four units (two each at Vogtle and VC Summer) under construction in the USA.[106] The known costs were adjusted as they relate to the construction of reactors in pairs, whereas the costs estimated in Table 4.2 are for a single reactor. The analysis sought to apply costs to local conditions by estimating additional expenditure associated with establishing supporting infrastructure such as electrical connection, reserve capacity, roads and wharf facilities, and water supplies. Separate estimates were made for greenfield and brownfield sites, which took account of the proximity of existing infrastructure.

Table 4.2: Capital and supporting infrastructure costs for a large nuclear reactor (PWR) at a brownfield and greenfield site

Site	PWR (1125 MWe) (A$ 2014[a])
Brownfield site	$8962m ($7966/kW)
Greenfield site	$9323m ($8287/kW)

a. Includes pre-construction, licensing, supporting infrastructure and connection costs.
Note: Megawatt electric (MWe); per kilowatt (/kW).
Data sourced from WSP/Parsons Brinckerhoff, *Final report: Quantitative analysis and initial business case – establishing a nuclear power plant and systems in South Australia*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2016, section 6.

Because of the potential for plants with smaller capacity to successfully integrate with the South Australian NEM, the Commission considered the viability of light water SMRs of less than 400 MWe. Because even the most advanced designs for such SMRs have not been commercially licensed, there are no available benchmarks.

The Commission undertook the analysis based on two of the more advanced SMR designs, which are in the process of licensing and appear to have prospects for commercial deployment.[107] In the absence of a demonstration of the SMR's actual costs, the Commission was not prepared to accept the projections of costs made by nuclear power plant vendors. These projections ranged from A$7000 to A$8000 per kilowatt, which is substantially lower than the Commission's analysis.[108] While the Commission accepts that the projections represent the target for vendors, and are in some cases their best estimate of costs, it could not confidently proceed on that basis.

Given this, the capital costs of SMR systems for the purposes of the Commission's study was estimated to be 5 per cent higher than that of the large-scale PWR costs presented in Table 4.2, on the basis that a small plant has not been demonstrated to achieve the economies of scale of a large plant.[109] The costs of licensing and project development were added to that. The cost estimates used by the Commission for constructing two types of SMR, including supporting infrastructure, on either a brownfield or greenfield site are set out in Table 4.3.

Table 4.3: SMR capital and supporting infrastructure for two designs

Site	SMR (285 MWe) (A$ 2014[a])	SMR (360 MWe) (A$ 2014[a])
Brownfield site	$2942m ($10 323/kW)	$3302m ($9173/kW)
Greenfield site	$3331m ($11 689/kW)	$3692m ($10 256/kW)

a. Includes pre-construction, licensing, supporting infrastructure and connection costs.
Note: Megawatt electric (MWe); per kilowatt (/kW).
Data sourced from WSP/Parsons Brinckerhoff, *Establishing a nuclear power plant*, tables ES1–8.

The cost estimates used by the Commission are, in the case of a large nuclear reactor (PWR), substantially higher than those used in the Australian Energy Technology Assessment 2013 Model Update (AETA 2013), but similar to those used in the Australian Power Generation Technology Report in 2015, set out in Table 4.4.[110] Internationally, the IAEA and the International Energy Agency (IEA) have published costs in the same order as the AETA 2013 costs. The Commission's higher costs are substantially explained by its use of a lower exchange rate (the long-term average), inclusion of pre-construction and project development costs (excluded in the AETA analysis), and supporting infrastructure such as port facilities.

Table 4.4: PWR and SMR capital and supporting infrastructure costs for a brownfield site

	PWR	SMR
Australian Energy Technology Assessment 2013 Model Update (first-of-a-kind costs)[a]	$6392/kW	$11 778/ kW
EPRI/CO_2CRC Australian Power Generation Technology Report (2015)[b]	$9000/kW	N/A

a. Bureau of Resources and Energy Economics, Australian Government, Canberra, 2013.
b. Electric Power Research Institute, 2015, p. 127.
Note: Per kilowatt (/kW).

TIMEFRAME FOR INTRODUCTION AND LIKELY DEMAND AT THAT TIME

The Commission considers 2030 to be the earliest that a nuclear power plant could reasonably be expected to start operation in South Australia. This allows 14 years for establishing regulatory systems and expertise, undertaking a detailed assessment of the nuclear supply chain before pre-licensing activities, licensing, project development and construction for a large plant. This is an ambitious timeframe, but the Commission considers it reasonable if there were an imperative for development.[111]

Total network demand at that time will depend on the extent to which some renewable generation, energy storage and electric vehicle technologies are deployed. While increased roof-top solar PV would reduce demand, electric vehicles would both increase total consumption and change the demand profile. The extent to which these technologies may be deployed will be substantially driven by cost reductions that may be realised up to 2030.

To account for this uncertainty, the Commission's analysis of future demand in the NEM is based on separate projections for the residential, business and industrial sectors (incorporating network losses), including reducing demand to take account of solar PV generation and storage 'behind the meter', that is, local storage within businesses and residences. Different projections were made, taking account of growth in demand for electric vehicles, other economic activities (including population growth) and the effect on demand caused by consumers' response to increasing prices.

COMPETING GENERATION TECHNOLOGIES

To determine which technologies would be able to offer the lowest overall wholesale electricity prices to meet expected demand in 2030, the Commission used the most recent Australian estimates of costs published in the *Australian Power Generation Technology Report* (2015).[112] It also took account of expected reductions in cost previously published as part of the AETA 2013 update[113], as shown in Figure G.3 in Appendix G.

The cost of nuclear power plants is assumed to remain stable to 2050. Responses to the Tentative Findings have criticised that position, suggesting that cost reductions should have been assumed in response to rising global deployment. In the Commission's view there is significant uncertainty in relation to realising such cost reductions, given the lack of demonstrated evidence to date in Western democracies.

IMPACT OF CARBON ABATEMENT POLICIES

The mix of generation technologies likely to be competing with a nuclear power plant and their wholesale costs would also be affected by the scope and timing of policy measures to reduce the CO_2 emissions intensity of the energy sector. Such measures could affect the wholesale price of electricity and, if they are targeted, advantage particular technologies. The modelling undertaken for the Commission took this into account.

Significant uncertainty remains in relation to the policy measures that are likely to be implemented. To reasonably account for the likely impact of such measures, the Commission developed what it considers are plausible scenarios. These scenarios are based on existing measures (for example, the emissions reduction fund and LRET), recent policies (for example, a carbon price and emissions trading scheme), and the Australian Government's emissions reduction goals for 2030.[114]

Based on each of the above inputs, market modelling was undertaken to determine the lowest-cost mix of generation in the wholesale market that would make up the NEM to 2050. The model also determined the price of electricity that would correspond to this mix. This is discussed in further detail in Appendix G.

Nuclear power, on current costs, was not part of the lowest-cost mix.[115] Instead, significant growth in intermittent renewable generation was estimated to be supported by a combination of 900 MWe of combined cycle gas turbine capacity, the current level of peaking gas generation of 950 MWe and behind-the-meter energy storage. The mix of installed gas generation was found to comprise about 25 per cent of South Australia's total generation in 2030 and 22 per cent in 2050.[116]

46. The conclusion that nuclear power is not viable in South Australia remains the case:

a. on a range of predicted wholesale electricity prices incorporating a range of possible carbon prices

The Commission undertook analysis to determine whether the implementation of various carbon abatement policy measures could improve the viability of a nuclear power plant in South Australia. The analysis included hypothetical scenarios ranging from less stringent measures to more. They were:

- a continuation of the emissions reduction fund to meet abatement objectives of 26–28 per cent of 2005 levels by 2030 and implementation of a carbon price beyond 2030 to meet an emissions reduction of 80 per cent of 2000 levels by 2050 (Current Policies scenario)[117]
- the implementation of a carbon price in 2017 to meet the same emissions reduction objectives as those achieved under current policies (New Carbon Price scenario)[118]
- the implementation of a carbon price in 2017 to meet an emissions reduction objective of 65 per cent of 2005 levels by 2030 and complete decarbonisation by 2050 (Strong Carbon Price scenario).[119]

Only the Strong Carbon Price scenario would achieve emissions abatement consistent with the 'well below 2 °C' target affirmed at the 2015 United Nations Climate Change Conference in Paris.[120] Such a scenario significantly increased the wholesale price of electricity under current market rules (see Figure 4.12).

As would be expected, the potential viability of a nuclear power plant in South Australia improved under more stringent carbon policies, but remained unviable even under the Strong Carbon Price scenario.

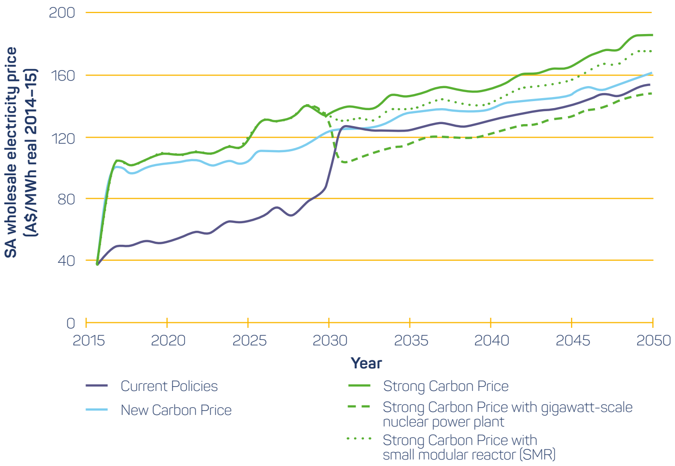


Figure 4.12: Annual average real wholesale electricity price in South Australia, 2014/15 prices

Data sourced from Ernst & Young, *CGE modelling assessment*, section 5.9, figure 47

Further, the construction and operation of a nuclear power plant were found not to have a positive rate of return at a commercial cost of capital of 10 per cent under any of the carbon abatement scenarios. The estimations of viability presented in Table 4.5 represent the best-case scenario for nuclear, operating as a baseload plant in South Australia with an expanded interconnection of up to 2 gigawatt electrical (GWe), if it were commissioned in either 2030 or 2050.

Table 4.5: Profitability at a commercial rate of return (10 per cent) of large and small nuclear power plants commissioned in 2030 or 2050 under the New Carbon Price and Strong Carbon Price scenarios

	Net Carbon Price Net present value (A$ billion 2015)		Strong Carbon Price Net present value (A$ billion 2015)	
Year of commission	**2030**	**2050**	**2030**	**2050**
Small modular reactor (285 MWe)	–2.2	–1.9	–1.8	–1.4
Large nuclear power plant (1125 MWe)	–7.4	–6.4	–6.3	–4.7

Data sourced from DGA Consulting/Carisway, *Final report for the quantitative viability analysis of electricity generation from nuclear fuels*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2016, section 6, tables 35–36).

b. for both large or proposed new small reactor designs

The establishment of a large nuclear power plant in the South Australian NEM was assessed to lead to an almost one-quarter decline in average wholesale prices (see Figure 4.12). While positive for South Australian consumers, this would dramatically affect the revenue earned and thus the viability of such a plant in this market.

This effect on wholesale prices is due to the relatively small size of the South Australian market. The introduction of a large nuclear power plant would be likely to have a much smaller impact on wholesale prices in Victoria and New South Wales because its output would form a much smaller portion of total demand. The modelling undertaken for the Commission indicated that a large nuclear generator in South Australia selling half its electricity in Victoria (through transmission) would only decrease wholesale prices in Victoria by 3 per cent.

A small nuclear power plant was not viable. This is not due to its effect on reducing wholesale prices, which fell by only 6 per cent (see Figure 4.12). Rather, its viability was mainly affected by its anticipated 15–30 per cent higher construction cost per kilowatt when compared with a large plant. This underscores the need to carefully follow the actual costs in small nuclear plant developments globally and any potential relevance to South Australia.

c. under current and potentially substantially expanded interconnection capacity to Victoria and NSW

Modelling showed that under current levels of interconnection, up to half of all nuclear generation from either a small or large nuclear power plant in South Australia would not be used (generation shedding). This would have a significant effect on the viability of a nuclear power plant, doubling the levelised cost of energy generation. It would also lead to the less efficient operation of the installed level of renewable generation, as about 40 per cent of output would be unused over a year unless grid storage systems were developed.[121]

However, as the penetration of intermittent generation in South Australia increases, so too will the viability of additional interconnection capacity between the state and the rest of the NEM.[122] This is to facilitate both the export of renewable electricity and the reduction of peak electricity prices in South Australia when there is reduced supply from intermittent sources. A joint AEMO/ElectraNet study in 2011 that assessed the viability of transmission upgrades found that only a relatively small upgrade to the Heywood interconnector was justifiable at that time. However, it anticipated that under some carbon abatement scenarios, consistent with the strong policies analysed by the Commission, an expansion of capacity to 2000 MWe would be viable in 2025.[123]

For those reasons the modelling undertaken for the Commission analysed the effects on viability of a South Australian nuclear power plant if transmission were substantially expanded to 2000 MWe, enabling the plant to export substantial additional electricity into the eastern regions of the NEM. Even with such exports, the analysis showed that a large nuclear plant was not viable.[124]

d. under a range of predictions of demand in 2030, including with significant uptake of electric vehicles.

Nuclear was not viable even on more optimistic views of future demand. The Commission analysed demand on a number of bases, including those with the largest forecast uptake of electric vehicles. Electric vehicles would be expected to add to grid demand through fuel switching from oil and to alter demand profiles depending on the time of charging, but also to contribute to storage in the network. Even in more optimistic scenarios of uptake, equal to 20 per cent of the light vehicle fleet in South Australia, neither a large nor small nuclear power plant in South Australia was assessed to generate a positive rate of return.

47. Off-grid nuclear power is also unlikely to be viable in South Australia in the foreseeable future because of low demand, even assuming optimistic growth of mining activities, and the likely location of that demand.

An off-grid electricity market, not connected to the NEM, supplies mining and remote communities in South Australia.[125] There is currently 77 MWe of installed off-grid generating capacity, dominated by diesel and natural gas generators, to meet 236 GWh of demand.[126] More than 80 per cent of the electricity consumed meets the requirements of industrial customers, predominantly mine operators.[127] However, the off-grid industrial sector is a small subset of the total electricity requirements of the mining industry in South Australia.

In 2014, studies undertaken at the request of the South Australian Government estimated that total electricity demand from the mining sector was 1.7 terawatt hours (TWh) and was estimated to rise to up to 6 TWh by 2023–32, under ambitious scenarios.[128] Even if those outcomes were realised, it is unlikely that new nuclear power plants would be the economic option to supply the required electricity, for three main reasons:

1. Mining operators require flexible energy systems that are able to scale up and down in response to fluctuations in operational requirements.[129] This affects the capacity utilisation of a generator. A nuclear power plant, because of its high capital costs, requires high levels of utilisation to be viable.
2. The construction and operation of a new nuclear plant in a remote location is likely to increase capital costs, making it less attractive than established alternatives.[130]
3. Even if a mining region were likely to generate the large and stable demand necessary to support a nuclear power plant, it may nevertheless be more cost effective to connect that mining region to the NEM for its power needs, the cost of which could be estimated with greater certainty than a nuclear power plant.[131]

48. While nuclear generation is not currently viable, it is possible that this assessment may change. Its commercial viability as part of the NEM in South Australia under current market rules would be improved if:

a. a national requirement for near-zero CO_2 emissions from the electricity sector made it impossible to rely on gas generation (open cycle gas turbine and combined cycle gas turbine) to balance intermittency from renewable sources

Gas-fired generation plays a significant role in providing reliable supply under all future low-carbon scenarios for the electricity sector. Under the Commission's model of a Strong Carbon Price scenario, gas was estimated to deliver more than 30 per cent of generation across the NEM by 2050.[132] Combined cycle gas turbine generation, even under a Strong Carbon Price scenario, was estimated to be profitable despite greater emissions intensity than nuclear.

However, implicit in the Commission's and other models of a future low-carbon electricity sector is that international carbon permits could be acquired to offset gas-fired generation emissions. The viability of gas-fired generation would be affected if either the cost or the credibility of emissions permits did not meet expectations.[133] Either outcome would result in a higher domestic carbon price that would improve the relative viability of nuclear power generation as part of the lowest-cost, low-carbon mix of energy generation.

SOUTH AUSTRALIA'S FUTURE ENERGY GENERATION MIX

There is considerable optimism about the potential of renewable technologies to meet South Australia's electricity needs. However, even with anticipated substantial reductions in costs, wind, solar PV and energy storage alone will not provide the lowest-cost mix of electricity generation.

Developments in renewable electricity generation technologies, particularly wind and solar, are of considerable interest and importance to the community. Reductions in the costs of such technologies during the past decade have been faster than anticipated, and further reductions are forecast. Modelling undertaken for the Commission and others suggests that intermittent renewable generation and storage technologies will make up a substantial share of the future lowest-cost mix of supply.[1]

However, the output of those models shows that even with expected cost reductions and favourable carbon emission abatement policies, the lowest-cost generation mix does not consist of wind, solar and storage alone.[2] In most cases, it also incorporates a significant level of firm, dispatchable fossil fuel-based generation capacity to constantly match demand with supply.[3] That is the case even under strong climate action scenarios.

This is due to a combination of our electricity demand profile, the intermittent nature of wind and solar generation, and the cost of installing new capacity. Given the demand peaks experienced in South Australia, the amount of wind, solar and storage capacity that would be required to reliably meet those peaks is substantial. However, as each additional wind, solar or storage unit is installed, it is likely to be required only to supply electricity to meet an increasingly smaller portion of demand.[4] Based on such limited utilisation, the revenue able to be achieved will eventually be insufficient to recover the costs of the unit's installation.

It is cheaper overall for gas-fired generation to be deployed to meet the highest peaks of demand, as gas plants are generally profitable as long as they can supply a sufficient level of demand at a higher price than the cost of fuel. This may have adverse implications for the cost of decarbonisation of the electricity sector if expected price reductions in renewable energy technologies are not realised.[5]

This is the reason future scenarios for an electricity system comprising only renewable energy sources often include a substantial share of geothermal and/or pumped hydro generation. The question remains as to whether either of these technologies is commercially feasible and cost effective at the required scale, as compared to gas-fired and/or nuclear, as discussed at Findings 51–54.

[1] Ernst & Young, *CGE modelling assessment*, section 6.

[2] DGA Consulting/Carisway, *Final report for the quantitative viability analysis of electricity generation from nuclear fuels*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2016, sections 4.6–4.7.

[3] Ernst & Young, *CGE modelling assessment*, section 5.5.8.

[4] Khalipour & Vasallo, 'Leaving the grid: an ambition or a real choice', *Energy Policy* 82, July 2015.

[5] DGA Consulting/Carisway, *Final report*, section 5.2.2; Ernst & Young, *CGE modelling assessment*, section 5.5.8.

b. the intermittency of renewables could not be supported adequately by cost-effective storage at scale or by new demand sources such as 'power to fuel', which converts surplus power into a transport fuel source

Residential and grid-scale energy storage offers the potential to store surplus energy from intermittent wind and solar generation when supply exceeds demand, and to later release that energy when demand exceeds supply.[134] Although residential storage is not yet commercially viable[135], all current modelling assessments, including those undertaken for the Commission, see storage playing a significantly larger role in supporting the establishment and integration of additional intermittent renewable generation capacity.[136]

Similarly, other emerging technologies such as power-to-fuel arrangements may offer the potential to convert surplus electricity to a transport fuel in the form of hydrogen.[137] However, these technologies are yet to be demonstrated at scale in Australia.

Storage and power-to-fuel technologies also offer the potential to displace capital expenditure on the transmission and distribution networks. However, if the expected reductions in the cost of these technologies are not realised, the potential for nuclear power to provide reliable generation capacity to balance the intermittency of wind and solar would be improved.

c. system augmentations required to support substantially greater wind generation and commercial solar PV were more expensive than anticipated

Intermittent generation capacity requires electricity network support, therefore potentially increasing costs in several ways.

For example, it requires additional capacity to be installed that substantially exceeds the demand for energy from the network. That overcapacity is required to manage the intermittency of supply and allow for the storage of sufficient energy in the system so that it may be released during periods of low supply.[138]

Further, new wind and commercial solar PV generation plants need to be connected to the NEM. As the optimal locations for such plants within reasonable proximity to the existing transmission network reach capacity, extensions to the transmission network would be required to connect increasingly more remote locations.[139] The increasing costs of that network augmentation have not been studied in detail.[140]

Integrating more intermittent generation in the NEM would also require augmentation of the transmission and distribution networks to reduce congestion during periods of peak supply from roof-top PV and wind generators when instantaneous generation exceeds transmission capacity. A 2013 AEMO study estimated that without such augmentation in South Australia, up to 15 per cent of the installed total energy output of wind generators may be curtailed by 2020–21 due to transmission constraints.[141]

If system augmentations are more expensive than current estimates, the cost of deploying additional wind and solar PV generation would increase. This would improve the relative viability of a large or small nuclear power plant because it is likely to be able to be integrated into existing networks without significant augmentation.

d. the costs and risks associated with demonstrating and integrating carbon capture and storage with fossil fuel generation at scale are greater than presently anticipated

Carbon capture and storage integrated with combined cycle gas turbine generation was estimated by both the Future Grid Forum's and ClimateWorks Australia's analyses of future low-carbon energy systems to meet a significant share of generation by 2050.[142] In the modelling undertaken for the Commission, the technology was also shown to be viable under current estimates.

However, as discussed at Appendix G, those outcomes are premised on cost projections assuming technical solutions that are yet to be realised. If these solutions do not eventuate, or their costs are more expensive than currently anticipated, the potential role of a nuclear power plant as a low-carbon source of reliable electricity generation would be greater.

e. current capital and operating costs of nuclear plants were substantially reduced, which would require overcoming complexities and inexperience in project construction. Some reductions in costs have been partially demonstrated for recent plants constructed in China, but not yet in Europe or the USA

The viability of a large or small nuclear power plant is highly sensitive to the cost of its construction. Capital expenditure including the cost of project development, licensing, construction, connection, ancillary infrastructure and accrued debt interest contributes to about three quarters

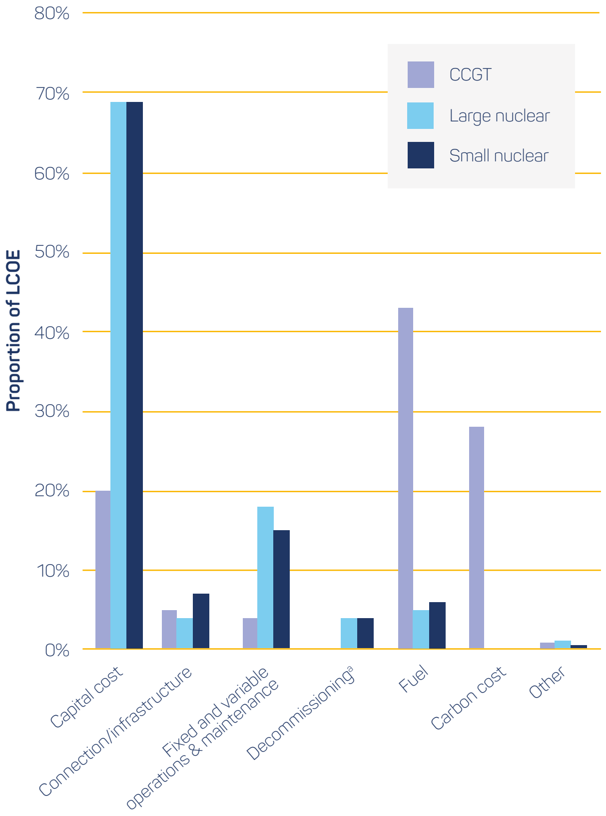


Figure 4.13: The contribution of cost components to the levelised cost of electricity (LCOE) from small and large nuclear power plants and combined cycle gas turbine (CCGT) generation[143]

[a]Decommissioning costs not included for CCGT

of the levelised cost of electricity (LCOE) generated by a nuclear power plant, as shown in Figure 4.13. The contribution of these elements to the LCOE is slightly larger for the small plant because of its lower energy output. Figure 4.13 also shows that more than 70 per cent of the LCOE of a combined cycle gas turbine generator is due to the cost of fuel (43 per cent) and carbon emissions (28 per cent), assuming a carbon price of about $120 per tonne (/t) in 2030 and $255/t in 2050.

Based on the Commission's analysis, for a nuclear power plant to achieve an LCOE competitive with a combined cycle gas turbine plant, capital and infrastructure costs for the nuclear power plant would need to decrease by about 25 per cent.[144]

Reductions in costs have been partially demonstrated for plants constructed in China, but this is not apparent in Europe or the USA. The feasibility of achieving such cost reductions for a nuclear power plant project in Australia is highly uncertain. It will be significant for South Australia to follow developments in international build programs that will show whether or not the nuclear energy industry is capable of applying lessons learned to reduce construction costs. Importantly, the conditions to make such reductions possible in the build country would also need to apply in South Australia.[145]

f. changes to government policy resulted in a combination of:

i. a price on carbon emissions in the economy (including from electricity generation)

The Commission's modelling suggested that a nuclear power plant would not be viable in South Australia even under carbon pricing policies consistent with achieving the 'well below 2 °C' target agreed in Paris in December because other low-carbon generation would be taken up before nuclear.[146] However, more stringent emissions abatement policies have the potential to improve the viability of nuclear power in combination with other measures.

ii. finance at lower cost than available on the commercial market (that is, a form of loan guarantee)

The Commission's analysis showed that the viability of a new nuclear power plant would be highly sensitive to the cost of capital. While not viable at a commercial weighted average cost of capital equal to 10 per cent, a large or small plant would offer a marginally positive return on investment assuming a cost of capital of 6 per cent, and the strongest emissions abatement scenario consistent with achieving the 'well below 2 °C' target.[147]

This is significant given that such a cost of capital is typical for the financing of public projects by government.[148] It can be obtained for the private sector in circumstances where a government guarantee is available. Such arrangements were used to secure the guarantee of the loan provided to develop the Vogtle 4 and 5 nuclear power plants in the USA.[149]

This observation is not a comment on the suitability of taking such a course. It would be a decision to be taken in the context of the commercial and public circumstances faced by a government were it seeking to secure particular types of electricity generation in the public interest.[150]

iii. long-term revenue certainty for investors.

For capital-intensive projects, in the absence of public funding, revenue certainty is important to secure investment.[151] In a market-based electricity system such as the NEM, revenue certainty could only be secured if a long-term power purchase agreement could be established.[152]

Such arrangements are in place in Australia for renewables (including most recently by the Australian Capital Territory Government in an auction for 200 MWe of wind generation capacity)[153] and internationally by other mechanisms such as the Contract for Difference model that was established in the United Kingdom to fund a range of technologies, including both renewables and the Hinkley Point C nuclear power project.[154]

49. The challenges to the viability of nuclear power generation under current market conditions in South Australia should not preclude its consideration as part of a future energy generation portfolio for the NEM. There is value in having nuclear as an option that could be implemented readily.

To achieve deep emission reductions, there is a need for substantial investment in low-carbon generation capacity between now and 2030.[155] The only low-carbon technologies that have been commercially deployed in Australia are wind and solar PV. With increasing reliance on such intermittent generation technologies, there will be a need for substantial investment in reliable generation supply to meet the balance of demand when sufficient wind or sunlight is not available.

Gas-fired technologies will continue to play a significant role in this respect.[156] However, an electricity system that relies only on intermittent renewables and gas risks depending on a single source of supply (gas) at an acceptable price. Gas-fired technologies are not, however, low carbon.

Other renewable technologies including enhanced geothermal systems, grid-scale energy storage, and carbon capture and storage could also play a significant role in helping to balance the intermittency of wind and solar, but their deployment would face significant technical and commercial challenges.

Nuclear power is a mature and deployable low-carbon option that provides reliable electricity supply at almost all times. It is therefore a credible alternative or complement to gas-fired generation in terms of assuring security of supply.[157] Although currently more expensive than combined cycle gas turbine generation, nuclear technologies may achieve cost reductions if expectations of increased global deployment were realised.[158]

50. A future national electricity supply system must be designed to be low carbon and highly reliable at the lowest possible system cost. Resolving this 'trilemma' will be difficult and will require carefully considered government policies.

To meet carbon abatement targets, the electricity sector will need to be one of the first sectors to be decarbonised. A low-carbon electricity system would also need to maintain current levels of reliability. It should be an objective of policy-makers to ensure that those outcomes are delivered at lowest possible cost.[159]

There is a substantial challenge in meeting the three requirements of low carbon, high reliability and low cost.[160] No single option for electricity generation currently commercially available in Australia meets all three criteria because of the intermittency of renewables, the emissions intensity of fossil fuel generation, and the high capital costs of developing nuclear power.

Policy interventions to deliver a transition from the current system to a future system would need to be planned carefully. There is a range of available options to achieve those outcomes, and lessons to be learned from past experience.[161]

The Australian Government has already intervened in the NEM to achieve emissions reductions by offering incentives to install new renewable capacity.[162] The LRET scheme provides an incentive to install new capacity by requiring retailers to purchase electricity from renewable generators[163], and has been successful in driving the installation of significant wind generation capacity. Substantial amounts of roof-top solar PV have resulted from feed-in tariff schemes and direct subsidies to households on the purchase costs of those systems.

While those interventions have reduced the emissions intensity of the electricity sector, they also have had significant effects on the market in the following ways:

1. Intermittent renewable generation capacity has contributed to increased price volatility in the NEM and risks to power system stability. The integration of significant intermittent generation affects the capability of the network to automatically and continuously match supply and demand.[164]

2. The profitability of gas generation has improved, given its ability to respond rapidly to meet shortfalls in supply.
3. The profitability of baseload forms of generation has decreased, thereby discouraging new entry for baseload capacity.[165]
4. The installation of roof-top solar PV has reduced operational demand from the network and required augmentation to the distribution network, as well as encouraged the installation of storage technologies.[166]

The likely impacts of any future energy policy options on the electricity market as a whole must be fully understood before implementation.

51. There are many combinations of generation technologies for a future low-carbon electricity system: it is not a simple choice between nuclear or renewables.

There are many possible combinations of technologies that could form a future low-carbon energy system.[167]

The view put to the Commission that 'we should develop our wind and solar power instead of nuclear' ignores the unique attributes of different generation technologies and their combinations in an electricity network.[168] While wind and roof-top solar PV will continue to play a significant role, their intermittency means they need to be combined with other technologies.[169] There is a wide range of choices of generating technologies to meet the balance of demand, including combinations of lower emission gas technologies, nuclear, geothermal, concentrated solar thermal and energy storage.[170]

Arguments that the choice is between renewables and nuclear fail to address the cost of each system, and the reality of which combination of particular technologies would meet reliability requirements in terms of being capable of deployment when needed.

The need for a combination of technologies is due to the characteristics of electricity demand.[171] The components of that demand (its minimum, average and peaks) dictate the necessary mix of generators. The suitability of generators depends on their operating characteristics and cost. Specifically, the viability of generators with high capital costs and low operating costs is driven by continuous operation or, in the cases of wind and solar PV, when the resource is available.[172] In comparison, the cost structure of gas generation is such that electricity is only produced when prices exceed their variable operating costs (based predominantly on the cost of fuel).

Based on a number of studies undertaken in Australia, including for the Commission, the mix of technologies that will make up the future electricity sector is diverse.[173] While the future market share of generating technologies modelled shows there are several options for achieving emissions abatement, it is equally important for decision-makers to contemplate how those technologies could be made available at scale, and the cost of doing so.

52. Identifying whether a particular generation portfolio would deliver electricity at the lowest possible cost requires an analysis of the future cost of the system as a whole.

Identifying which combination of technologies would be the lowest cost, including whether that mix included nuclear, would require an analysis of the future cost of the whole electricity system, that is, the total costs of electricity generation, transmission and distribution.

This would require a more sophisticated analysis than that advanced in numerous submissions by proponents of particular technologies based solely on the cost per unit of energy generated (LCOE). A variation on that argument was that, because a technology was expected in future to have a lower cost per unit generated, it would outcompete a rival. Such arguments were made both against and in favour of nuclear.[174]

These arguments fail to take account of the system costs of a technology, and also the varying value of electricity produced at different times depending on demand (and therefore customer willingness to pay). LCOE does not, therefore, reflect the revenues that a generator would receive, which is relevant to whether an investor would be willing to build new capacity. LCOE has limits as a tool for making decisions about the relative viability of different generators.[175]

LCOE does provide a baseline measure for comparing the competitiveness of different generating technologies.[176] It captures the cost of building, operating and decommissioning a generating plant over its financial life and its availability over that time (net of scheduled and unscheduled shutdowns).[177] However, LCOE does not take account of the costs of integrating that generation as part of the system, specifically the cost of:

- reserve generation capacity that may be required to meet total demand when the variable renewable energy technology is not available[178]
- additional inter- and intra-regional transmission, distribution and storage infrastructure to ensure generation from geographically disparate locations is transmitted to demand centres.[179]

For those planning a future electricity system (and the market in which it will operate), the relevant issue is the total systems cost, accounting for the cost of generation, connection, inter- and intra-regional expansion of transmission and distribution networks, and grid support costs.

AEMO's 2013 *100% renewables study* gave an indication of the potential total system costs of a hypothetical generation system comprising only renewable energy sources.[180] It was found that the total cost of developing such a system would be $250 billion, which is 200 times the annual value of electricity sold.[181] This assessment took into account anticipated reductions in the cost of renewables, and therefore their expected cost competitiveness with other generation options. How such a system could be funded, and whether it could be developed through private investment alone, is questionable.

53. At present, there is no analysis of a future NEM that examines total system costs based on a range of credible low-carbon energy generation options. Such an analysis would be required before it could be asserted that any option would deliver reliable, low-carbon electricity at the lowest overall cost—with or without nuclear power.

There have been few analyses of the total cost of developing a low-carbon future energy system in Australia, other than AEMO's *100% renewables study*. Other studies undertaken through the Future Grid Forum (FGF) in 2013 and 2015 and ClimateWorks Australia in 2015 have added significantly to discussion and understanding in this area.[182] However, none of these analyses was designed to provide the type of comprehensive investigation required. For policy-makers to consider the implications of different scenarios and avoid unintended consequences of policy interventions, assessments need to be undertaken on the basis of realistic expectations of technology deployment, taking into account the current level of investment and development.

Further study is needed into whether there will be sufficient returns in the electricity market to drive the commercial deployment of desirable, low-carbon energy generation technologies by the private sector. Many of the desirable types of generation technology have substantial upfront capital costs, making viability highly susceptible to the cost of finance.[183]

Further, the studies mentioned indicate that currently commercially unproven generation technologies will assume significant roles as part of a future energy system. In the case of the FGF and ClimateWorks studies, geothermal and/or carbon capture and storage paired with fossil-fuel technologies occupy more than one-fifth of generation by 2050.[184] The FGF and AEMO models assume a significant role for geothermal. Additional investigation is required into the impact of including and excluding those technologies to take account of the fact that they might not be available.[185]

The assessments to date also do not take account of the uncertainty surrounding assumed cost reductions in some technologies. While the costs of nuclear, solar PV and wind are based on established benchmarks, the same is not true for other technologies. Further analysis should be undertaken that includes the true cost of demonstrating technical feasibility, and thus enables 'like-for-like' cost comparisons with mature technologies. Such an approach would also enable certain classes of technologies to be excluded from system studies on the basis of expected costs of demonstration and the likely timeframe for availability.[186]

TIDAL AND GEOTHERMAL RESOURCES

Australia has no commercial-scale ocean energy projects at an advanced stage of development. Pilot-scale projects of less than 1 MWe, developed with substantial government support, are at an early stage of development and are yet to be demonstrated as commercially viable. Prospective reductions in cost depend on outcomes from research, development and demonstration. The deployment of tidal and geothermal technologies also is challenged by the remoteness of resources from grids and siting.[187]

There has been no commercial demonstration of enhanced geothermal systems in Australia. Following initial optimism, there has been substantial disinvestment given the failure to demonstrate permeability at depths suitable for electricity generation, high drill costs and the need to better understand the potential for induced seismicity. Direct-use geothermal, while it has cost advantages in specific settings, has to date had limited ability to contribute to electricity generation and supply in the NEM.[188]

BIOMASS

Existing commercial bio-energy applications are focused on the localised use of sugarcane residues and wood waste and the capture of gas from landfills and sewage plants. The expansion of the use of this resource is limited by a combination of economic factors: its seasonality, the value of biomass or the land on which it is cultivated for other uses, the energy consumed in its cultivation and transport, and its low-energy density.[189]

CARBON CAPTURE AND STORAGE

Carbon capture and storage (CCS) remains commercially unproven at scale in Australia and internationally. The retrofitting of capture systems with existing natural gas- or coal-fired power stations is not currently commercially viable and there are technical challenges in demonstrating the long-term stability of CO_2 in underground formations.[190] Optimism in the last decade about cost reductions in these systems has not been realised, despite the demonstration of the technical feasibility of injecting carbon dioxide into underground formations in the Boundary Dam (Canada) and the Gorgon Basin (Western Australia) oil recovery projects.[191]

While it is proposed that substantial investment in research and development may prove the feasibility of CCS in Australia[192], options modelling undertaken for the Commission suggested that a substantial portion of that investment would need to be publicly funded. A private investor would have insufficient revenue certainty from future generation plants integrating CCS to recover the capital and interest costs of research and development. In any event, the wide deployment of CCS also will be significantly affected by economic factors associated with the price of oil and gas, the efficiency of carbon dioxide separation, and constraints associated with siting and delivering community consent.[193]

ENERGY STORAGE

While battery storage technologies for a range of South Australian commercial and residential consumers are likely to be viable in the near future (particularly for those with time-of-use or capacity-based tariffs and who can integrate photovoltaic systems), the same is not true for on-grid storage. Battery, thermal or pumped hydro storage may have a future role by displacing additional transmission capacity and/or peaking generation capacity. A recent CSIRO analysis, based on expected declines in battery prices, concluded that the levelised cost of energy from lithium-ion batteries could be competitive with gas peaking power plants by 2035, but only in parts of the network such as South Australia and Queensland where there is a significant requirement for peaking capacity.[194]

54. A critical issue to be determined in a total systems cost analysis of a future NEM is whether nuclear could lower the total costs of electricity generation and supply.

Some of the additional systems costs required to support low-carbon electricity systems incorporating substantial market shares of wind and solar PV paired with storage capacity have been discussed previously. Other combinations of low-carbon generation may not impose the same costs.

Nuclear power may offer the potential to reduce total system costs by reducing the need for the measures discussed in Finding 52 and their associated costs. While nuclear power requires some reserve capacity to address outages during refuelling, it does not require measures to address intermittency and could if appropriately sited be integrated with the existing transmission network.[195]

In addition, nuclear power generation facilities have an expected operational life of at least 60 years, with possible extensions beyond that, whereas wind and other conventional renewable generation systems have asset lives of less than 25 years.[196] The extent to which the installation of nuclear may, over its lifetime, obviate the need for capacity that would otherwise have to be installed is an important consideration in an assessment of its value in a network.[197]

Whether nuclear would, in light of its current higher costs, result in lower total system costs is unknown. That would require further study including an analysis of a realistic timeframe of deployment in Australia in substitution for other technologies and system upgrades.

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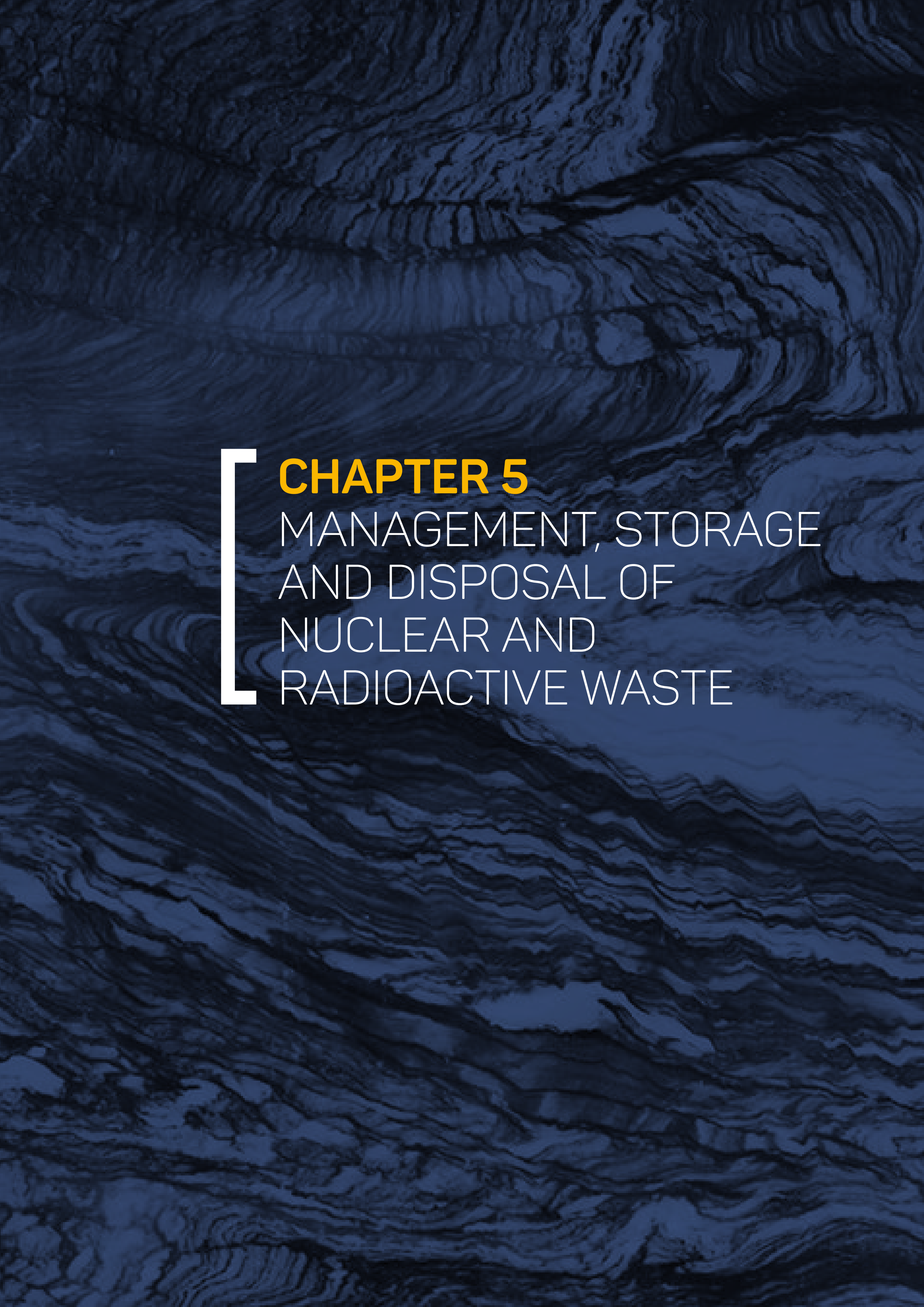

CHAPTER 5

MANAGEMENT, STORAGE AND DISPOSAL OF NUCLEAR AND RADIOACTIVE WASTE

CHAPTER 5: MANAGEMENT, STORAGE AND DISPOSAL OF NUCLEAR AND RADIOACTIVE WASTE

The activity under consideration is the management, storage and disposal of nuclear and radioactive waste from the use of nuclear and radioactive materials in power generation, industry, research and medicine (but not from military uses).

55. The activity of storing and disposing of wastes produced domestically from industry, research and medicine presents different risks and opportunities than storing and disposing of international waste from power generation. They need to be addressed separately.

The activity of storing and disposing of Australian-origin low and intermediate level waste is to be distinguished from the potential commercial activity of storing and disposing of international used fuel and intermediate level waste. This is because:

- domestic waste produced in Australia is a result of the past and continuing actions of Australians who have derived benefits from nuclear medicine and other industrial and research activities. The current generation of Australians has an obligation to future generations to properly manage and dispose of the waste that it has created
- the receipt of international waste would be a commercial activity that requires a choice by South Australians as to whether they want to engage in that activity
- the nature and level of risk associated with storing and disposing of Australian-origin low and intermediate level waste is different to the nature and level of risk associated with storing and disposing of international used fuel. Low and intermediate level waste is less hazardous as it emits less radioactivity overall and generates low levels of heat.

For these reasons, the application of principles for negotiating social and community consent, as explained in Chapter 6, would differ for different waste streams. The social and community engagement that would be required would be determined by the amount of waste involved, the level of hazard, the timeframes for decision making and the nature of the communities involved. The two activities are discussed in this chapter.

56. The safe management, storage and disposal of Australian and international waste require both social consent for the activity and technical analyses to ensure the waste is contained and isolated. Of the two, social consent warrants much greater attention than the technical issues during planning and development.

There are two broad aspects to the development of a waste disposal project: technical and social. The technical aspects include analyses of geology, engineering, land use, climatic, meteorological and environmental conditions. They require sophisticated planning and scientific work. The social aspects involve developing community understanding, providing information, and obtaining and maintaining community support for the activity. Social issues warrant much greater attention than technical issues during planning and development.[1]

International experience in developing radioactive waste facilities shows that processes that focus on technical issues at the expense of social issues are likely to fail.[2] Examples include the failed process to establish the Yucca Mountain facility in the United States[3], the failed process to establish a facility in Cumbria in the United Kingdom[4] and early approaches to siting facilities in Belgium, France, Germany, South Korea and Spain.[5] Detailed accounts of siting processes can be found in Appendix H: Siting significant facilities— case studies.

Without public and community support, projects typically have not proceeded, irrespective of their technical merits and whether or not the actual risks corresponded with the community's perceptions. Careful, considered and detailed technical work needs to be undertaken to ensure community support. Where social issues have been prioritised, there are international examples of project success.[6]

AUSTRALIAN LOW LEVEL AND INTERMEDIATE LEVEL WASTE

WHAT ARE THE RISKS?

57. Australia holds a manageable volume of domestically produced low and intermediate level radioactive wastes. The wastes result from science, medicine and industry, the products of which have served current and past generations of Australians.

A total of 4250 cubic metres (m^3) of low and intermediate level waste is stored around Australia, awaiting disposal, at many facilities.[7] These low level wastes comprise contaminated soils, decommissioning waste from research reactors, and equipment and laboratory items from the operation of Australia's research reactors and medical facilities.[8] The Australian Government is responsible for 4048 m^3 of this waste (see Table 5.1). The balance, approximately 200 m^3, is managed by the states and territories, with 22 m^3 of South Australian origin.[9]

Australia has 656 m^3 of intermediate level waste in storage, of which 551 m^3 is the responsibility of the Australian Government.[10] This inventory includes operational wastes from ANSTO's radiopharmaceutical production and some materials from the decommissioning of research reactors.[11]

Table 5.1: Current inventory of Australian Government radioactive waste

Waste type	Volume of waste (m^3)	Current storage location
Lightly contaminated soil: a legacy waste from ore processing research in the 1950s–60s	2100	Woomera Prohibited Area, SA
Operational waste from the Australian Nuclear Science and Technology Organisation (ANSTO)	1936	ANSTO, Lucas Heights, NSW
Defence waste: electron tubes, instrument dials, sealed sources, etc.	12	Department of Defence

Data courtesy of Department of Industry, Innovation and Science

Most of that waste (approximately 451 m^3) is held at ANSTO's Lucas Heights facility. An estimated 105 m^3 of intermediate level waste is held by the states and territories. Australia has 394 kilograms of used fuel assemblies from the OPAL (Open Pool Australian Lightwater) reactor[12], all stored at the ANSTO site. All the used fuel from ANSTO's previous reactors has been shipped overseas for either permanent management or reprocessing. Some byproduct materials of the reprocessed fuel were returned to Australia as intermediate level waste in 2015.[13]

The waste products from the reprocessing of Australian used fuel are mixed with molten glass in a process called vitrification, which produces a solid, durable waste form. The vitrified waste is contained in stainless steel canisters that are inserted into specifically designed casks for transport by road, rail or sea. The casks are made from forged steel, have walls that are 20 centimetres (cm) thick and weigh more than 100 tonnes: features that provide the appropriate level of radiation shielding.[14]

58. Low level wastes, typically items contaminated with radionuclides, do not generate heat. They require containment and isolation from the environment for up to a few hundred years. Intermediate level wastes need a greater degree of containment and isolation. The hazard posed by both kinds of waste reduces over time.

Low level waste (LLW) is broadly categorised on the basis that the physical amount of radionuclides contained in the waste 'package' is below levels[15] prescribed in national regulations.[16] Much of the LLW generated in Australia is derived from the manufacture and processing of radioactive products for research, industry and medicine, and this material typically contains radionuclides with relatively short half-lives (about 40 years or less).[17] Other LLW contains small amounts of naturally occurring uranium and thorium and their natural decay daughters—these parent elements have long half-lives.[18] A key attribute of LLW is that it does not require shielding to protect workers from excessive radiation doses during normal handling, transport and storage.[19] Nevertheless, best management practice requires that it be contained and isolated from the environment for up to a few hundred years to reach natural background levels.[20] LLW does not contain enough radioactivity to generate heat as a byproduct of the radioactive decay process.

Intermediate level waste requires a greater degree of containment and isolation than LLW due to its higher radioactivity and possible higher proportion of long-lived radioactive materials. It can be stored in surface facilities with sufficiently protective walls, although disposal of this material is best achieved using geological disposal.[21] Intermediate level waste requires shielding during storage and transport. It does not generate significant quantities of heat.

Both types of wastes should be durable and non-volatile solids at the point of disposal.[22] The risks posed by waste should be assessed based on the measures in place to ensure its containment and isolation. The hazards associated with radioactive material must be managed from the perspectives of both environmental protection and human safety. As the radioactivity increases, so, too, do the containment requirements and the need to isolate the material from the living environment.[23]

Figure 5.1: Storage of drums containing low level waste at ANSTO's Lucas Heights facility

Image courtesy of the Australian Nuclear Science and Technology Organisation

IS THE ACTIVITY FEASIBLE?

59. The federal government controls and manages most Australian low level and intermediate level waste, with the balance managed in the states and territories. There appear to be advantages in terms of managing long-term risks in a purpose-built, centralised facility.

As noted, the Australian Government is responsible for approximately 95 per cent of the nation's radioactive waste inventory.[24]

Australia's two largest stores of LLW are in the Woomera Prohibited Area (WPA) and at ANSTO's Lucas Heights facility.[25] The waste in the WPA is stored in 10 000 steel drums at a location called Evetts Field. The drums contain contaminated soil from CSIRO research in the 1950s and 1960s, and are considered a legacy waste.[26] Under the terms of CSIRO's interim storage licence, the site is inspected annually by CSIRO and the Australian Government's nuclear regulatory body, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).[27]

ANSTO stores its LLW in dedicated buildings on site at Lucas Heights. The waste is reduced in volume and placed on racks, contained in 200-litre steel drums (see Figure 5.1). The drums are scanned to determine their radionuclide content and then labelled, with the relevant information recorded in a database.[28]

The remaining LLW is held in a significant number of facilities dispersed around the country, including universities, hospitals and industry, pending final disposal.[29] While these storage facilities are licensed for this purpose, they are managed by organisations whose primary function is not the storage and disposal of radioactive waste.[30] The waste is often small in volume and held in stores that were not designed for long term storage or are nearing their capacity limits.[31] Radioactive waste is stored at 78 different facilities across South Australia, which are licensed through South Australia's Environment Protection Authority (EPA).[32] The approximate locations of these facilities are shown in Figure 5.2.

Australia does not have a central storage or disposal facility for its low and intermediate level wastes. A central facility offers advantages to the management and storage of radioactive waste. In particular, it would[33]:

- make it easier to impose consistent, stringent environmental, safety and security measures, rather than apply them across a number of individual sites. A central facility would have the potential to benefit from an enhanced safety culture and strong professional relationships with service providers because of the consistency of the management tasks
- likely be more cost effective than storage at several smaller, individual sites. There are potential economy-of-scale benefits, for example, in terms of administration and staffing of waste management tasks, such as reducing the cost of complying with regulatory obligations. It would also reduce costs for the regulator in monitoring compliance
- provide for continuity of control of the waste. This includes both physical control of the material and the retention of information of the waste type and characteristics. In the past, issues have arisen when organisations have disbanded or relocated, and corporate knowledge has been lost. This has resulted in unnecessary waste-handling transportation issues, inadequate control of radioactive material, or 'orphan sources' (sources no longer under proper management)[34]
- allow for the design of a purpose-built facility that includes specific features to provide for monitoring and compliance. A dedicated store would involve engineered facilities and staff who specialise in managing radioactive waste, to ensure continuing safe management of the waste.

Further, and as discussed in Chapter 9, there have been many thousands of shipments of LLW in Australia, without any accident resulting in harm to workers, the public or the environment. As the risks associated with transportation of LLW are low,[35] the benefits of centralisation outweigh any transportation risk. This experience supports the view that the overall risk to the community would be reduced if low and intermediate level wastes were moved from the hundreds of storage locations to one properly engineered waste management facility.

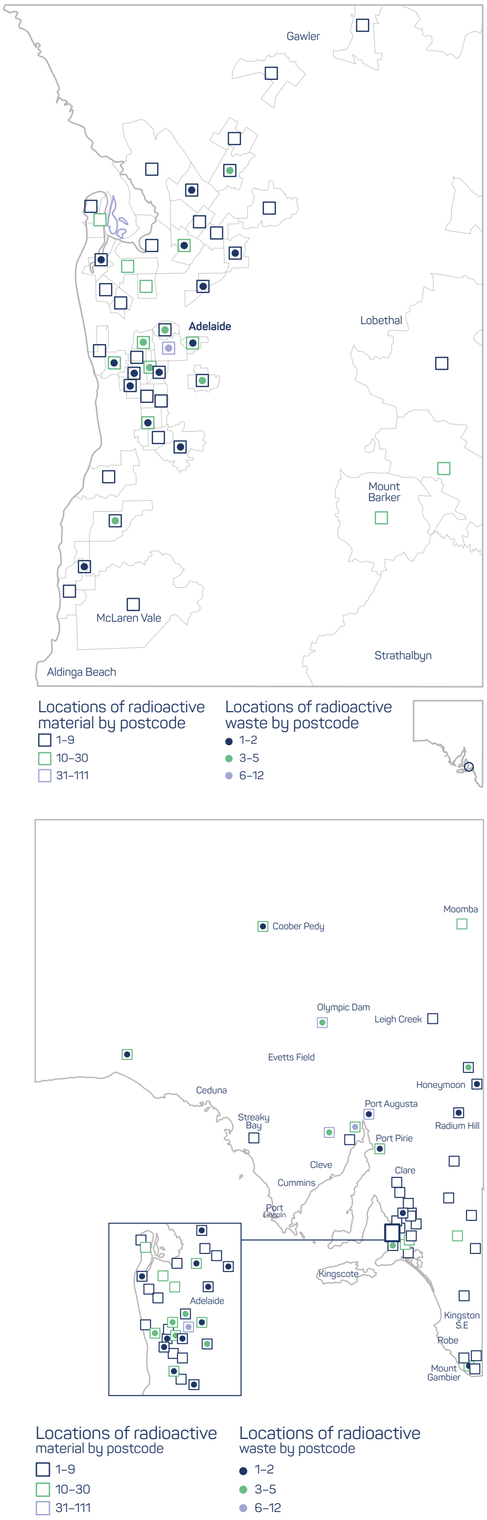

Figure 5.2: Number of locations of radioactive material and waste in the Adelaide metropolitan area (top) and across the state of South Australia

Data courtesy of the Environment Protection Authority, South Australia

60. Many countries, including Finland, France, Hungary, South Africa, South Korea, Spain and the United Kingdom, have developed and operate purpose-built low level waste repositories. These repositories handle volumes far greater than exist in Australia.

Most countries that have longstanding nuclear power or other nuclear fuel cycle facilities also have dedicated facilities for the disposal of LLW.[36] There are more than 100 proposed, operational or closed LLW repositories operating in Asia, Europe and the Americas.[37] A number of these facilities are licensed to handle volumes of waste that are many times larger than Australia's LLW inventory.[38] For example, the Federal Waste Facility in Texas has a licensed capacity of 736 000 m^3 and is one of four operating LLW disposal facilities in the United States.[39]

The characteristics and size of the international facilities vary and many have operated for long periods. Table 5.2 details key international waste facilities by type. Australia already has an established near-surface facility for the disposal of LLW at Mount Walton East in Western Australia. It commenced operations in 1988 and is managed by the state government.[40]

Facilities in other countries are being developed. Belgium is fulfilling its obligation to provide a national solution for disposing of LLW and short-lived ILW with the cAt project in Dessel (see Figure 5.3). After a long public consultation and site selection process, the facility is expected to start accepting waste in 2022.[41] The surface disposal facility is licensed to hold 70 500 m^3 of waste.[42] It will accept waste over an indicative duration of 50 years, followed by 250 years of institutional control (see Appendix H: Siting significant facilities).

61. Overseas waste disposal facilities have been developed on a range of sites and in a variety of climates—many of which are much less favourable for this purpose than conditions in South Australia. There is substantial international experience in their design, management, operation and monitoring.

Climatic and meteorological conditions such as rainfall, temperature, erosional processes and groundwater levels affect a waste disposal facility's ability to isolate the hazardous radionuclides in LLW from the environment.[43] Water is the main potential transport mechanism of radioactive materials from a waste package to the environment.[44] Therefore, characterising the hydrogeological features of a site is critical when designing for long-term containment. Sites with low groundwater flow rates, long flow paths or low water tables are preferable.[45]

Table 5.2: Key international low level waste facilities

Country	Facility name	Capacity (m^3)	Waste type	Start of operation
Tunnel-type facilities				
South Korea	Wolsong	214 000	LLW, ILW	2015
Sweden	SFR	63 000	LLW, ILW	1988
Hungary	Bátaapáti	40 000	LLW, ILW	2008
Finland	VLJ	8432	LLW, ILW	1992
Highly engineered surface facilities				
France	Centre de l'Aube	1 000 000	LLW, ILW	1992
Spain	El Cabril	100 000	LLW	1992
Belgium	Dessel (under construction)	70 500	LLW, ILW	2016
Near-surface type facilities				
USA	Federal Waste Facility	736 000	LLW	2013
South Africa	Vaalputs	Not specified	LLW, ILW	1986

Data sourced from KORAD, NEA, NECSA, SKB

1. Quay and access road
2. Caisson plant
3. Monolith production facility
4. Disposal modules
5. Access cluster
6. Storage building for low level waste
7. Communication centre
8. Demonstration test and test cover

Figure 5.3: An overview of the proposed cAt project site in Dessel, Belgium

Image courtesy of ONDRAF/NIRAS

That said, facilities have been developed in places with high rainfall, near-surface water tables, areas potentially affected by permafrost, and even in areas where the accurate characterisation of the local hydrogeology has been difficult.[46] In such cases, the design of the facility and its engineered barrier system must play a greater role than the surrounding geology in ensuring the isolation and containment of the waste while it remains hazardous. For example:

- The French Centre de l'Aube LLW facility is situated in a high rainfall area that typically receives 500–1000 millimetres a year. The geological foundations of the facility contain a water-resistant formation of clay that creates a natural barrier against radioactive elements entering the groundwater.[47]
- The Finnish LLW/ILW disposal facility, VLJ, at the Olkiluoto site, has been built to take into account the local climate, which is characterised by potential permafrost. It uses an underground silo design, consisting of an access tunnel, a shaft and two rock silos at a depth of 60–100 metres where the waste is held.[48]
- The Spanish LLW facility, El Cabril, has been designed to rely completely on engineered barriers to isolate the waste from the environment. The barriers are robust enough that the facility could be located on almost any site.[49]

There is substantial international experience in the operation of low and intermediate level waste facilities. Some have operated since the 1950s, and one has closed, entering post-closure monitoring in 2003.[50] This experience has been used to develop international standards for the design, management, operation and closure of LLW and ILW facilities.[51]

In particular, the ability to assess the performance of these waste facilities through long-term monitoring programs is being built into new facilities. Belgium's cAt facility has developed an extensive long-term site characterisation and monitoring program to verify the performance of the repository during operation. This includes initial site characterisation before operation to establish a baseline for performance. This is followed by continual monitoring of the structure of the repository and the drainage water, and groundwater measurements to predict the potential migration of pollutants. Inspection areas and galleries have been included in the design of the facility at the request of the local community to monitor concrete floors and containment, and detect leaks in the disposal area.[52]

62. The disposal of low level and short-lived intermediate level waste need not rely on the technical characteristics of the site. There is no need for a perfect site; rather, a sufficient one.

The emphasis is placed on a facility design that is engineered with sufficient barriers that, in combination, provide for long-term containment and isolation of radionuclides.

The nature of low level and short-lived intermediate level waste means that such material should be isolated from the environment for up to a few hundred years.[53] Over this time, anthropogenic short-lived LLW radionuclides will fully decay.[54] For LLW containing thorium and uranium, the 'activity concentrations' of these elements are already lower than that of many naturally occurring radioactive ores and materials. Architectural history and expertise suggest it is feasible to build structures that assure containment for this period.[55]

The primary focus in designing a facility for disposing of LLW is to provide sufficient engineered barriers to assure that waste radionuclides do not migrate from their packages into the environment. A facility may rely on both engineered and intrinsic natural barriers at the site. Collectively, the natural and engineered barriers should contain the waste at least until the radioactivity content has diminished to natural levels.[56]

When disposed of in near-surface facilities, the risks of radionuclides migrating from LLW packages into the natural environment are managed by[57]:

- ensuring that the waste radionuclides are in a solid, non-volatile and durable form. This greatly restricts the mobility of the radionuclides. The migration of radionuclides is hindered by binding the waste to an immovable material or reducing their solubility

Figure 5.4: An example of a concrete overpack from the proposed cAt low and short-lived intermediate level waste facility in Dessel, Belgium

Image courtesy of ONDRAF/NIRAS

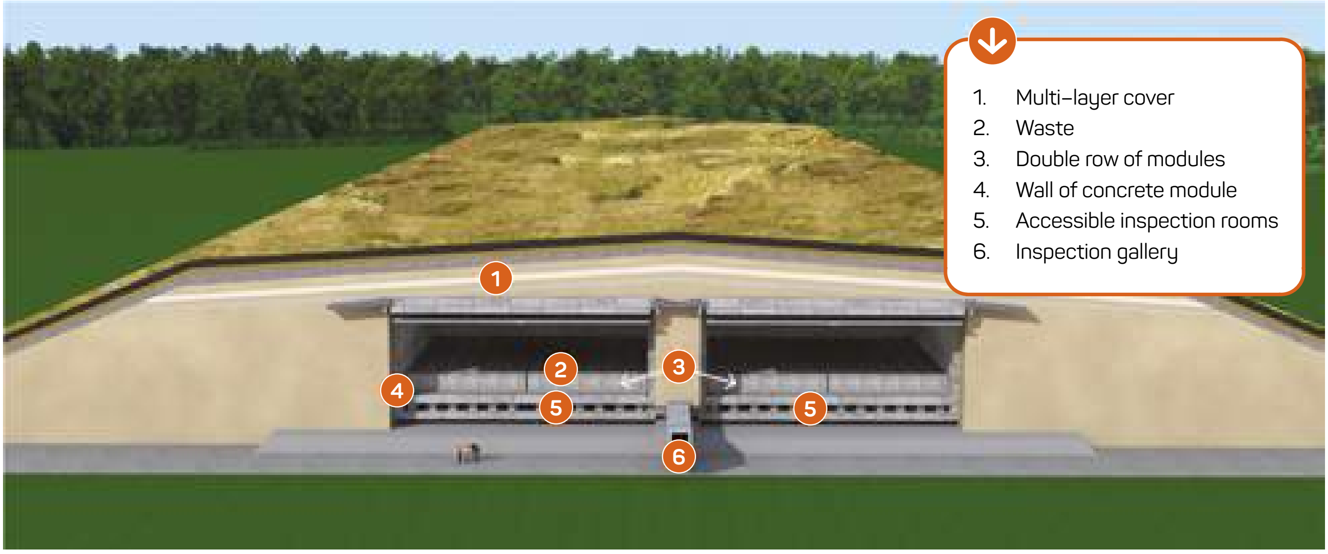

Figure 5.5: A conceptual drawing of the proposed cAt project in Belgium detailing the multiple barriers that isolate the waste from the environmen

Image courtesy of ONDRAF/NIRAS.

- containing the waste in a purpose-built package. The purpose of waste packages is to provide a primary protective layer for the length of time the waste remains hazardous. While the container is intact, the radionuclides cannot migrate from the waste package
- adding, where necessary, a steel or concrete barrier around the primary waste package. The use of such 'overpacks' made from robust materials can extend the duration of containment and increase protection from radiation hazards. Compound waste container systems can be designed to provide containment for hundreds of years. An example of a concrete overpack or 'monolith', is shown in Figure 5.4.
- designing and building the facility in a way that prevents moisture entering from the natural environment. The construction and design of the facility may be such that the site provides a natural barrier. The design and construction of the facility should ensure that operational activities do not compromise site or engineered barriers.

The cAt project in Dessel is an example of a LLW and short-lived ILW waste facility that provides robust isolation of waste using engineered and natural barriers.[58] Figure 5.5 is a conceptual drawing of the proposed site and provides details of the layers of isolation.

63. Key elements of the successful development of a low level and intermediate level waste facility are acceptance by society that it has an obligation to manage the waste it has created, and compensation to communities that host facilities for the service they provide.

The experience of countries that have attempted to site facilities for managing LLW and ILW shows that success is most likely achieved if the affected host community is compensated for the service it provides to the broader society.[59] This is clearly shown in the cases of Belgium and South Korea, which are discussed in further detail in Appendix H: Siting significant facilities—case studies. Both countries initially adopted approaches that did not provide benefits, and which failed to obtain community consent. These approaches were subsequently changed.

It is an international principle of radioactive waste management that the society that generates waste is responsible for managing it.[60] There also is a moral basis for communities that derive a benefit from the use of radioactive materials in science and industry to manage the waste that has been created. This ensures that an unfair burden is not placed on future generations. It is recognised that there may be circumstances in which the management of a country's waste is contracted to another country. This is permissible under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.[61]

IN WHAT CIRCUMSTANCES IS THE ACTIVITY VIABLE?

64. The federal government is currently managing a process to identify a site for the centralised, long-term disposal of its low level and intermediate level waste.

The Australian Government is working to identify a site for a National Radioactive Waste Management Facility for the long-term management of Australian LLW and ILW.[62] The proposed facility would permanently house Australia's LLW and serve as an interim store for its relatively small volumes (656 m^3) of ILW. Australia does not produce high level waste (HLW), and storage and disposal of HLW is prohibited at this facility.[63]

The facility will be owned and managed by the Australian Government and regulated through ARPANSA. The proposed design is a surface-type facility, similar to well-established operations in the UK and Europe.[64] The Spanish facility at El Cabril, built in 1992, is an example of a modern, purpose-built surface facility that uses the multi-barrier approach.[65]

The Australian site is being identified through a voluntary nomination process, where willing landowners have nominated their land for consideration. Phase 1 began in 2015 and involved the consideration of 25 of the eligible nominated sites. Six were shortlisted, based on a multi-criteria analysis of each site.

This was followed in 2016 by a consultation process at the shortlisted sites to engage with the community and provide information on the infrastructure specifics, risks and safety cases, employment opportunities and community benefits measures. The government will then seek broad community support for hosting the facility at one or more of the shortlisted sites before moving on to the next phase.[66] In April 2016, the Australian Government authorised a single site at Barndioota, South Australia, for further community consultation.

Due to the Australian Government's ongoing process to find a storage site, the Commission has not conducted any viability analysis into the proposed storage and disposal of Australian LLW and ILW.

65. In the event that the process currently underway is unsuccessful, there is no reason why such a facility could not be safely developed in South Australia with the support of a host community.

There is no credible evidence on technical and environmental grounds to suggest that a LLW and ILW disposal facility could not be safely operated and in due course closed in South Australia. Indeed, the risks associated with such a facility have been demonstrated to be manageable. Australia has the significant advantage of being able to draw on a considerable body of international experience in developing such a facility (see Appendix H).

Such a process in South Australia would, however, need to address the economic and social justifications for the activity and how the risks would be managed. Were a process to be adopted that drew on the principles outlined in Chapter 6: Social and community consent, there would be no reason for a South Australian community not to consider and learn about hosting a facility. Should a community choose to proceed beyond this initial stage, it would then need to discuss and negotiate the economic benefits for engaging in the activity. The experiences of Belgium and South Korea in engaging with and informing interested communities and, subsequently, developing facilities provide useful lessons in this regard (see Appendix H).

Although social and community consent for establishing a radioactive waste management facility would be required for international HLW, which would be undertaken as a commercial activity (discussed in this chapter), there is a qualification with regard to Australia's own LLW and ILW. The Australian Government has a responsibility to safely manage Australian-origin radioactive waste on behalf of current and future generations.[67] Failure to select a site in the manner proposed by the Commission would not negate the need to find a location for safe long-term storage and disposal.

Countries, including Australia, that are signatories to the Joint Convention recognise their binding legal obligation to manage their wastes safely for the long term.[68] While seeking willing volunteer communities, the UK, for example, has reserved its right to use other approaches should a consent-based approach not result in site selection.[69] Given that, Australia has little choice but to continue to seek a long-term solution for the safe management of its radioactive waste, irrespective of whether a volunteer host community presents itself.

INTERNATIONAL USED FUEL (HIGH LEVEL WASTE) AND INTERMEDIATE LEVEL WASTE

WHAT ARE THE RISKS?

66. Used fuel is hazardous due to its high radioactivity and heat generation.

Used fuel when discharged from a nuclear reactor is a solid ceramic that remains sealed in its metal cladding (see Figure 5.6). It has the same outward appearance as when loaded into the reactor. [70] Inside the fuel rods, the ceramic fuel pellets undergo changes due to the high temperatures and the generation of new radionuclides. They are fission products and heavy by-products (otherwise known as transuranics) (see Figure 5.7). [71]

Used fuel is hazardous mainly because of its radioactivity, but also because it generates substantial amounts of heat.[72] The radioactivity is produced by the many different radionuclides that result from the fission or capture of neutrons by some of the uranium atoms in the fuel pellet.[73] As well as presenting an external radiation hazard, these new radionuclides are highly toxic if inhaled or ingested (see Box: Radiotoxicity). Although these new substances constitute only about 5 per cent of the used fuel (the balance is uranium), they increase the radioactivity of the fuel at the time of discharge by about 100 000 times the level at the time the fuel was loaded.[74]

67. The hazard created by used fuel diminishes significantly over time. Within 500 years the most radioactive elements have decayed. However, used fuel requires isolation and containment from the environment for at least 100 000 years.

The amount of heat and radioactivity produced by a used fuel assembly is determined by the length of time that the fuel has been used in the reactor core (the level of 'burn-up' of the fuel). The longer the period, the greater the amount of radioactivity and heat when it is removed from the reactor.[75]

The scale of the reduction of the hazard through the predictable process of radioactive decay is illustrated in Figure 5.8. Most of the hazardous radionuclides in used fuel are fission products, which include caesium and strontium, which decay within the first 500 years.[76] However, some radionuclides, particularly heavy by-products such as plutonium and americium, will remain for at least 100 000 years.[77] Used fuel therefore requires careful management over a long time to ensure its hazardous contents remain inaccessible to humans and the environment.[78]

As shown in Figure 5.8, the radiotoxicity of used fuel initially declines rapidly and then more slowly until, after about 300 000 years, it reaches the same level as natural uranium ore. The decline occurs because the radionuclides in the used fuel decay into stable non-radioactive elements. In Figure 5.8, the circles show the percentage of radiotoxicity compared to used fuel one month after its discharge from a reactor. The high initial radiotoxicity is associated with fission products. Following the decay within the first 500 years of almost all the fission products, the lower residual levels of radiotoxicity are associated with long-lived heavy by-products.

When managing, storing and disposing of used fuel, the main concerns are to prevent humans and other organisms:

Figure 5.6: Fuel assembly for a commercial light water reactor

Image courtesy of AREVA

Figure 5.7: The chemical make-up of used fuel

RADIOTOXICITY

Radiotoxicity describes the harm which a radioactive substance can cause if people are exposed to it.

It specifically describes the potential for an impact on health where a radioactive substance enters the body, through inhalation or ingestion, and emits radiation there.

As a measure it takes into account both the biochemical nature of the radionuclide, or a number of them, as well as the type and energy of radioactivity it emits. It is measured in sieverts.

Source: Hedin, *Spent nuclear fuel—how dangerous is it?* SKB, Sweden, 1997, p. v

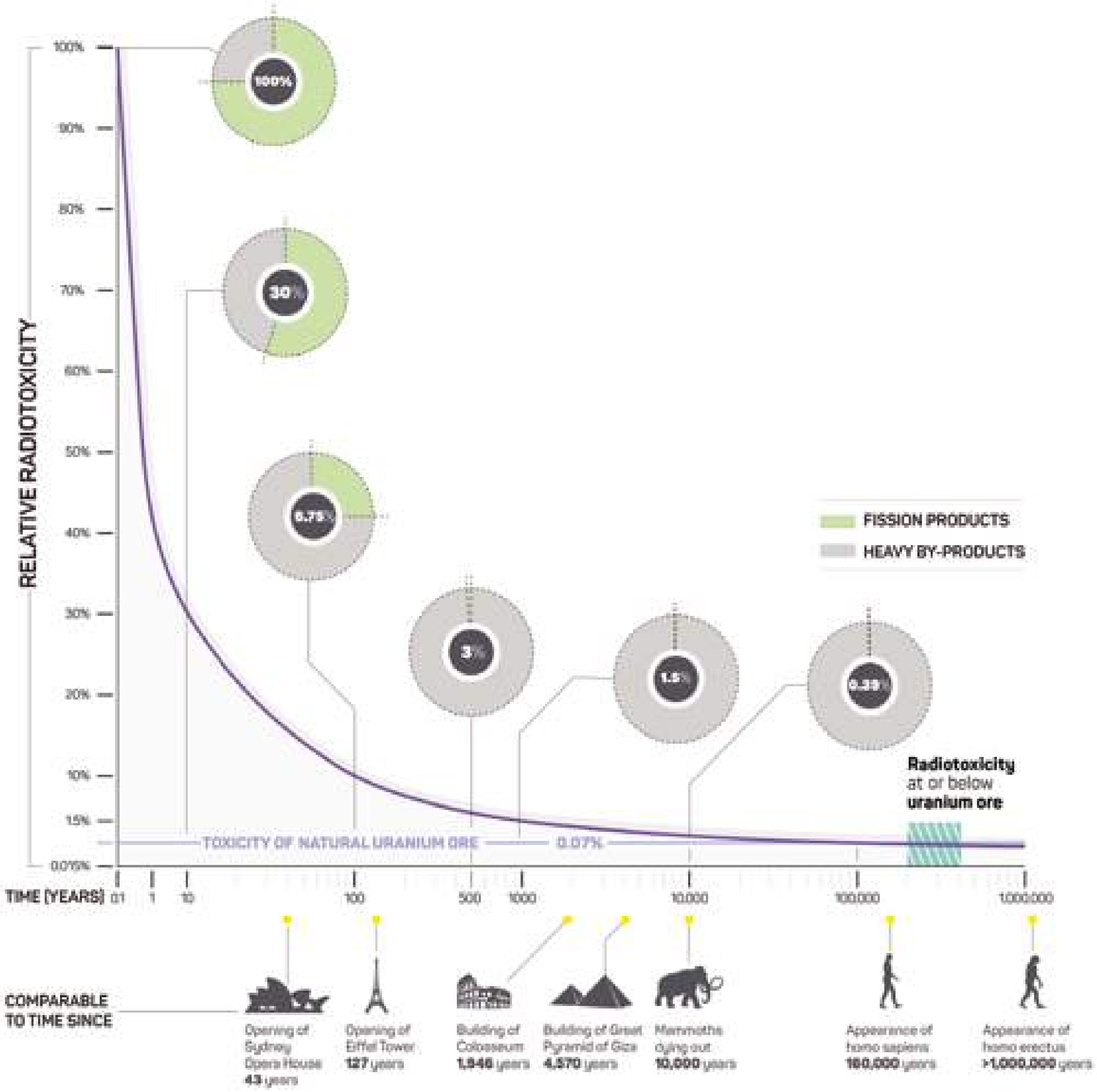

Figure 5.8: Radiotoxicity of used nuclear fuel over time[79]

- being exposed to the external radiation produced. This is primarily prevented by appropriate shielding
- inhaling or ingesting the hazardous radionuclides.[80] This is achieved by isolation and containment to prevent radionuclides migrating from the used fuel into the natural environment.[81]

The diminishing hazard over time means that the approach to managing used fuel can similarly evolve—from wet storage initially to dry storage and ultimately to disposal.[82]

The initial and main hazard following the discharge of a used fuel assembly from a reactor is the gamma radiation produced by the decay of the short-lived radionuclides.[83] A person standing one metre from an unshielded used fuel assembly would receive a lethal dose of radiation in a few seconds.[84] Shielding and remote handling of the used fuel protects people and organisms from exposure to such high levels of radiation.[85]

Similarly, on discharge from a reactor, used fuel assemblies need to be cooled for several years to ensure they remain below melting temperatures by a large margin of safety. This heat is managed in the short term (typically for up to 10 years) in a wet storage pool at the reactor site.[86]

During that time there is both a substantial reduction in the radiotoxicity of the used fuel (see Figure 5.8) and in the amount of heat generated. After removal from the wet storage pools, the used fuel assemblies are typically stored in large, dry storage casks, allowing the used fuel to cool further. [87] A total of about 50 years of storage is required for used fuel to cool sufficiently before it can be permanently disposed of underground.[88]

During that period, the radiotoxicity of the used fuel falls to about 15 per cent of the level one month following its discharge from a reactor.[89] At that time, the rate of heat output (per tonne heavy metal) is comparable to that of a powerful domestic toaster.[90]

Within 500 years, the most radioactive elements in the used fuel will have decayed. [91] At that point the radiotoxicity is dominated by the presence of radionuclides of plutonium and americium, which have very low solubility and mobility when underground, given their strong tendency to adhere to surfaces of rock and clay.[92] After 1000 years, the radiotoxicity of the used fuel is only about 1.5 per cent of initial levels following discharge from a reactor, and the rate of heat output is comparable to that produced by an adult human.

It will take more than 100 000 years for used fuel to reach similar radiotoxicity levels to natural uranium, primarily due to the presence of some of the longer-lived radionuclides that remain hazardous[93], even in trace amounts, to humans and other organisms if inhaled or ingested. Therefore, the potential for these radionuclides to migrate into the living environment must be managed over such timeframes.[94] The rapid decline in radiotoxicity means that the most critical period during which isolation and containment of the used fuel must be assured is relatively short in geological terms (up to 10 000 years).[95] This has important implications for the design of facilities for the disposal of used fuel and the combination of engineered barriers and geology used for isolation and containment.

68. There is international consensus that geological disposal is the best technical solution currently available for the disposal of used fuel. Two countries, Finland and Sweden, have successfully developed long-term domestic solutions.

The geological disposal concept involves placing solid radioactive waste in robust, multi-layered engineered containers that are in turn placed in specifically constructed openings in a disposal facility a few hundred metres or more below the earth's surface.[96] The facility is ultimately closed and sealed. Over hundreds of thousands of years the facility and the wastes decay to become part of the natural subsurface environment.[97]

In a geological disposal facility, the twin objectives of isolation and containment are achieved through a combination of suitable geology and specifically engineered barriers. Engineered barriers initially isolate and contain the waste to restrict the ability of radionuclides to reach people and the natural environment. [98] These barriers will degrade progressively after tens to hundreds of thousands of years, eventually losing their ability to contain the waste.[99] Isolation is then provided by deep, stable geology. At this stage, the remaining long-lived radionuclides have low solubility and mobility, significantly retarding their migration through the natural environment.[100]

The combination of geological and engineered barriers is designed to provide a robust system in which safety is not reliant on the performance of any single item.[101] Each barrier performs a specific, complementary role to ensure that a single failure does not lead to a failure of the system (see Figure 5.9).[102]

Compared to above-ground cask storage, geological disposal via a multi-barrier system is a permanent, passive solution, removing the need for future generations to manage the used fuel.[103] The engineered barriers must be designed and constructed within the subsurface geology to ensure safety after closure, without ongoing maintenance or monitoring.[104]

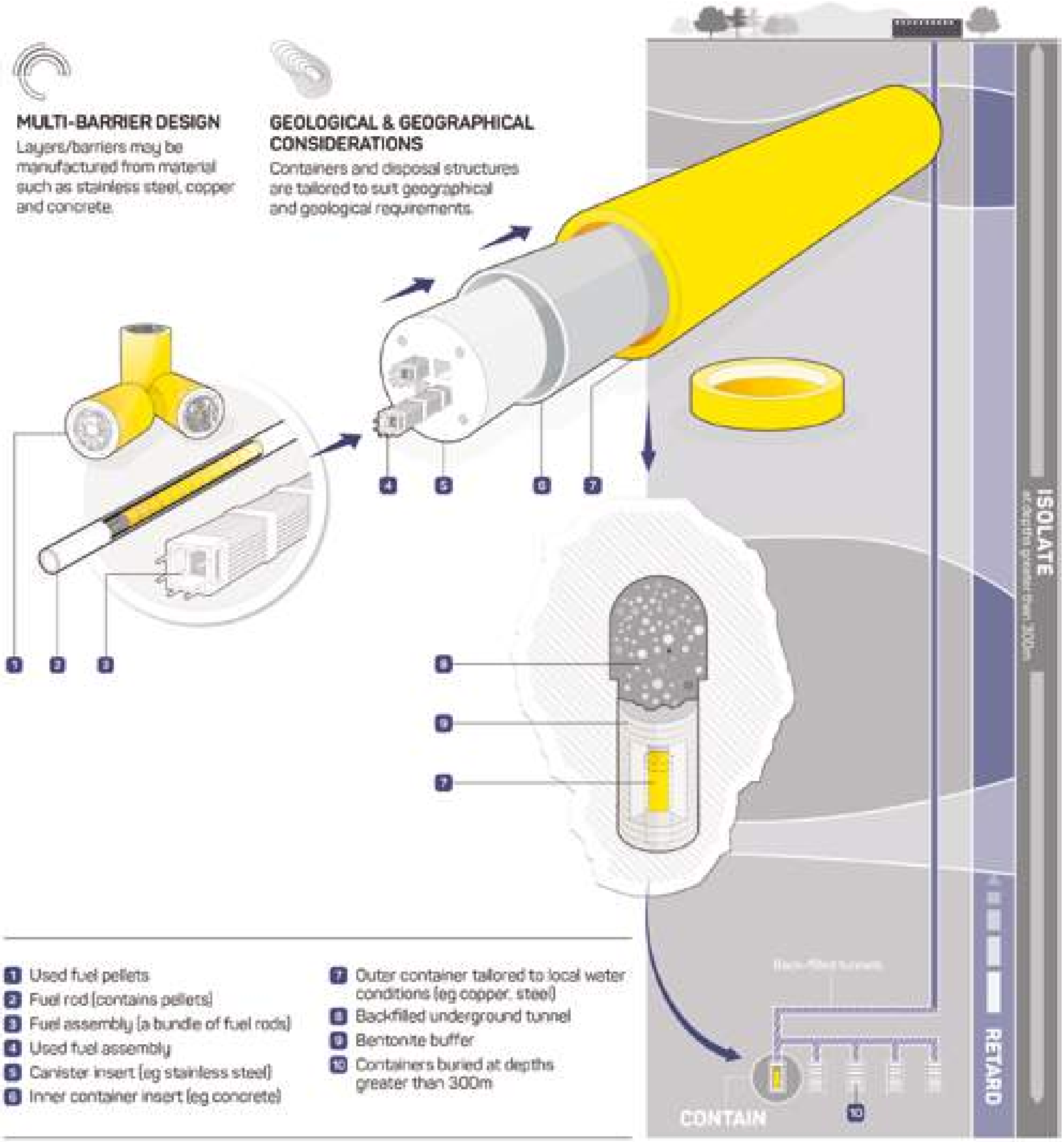

Figure 5.9: Generic multi-barrier system for the disposal of used fuel

Geological disposal research has been conducted since at least the 1950s.[105] There is international consensus that geological disposal is presently the best technical solution for the disposal of used fuel, high level waste and other long-lived radioactive waste.[106] That consensus has arisen following careful reviews of other options for disposal, including used fuel reprocessing, and of the scientific basis for geological disposal in several countries. Although future technological advances may result in new solutions in radioactive waste management, geological disposal is accepted to be the best available option.

Assessments in Belgium, Canada and the United Kingdom have also studied geological disposal from a social perspective, including the distribution of risk, fairness and benefits across generations. They have concluded that it represents the best management option overall.[107] Geological disposal is national policy in many countries including Belgium, Canada, Finland, France, Germany, Sweden, Switzerland, the United Kingdom and the United States of America.[108]

Geological disposal concepts have been developed for a range of host geologies. The two most advanced countries in this area are Finland and Sweden, which have successfully developed the KBS-3 concept for crystalline rock and found host communities for disposal facilities.[109]

Finland has had an underground research laboratory at Olkiluoto for many years. Posiva, the Finnish organisation responsible for used fuel management, was granted a construction licence in 2015 to expand the facility to accept used fuel.[110] A separate licence must be granted before this can occur. Operations are expected to start in the early 2020s.[111] Sweden also has an underground research laboratory.[112] A construction licence application was submitted to the government in 2011, with construction expected to begin in the early 2020s and be completed in about 10 years.[113]

Other countries have different geological disposal concepts. For example, Belgium, France and Switzerland have developed concepts for disposal facilities in geologies with clay.[114] The most advanced of these projects is in France, which has submitted a licence for the construction of a disposal facility near the Meuse/Haute-Marne border.[115] The site, which already hosts an underground research laboratory in the Callovo–Oxfordian formation, is expected to begin operations in 2030.

Some countries are also exploring salt deposits and other geologies for the disposal of used fuel. In the USA, the Waste Isolation Pilot Plant facility in New Mexico, which is a mined disposal facility in a bedded salt layer, has received long-lived intermediate level waste that was produced by the country's defence program.[116] It is proposed that the plant will receive further national wastes later in 2016.[117]

69. Development of a geological disposal concept requires comprehensive identification, understanding and analysis of the physical and chemical processes that may occur over at least 10 000 years and up to a million years.

To assess the safety of a geological disposal concept, it is necessary to demonstrate that the host geological environment that has been selected and the engineered barriers that have been designed will be effective in combination to prevent harmful releases of radioactivity.[118] This will assess the potential for the release of radionuclides, notwithstanding this will not happen for many tens of thousands of years.[119] This is done by constructing a 'safety case' (for examples, see Appendix I: Safety cases for geological disposal facilities).

A safety case is a structured argument supported by evidence to justify that a disposal system is acceptably safe.[120] According to the International Atomic Energy Agency (IAEA), a safety case is

> *… the collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all the safety-related work associated with the disposal facility.* [121]

The use of safety cases is not unique to the nuclear industry.

The guiding parameters for the safety of geological disposal are often fixed by national regulations, based on international expert consensus. The regulations specify maximum levels of radioactivity to which a person may be exposed were that person, for example, to drink water from a well or aquifer above the disposal facility within 100 000 years following its closure.[122] The upper allowable annual dose limit used in many jurisdictions is 0.1 millisieverts (mSv) from these exposures, which is the equivalent of an arm x-ray. This means that a safety case would need to be developed that demonstrates as far as possible that in at least the first 100 000 years following closure of the facility, the maximum dose of radiation that a human at the surface could expect to experience would be less than 0.1 mSv.[123]

A safety case typically consists of a reference case and alternative scenarios.[124] The reference case comprises the best estimate—based on a range of realistic (albeit conservative) assumptions—of how the used fuel, engineered barriers, geological environment and surface environment will evolve following facility closure.[125] The alternative scenarios consider the system's behaviour and performance under less likely events, such as a fault caused by an earthquake and include pessimistic 'what if?' events[126], such as unintentional human intervention by accidental drilling.[127]

The reference case and alternative scenarios are then analysed systematically to determine the likely range of radiation exposures to humans and other organisms that might result.[128] As the actual events many hundreds of thousands of years into the future cannot be known, safety cases include assessments of a wide range of possible geological and climatic events and performance of the engineered barriers.[129] The objective of the assessment is to account for a range of likely and less likely outcomes.

To achieve this, modelling structured around accepted and testable physical processes is used, based on data gathered over a long time from previous international research at proposed sites. Figure 5.10 shows the relationship between the various inputs for a safety case.[130] Data-gathering occurs during site investigations and continues during construction, operation and even once the facility has closed.[131] The data is used to build, check and refine models of site behaviour, and to confirm the system is behaving as expected.[132] For this reason the safety case will evolve, and will become more detailed and specific as the project progresses through different stages.[133]

Safety case analyses have been undertaken by geological disposal facility proponents at various stages of project development in Belgium, Canada, Finland, Japan, Sweden, Switzerland and the USA, and accepted by independent nuclear safety regulators in Finland, Switzerland and the USA.[134] While each proposed facility and geology differs under each scenario analysed, the doses that might affect hypothetical people only occur in the most distant future and are so small that their effects would be undetectable.[135]

70. The role of the host geology is critical to the long- term safety of geological disposal. The geological conditions therefore need to be thoroughly analysed and understood.

A geological disposal facility for used fuel must be sited in geological conditions that naturally limit the potential pathways for radionuclide migration. Such conditions include a combination of:

- depth: disposal at sufficient depth provides protection against climatic and meteorological conditions, including aridity, fire, sea-level rise, erosion and glaciation. The disposal depth provides a significantly oversized shield from external exposure to gamma rays. Similarly, the depth of disposal removes waste from areas of human activity, reducing the risk of inadvertent intrusion[136]
- low seismicity and low geohazard potential: the host rock should be demonstrably stable to reduce the risk of faulting affecting the facility[137]
- low water flow: the main mechanism for radionuclide transport is groundwater flow. In crystalline rock, groundwater flow is restricted to the fracture network, while in sedimentary formations, groundwater flow occurs slowly through porous and permeable pathways. At depth, groundwater moves even more slowly[138]
- an absence of other mineral resources: this reduces the risk of inadvertent intrusion from exploration and mining[139]
- appropriate host geology: some geologies are better than others at isolating the radionuclides. For example, in salt and other dry environments, there is no groundwater flow. In clay environments, a high degree of sorption (retention) by clay minerals prevents radionuclides from migrating into the groundwater.[140]

Careful characterisation over several decades is required to confirm the suitability of the geological conditions. [141] It is necessary to attempt to assess the full range of possible changes to geological and climatic conditions over time, including likely and more remote developments as a result of climate change, such as sea level rises and glaciation.[142] While this process is complex, sound predictions can be made about the future development of geological formations by studying how those formations have behaved throughout history.[143] For example, the chemistry of the groundwater gives an indication of how slowly it moves, where it originated and, as a result, how it is likely to behave in the future. Similarly, seismic investigation of the local and regional geology allows trends in tectonic processes, such as uplift and compression, to be identified.[144] A phased approach is appropriate for this, starting with surface-based investigation and continuing on to underground investigation if warranted[145], initially via borehole sampling and then moving to construction of an underground research laboratory.[146]

Other considerations are also taken into account to validate the appropriateness of the assumptions made and the calculated results. Much useful scientific information has arisen from studying natural analogues: for example, how naturally radioactive elements in deep geological systems can be mobilised by groundwater, or fixed by interaction with the geology.[147]

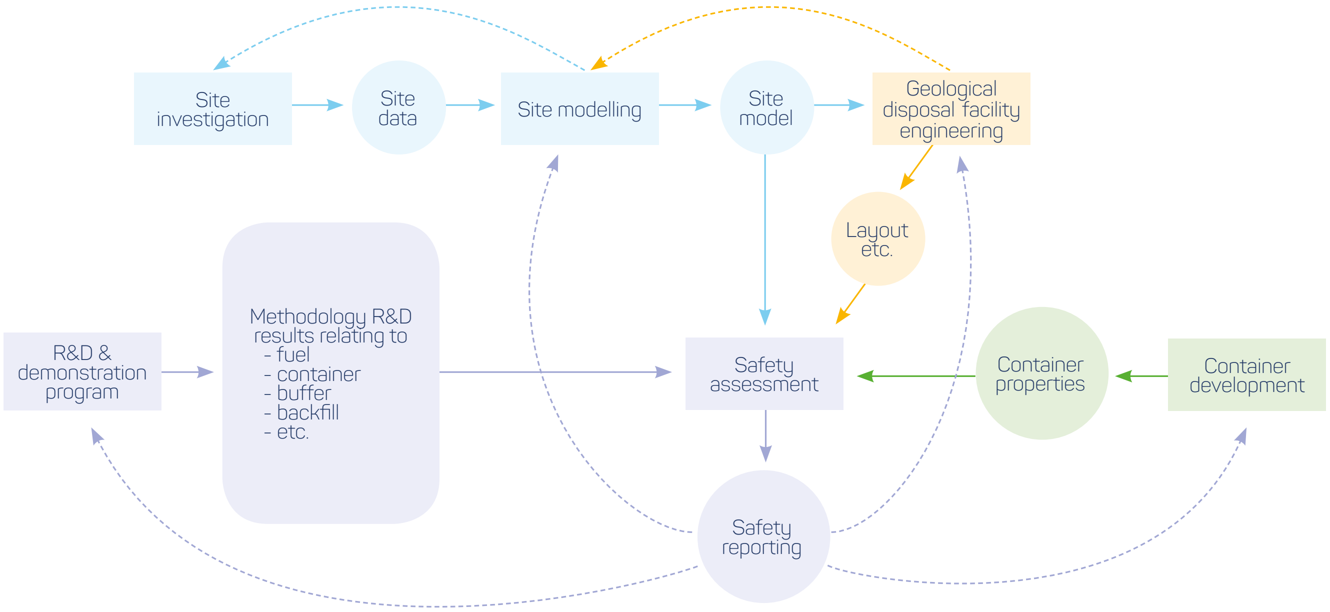

Figure 5.10: The relationship between the safety case, site investigation and other key activities.

Notes: Activities are shown in rectangles and outputs in circles. The dashed lines represent feedback loops
Data sourced from SKB

The overall impacts to humans and the environment are not evaluated based on geology alone, but on a combination of geological and engineered barriers.[148] This is explained in Finding 71.

GEOLOGICAL BARRIER FOR THE DISPOSAL FACILITY AT OLKILUOTO, FINLAND

Finland's deep geological disposal facility will be located at Olkiluoto in crystalline rock. The site, which has been investigated for 25 years, has been shown to have naturally isolating characteristics (Appendix I: Safety cases for geological disposal facilities) including:[149]

- a tectonically stable location in the Precambrian Fennoscandian Shield, away from active plate margins. Super blocks, of some several kilometres squared in size, formed in the region a long time ago and move separately from each other.[150] Consequently, the blocks are not susceptible to internal fracture by seismic activity.[151]
- groundwater flow conditions that will limit the movement of radionuclides. This includes naturally slow flow between sparse fractures in the rock, with a hydraulic conductivity of 3×10^{-11} m/s (which equates to 1 mm a year) at the disposal depth.[152] It also includes chemically reducing conditions that will limit the movement of radionuclides—these chemical conditions are not particularly corrosive.[153] Furthermore, multiple ore bodies in equivalent geology in the Fennoscandian Shield have been isolated over long periods in the past, indicating that used fuel emplaced in engineered barriers can also be isolated over the long term.
- no natural resources, reducing the risk of future human intrusion.

GEOLOGICAL BARRIER FOR A DISPOSAL FACILITY IN OPALINUS CLAYSTONE, SWITZERLAND

Switzerland is planning to locate its deep geological disposal facility in claystone, in the Opalinus Clay formation. The formation, which extends over much of Northern Switzerland, has been investigated at the Mont Terri underground research laboratory for more than 20 years.[154] It has been shown to have naturally isolating characteristics (Appendix I) including:

- tectonic stability, with the capability to self-seal in the event of seismic shear
- groundwater flow conditions that will limit the movement of radionuclides. This includes extremely slow flow, which is controlled by the rate of diffusion between pores in the claystone. It also includes chemical conditions that buffer the movement of radionuclides through sorption and other processes
- no natural resources, reducing the risk of future human intrusion.

71. Engineered barriers are designed to work in combination to greatly delay the exposure of the fuel to groundwater and ensure that if the radionuclides migrate into the natural environment, the level of radioactivity would be below that produced by natural sources.

Engineered barriers are designed to support the geological barrier in containing and isolating the waste. Their primary functions are to contain the waste for the period of time that its radiotoxicity is greater than that presented by natural uranium, or around 100 000 years (see Figure 5.8). [155]

The host geology plays a large role in determining the types of engineered barriers that might be suitable. Engineered barriers need to be chosen to complement the naturally isolating characteristics of the host geology.[156] For example, the groundwater chemistry in clay geologies may not be particularly corrosive to steels, but the same may not be true for water in crystalline rock environments.[157] Similarly, the materials used for engineered barriers need to be chosen such that the corrosion and degradation products do not adversely affect other barriers, such as by reducing sorption properties.

Using multiple engineered barriers that work in concert with one another and with the host geology provides protection against a single failure severely challenging the performance of all safety barriers.[158] There is significant complexity in analysing the likely interactions between barriers in a disposal environment, but much research has been undertaken around the world in this field.[159]

Engineered barriers include:

- solid form waste, i.e. radionuclides that are fixed within the waste form and not easily released from it[160]
- a purpose-built canister to protect it from mechanical loads[161]
- the canister being deposited inside an additional container to prolong containment. Containers provide a principal protective barrier to the waste—radionuclides cannot migrate while the container is intact. Different materials and different numbers of layers can be used to extend the duration of total containment. Even if a container(s) is perforated by corrosion, the corrosion products might limit radionuclide migration, thus still acting as a partial barrier. Containers have been assessed as being capable of providing containment for tens to hundreds of thousands of years[162]
- a buffer to impede moisture entry and thereby reduce corrosion. Buffers can work in three main ways: some buffers such as bentonite clay swell on contact with water, reducing the flow through porosity and permeability pathways[163]; some buffers provide sorption, limiting the ability of radionuclides to move through the buffer; some buffers are chosen to provide chemical conditions that are not particularly corrosive to the waste containers, packages and waste form.[164] Buffers can provide isolation for hundreds of thousands of years, and can also be used to limit movement from seismic activity
- backfill and plugs to provide structural support to the tunnel and impede groundwater flow.[165]

Further, the facility must be designed and constructed in a way that acts as a geological barrier, such that construction and operations activities do not compromise the performance of the geological or engineered barriers.

UNDERGROUND RESEARCH LABORATORY

The construction of an underground research laboratory is a key step in understanding the suitability and performance of the geological conditions for prospective sites or geology. An underground research laboratory is situated several hundred metres underground and is accessible by tunnel or shaft. It is important that it is located in geological conditions similar to those being considered for the disposal facility itself. This allows an accurate characterisation of the geological and groundwater properties at depth. It also allows experiments to be undertaken that provide realistic results on the performance of the engineered barrier system, including corrosion rates of the selected materials. Some countries have subsequently chosen to locate their disposal facility at the same location as their underground research laboratory, while others have chosen or will choose other sites.

THE ENGINEERED BARRIER SYSTEM FOR THE DISPOSAL FACILITY AT OLKILUOTO, FINLAND

Finland's deep geological disposal facility will use an engineered barrier system at the Olkiluoto site. This concept, which has been developed and refined in conjunction with Sweden for more than 30 years,[166] has features that support containment and isolation, including:[167]

- used fuel, in solid, ceramic form[168]
- a cast-iron canister inside a copper container, providing containment over very long timeframes. Copper is not

easily corroded by conditions in the Fennoscandian Shield.[169] Evidence of the long term behaviour of copper in the Fennoscandian Shield is provided by native copper deposits, which have retained their elemental form for over a billion years[170]

- compacted bentonite clay, which surrounds the container.[171] The clay restricts moisture entry by swelling on contact with water.[172] It also makes the local chemistry less favourable for corrosion, reducing the mobility of radionuclides. The function of the clay is to provide isolating properties over hundreds of thousands of years [173]
- backfill of underground openings to help restore the site to natural conditions.[174]

THE ENGINEERED BARRIER SYSTEM FOR A DISPOSAL FACILITY IN OPALINUS CLAYSTONE, SWITZERLAND

Compared to the Finnish concept, the geology of Switzerland requires less reliance on the engineered barrier system. Switzerland's deep geological disposal facility will use an engineered barrier system that has been tailored to their geological conditions. This concept has features that support containment and isolation, including:

- high-level waste immobilised in a solid glass (vitrified) matrix and used fuel in solid, ceramic form
- a steel container, providing containment for several thousand years.[175] If, after 10 000 years or more, the containers are penetrated by corrosion, the corrosion products would further isolate the waste by helping to provide a reducing chemical environment that limits the solubility of the radionuclides, and by reacting with and thus further binding them
- compacted bentonite clay which surrounds the container. The clay has similar properties to the host rock. The bentonite restricts moisture penetration by swelling on contact with water. It also makes the local chemistry less favourable for corrosion, reducing the mobility of radionuclides. The function of the clay is to provide isolating properties over hundreds of thousands of years.[176]

IS THE ACTIVITY FEASIBLE?

72. For the management of used fuel and intermediate level wastes, South Australia has a unique combination of attributes that offer a safe, long-term capability for the disposal of used fuel in a geological disposal facility.

The attributes that offer a long-term capability for the disposal of waste include the physical attributes of the state—underlying geology, low seismicity, an arid environment— as well as social attributes including a mature and stable political, social and economic structure, and sophisticated pre-existing frameworks for securing long-term agreement with rights holders and the broader community. Each of these is discussed below.

THE UNDERLYING GEOLOGY OF SOUTH AUSTRALIA

The underlying geology of South Australia is old and stable. It encompasses different geological environments that are suitable for the disposal of used fuel, namely, hard crystalline rock and appropriate sedimentary formations, including clay.[177] This means that there are various disposal concepts that could be employed, depending on the site.

The fundamental geological building blocks of South Australia are the Gawler Craton and the Curnamona Craton.[178] This geology is composed of hard crystalline rock, which formed about 2.5 billion to 1.5 billion years ago.[179] There have been several episodes of volcanic activity, beginning around 1.6 billion years ago, shown in the connecting material between the cratons.[180]

The more recent erosion of the geology of South Australia has resulted in a thick accumulation of retained sediments within basins that overlie hard crystalline rock in various locations across the state.[181] These sedimentary sequences extend more than a kilometre in depth[182], and are characterised by siltstone, sandstone, shale, limestone and conglomerates.

LOW SEISMICITY

Although South Australia is the most tectonically active state or territory in Australia, on a global scale that activity is very low. This is especially when compared to countries in the Pacific 'Rim of Fire', including Japan and Indonesia, and in zones in parts of Asia, such as the Himalayas, Iran and Turkey, which are located on active plate boundaries.[183]

A prominent fault system extends from the Mt Lofty Ranges to the Flinders Ranges, and remains active.[184] The highest risk area in South Australia is the Adelaide Geosyncline (the Adelaide Hills and Flinders Ranges).[185] The largest magnitude earthquake in South Australia was 6.5 in 1897 at Beachport near Mount Gambier.[186] The state has recorded about 40 earthquakes over a magnitude of 4.5 since 1872.[187] By way of comparison, Japan routinely records more than ten of these magnitude earthquakes in a month.[188]

AN ARID ENVIRONMENT IN MANY PARTS OF THE STATE

The climate in South Australia is considered to be arid, with annual evaporation exceeding rainfall. For example, in Adelaide, the mean annual rainfall is about 540 mm and the annual mean evaporation is 1460 mm per year.[189] In the central northern regions of South Australia, at Woomera for example, the annual mean rainfall is 182.2 mm and annual mean evaporation is 3139 mm.[190] However, the arid climate does not preclude flooding due to short duration heavy rainfall, or from floodwaters migrating towards South Australia from other states, including waters migrating from Queensland towards Lake Eyre.[191]

There are two major freshwater aquifers in South Australia, the Great Artesian Basin and the Murray–Darling Basin. Aside from these aquifers, groundwater exists at varying salinity, volume and depth across South Australia. At depth, the hydrogeology of the majority of the state would support further consideration for hosting a geological disposal facility.

A MATURE AND STABLE POLITICAL, SOCIAL AND ECONOMIC STRUCTURE

The planning, development and construction of a geological disposal facility would take several decades. By the time of closure, about 100 years would have passed. Stable and consistent management of such a project would be required for this duration.

South Australia has a stable representative democratic political system that has not significantly changed since Federation in 1901. Under this system, there are established processes for debating and passing legislation and budgets, and addressing issues of public importance before the parliament. As a result, significant public and private sector projects have been successfully undertaken.

SOPHISTICATED PRE-EXISTING FRAMEWORKS FOR SECURING LONG-TERM AGREEMENT WITH RIGHTS HOLDERS

The nature and longevity of hazards associated with a geological disposal facility raise complex and intergenerational issues that require social and community consent (see Chapter 6: Social and community consent). This requires sophisticated and respectful engagement with all stakeholders.

There are frameworks for securing long-term agreements with rights holders in South Australia, including Aboriginal communities. These include Indigenous Land Use Agreements, Cultural Heritage Management Plans, mining agreements, land access agreements and exploration permits. These frameworks provide a sophisticated foundation for securing agreements with rights holders and host communities regarding the siting and establishment of facilities for the management of used fuel.

73. The storage and disposal of international used fuel and intermediate level waste in a South Australian location are likely to be technically feasible. However, detailed investigations to demonstrate suitability would be required once prospective sites were identified as part of a wider consent based siting process.

Above-ground radioactive waste storage has been undertaken around the world for decades. Such facilities are already in use in other countries in a range of environments. These facilities, in which the used fuel assemblies are stored in large steel and concrete casks placed in above-ground structures or buildings (see Figure 5.11), are largely independent of site conditions. A number of types of casks can be employed for both the transport and storage of used fuel. During storage, casks weighing more than 100 tonnes are typically positioned on concrete pads for storage and monitoring until they are transported to a geological disposal facility. The casks allow for the safe containment of radioactive materials, continuous transfer of heat out of used fuel by natural ventilation, and minimisation of occupational and general public exposure to radiation both during normal operation and in the case of accidents or other malevolent acts (as discussed within the Transport section of Chapter 9: Transport, regulation and other challenges). Such dry cask systems have now been commercially licensed to operate for 100 years or more.

In the case of geological disposal, and as discussed above, concepts have been developed over many decades in other countries covering a range of geologies. These are at varying levels of regulatory approval. The technology for the construction of a geological disposal facility is not new, and is similar to that already used in South Australian mining operations. Furthermore, the geologies being considered have similarities with those found in South Australia, making it highly likely that technically suitable sites can be found. While cask and facility designs continue to be refined, there are few characteristics that would make a prospective site unsuitable.

It must be acknowledged that poor planning and implementation, and lack of a strong safety culture, can result in unintended releases of radioactivity from radioactive waste disposal facilities. This has been borne out at both the geological disposal facility for low level waste at Asse, Germany, and the Waste Isolation Pilot Plant (WIPP) for intermediate level waste in Carlsbad, New Mexico, USA.

The low and intermediate level waste facility at Asse in Germany received waste from 1967 for research purposes. Before this time, the disposal facility was mined for potash

Figure 5.11: Dry cask storage facility, depicting casks stored in horizontally configured modules (left) and in a vertical configuration (centre)

Image courtesy of AREVA.

salt and rock salt. As the disposal of radioactive waste in the mine was not originally envisaged, some chambers were mined until they reached the edges of the salt layer, compromising the ability of the geology to effectively isolate and contain the waste. At the time disposal ceased in 1978, no formal assessment was undertaken as to the measures required to safely close the facility, and the chambers and tunnels were not reinforced or sealed. Pressure from the overhead geology has allowed pathways for groundwater penetration. It is planned to retrieve the waste and manage it at a separate location where long-term safety can be assessed.[192]

The operation of the WIPP facility in New Mexico is currently suspended following an accident in February 2014. The accident was caused by a failure to follow strict protocols in packing a waste drum. Incompatible materials were packed together, which caused a chemical reaction that opened the lid of the drum. The accident resulted in the exposure of 21 employees to small doses of radiation (equivalent to a chest x-ray) following its release to the environment.[193] It is planned to reopen in late 2016.

Given the different type of waste disposed of at Asse and WIPP, neither of these examples has direct technical relevance to the storage and disposal of used fuel. However, they are salient reminders that, despite broad international scientific consensus that geological disposal of used fuel can be achieved safely, it can also be implemented poorly. The consequences of human error and 'normal' accidents must be anticipated, expected and planned for in system design and operation.

An authoritative decision on the suitability of a disposal site, and on the disposal concept for that site, cannot be made without detailed site investigations.[194] Such site investigations, which should be transparent and open to scrutiny, are part of the process for characterising the geology of a proposed site, as discussed at Finding 70. The identification of prospective sites is not part of the Commission's Terms of Reference. Any future siting process would require sophisticated planning and consent-based decision making outlined in Chapter 6: Social and community consent.[195]

74. The timeframe for the development of a geological disposal facility for used fuel on the Finnish and Swedish models is long. Any future proposal could draw on these experiences to reduce licensing and construction timeframes.

By the time used fuel is received at the Finnish and Swedish facilities in the 2020s, these projects will have taken more than 40 years to develop.[196] As used fuel needs to cool for several decades prior to disposal, the facilities were not required earlier.[197] Nevertheless, the timeframes have been dominated by the need to concurrently develop the disposal concept, design new equipment, test disposal methods, and identify and characterise prospective sites.[198] The development of concepts for the disposal of used fuel in other geological environments has been similarly long.

Any site investigation and characterisation program for a geological disposal facility could take around two decades.[199] However, any future proposal could draw on the concepts, methods and technology developed in Finland, Sweden and other countries with underground research laboratories to reduce overall licensing and construction timeframes.

IN WHAT CIRCUMSTANCES IS THE ACTIVITY VIABLE?

75. Globally there are substantial quantities of used fuel from nuclear reactors in temporary storage awaiting permanent disposal.

Internationally, there are significant quantities of used fuel discharged from nuclear reactors. While this waste is safely and securely stored in wet storage within nuclear reactors, or in dry cask storage in purpose-built facilities, in many countries there are no facilities available for its permanent disposal.[200]

The reasons for this vary. In some cases, it is a result of governments delaying development of permanent disposal until there are sufficient quantities of fuel available for disposal, and in others, it is a result of the failure of earlier processes to secure societal and community consent to develop a domestic disposal facility.[201] Further, some countries, including those with challenging geological conditions unsuited to a disposal facility, intend to develop programs to reuse the fuel by developing reprocessing (although wastes from reprocessing also contain highly radioactive materials which themselves require disposal).

All countries are required to periodically report the quantities of used fuel and intermediate waste they have in storage as part of their obligations under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (the Joint Convention).[202] In total, the IAEA reports that there were global inventories of 390 000 tonnes of used fuel and reprocessed waste and 9.9 million cubic metres of intermediate level waste in storage as at 2015.[203]

76. International conventions require that countries generating used fuel must address its management domestically; however, the development of international or regional solutions for disposal are permitted.

The international management of used fuel is governed by the Joint Convention. That agreement, to which Australia is party, dictates countries' responsibilities for managing their radioactive wastes, including used fuel.[204] The Joint Convention stipulates that while responsibility to develop arrangements for domestic management rests with the country that created the waste, in some cases international or regional facilities may be beneficial.[205] Some countries such as Switzerland and the United Arab Emirates are investigating a domestic option for disposal of their used fuel, while keeping the international option open.[206] Other countries have not defined their position.

There are international models that address the transfer of waste between countries. The Basel Convention, which applies to hazardous wastes other than radioactive waste, imposes requirements upon the transfer of hazardous wastes between countries; namely the transfer shall only take place where prior informed consent has been received and only if the transfer represents an environmentally sound solution.[207] Hazardous wastes are commercially transferred under this regime. While the Joint Convention applies equivalent requirements to transfers of radioactive waste between countries, there are no operating models for the commercial transfer of used fuel for disposal.[208]

Various organisations have looked into potential concepts.[209] There are, however, commercial models for the transfer of used fuel between countries for reprocessing, as well as the take-back of fuel from reactors built by Rosatom, the Russian state nuclear corporation.[210] Similarly, the United States had a program to take back research reactor fuel of US origin as part of its non-proliferation policy.[211] The United Kingdom has reprocessed used fuel for many countries but does not accept the waste products for disposal. In all cases, transfers can only take place if the recipient country has the capacity to manage the waste safely and where such transfer has been agreed between the countries concerned.[212]

Under the Joint Convention, any proposal to store and dispose of used fuel in South Australia would require agreement between the countries concerned.[213] In Australia, treaty level agreements would need to be developed between the federal government and the relevant overseas government. An agreement would also need to specify arrangements between the Australian Government and the Government of South Australia, to ensure these commitments were fulfilled. Further agreements may be required with third party countries: for example, if they have supplied uranium to the country wishing to store and dispose of used fuel in South Australia.

77. Used fuel management is an issue of global concern and, like other countries that participate in its supply chain, Australia has a direct interest.

Used fuel management is an issue of global concern for several reasons. As a supplier of uranium, Australia has special interests in ensuring it is used for peaceful purposes. In addition to the IAEA safeguards[214], Australia requires further assurance on the peaceful uses of Australian obligated uranium material.[215] This includes accounting for material through the whole fuel cycle.[216] As a result, Australia has an interest in how and where radioactive waste is managed around the world.

Similarly, Australia has an interest in ensuring that nuclear materials are securely handled for both Australian obligated uranium and other radioactive materials used by Australia in industry and science.[217]

As Australia is a net exporter of energy, it has a significant role to play in assisting other countries to lower their carbon emissions. This includes countries with less opportunity for large scale renewable energy deployment than Australia, for whom nuclear power makes a substantial contribution to their production of low carbon energy. For new nuclear entrants or countries with little prospect of siting their own used fuel disposal facilities, an international solution would remove a significant impediment to the new or ongoing use of nuclear power as a low carbon technology. As a result, Australia would derive a reputational and financial benefit by hosting a facility for the disposal of international used fuel.[218]

78. Given the quantities of used fuel held by countries that are yet to find a solution for its disposal, it is reasonable to conclude that there would be an accessible market of sufficient size to make it viable to establish and operate a South Australian disposal facility.

The current global inventory of used fuel is estimated to be in the order of 390 000 tHM. By 2090 this global inventory is anticipated to be in excess of 1 million tHM, based on existing reactors and new reactors in the advanced stages of planning. The ILW global stockpile is presently just under 10 million m^3 and is expected to be nearly 24 million m^3 by 2090.[219]

To make a conservative estimate of an accessible market for a disposal facility in South Australia, it is necessary to exclude used fuel and intermediate level waste stored in the United States, France, the United Kingdom and Canada, as they are committed to developing national solutions or already have structured programs leading to a domestic facility.[220] Countries which have national laws that prohibit their export of waste, such as Sweden and Finland, should also be excluded.[221]

Other than those countries, the overall current and forecast quantity of used fuel and intermediate waste which is not committed to a national solution is presented in Table 5.3.[222]

The forecast includes only quantities of used fuel and intermediate level waste from existing reactors and from those that are currently under construction, such as in the UAE, or are in the advanced stages of development. To ensure the figure is conservative, no account has been taken for any new reactors being constructed beyond 2030 and the waste they would produce.[223]

In response to the Tentative Findings, comment was made concerning the inclusion of some new entrants in the forecast.[224] First, their combined contribution to the figure is small, meaning that if none ultimately developed programs, it would make no material difference to the conclusion that there is a large accessible market. Second, their inclusion is more than counterbalanced by two potential sources excluded from the analysis: used fuel from a new nuclear reactor developed after 2030 and used fuel from countries with domestic programs that might pursue an international disposal arrangement if it became available.

To provide some context, the current and forecast figures in Table 5.3, comprise about 25 per cent of current and forecast global used fuel inventories.[225]

Bearing those matters in mind, the Commission considers this estimate of a potentially accessible market to be conservative.

79. There is no existing market to ascertain the price a customer may be willing to pay for the permanent disposal of used fuel. However, willingness to pay may reasonably be inferred from analysing, in combination:

a. the costs that the customer might avoid in receiving the service

b. the costs of disposal estimated in countries with domestic permanent disposal programmes

c. the costs associated with reprocessing, being the only alternative long-term used fuel management strategy

d. the savings in capital costs for new nuclear power plants that might be enjoyed where access to permanent used fuel disposal reduces project risk and therefore lowers the cost of finance

e. distress costs, being the costs a nuclear utility may be willing to pay to avoid plant shutdown due to a lack of used fuel management options.

Countries with domestic nuclear power programs, and their nuclear power utilities, incur real costs associated with the storage and management of used fuel, such as developing and operating temporary storage, as well as identifying and developing options for long term permanent disposal domestically.

Because those entities and governments have an incentive to reduce expenditure where they can, such costs indicate what they might pay to avoid incurring their current liability for storage and disposal.[226] Rationally, they would be expected to be willing to pay an amount up to the present value of these future liabilities. This allows for a reasonable

Table 5.3: Total current and forecast used fuel and intermediate level waste inventories excluding countries committed to a national used fuel disposal solution

Total	Currently available	Forecast growth from 2015 to 2090 (current and declared new programs)	Total (2090)
Used fuel (tHM)	89 979	186 541	276 520
Intermediate level waste (m^3)	269 471	512 959	782 430

Source: Jacobs & MCM

estimation of willingness to pay in the absence of an existing market for international used fuel disposal. This approach is not unusual: for any new service that is proposed to be offered by a commercial entity, this is precisely the question it must contemplate in fixing a price for its service.

It has been suggested in a response to the Tentative Findings that such an approach seeks to price an environmental externality.[227] Externalities are the costs, for example, that emitters of pollutants impose on the wider community at large but do not bear themselves. The cost of used fuel management and disposal is not an externality—it is a cost actually incurred by those utilities that must fund used fuel storage and disposal.

COMPONENT OF LCOE OF NUCLEAR ASSOCIATED WITH WASTE DISPOSAL

In analysis undertaken for the Commission, the relevant costs incurred by utilities were estimated based on the fraction of the levelised cost of electricity (LCOE) that can reasonably be attributed to used fuel storage and disposal. From this analysis it was estimated that the cost of transport, storage and disposal of used fuel was just under A$1.4 million per tonne, based on LCOE estimates used in the OECD's 2015 publication entitled *Projected costs of generating electricity*.[228] That LCOE estimation is robust because it averaged a spread of results for different reactors in nine OECD and non-OECD countries.

In a response to the Tentative Findings it was suggested that the analysis should have been based on the LCOE estimated by the Electric Power Research Institute.[229] Because the LCOE estimate used in the Institute's analysis is higher, it results in a higher estimate of inferred willingness to pay for waste disposal than that stated above—in fact more than 50 per cent higher as set out in Table 5.4.

The same response asserts that this approach is 'speculative' because the share of disposal costs for used fuel that forms part of LCOE remains unknown, given that no geological disposal facility has yet been constructed.[230] However, geological disposal projects are currently under construction in Finland, and there are others at an advanced stage of development elsewhere. The reported costs associated with such projects offer a valuable guide, and have been incorporated into recent LCOE analyses. As various projects advance, such costs will become more certain. There is sufficient information available to ensure that the approach used by the Commission is not speculative.

As part of seeking to determine a sound indication of willingness to pay, the Commission has considered that information in combination with other independent sources.

ESTABLISHED WASTE FUNDS

Along with costs to nuclear power utilities for used fuel disposal which might be avoided, the Commission has also considered the amount of funds held, and provisions made, for the future management, storage and disposal of used fuel by countries with nuclear power plants.

This approach takes advantage of the fact that in most countries with nuclear power programs, funds are put aside to address the costs of used fuel management, storage and disposal. The amount held in those funds is determined within those countries on the basis of domestic estimates of the future liability for used fuel storage and disposal. The additional benefit of utilising this approach is that such funds already exist. A reserve fund has been established sourced from a small margin on the cost of electricity sold. Those funds can only be used for the dedicated purpose of used fuel storage and disposal.

Detailed analysis undertaken for the Commission reported on the cost estimates used by a number of countries with domestic nuclear power programs for their domestic

Table 5.4: Calculation of used fuel storage, transport and disposal cost from the levelised cost of energy

	Levelised cost of electricity ($A/MWh)	Combined costs of fuel production and long-term management (A$/MWh)	Fuel storage, transport and disposal (A$/MWh)	Expected cost per tHM (A$ million)
OECD (2015)	147	9.6	3.40	$1.39
EPRI (2015)	180	21.3	5.33	$2.18

Notes: EPRI = Electric Power Research Institute, MWh = megawatt hour, tHM = tonne of heavy metal
Data sourced from OECD, Electric Power Research Institute

Table 5.5: Costs for used fuel disposal in countries with advanced projects

	Whole of life disposal costs (A$ million per tHM)
Finland	$0.65
Sweden	$1.13
Switzerland	$2.43

Note: tHM = tonne of heavy metal
Source: Jacobs & MCM

used fuel storage and disposal. That analysis arrived at an average disposal cost of about $A1.2m/tHM as an illustrative benchmark.[231] The Commission considers the most relevant and robust cost estimates are those from countries most progressed with geological disposal facility projects, including those which have constructed underground research laboratories. Costs estimated in those countries are set out in Table 5.5.

The key point to be drawn in Table 5.5 is not any single cost, but the range of costs for the advanced programs. Though the costs for the Finnish geological disposal facility are lower, they are not representative of the costs of advanced programs in Switzerland, Sweden and the United States. The Finnish costs are unlikely, for reasons of geology, to be representative of costs in other countries which require a domestic disposal capability. Therefore a median price for willingness to pay has been used.

REPROCESSING COSTS

The Commission has also considered the cost other countries are prepared to pay to manage waste, as such costs are an indicator of what they might pay for a permanent used fuel disposal service.

A tender was issued by the government of Taiwan to reprocess 1200 fuel assemblies (330 tHM) for an announced cost of US$356 million. This tender was later suspended by the Taiwanese parliament, which required approval of the budget and development of guidelines for the use of the Taiwanese fund for managing the disposal of used fuel. Though suspended, the arrangement was the policy of the utility and government and reflected the likely cost of that activity. That price represents, when converted, a willingness to pay $A1.54 million per tHM to manage its used fuel.[232] This is significant given that reprocessing does not eliminate the highly radioactive material, and it is still necessary to dispose of the immobilised vitrified high level waste. This means that Taiwan would, in addition, still face disposal costs for the waste remaining after reprocessing. This suggests its willingness to pay for disposal for used fuel is higher.

A response to the Tentative Findings claimed that the reprocessing cost could not be used without offsetting the value derived from 'the sale of the reclaimed fuel'.[233] It was said this might mean the activity was cost neutral or 'could even have been a net profit'. This is incorrect. Reprocessing does not produce usable nuclear fuel. Rather it would be necessary to re-enrich the uranium and to undertake a further specific fuel fabrication process (to produce mixed oxide fuel), in addition to reprocessing, to make usable nuclear fuel. This additional process is itself very costly, and more expensive than the cost of fabricating fuel from natural uranium.[234] Furthermore, mixed oxide fuel, once used in a reactor, creates its own used fuel burden.

Moreover, the Taiwanese price has independent support. The quoted price for reprocessing is consistent with the fees charged to Japanese power companies under the Spent Nuclear Fuel Reprocessing Fund Act (Japan). The fee is ¥0.5 kWh generated (A$0.0055 kWh). This equates to A$2.24 million per tHM. [235] The total of secured funds held was reported to total ¥2.4 trillion (around A$26 billion) in March 2015.

REDUCED CAPITAL COSTS

A further approach in considering willingness to pay can be drawn from reductions in project risk and the resultant cost of capital by having reliable, fixed-cost waste disposal.[236] Nuclear power plant projects, as explained in Chapter 4, have high upfront capital costs and associated costs of finance. The cost of finance takes account of project risk, a component of which is the availability of a disposal solution for used fuel. If that risk can be reduced, or eliminated, it could lower the costs of finance.[237]

The significance of a lower rate of interest on debt to the ultimate cost of electricity generated is shown in Figure 5.12. It shows that the cost of electricity increases by US$7–$8 per MWh (about A$9–$10) for every additional 1 per cent increase in interest rates.

If a secure, waste disposal solution was able to reduce project risk and the cost of finance by the relatively small amount of 0.5 per cent, then it would have a value to the project developer equivalent to A$1.9m to $2.6m/tHM of used fuel. This would have a significant bearing on willingness to pay to secure such a long term arrangement.[238]

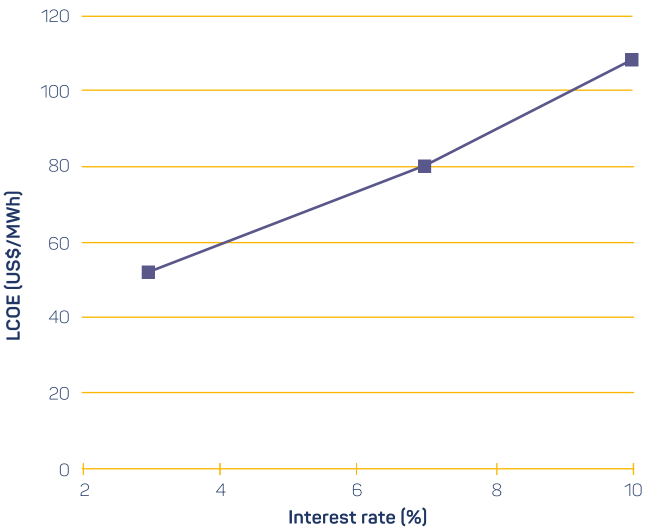

Figure 5.12: Variation in nuclear power LCOE with cost of capital

Note: LCOE = levelised cost of electricity.
Source: Jacobs & MCM.

DISTRESS PAYMENTS

A further approach is to consider distress payments or the payments that a nuclear utility may make to move used fuel to avoid unscheduled plant shutdowns. Given their capital intensity, nuclear power plants are required to operate for as much of the year as possible in order to be commercially viable. One potential reason for plant shutdowns is that the used fuel pools associated with those reactors are full and cannot be expanded, so options are not available to move fuel into dry storage. In that circumstance, the plant would have to shut down until a solution could be found. Plant operators would be willing to pay an amount up to or equal to the cost of the shutdown to avoid that outcome. Estimates based on the levelised cost of electricity suggest that this could be up to A$42m/tHM.[239]

80. A conservative baseline price for permanent disposal is A$1.75m/tHM for used fuel and $40 000 per m^3 for intermediate level waste. These figures are not recommended prices. A higher figure could be negotiated in a range of circumstances.

Based on detailed analysis, the Commission considers that a reasonable baseline price for the purpose of assessing viability would be A$1.75m/tHM for used fuel. This is based on a reasonable baseline 'willingness to pay' estimate of A$1.95m/tHM, less A$0.2m/tHM to account for costs incurred by customers in preparing and delivering the waste to South Australia.

The financial modelling derived the baseline 'willingness to pay' figure of $A1.95m/tHM as a mid-point between the estimated highest and lowest willingness to pay.[240] Willingness to pay varies depending on a country's domestic circumstances. The lowest figure, being A$1.3m/tHM, represents the willingness to pay from countries with advanced programs for the disposal of domestically generated used fuel.[241] The highest willingness to pay figure was taken at A$2.6m/tHM, based on the position of countries without domestic disposal programs and/or with unfavourable domestic circumstances, such as small volumes of used fuel which would adversely affect economies of scale, and those nations with unfavourable geology.[242] For such countries, A$2.6m/tHM falls at the lower end of the range of benefits that are estimated to accrue if safe and secure used fuel disposal services were available.

The Commission considers this baseline 'willingness to pay' figure is reasonable based on the combined force of estimates derived from the range of sources explained earlier, many of which are higher, as shown in Figure 5.13.

The Commission does not consider that A$1.75m/tHM represents a price that any future program should charge any particular customer. It is simply a reasonable estimate for the purposes of viability analysis. As discussed above, there may be considerable opportunity for negotiating a higher price based on local circumstances in a customer country. A lower price may also be negotiated in return for the willingness of that customer, by pre-commitments or through finance, to assist in the development of the overall program.

The management and disposal of intermediate level waste commands a far lower willingness to pay than for used fuel.[243] This is due to a country's ability to stockpile intermediate level waste arising from nuclear power plants or other sources (such as decommissioned nuclear facilities) within shielded containers far more readily than used fuel.[244] Unlike used fuel, there are also no maximum limits for intermediate level waste storage at nuclear power plant sites.[245]

However, a 2011 report from the UK Department of Energy and Climate Change has suggested that £25 900 per m^3 (in current terms, A$66 000 per m^3) represents a levy that ought be imposed on nuclear power plant operators to reflect current costs and the potential for future increases.[246] In the interests of conservatism, and to address the costs of packaging and transport (which are not as well defined as for used fuel) a price to charge of A$40 000 per m^3 is considered appropriate for the purposes of a viability analysis. It does not represent a recommended price for the same reasons explained in relation to used fuel.[247]

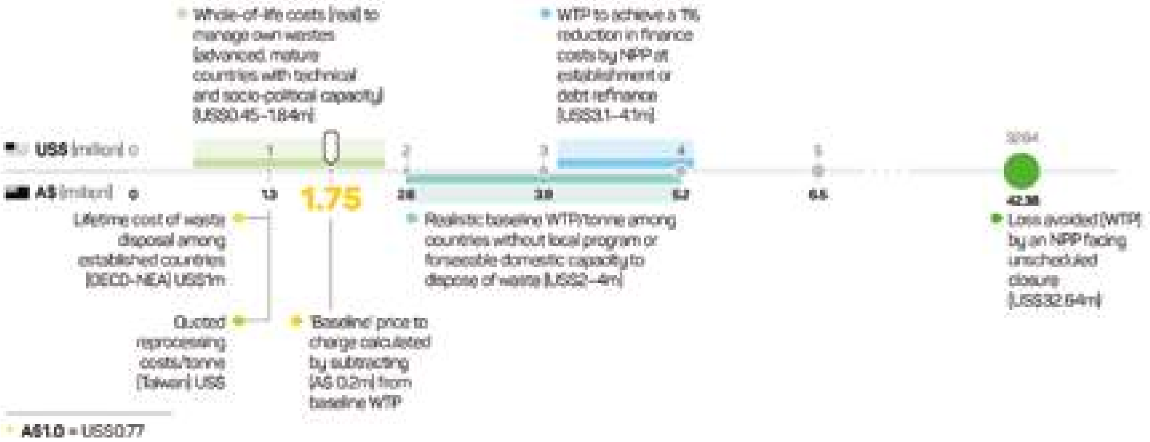

Figure 5.13: Summary of willingness to pay (A$ and US$ per tHM) based on published data and enhancements.

Notes: NPP = nuclear power plant, WTP = willingness to pay
Source: Jacobs & MCM

COMPETITION

It has been suggested in a response to the Tentative Findings that the estimated price has not taken account of currently non-commercial competition from other countries.[248] The Commission has taken account of the potential for competition in considering the necessary market share that would need to be captured for a proposed disposal facility in South Australia to be viable. Based on the financial analysis undertaken for the Commission, and assuming a range of prices charged per tonne of heavy metal received (including as low as $A1m), the facility would be viable if it received only 25 per cent of the accessible market discussed in Finding 78. It should be underscored that there is significant potential for other countries to develop a domestic solution, and for the project to still remain viable.

However, something more should be said about the claimed competition from Russia or China. Australia offers a unique political arrangement given its economic and political structures and international confidence in its non-proliferation credentials, as discussed in Chapter 8. This would make it an attractive disposal site to other countries.

That response to the Tentative Findings also suggests that competition might come from borehole disposal, which would be cheaper—asserting a cost of A$200 000/tHM from a single source.[249] That technology is, however, unproven. Recent reports suggest that substantial efforts towards demonstrating technical feasibility remain to be made (including in the report cited by the response for the cost estimate).[250] Recent analysis suggests the timeframe for implementing a borehole disposal facility is similar to those for a mined disposal facility.[251] Finally, there is no basis for the claim that interim storage facilities would be in competition with geological disposal. They are not regarded by any country as a long-term disposal arrangement.

It was also suggested that advanced reactor designs, such as fast reactors, might also compete with international used fuel disposal services[252], given that some designs can utilise reprocessed used fuel. Significant barriers to commercial deployment of fast reactors remain, as explained in Appendix E: Nuclear power—present and future. They have not been demonstrated to be cost competitive with conventional light water reactor designs. This suggests it is implausible that a fleet of fast reactors could be rapidly deployed internationally with the ability to consume existing and future inventories of used fuel. This is consistent with the findings of the Blue Ribbon Commission on America's Nuclear Future, following consideration of fast reactors as a means of recycling used fuel, that geological disposal is the best long-term solution for the United States.[253]

81. The project concept analysed comprises an integrated above-ground interim storage facility as well as an underground disposal facility.

Detailed analysis undertaken for the Commission assessed the viability of a proposed project for the storage and disposal of used nuclear reactor fuel and intermediate level waste based on the construction of both an above-ground interim storage facility and a separately located underground disposal facility. As discussed at Finding 84, an above-ground interim storage facility is required to generate sufficient cash flow to allow for construction of the underground disposal facility.

Figure 5.14: Conceptual layout of an interim storage facility

Image adapted from Jacobs & MCM

The viability analysis required assumptions to be made with respect to facility capacity. As a baseline scenario, it was assumed that a South Australian facility would be able to capture 50 per cent of the assessed accessible market discussed at Finding 78.[254] On that basis, the projected final capacity of the proposed geological disposal facility and intermediate depth facility would be 138 000 tHM of used fuel and 390 000 m^3 of intermediate level waste.[255] That figure does not represent a recommended capacity for a facility—nor the profit maximising capacity. Rather, it was a reasonable basis around which profitability could be assessed. Sensitivity analysis was undertaken on smaller and larger quantities. The results are explained later in Finding 83 and in further detail in Appendix J: Radioactive waste storage and disposal—analysis of viability and economic impacts.

INTERIM STORAGE FACILITY

An interim storage facility enables the safe above-ground storage of used fuel inside heavily engineered, purpose-built casks, as discussed at Finding 73.[256]

There are a number of conceptual designs for a used fuel storage facility. The design used for the costings in the financial analysis is based on a proposed facility in the United States shown in Figure 5.14.[257] This facility design has been subject to a comprehensive environmental impact assessment in the United States and two independent cost studies. With capacity to handle a volume of 4000 casks, the facility has a total footprint of 3.3 km^2, with the inner 0.4 km^2 designated as restricted-access to be used for used fuel storage. The facility would be directly accessible by road and rail, with cranes used for the transfer of casks.

DEEP GEOLOGICAL DISPOSAL

The disposal of used fuel in a geological disposal facility comprises two elements: a system of tunnels mined deep underground into geology designed to isolate the waste, and the containment of waste in specially designed containers, as discussed at Findings 70–71.

The financial analysis was undertaken on the basis of a design similar to the disposal facility on which construction has commenced at Olkiluoto in Finland at 400–450 metre depth.[258]

In the analysis, the geological disposal facility for used fuel is notionally collocated with an intermediate level waste facility, where those packages are placed in medium-depth vaults of 50–250 m.[259] A conceptual model for the intermediate level waste facility comprises medium-depth concrete caverns with overhead crane structures for the placement of waste packages, as illustrated in Figure 5.15.

The actual size of any facility underground depends on its design. This is affected by the heat emitted from the emplaced waste and by properties of the host geology. For the purposes of the viability analysis, horizontal emplacement caverns were assumed to be spaced apart by approximately 30 m and are accessed from parallel service tunnels. To deal with the quantities modelled, a total length in the order of 10 km would be required.[260]

Figure 5.15: Schematic illustration of a medium-depth ILW disposal facility, with artist's rendering of a disposal vault with overhead crane for ILW disposal

Note: ILW = intermediate level waste
Images courtesy of Jacobs & MCM and Radioactive Waste Management

The surface footprint would be comparatively small, with land area needed to accommodate road and rail access, underground access headers, waste reception and other supporting infrastructure, such as a site security and an administration building, as illustrated in Figure 5.16. Upon final storage and completion of underground backfilling, the surface facility would be removed and the land remediated.

82. Integrated facilities with the capacity to store and dispose of used fuel would be viable. They would be highly profitable at the target price of A$1.75m/tHM capturing only a relatively small share of the global inventory.

Integrated facilities with capacity to store and dispose of used fuel would be viable. On a number of realistic scenarios, such a facility would be highly profitable.[261]

The Commission draws that conclusion as a broad implication of financial analysis undertaken at its request. The critical significance of that analysis is not the conclusion that any particular concept is viable—rather it is the scale of the profitability and the wide range of scenarios under which a facility would be viable.

Forming a view about viability required estimations to be made as to the timeline over which facilities would be developed, the capital and operating costs, and revenues. It is important that those estimates be comprehensive and as far as possible be based on realised costs.

ESTIMATED TIMELINE FOR CONSTRUCTION AND OPERATION

The necessary steps of conceptualisation and planning, regional area surveys, detailed site investigations, site confirmation, facility design and construction were estimated to take between 20 and 30 years for the geological disposal facility and intermediate depth facility. This includes development of legislative and regulatory frameworks, and establishment of an underground research laboratory. [262]

That schedule is consistent with a program that capitalises on international experience in siting, designing and constructing geological disposal facilities and associated supporting infrastructure.

On that basis the conceptual timeline for the operation of those facilities involved:

- establishing an interim storage facility and associated transport infrastructure, including harbour, port and rail—11 years after project commencement[263]
- transferring used fuel and intermediate level waste from the interim storage facility to the geological disposal facility and intermediate depth facility—28 years after project commencement[264]
- ending the import of used fuel and intermediate level waste to port and interim storage facility—83 years after project commencement

Figure 5.16: Illustration of the surface facility for a geological disposal facility

Image courtesy of Radioactive Waste Management

- decommissioning and backfilling of geological disposal facility, triggering the commencement of the post-closure monitoring phase—120 years after project commencement.

ESTIMATED CAPITAL COSTS

To form a view about the full life cycle of costs, it was necessary to estimate the costs of the preliminary concept development, construction, operation, decommissioning and monitoring. Costs for enabling infrastructure (port facilities, rail, airport, road, electricity and water), site preparation, site services and buildings for onsite facilities, underground excavations and facilities and capital renewal also had to be included in the estimates.[265]

Capital costs were estimated as summarised in Table 5.6. The estimated capital cost of the integrated facilities was A$41 billion (current dollars, real and undiscounted).[266]

The capital costs estimated for individual facilities can be compared with the capital costs from similar completed or more advanced planned international waste disposal projects, as set out in Appendix J: Waste storage and disposal—analysis of viability and economic impacts.

The cost estimates in Table 5.6 include a projected additional contingency of 25 per cent to account for potential optimism bias.[267] This contingency takes account of external factors that might affect costs such as the potential for delays associated with regulatory approvals. The figure chosen reflects the measured difference in costs between the time of original announcement and the point of final project delivery for Australian public–private partnership projects. While a recent analysis conducted in the United Kingdom proposed a contingency of as much as 66 per cent, [268] a comparative Australian study showed that Australian projects outperform UK projects on the basis of cost.[269]

ESTIMATED OPERATIONAL, DECOMMISSIONING AND MONITORING COSTS

Operational costs were estimated from the detailed modelling that has been undertaken for the Olkiluoto facility in Finland and are summarised in Table 5.7. More than half of those costs were attributable to the waste encapsulation facility required for the purpose of containing the waste for long-term disposal.

Although the project is assumed to be closed and decommissioned 120 years from the year of commencement,

Table 5.6: Estimated capital costs for used fuel storage and disposal under the base case scenario

Facility	Capital costs (A$ 2015 million)	Size of facility	Cost per unit waste stored (A$ in 2015)
Low level waste disposal facility	820	81 088 m³ (LLW)	10 100 per m³
Interim storage facility	2200	72 000 tHM (used fuel)	30 600 per tHM
Geological disposal facility and intermediate depth disposal	38 000	140 000 tHM (Used fuel) 400 000 m³ (ILW)	-
Total capital cost	41 020	N/A	N/A

Note: ILW = intermediate level waste, LLW = low level waste, N/A = not applicable, tHM = tonnes heavy metal
Source: Jacobs & MCM

Table 5.7: Estimated operating costs for all facilities

Operating costs	Consumables, equipment leasing, land transport and utilities (A$ million per annum (2015)	Labour (A$ million per annum (2015)	Facility maintenance and upgrades (A$ million per annum (2015)
Combined facilities (before Year 40)	673	125	80
Combined facilities (Years 40 to 120)	560	125	80

Source: Jacobs & MCM

a provision was made in the form of a reserve to fully fund the costs of decommissioning, remediation of surface facilities, closure, backfill of underground facilities and the ongoing, post-closure monitoring phase. That reserve fund is funded from the operating revenues of the facility. Estimates of its growth are based on a low risk investment strategy.

On a baseline scenario, where the funds were drawn from operating revenues so as to maximise the profitability of the facility, the reserve fund would generate about $32 billion by year 83.[270] The criterion that it be profit maximising means that funds begin to accumulate in year 45 of the project, just under four decades before they are required.

The costs that a reserve fund would finance include an annual surveillance allowance of $550 000 for 1000 years for both an interim storage facility and a geological disposal facility.[271] Such funds are necessary at disposal to assure both the community and the monitoring staff that the passive safety features of these facilities are functioning as expected. However, it is important to note that a contingency for surveillance and possible intervention is not an alternative to developing a geological disposal facility that is passively safe.

Responses to the Tentative Findings suggested that the Commission give consideration to the effect of resourcing the fund as soon as revenues are received and without discounting some future liabilities. Taking account of those responses, the Commission considered an alternative scenario for the reserve fund, with 10 per cent of annual operating profits being collected from year 11 and put into a reserve fund. Further, ongoing operating costs were assumed to be undiscounted and equal to A$5.5 million per year, growing at 1 per cent per year in real dollar terms for 1000 years. The reserve fund on that alternative scenario basis would accumulate approximately A$46 billion (in current dollars) by year 60. That amount would significantly exceed estimates of future liabilities.

ESTIMATED REVENUE

The Commission analysed the stream of revenues that would be earned on the basis that it received 138 000 tHM of used fuel over 70 years. It was assumed that the facility would have the capacity to receive and handle the annual rate of imports presented in Table 5.8.

Estimated revenues have been assessed on the basis that payment in full would be made upfront on delivery of fuel to a South Australian port. As discussed in Finding 86, a pre-commitment before project commencement would provide added assurance that capital costs are fully covered before construction began.

A similar profile for importation rates was developed for intermediate level waste on the assumed import rates. The result is that the bulk of revenues are earned over about the first half to two-thirds of the facility's operational life. As can be seen in Figure 5.17, revenues commence being earned a decade after the project begins operation and cease a little more than 70 years later when used fuel stops being delivered.

Given that costs are incurred, and revenues earned, in the future, the value of future revenues and costs needs to be 'discounted' to reflect that a dollar earned a year from today does not have the same value as a dollar today. This assessment was undertaken using a discount rate for project cash flows at both 4 per cent and 10 per cent to reflect discount rates commonly used for investments made by either public or private entities respectively. The effect of the application of each discount rate on project viability is shown in Table 5.9.

83. An integrated storage and disposal facility remains viable even in the event of:

a. large cost overruns

b. the receipt of a significantly lower price for providing a disposal option for used fuel and intermediate level waste

c. smaller market share

d. delays in the development of the facility

An integrated interim storage facility and deep geological disposal facility would be viable in the face of a wide range of more adverse circumstances or market conditions either taken individually, or in combination.

It is significant to appreciate, however, that the risk presented by adverse circumstances or conditions is mitigated by the fact that the proponent has a choice as to whether to proceed with the project. The facility would not be developed unless the proponent could secure a pre-commitment of used fuel volumes at a price to fully fund the development of the project (see Finding 86). This mitigates risks presented by adverse market conditions.

Table 5.8: Annual quantity of used fuel received by South Australia over project life (rounded figures)

Years	Used fuel received (tonnes HM per year)
0–11	0
11–38	3 000
39–64	1 500
65–74	950
75–84	400
85–120	0

Note: HM = heavy metal
Source: Jacobs & MCM

Table 5.9: Project net present value on a real, pre-tax basis under the baseline scenario

Discount rate	Project net present value (A$ 2015)
4%	51.4 billion
10%	14.4 billion

Source: Jacobs & MCM

The project remains viable if costs are significantly higher than estimated. As discussed at Finding 82, cost estimates already include a 25 per cent uplift to account for optimism bias reflecting the potential to underestimate actual project costs. Even when substantial additional margins (50 per cent) representing cost overruns are added to projected costs (either to capital or operating costs, or both), the conceptual facility remains highly viable, as shown in Table 5.10.

The project also remains viable at a significantly lower range of potential prices for used fuel and intermediate level waste than that identified by the Commission as the reasonable baseline (A$1.75 million), including at a price of $750 000 per tHM assuming 50 per cent of the accessible market is secured. This is depicted at Figure J.7 in Appendix J.

The project also remains viable where only a quarter of the forecast accessible market is able to be secured (69 000 tHM).[272] Figure J.6 at Appendix J shows the viability of the project at three assumed market shares at a range of prices. The project is viable, even in the event of both a smaller market share and a lower price than that the Commission considers as the reasonable baseline estimate.

84. In addition to smaller scale integrated storage and disposal facilities, other facility configurations would also be viable provided that they incorporate an interim above ground-storage facility.

An interim storage facility is required as part of any project concept to enable revenues to be secured early so that later investments to develop the capital intensive underground disposal facilities can be financed.

Financial analysis undertaken for the Commission, in addition to assessment of an integrated storage and disposal facility, assessed other facility configurations.[273]

The analysis showed that the collocation of some facilities that make up the integrated waste storage and disposal concept would deliver substantial cost savings by not duplicating common use transport infrastructure.[274] It further showed that if all, and not just some, facilities were located at a single site, some of these benefits would be lost by increases in other costs.[275] This is a result of the challenges and additional time associated with designing, licensing and constructing a range of facilities at one location.

85. Facilities for the storage and disposal of used fuel would need to be owned and controlled by government.

The level of assurance required to secure the long-term trust and confidence of potential customers for such facilities would be more easily conveyed were the proposed facilities to be subject to government ownership and control, as well as independent oversight. Further investigation and development of potential long-term international used fuel storage and disposal facilities would need to proceed over many years. In the early phases of any further and more detailed assessment of the viability of a proposed project, discussions and then negotiations would need to occur between the project proponent and potential customers overseas. Such discussion and negotiation will need to proceed subsequent to, or in parallel with, similar discussions at the nation to nation level, in order to provide assurance as to the credibility of the project, and commitment to compliance with international requirements for safety, security and non-proliferation.

Further, risk and reward should be linked. Assuming responsibility for the safe and secure storage and disposal of international used fuel carries with it significant risks, which, given the long-term radiotoxicity of such high level waste for humans and the environment, potentially affect future generations of South Australians. The potential substantial economic benefits associated with this activity in part result from the complexity and duration of the risk. It is, therefore, appropriate that those benefits are secured for future South Australians.[276]

A response to the Tentative Findings suggested that, given the extent of the risk involved, control and ownership of storage or disposal facilities ought to rest in private hands, along with the associated responsibility.[277] This argument fails to link risk with reward. The public is also more likely to be assured of the safe and effective management of the relevant risks over the long term where the facilities are government owned and controlled, rather than operated by a profit-driven entity whose ongoing presence cannot be guaranteed. A special purpose project company owned by the South Australian government would be able to source and engage appropriate private sector expertise in developing and operating any such facilities.[278]

86. Through pre-commitment from client countries the state would not need to assume significant commercial risks in incurring capital costs to develop the project.

The development of the integrated storage facility would require an initial investment of about $2.4 billion over ten years, in advance of revenues from used fuel being received.[279] Those expenditures would need to be financed. As shown in Figure 5.17, projected revenues received within the first two years of waste being received would repay these costs.

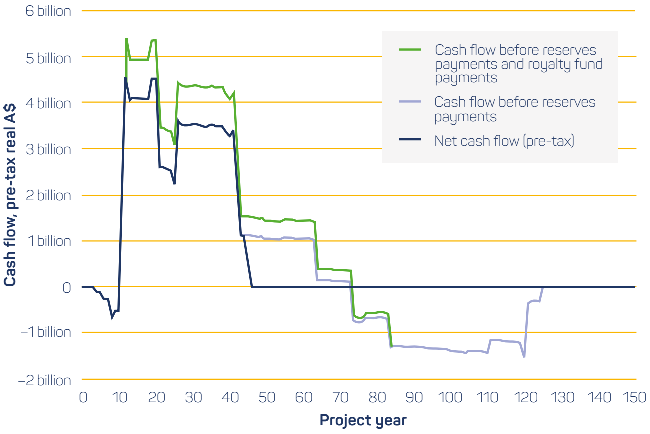

Figure 5.17: Cashflows for an integrated waste storage and disposal facility

Source: Jacobs & MCM

Table 5.10: Sensitivity of project viability to overruns in capital and operating costs, including State Wealth Fund net present value

Discount rate	Project net present value at 10% discount rate (A$ 2015 billion)
Baseline	14.4
Capital costs + 50%	12.8
Operating costs + 50%	13.3
(Capital and operating costs) + 50%	11.7

Source: Jacobs & MCM

However, incurring those costs does not mean that the state should assume significant commercial risk.[280] A prudent operator would not commence construction of the integrated storage facility and initial development of the disposal facility without having obtained sufficient contractual pre-commitment to the disposal of used fuel. In short, because the state has a choice as to whether or not to engage in the development, it need not incur substantial expenses until it is certain that these will be covered by future revenues.

Financial analysis undertaken for the Commission shows that a pre-commitment of 15 500 tHM of used fuel at a price of $1.75m/tHM would be sufficient to meet the cost of developing not only a storage facility but a minimum scale disposal facility based upon the modelled infrastructure.[281] That quantity is equivalent to the used fuel already held by a number of individual countries within the accessible market.[282]

Separate to a contractual pre-commitment there are other means of ensuring that the commercial risk of development can be addressed. One such means would be to secure direct investment in the project by a country seeking to dispose of its used fuel in the facility. Another might be to secure project finance in return for a right to dispose of used fuel.

87. Both an analysis of financial viability, and a risk assessment in the form of a safety case, must be conducted and considered together in order to decide whether to proceed with the development of a disposal facility.

Financial viability and safety of a disposal facility can be assessed in a two-staged approach.

The first step is to prepare a financial assessment of expected revenue and cost flows to determine the profitability of the project.

The second step is to undertake a formal long-term risk assessment in the form of a safety case for a geological disposal facility. As discussed at Finding 69, this requires an objective and detailed consideration of a baseline case and a range of possible alternative future scenarios, based on the chosen geology and engineered barriers.

The results from both stages must then be weighed together, with careful consideration of the nature of institutional arrangements, to ensure that benefits endure and the risks can be managed.

The risk assessment is necessary only for proposals that first pass financial assessment. If the project is not considered profitable, the process goes no further. This is why the risks associated with the construction of a large nuclear power station in South Australia have not been addressed in detail in this report.

In the case of nuclear waste storage, however, the findings from the financial assessment are positive, as explained in Findings 75–86. The financial assessment has assumed the establishment of institutional arrangements, namely a State Wealth Fund and a Reserve Fund, to provide enduring benefits and to cover the cost of post-closure risk management.

The Commission has in Findings 66–74 described the hazards associated with the disposal of used fuel and made a preliminary assessment of the associated long term risks. A more detailed assessment in the form of a safety case would be required before any decision to develop such a facility in South Australia. The significant timeframe over which this would be undertaken and the associated costs are outlined in Appendix J, Table J.9.

This two staged approach takes full account of the long term safety implications of developing a facility. It is not necessary, or meaningful, therefore in the financial analysis to attempt to cost potential adverse outcomes (and in doing so to assess the chance of them occurring far into the future) as has been suggested in one response to the Tentative Findings.[283]

ECONOMIC IMPACTS

88. An integrated interim waste storage and disposal facility has the potential to generate substantial profits and significant direct employment.

An integrated interim waste storage and disposal facility, which received 138 000 tHM of used fuel and 390 000 m^3 of intermediate level waste at the baseline price estimates of $1.75m/tHM for used fuel and A$40 000 per m^3 for intermediate level waste, is assessed to generate:

- total revenue (in undiscounted terms) of more than $257 billion, with total costs of $145 billion.[284] The undiscounted revenues and costs give a clear perspective on the current dollar costs incurred and revenues earned by the operation. This offers a sense of the substantial scale of the operation, and its potentially significant impact on a small economy.
- total annual revenue of $5.6 billion a year over the first 30 years of operation and about $2.1 billion a year until waste receipts were notionally planned to conclude 43 years later.
- over the life of the project, a net present value of profits of more than $51 billion at a discount rate of 4 per cent.[285]
- throughout the establishment phase of the project, between 1500 and 4500 full-time jobs are estimated to be created, peaking during construction of the underground facilities in years 21 to 25 of the project. About 600 jobs, in operations at both sites, and at a head office, are expected to be created once facility operations begin.[286] In the absence of a detailed construction program, it is difficult to estimate levels of direct employment with any certainty. In the analysis undertaken for the Commission, estimates as to direct employment have been made, based on an allocation of a reasonable proportion of construction costs to labour requirements.

The presence of such a large specialist industry in the state would be likely to support the development of associated industries serving both local and international markets, including: specialist transport and logistics equipment (shipping, rail and road), and possibly including used fuel storage cask design and manufacture for transport and interim storage; and used fuel encapsulation containers for final disposal.[287] The Commission has not analysed the potential development of these ancillary industries in any detail. The Commission did, however, visit the Holtec Manufacturing Division (HMD) plant in Turtle Creek, Pennsylvania. HMD performs heavy manufacturing of dry cask storage systems for used nuclear fuel and ancillary equipment, as well as heat exchanger components for nuclear reactors, using predominantly stainless steel, carbon steel and concrete. The manufacturing plant employs around 400 people, predominantly as welders and machinists, and supplies around 50 per cent of the international market for used fuel transport and storage casks. It appeared to the Commission that this type of activity would be feasible in South Australia.

89. Investing in such facilities would have additional benefits for the whole South Australian economy with:

a. substantial addition to gross state product estimated to be an additional 4.7 per cent by 2029–30 (A$6.7 billion)

b. substantial contribution to employment of an additional 9600 jobs by 2029–30.

In addition to the revenues that are derived from the operation of facilities to receive used fuel, other benefits flow to the economy.

Those benefits arise from the consequences of expenditures in South Australia to construct and operate the facilities, expenditures by companies and individuals who earn an income from the activities, or by providing services to it, and government expenditure of some of the profits. There are other indirect effects, including those generated from investments made by government in order to grow the funds in special arrangements for the benefit of future generations.

Economic modelling analysis undertaken for the Commission to estimate the potential flow-on benefits across the wider economy of engaging in these activities is described in detail in Appendix J: Waste storage and disposal—analysis of viability and economic impacts.

That modelling estimated that an integrated waste storage and disposal facility would:

- grow gross state product by an additional 4.7 per cent (A$6.7 billion) by 2029–30[288]
- grow total employment by 1.9 per cent or 9600 full time jobs by 2029–30 (including the direct employment already discussed)[289]
- add $3000 per person to gross state income in 2029–30 in current dollars.[290]

Those benefits will accrue beyond 2029/30 over the operational life of the facility. Table 5.11 shows the potential benefits to the economy in 2029/30 and beyond 2049/50.

Those estimates were calculated using South Australia's projected share of GST revenue to 2019 released by the Commonwealth Grants Commission. That share was assumed not to change thereafter because the

Table 5.11: Economic benefits of investment in an integrated waste storage and disposal facility

	2029–30	2049–50
Growth in gross state product (A$ 2015)	4.7% ($6699 million)	3.6% ($7367 million)
Growth in gross state income (A$ 2015)	5.0% ($6837 million)	3.6% ($7290 million)
Total employment (full-time jobs)	1.9% (9603 FTE)	1.4% (7544 FTE)

Note: FTE = full time equivalent
Source: Ernst & Young

Commonwealth Grants Commission does not outline a method for determining any state's share of GST revenue over time periods greater than two to three years.[291]

A separate analysis was undertaken to evaluate how the development of an integrated waste storage and disposal facility would affect the South Australian Government's share of GST revenue. While the determination of a state's share of GST revenue is complex and dependent on a range of factors, the greater the level of economic activity in a state, the lower that state's share of GST revenue would be expected to be. The assumptions on which that analysis are based are explained in Appendix J: Waste storage and disposal—analysis of viability and economic impacts.[292]

That analysis showed that South Australia's share of GST in 2050 would be about $1.25 for every dollar of GST generated in the state, which is similar to its present level and slightly above its average over the last decade.[293] That is a result of the fact that South Australia's share of GST revenue is expected to sharply increase in the next two to three years with the further decline of manufacturing, and that revenues from this activity would then return the state's share to about their present level: see Figure J.10 in Appendix J:

90. Given the intergenerational nature of the proposed activity, it would be essential to develop enduring mechanisms to:

- **a. secure funds to ensure that benefits are shared across the community, in the form of a State Wealth Fund**
- **b. secure funds for decommissioning, remediation and long term monitoring, in the form of a Reserve Fund**
- **c. establish scientific and research capabilities to ensure knowledge and skills are developed which focus on used fuel and its disposal.**

The facilities proposed are intergenerational in nature. They would take decades to develop, operate for a century, and be monitored following their closure. Such a facility would require special arrangements to be established to ensure the benefits of engaging in the activity flow to all future generations of South Australians and that there are resources to manage the risks associated with assuming responsibility for the safe, secure storage and disposal of international used fuel.[294]

STATE WEALTH FUND

A specific, legislated fund would need to be established to secure a proportion of the profits derived from the storage and disposal activities for the benefit of future generations. It would need to be segregated from state consolidated revenue.[295]

Payments out of the fund would need to be restricted and depend upon assessment, by an appropriately expert and independent body, against criteria aimed at securing benefits for current and future generations of South Australians. A portion of the fund might also be quarantined from withdrawal in order to ensure that a predictable level of interest payments might be guaranteed each year, which can be applied for activities of broad public benefit.

Modelling suggests that the value of such a fund could be substantial. For example, based on the project concept and associated revenues discussed at Finding 87, a State Wealth Fund into which all project dividends are deposited and on which interest accrues annually at 4 per cent would, even if half of the interest were withdrawn each year, grow on average at more than $6 billion a year for more than 70 years to reach about $445 billion before notional waste deliveries are planned to cease.[296]

The strategic objectives of the fund would be for the government to develop, in consultation with the South Australian community. Potential options for use of funds could include, for example, projects to advance the interests of Aboriginal communities, the rehabilitation and improvement of the natural environment, and the development of state infrastructure.

RESERVE FUND

Public assurance as to the state's ability to safely manage the long-term risks inherent in used fuel storage and disposal would be enhanced by the establishment of a separate and quarantined fund to finance decommissioning, remediation, closure and long-term monitoring activities.[297] Such a fund, referred to here as a Reserve Fund, would serve a different purpose than, but should be established in addition to, a State Wealth Fund. A Reserve Fund, if properly managed and secured, would guarantee the availability of a reasonable amount of funds to cover both anticipated and unanticipated costs of operating and closing the facilities, and remediating the sites. The proposed scope and operation of a Reserve Fund, as modelled in the financial analysis undertaken for the Commission, has been discussed at Finding 82.

RESEARCH AND SCIENTIFIC CENTRE OF EXCELLENCE

Research capabilities to support the nuclear waste disposal industry would need to be developed in parallel with an education and skills building program.[298] This could involve establishing an associated Centre of Excellence within the state to undertake research focused on long-term characteristics and behaviour of used fuel and high level waste, and its disposal. Research could include, for example:[299]

- alternative forms of disposal including innovations in disposal concepts
- alternative forms of processing and packaging used fuel for storage and disposal
- waste volume reduction techniques
- geological emplacement techniques
- degradation of used fuel while in storage and in a disposal facility
- security and anti-intrusion systems.

A Research Centre of Excellence, based at one of the South Australian universities and modelled on those developed in Australia in relation to other disciplines such as quantum technologies, could be integrated into the existing national nuclear research and expertise capability.[300] It could partner with national and similar overseas institutions and potentially serve a global client base.

Such a Centre of Excellence might also partner with the geological disposal facility proponent to establish and operate an underground research laboratory. The development of such a facility should precede and support detailed site characterisation by allowing for in-situ experiments, so as to inform underground disposal facility design and construction.[301] Many overseas programs for the development of long-term high level waste underground disposal facilities have benefited from the early establishment of an underground research laboratory.[302] For example, in developing the safety cases for their high level waste disposal facilities, the Swiss and French proponents relied heavily on extensive investigations and testing undertaken in their underground research laboratories.[303] The costs of developing an underground research laboratory have been included as part of the project concept which was assessed for viability in modelling analyses undertaken for the Commission.

91. Legislative amendments would be required and regulatory arrangements would need to be developed for the licensing, management and operation of a facility.

The construction or operation of a facility for storage and disposal of nuclear waste, along with the importation or transport of nuclear waste, is unlawful in South Australia.[304] The amendment or repeal of the *Nuclear Waste Storage Facility (Prohibition) Act 2000* (SA) would therefore be required prior to any substantive progress being made in further developing any proposal. Supportive regulatory arrangements are a key component to building confidence in prospective customers.

While not prohibited under federal laws, constructing a facility for the storage or disposal of radioactive waste would require approval under both the *Nuclear Non-proliferation (Safeguards) Act 1987* (Cth), pursuant to Australia's treaty obligations under the Nuclear Non-proliferation Treaty, and the *Environmental Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act), as a 'nuclear action' likely to have a significant impact on the environment.[305] The EPBC Act incorporates a requirement for any proposal to undergo a general environmental assessment, and confers approval authority on the Federal Minister for the Environment. It is not a regime specifically targeted to the regulation of nuclear facilities.

The *Australian Radiation Protection and Nuclear Safety Act (1998)* (Cth) would not apply, given its application only to Commonwealth agencies, entities and contractors as 'controlled persons' under that Act.[306] This means that, based on current federal legislation, the role of Australia's present peak radiation safety authority, ARPANSA, would be limited to providing advice to the Federal Minister in relation to an EPBC Act application and to approving permits for the importation of consigned material.

General environmental assessment requirements would also apply at the state level to the development of these types of facilities due to the application of both the *Development Act 1993* (SA) and *Environment Protection Act 1993* (SA). However, as laws directed to regulating a wide range of activities, neither of these regimes and the regulations made under them contain specific provisions directed to assessing the development of waste facilities.

The radiation protection regime set out in the *Radiation Protection and Control Act 1982* (SA) would apply to any entity wishing to construct or operate a storage or disposal facility, and require a licence from the Environment Protection Authority (EPA). A licence to construct or operate such a facility will only be granted if the applicant establishes it is fit to hold a licence, and that it holds appropriate knowledge and expertise to safely carry out the activities authorised by the licence.[307] As part of this, the applicant must show that the facility it proposes to construct will comply with all regulatory requirements.[308] An applicant must also comply with any conditions imposed on the licence by the EPA, which may be imposed at the time of granting the licence, or subsequently. This regime currently only applies to the storage of low level waste throughout South Australia.

While elements of each of these differing regimes are relevant to the regulation of the development, construction, operation and closure of radioactive waste storage and disposal facilities, new regulatory arrangements would need to be established. Such arrangements would need to provide appropriately stringent and targeted requirements, including a specific licensing regime and the establishment of an appropriately independent and credible nuclear safety regulator at either the state or federal level. Although legislation at both levels is likely to continue to be required, it needs to be developed and implemented as part of a coherent and coordinated regime. A specific regime is also required to provide project certainty to any project proponent, and assurance to the public, potential customers and the international community as to the preparedness and commitment of the state and federal governments to the safe and secure development of the industry in South Australia.

There is significant international guidance available from both the IAEA and overseas regulators charged with overseeing high level waste management in various countries that can be drawn upon.[309] Further discussion as to the regulatory arrangements likely to be required is set out in Chapter 10.

FUEL LEASING

92. Storage and disposal of used fuel potentially offers a pathway to engage in other fuel cycle activities in South Australia through the business model of fuel leasing.

'Fuel leasing' is used to describe a number of commercial nuclear fuel supply arrangements. In this discussion, it is concerned with the sale of UOC or a value-added form of nuclear fuel from South Australia to overseas nuclear power utilities before its return to this state for storage and eventual disposal.[310] It could include, for example, arrangements where a South Australian entity:

- arranges to 'lease' locally mined uranium to a nuclear power utility, on the basis that the resulting used fuel would be returned to South Australia after a certain period of time. The utility would, as per current arrangements, continue to arrange for the conversion, enrichment and fuel fabrication of that uranium with existing service providers
- offers a 'cradle to grave' nuclear fuel service to a nuclear power utility, by arranging for nuclear fuel to be fabricated and delivered to the utility's power plant in its final form, on the basis that the used fuel would be returned to South Australia after a certain period of time.

Fuel leasing has the potential to address the two principal objections to the export of uranium, being non-proliferation concerns, and safe and reliable used fuel management:

- An assured supply of nuclear fuel through a leasing arrangement can potentially discourage the development of domestic proliferation-sensitive nuclear technologies, namely enrichment capabilities.[311] In addition, the return of used fuel for disposal removes the rationale for reprocessing and allows for the used fuel to be consolidated in one location. The siting of that disposal facility in a nation with strong non-proliferation credentials, coupled with appropriate regulatory oversight, would ensure that the material remained accounted for over the long term.[312]
- Given the considerable expense and uncertainty for utilities (and nations) inherent in the long-term storage and management of used fuel, the ability to offer a safe and secure disposal opportunity along with fuel supply services could be of significant value.[313] It may in particular be attractive to nuclear newcomer countries, in terms of offering an acceptable solution to used fuel management, which might assist in achieving and maintaining social consent for new nuclear power facilities. It might also be attractive to nations with relatively modest nuclear

power programs (and without significant market power) to avoid the need to construct domestic geological disposal facilities, or negotiate multiple front-end service contracts in unfamiliar markets.[314] The ability for nuclear power utilities to structure their nuclear fuel supply as a lease rather than a capital acquisition might additionally have positive financing or taxation implications, depending on local laws.[315]

Any fuel leasing arrangement in South Australia would, however, be dependent upon it establishing an international or regional long-term storage and geological disposal facility for used fuel.

The fuel leasing concept is not new and has generated global interest, including endorsement by the International Atomic Energy Agency Expert Group on Multilateral Approaches to the Nuclear Fuel Cycle.[316] While the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management requires countries to manage their own waste, it does not preclude the return of used fuel as part of a fuel leasing arrangement. Organisations such as the International Framework for Nuclear Energy Cooperation continue to explore how such arrangements might be practically implemented.[317] Along with international or regional used fuel disposal facilities, and international fuel banks, fuel leasing services may meet non-proliferation objectives by reducing the need for additional enrichment or reprocessing facilities to be established in multiple countries.[318] Australia's strong non-proliferation credentials, discussed further in Chapter 8, would support its hosting of such international or regional nuclear fuel cycle services and facilities.

Despite significant international analysis and discussion, Russia is the only country to date to undertake a type of fuel leasing service, via the state-owned Rosatom Overseas Inc. (Rosatom).[319] Rosatom offers international customers a variety of integrated services associated with the construction and operation of its nuclear power plants, including guaranteed fuel supply, and take-back of used fuel for storage and eventual reprocessing.[320] Russia, however, does not have a permanent repository for the long-term disposal of nuclear waste.[321]

A number of countries, such as Iran, Turkey and Vietnam, have entered agreements with Rosatom for nuclear power plant construction combined with fuel supply and take-back services, indicating that such services are potentially viable as part of a bundled offering.[322] Other nations have also expressed positive interest in the fuel leasing concept. The 2008 Policy of the United Arab Emirates on the Evaluation and Potential Development of Nuclear Energy states that the UAE would 'prefer to source nuclear fuel via fuel leasing or similar arrangements that relieve it of any of the requirements of safeguarding spent fuel.'[323] The High Level Bilateral Commission established pursuant to the nuclear cooperation agreement signed by the USA and South Korea last year has been tasked with examining the management of used nuclear fuel, the promotion of nuclear exports and assurances of nuclear fuel supply, including the potential for South Korea to participate in fuel leasing services in future.[324] There are a number of other jurisdictions that may be interested in used fuel take-back options in the medium to long term given their domestic circumstances.[325]

As discussed in Chapter 3: Further processing and manufacture, neither the conversion nor enrichment of uranium, nor nuclear fuel fabrication, are likely to be viable as standalone or combined activities in South Australia in the coming decades. However, the ability to combine further processing services with a guaranteed take-back option for the safe and permanent disposal of the used fuel would provide a unique market offering. In this way, the establishment of a used fuel geological disposal facility in South Australia may provide an opportunity to enter new and otherwise closed markets.

At present, a new nuclear power plant is typically purchased by a power utility from a reactor vendor under a 'turnkey contract' whereby the new reactor is delivered ready to operate, and with around a 10 year supply of nuclear fuel. Once further fuel reloads are required, nuclear power utilities operate in a global market for 'front-end' uranium conversion, enrichment and fuel fabrication services, along with the market for the supply of uranium ore. Utilities typically contract with a number of different and competing service providers in procuring each separate step necessary for the supply of nuclear fuel.[326] There are also vertically integrated fuel suppliers, such as AREVA and Rosatom, who offer a fully fabricated fuel service to nuclear utilities. The offering of a 'back-end' solution as part of either a new nuclear reactor development, or ongoing nuclear fuel supply services, would be unique and potentially valuable.[327]

93. A staged process to the development of any fuel leasing service would seem to have the best prospects for success. There are, however, a number of challenges to the implementation of fuel leasing which would need to be overcome.

Potential customers are unlikely to be prepared to seriously consider any fuel leasing proposal until planning and development of a geological disposal facility is sufficiently progressed. Assuming that occurs, the following staged approach to fuel leasing might be explored:

Step 1: the operator of the South Australian geological disposal facility seeks to partner in a fuel leasing arrangement with either:

- a major LWR vendor competing in the market for new-build large nuclear power plants. Such a vendor may be interested in increasing their competitive strength by offering a fuel take-back service along with the construction of, and initial fuel supply for, their plant design.[328] The reactor vendor would remain, as at present, responsible for securing uranium supply, along with conversion, enrichment and fuel fabrication services
- a major SMR vendor competing in the market for new-build small nuclear power plants. Such an arrangement may be particularly attractive to an SMR vendor seeking to enter smaller, nuclear newcomer countries most suited to SMR deployment. The lack of resources and/or suitable geology to support domestic used fuel geological disposal in many such countries, along with proliferation concerns associated with long term storage of used fuel at multiple SMR sites, are seen as impediments to the future commercialisation of SMRs. The ability for an SMR vendor to offer a product that overcomes those impediments could facilitate market entry[329]
- a nuclear fuel vendor, and/or
- large nuclear utilities, which are experienced in obtaining uranium and other front end services as required.[330]

Step 2: If successful over time, sufficient business volume may accumulate to justify investment in multilateral conversion and enrichment facilities in South Australia, the products of which can be integrated into the fuel leasing arrangement.[331] This would include considering partnerships with existing commercial entities engaged in delivering those services, or seeking to commercialise new technologies for the delivery of such services, through new facilities in South Australia.[332]

There are a number of international and commercial considerations that would impact on the feasibility and viability of any fuel leasing proposal based on a South Australian geological disposal facility.

INTERNATIONAL CONSIDERATIONS

As with international used fuel storage and disposal, fuel leasing arrangements would require agreements to be concluded at both the international and commercial level.[333] Support from and via the IAEA could be helpful.[334] Australian Government support to conclude and maintain the necessary international agreements is essential to underpin any fuel leasing arrangements in this state, and would need to progress in advance of any commercial offers or negotiations.[335]

Supportive bilateral arrangements between Australia and a potential customer country, addressing at least regulatory arrangements for import and export authorisations, transport, and applicable liability regimes, would be required to provide the necessary foundation for commercial arrangements.[336] Beyond bilateral arrangements with customer nations, additional treaties may be required with other countries to provide advance consent for the import, export and retransfer of nuclear fuel subject to such consent rights.[337] These arrangements are likely to be significantly simplified where there is an established and operating geological disposal facility in South Australia, which complies with international requirements for safety, security and non-proliferation assurance. It may not be possible to conclude the commercial arrangements necessary to support fuel leasing in the absence of such assurances.[338]

COMMERCIAL CONSIDERATIONS

Assuming the existence of an appropriate geological disposal facility, and the necessary international support, any fuel leasing service would need to be commercially attractive and market-driven to be viable.[339] It would need to be economically attractive for a nuclear utility to enter into a bundled arrangement for their fuel supply, rather than accessing each of the services separately, including long-term storage and disposal of used fuel.[340] This would require detailed market analysis.[341]

Such a bundled service would likely need to be offered in competition with existing 'uranium only' local and international uranium producers, so that Australian uranium would continue to be available on the open market. Australian uranium producers have not been supportive of fuel leasing concepts in the past.[342] Structuring fuel leasing services as an optional market-based offering may overcome the potential difficulties with fuel leasing raised by some uranium producers.[343]

Assuming the existence of commercial customers for a South Australian fuel leasing service, the terms of any lease arrangement with a customer will need careful preparation and negotiation. There may be significant uncertainty surrounding how to appropriately cost and structure payments for fuel leasing services, particularly in advance of the costs of long-term used fuel storage and disposal being well understood.[344] Other complex matters that would need to be addressed include:

- the terms of the arrangement, and related matters including legal title to, and responsibility, liability and insurance for any damage caused by, the uranium or nuclear fuel throughout and at the conclusion of the agreement, including during transit

- warranties as to nuclear fuel quality and composition, and use within a reactor, so as to ensure the resulting used fuel would meet relevant storage and disposal facility waste acceptance criteria
- warranties as to the acceptance by the lessor entity of the used fuel, and as to the construction and operation of relevant storage and disposal facilities consistent with international requirements for safety, security and non-proliferation
- consequences of any failure to secure any necessary export and import authorisations
- how disputes between the parties would be resolved
- taxation and accounting implications.[345]

94. The economic analysis suggests fuel leasing, comprising conversion and enrichment facilities in South Australia, would provide modest additional economic benefits to the conduct of waste storage and disposal activities alone.

Analysis undertaken for the Commission by Ernst & Young has indicated that combining investment in both conversion and enrichment facilities in South Australia with waste storage and disposal has the potential to deliver economic benefits to the state beyond those that might be achieved by investment in waste storage and disposal alone.[346] The modelling suggests the additional benefits would be modest: an addition to gross state product of about 0.5 per cent in 2029–30 ($900 million), and an increase in employment of approximately 1000 jobs by 2029–30, continuing over the life of the conversion and enrichment facilities.[347]

That analysis, along with the analysis undertaken by Jacobs and MCM into the viability of long-term storage and disposal facilities alone, indicates that exploring a fuel leasing concept may provide the ability for South Australia to viably enter the front end of the nuclear fuel cycle. Some of the potential economic returns flagged within the Jacobs & MCM report as a result of developing international used fuel storage and disposal facilities could be directed to support the establishment of front-end facilities and services in this state.[348]

The construction and operation of conversion and enrichment facilities in South Australia would provide broader economic advantages in the form of new highly skilled employment.[349] As discussed in Chapter 3, establishing these facilities would require partnership with existing overseas suppliers in order to transfer the necessary technology for use in local operations.[350] It is conceivable that such technology transfer, and the establishment and operation of such facilities in this state, could foster additional local research and development into advances in front-end nuclear fuel cycle activities.[351] It is also conceivable that South Australia could become an important regional hub for nuclear fuel cycle services, if it is able to viably and securely establish and operate conversion and enrichment facilities, alongside international used fuel storage and disposal facilities.

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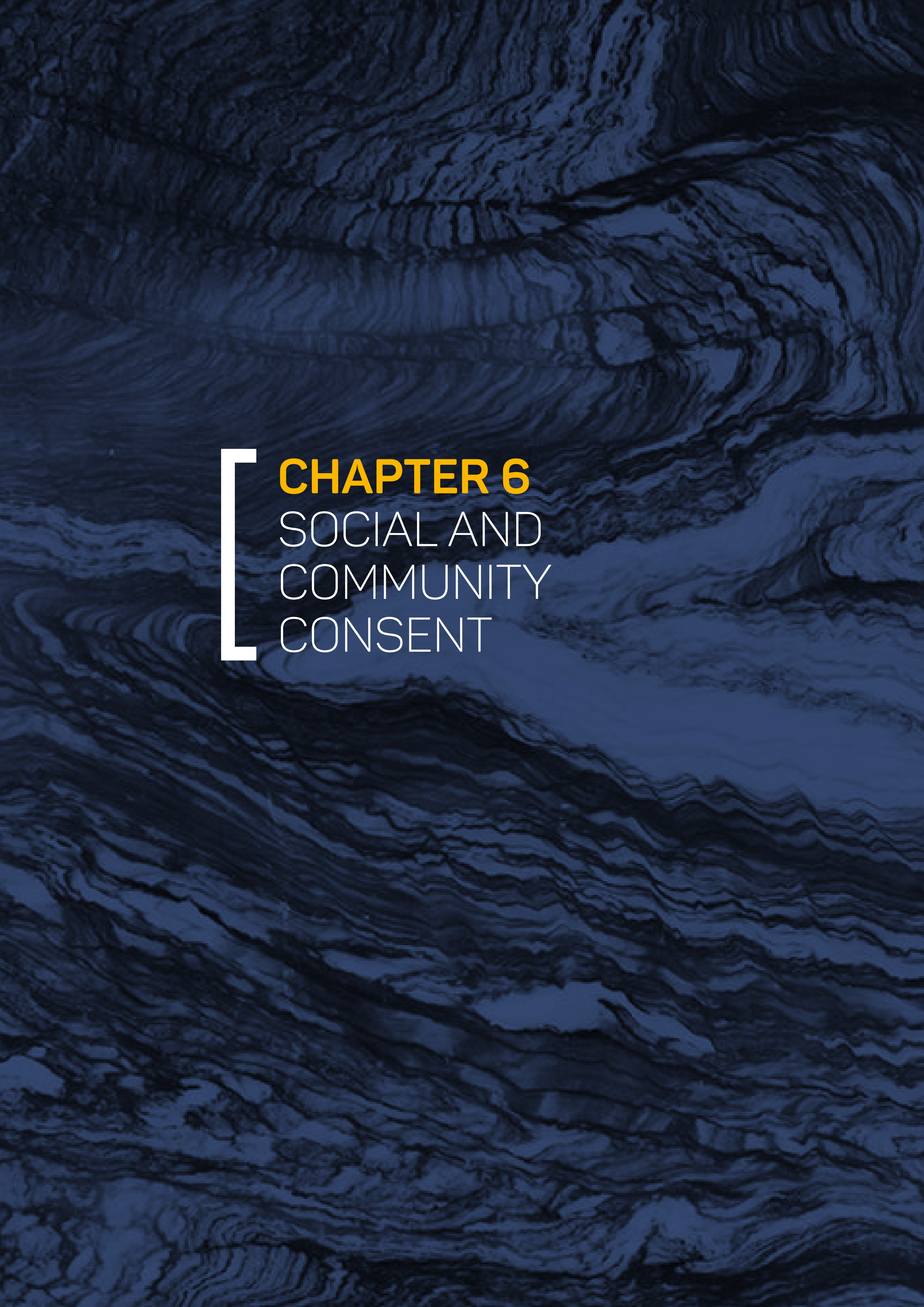

CHAPTER 6

SOCIAL AND COMMUNITY CONSENT

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CONSENT

95. Both broad social consent and specific community consent must be obtained for any new nuclear activity to commence in South Australia.

96. Social consent means obtaining broad public support culminating in legislative endorsement of an activity by the relevant parliament, and maintaining that support for the life of the project.

Social consent is the ongoing public support that is necessary for an activity to be undertaken in a society. It is contingent on confidence that the activity is, or will be, performed consistent with the community's expectations, standards and values.

Social consent is something that is commonly taken into account as part of a political process. It is not given once for the life of an activity. In the past, social consent has been held and later lost for activities across many industries, whether because community attitudes, standards and expectations have shifted or confidence in the activity has weakened. Settled community opinions against an activity also can be reversed with technological advances, as in fields such as genetic medicine.

Because of these shifts, a public vote on a proposal is not a reliable indicator of ongoing social consent: A vote for or against a proposal one day may not result in the same level of social consent one month later.

Social consent is fundamental to the feasibility of a new or expanded nuclear development in South Australia. In such cases, which often involve decades of project development and significant capital expenditure, all stakeholders would need to be confident that social consent was not only gained, but also could reasonably be expected to be sustained through both the development and life of the project.

To facilitate nuclear activities, it will be necessary to amend existing laws that prohibit the establishment of types of nuclear facilities and pass laws to regulate their conduct. This approval would hinge on a political judgement as to whether there is sustainable public confidence that the activity can be safely and securely undertaken. Further, major projects are, by nature, transgenerational, and require bipartisan and continuing political support that does not fall prey to the caprice of election cycles.

Chapter 10: Recommendations and next steps, identifies aspects of this process (respecting that it is in part political) that would be necessary to determine whether there is social consent for an activity.

97. Community consent, being informed agreement from an affected community, would be required for a specific proposal.

For any nuclear project to proceed successfully and sustainably, it must have the informed consent of the community in the project's location, in addition to that of rights holders who may be affected, including landowners or leaseholders, and native title holders or claimants. Community consent, as distinct from the broader concept of social consent, must be measured on a more localised basis.

To achieve this, the membership of the community would need to be defined.[1] This would require consideration of the potential impacts of the proposal and its associated infrastructure on, for example, the geographical area, proximity to residents and land users, other local industries, and the expected project life. The more far-reaching the proposal, the broader the extent of the community whose collective consent must be measured.[2]

There is no universally applicable definition of 'community' for the purpose of identifying whose consent would be required before a nuclear development could proceed. This is reflected in the various approaches taken by countries in siting nuclear facilities (see Appendix H: Siting significant facilities—case studies).[3] Some communities have been well defined and organised, with existing decision-making structures. This was the case in Belgium, Finland and France, where governments and proponents embarking on nuclear developments proceeded on the basis that the existing municipal boundaries determined the scope of the relevant community.[4] Where such clear definitions and structures do not exist, it may be necessary to create new structures that develop community capacity.

The threshold for consent will differ for each community according to its concerns, rights and values. It does not require unanimity. There is no universally accepted understanding of how consent for nuclear projects may be gained and measured.[5] Because of this, any project proponent should adopt a consultative approach to defining 'community' and 'consent' and encourage early community agreement on how decisions are to be made and who has the right to make and communicate decisions (including consent) in relation to a proposed development.[6] This might involve the proponent developing, in close consultation with the community, a 'consent plan' that is flexible and inclusive rather than prescriptive.[7]

98. With respect to new uranium mining projects, no measures to further regulate community consent or community engagement appear required.

Historically the subject of extensive public and political debate[8], today uranium mining in South Australia is a lawful activity that has bipartisan political support. Although a proposal for a new uranium mine would be opposed by some, uranium mining now has broad public acceptance.[9]

The uranium mining industry in Australia well understands the importance of having community support.[10] Genuine community engagement on a proposed development followed by obtaining the community's consent are widely accepted as critical to project success and sustainability.[11] Any project proponent should be able to provide evidence of engagement in accordance with the principles set out at Finding 100.[12]

99. Efforts over recent decades internationally to develop nuclear projects by focusing on technical considerations without an equal or even greater emphasis on systematic engagement with the community have commonly failed.

South Australia can learn valuable lessons on the importance of obtaining community consent from the numerous international attempts, both failed and successful, to site new nuclear facilities. In a number of cases from the 1970s to the 1990s, the process considered only site technical characteristics, including geology, seismology and safety. Communities were not consulted, nor did they provide consent. Where proponents and governments pushed ahead without community consent, developments failed.[13]

Since the mid-1990s, most governments and proponents have adopted a new approach that involved communities in siting decisions. For example, by volunteering to be involved in a phased and adaptive learning and decision-making process, communities' receptiveness to hosting a nuclear facility have improved.[14] South Australia can learn from these more recent experiences, particularly in Belgium, Canada (which shares many political and physical characteristics with South Australia), France, Germany and South Korea. Appendix H: Siting significant facilities—case studies provides details on some of these experiences.

100. Successful processes for engaging with a community to seek consent for a new type of nuclear facility have a range of key characteristics, such as:

a. transparency of the decision-making framework and requirements for licensing and approval, and a willingness to adapt that framework as necessary to meet new or unforeseen developments

Transparency requires that factual and timely information on a proposal is made available to the affected community.[15] Proponents, local governments, regulators and parliaments play significant roles in ensuring that communities understand what is being proposed and the requirements for licensing and approval.[16] Transparency among and from these agents helps to build trust in the regulatory oversight and safety of any activity.

Adaptability and flexibility have been key features of successful engagement processes in a number of countries including Canada and the United Kingdom. This has enabled participating communities to slow or accelerate their engagement based on their particular needs. The engagement processes have been flexible enough to evolve based on experience.[17]

b. willingness to accept longer community engagement timeframes than usual for typical developments and avoid fixing arbitrary interim deadlines

The technical and complex nature of nuclear activities and the timeframes required to effectively build community understanding about a proposal, means that the community engagement process would take longer than for other industrial developments. Deadlines set primarily for commercial and technical reasons, without considering the community's need to consider and digest information, can undermine community confidence and its willingness to ultimately provide consent. Setting arbitrary timeframes at the start of a process can undermine public confidence in the community engagement approach.

c. early and deep engagement with local communities to build their knowledge and understanding using a partnership model between the proponent and the community

International experience in siting nuclear facilities shows that involving communities in early decisionmaking can improve project outcomes.[18] Building community capacity to participate in or engage with developments can improve, for example, facility design or environmental monitoring by harnessing local knowledge.[19] At the same time, the community gains greater knowledge and understanding of the project.

Successful means of engagement and knowledge building used by nuclear project proponents include: site tours of similar developments or facilities, community meetings, visitor centres, newsletters, websites, and community shopfronts or reading rooms.[20] A partnership model for engagement, used successfully overseas, creates a forum in which stakeholders work together to develop conceptual designs for nuclear facilities, build knowledge and share information.[21] Such a model could also be the vehicle through which the threshold for community consent is defined and consent provided.[22] Members of partnerships may include the project proponent, affected communities, experts, the regulator and local government. The partnership model developed in Belgium for a nuclear waste management facility was particularly successful and could be adapted to suit the South Australian context. The precise model and membership structure would need to be developed in close consultation with any affected communities.

d. an ability for local communities to engage in a learning process about hosting a facility without being required to commit to the facility

Any siting process would need to allow interested volunteer communities to learn about a proposal and what would be involved in hosting a facility.[23] It would need to be clearly and broadly communicated that volunteering to participate in this learning process would not amount to consent for a siting decision. The process would need to enable communities to decide for themselves whether they wanted to progress to more detailed discussions regarding a proposal.[24] It is critical, drawing from the United Kingdom experience, that there is no threshold for decision-points to participating in the learning process. For local communities and their leadership bodies there are no small decisions on nuclear matters.

THE BELGIAN PARTNERSHIP MODEL

Figure 6.1: A site visit held as part of the Belgian partnership model. Image courtesy of ONDRAF/NIRAS.

The partnership model developed in Belgium successfully facilitated engagement between the country's nuclear waste management agency, ONDRAF/NIRAS, and three potential host communities that expressed willingness to receive information about a proposal for a low and intermediate level radioactive waste disposal facility.[1]

Partnerships were established to address both the technical and socioeconomic aspects of the proposal, including facility design, safety and health, research and information dissemination, and community development.[2] The partnerships were provided with resources to fund their own research into the proposal. They were conduits of information to and from the wider community.[3] The successful partnership in the municipality of Dessel worked with ONDRAF/NIRAS to modify the proposal design to incorporate additional monitoring mechanisms and to develop a benefits package that was important to the community.[4] See Appendix H for more details.

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[4] IPPA Project, Case study: Site selection, p. 2; ONDRAF/NIRAS, The cAt project in Dessel: A long-term solution for Belgian category A waste, Brussels, 2010, http://www.niras-cat.be/downloads/cAt_brochureENG.pdf.

It would become apparent at particular points in the learning process when a community needs the resources to engage more fully and deeply on a proposal. In this respect, the learning process is two-way: the proponent in turn should be able and willing to learn about the community and its needs, concerns and interests, and be prepared to respond accordingly. Such a continuous loop has been adopted and used successfully in Belgium, Canada and, in a revised process, the United Kingdom.

e. resourcing of a community organisation to:

i. deliberate and meet in relation to the proposal

ii. engage independent scientific advisors to assist it in relation to issues of importance and to review scientific information

Resources might include funds for communities to employ independent expert advisers, hold meetings and employ staff to manage the engagement and learning process; or to otherwise allow them to participate on equal terms in proposal deliberations without incurring expenses.[25] Examples of community resourcing include the funding of the Belgian partnerships by the proponent, ONDRAF/NIRAS, and of the Maralinga Tjarutja people in South Australia, where independent scientific advice on the land clean-up was funded by the Australian Government.[26] The level and purpose of community resourcing, including funding, would depend on the community's needs, the degree to which the community engaged with the proposal, and the aspects of the proposal being considered.

f. the presence of a regulator that is:

i. trusted and experienced

ii. accessible to the community and willing to provide information on both the regulatory process and its decision making, the proposal and its views on that proposal

A regulator that is trusted by and accountable and accessible to the community is fundamental to confidence in the proposed activity and, ultimately, to community consent and project success.[27] Public confidence is assisted by an independent and capable regulator that is able to independently verify assessments made by a proponent and willing to communicate its views and assessments to the community.

A function of the Australian Government's nuclear safety regulator, the Australian Radiation Protection and Nuclear Safety Agency, is to engage and provide information to the public.[28] Were a new nuclear activity proposed for South Australia, it would be important to have a regulator that performed that general role in addition to providing specific information and assessments and analysis of a proposal.

g. the availability of scientific evidence and, where necessary, multiple, corroborating bodies of evidence to demonstrate the effectiveness of steps taken to address risks

For communities to have trust in the environmental and public safety of nuclear activities or developments, scientific evidence needs to demonstrate that the risks of any proposal are adequately addressed. Accordingly, community members must have confidence in the accuracy of proponent data and modelling, and the measures proposed to address risks. Data collection processes must be transparent and made available to the public. Scientific evidence needs to be assessed and verified by independent experts and trusted regulators. At all times, steps should be taken to ensure that the information provided to communities is objective and intelligible.[29] Communities may want to engage independent expert advisers to satisfy themselves they clearly understand the risks and how they are to be managed.[30]

h. provision of a range of benefits, identified as important by the community, for the service it provides to the wider society for hosting that facility

South Australians can take advantage of opportunities and wisely manage any associated risks to create a positive sustainable legacy for the state, as well as for the local, affected communities. Should a nuclear development proposal receive social consent, the state government would need to lead community discussion to identify principles that would underpin decisions about the investment and distribution of benefits. Rarely have projects succeeded unless they have significant community benefits, and those benefits have been determined in conjunction with the community.

Care should be taken to ensure that any benefits would be sustainable and align with the particular community's goals. There should also be specific regard and planning for the long-term social and economic development of the community.[31] It would be important that benefits are applied broadly across local communities, and specified in advance where possible, to avoid the perception of bribes.[32] Benefits would need to be tangible, significant and negotiated, as with other elements of the proposal.[33] Money should not be paid to communities upfront. Instead, it should be received based on the phased development of the project.

Internationally, public support for siting radioactive waste management facilities has been shown to increase when the benefits are broadened, for example, by collocating such facilities with research institutions that are tasked with investigating disposal techniques, radiation safety and potential future uses of spent fuel.[34] This experience could be considered in South Australia. Research and development into new technologies, and health, social and cultural innovation, could also be supported.

i. consistency of individuals involved in the development and delivery of those projects.

The successful development and delivery of a nuclear project requires a long-term personal commitment from stakeholders to see that project through to fruition. Maintaining continuity of stakeholders over time allows relationships to be built and, accordingly, trust and understanding to develop. This is especially important for Aboriginal communities.[35] Engagement with Aboriginal South Australians requires relationships to be built on trust and integrity, viewed as a sustained relationship in which stakeholders work together to achieve shared goals.[36]

Stakeholders will change, and these transitions require planning and management. Efforts should be made to record and effectively transfer knowledge about the processes used to build relationships and any agreements that have been reached.[37]

101. Any engagement process with a potentially affected community needs to be designed with an understanding of and respect for the way in which that community has formed its views in the past.

South Australians' attitudes toward nuclear activities have been shaped by historical events in our lifetimes both in and outside the state. These include the British nuclear weapons testing at Maralinga in South Australia in the 1950s and 1960s, and nuclear reactor accidents at Three Mile Island in 1979, Chernobyl in 1986 and Fukushima in 2011.[38] Attitudes also have been influenced by broader cultural and political factors, the media, international influences and education.[39]

A project proponent would have to be able to demonstrate to the South Australian public and all affected or interested communities, how and why the proposed activity would be different to these significant historical events that have contributed to the formation of their attitudes. This reinforces the need for community engagement processes to be flexible and allow access to comprehensive information about a nuclear proposal, as well as to provide sufficient time to absorb and debate the proposal.

Site tours can be useful to show communities exactly what a proposed development would entail.[40] Site tours in this context should be differentiated from those used by industries or organisations as an element of public relations. Their focus must be on supporting informed consent through an opportunity to consider and relate a similar development to the particular circumstances of the interested community. Participants should include respected and trusted opinion leaders in their communities who are able to effectively report what they have seen.[41] Opinion leaders shape debates, and aid community understanding and acceptance of matters of public policy.[42] Therefore, engagement with such leaders would be central to general public and local community understanding of any proposal for a new nuclear development in South Australia.

102. Applied to the South Australian context, the impact of atomic weapons testing at Maralinga in the 1950s and 1960s remains very significant to Aboriginal people. Those tests, and subsequent actions, have left many Aboriginal people with a deep scepticism about the ability of government to ensure that any new nuclear activities would be undertaken safely.

The damage caused by the atomic tests carried out by the British Government is still felt profoundly by many Aboriginal South Australians, particularly those from communities that were directly affected. In these communities, nuclear activities in general are often associated with the detrimental effects of the events at Maralinga.[43] This sentiment was reflected in many submissions from Aboriginal individuals and groups received by the Commission.[44] In its submission, the Alinytjara Wilurara Natural Resources Management Board stated:

> *It must be remembered that the people of our region suffered significant personal, cultural and social harm as a result of the testing of nuclear weapons. The living memory of this phase of our shared history casts a long shadow over any contemporary conversation regarding the nuclear fuel cycle.*[45]

The 1985 report of the Royal Commission into British Nuclear Tests in Australia (the McClelland Royal Commission) recognised the harm that the testing caused Aboriginal people. It found that Aboriginal people in the Wallatinna area experienced radioactive fallout in the form of a mist or cloud, and that they suffered vomiting or temporary illness as a result of either radiation exposure or a 'psychogenic reaction', or both. On the evidence available, the McClelland Royal Commission could not reach conclusions on whether other illnesses suffered by Aboriginal individuals were caused by fallout from the tests.[46]

While the Nuclear Fuel Cycle Royal Commission is not tasked with examining the many far-reaching impacts of the atomic tests nor the acts of previous governments on this matter, aspects of the Maralinga legacy are relevant to the consideration of any future nuclear activity in the state. It would be important for any government and project proponent to understand the way historical events have shaped the attitudes of South Australians, particularly Aboriginal South Australians, towards nuclear activities.[47] Acknowledging the impacts of the past and enduring concerns would be fundamental to respectful communication and engagement with Aboriginal communities on nuclear issues.[48]

For a specific proposal on land in which there are Aboriginal rights and interests, it would be necessary to demonstrate to Aboriginal communities' satisfaction how the development would be different to the atomic testing and how lessons had been learned from the past.[49] A fundamental lesson, which should be applied from now, is that any new nuclear activity should not proceed unless and until the health and environmental risks are fully understood by the affected community.[50] To this end, a sustained, respectful and inclusive process for educating communities about health and environmental risks, adhering to the principles discussed at Findings 100 and 104, would be essential. Depending on the location and nature of the activity, this may need to address whether any particular risks arise for Aboriginal traditional and contemporary lifestyles.[51]

Another theme that has emerged throughout the Commission's inquiry is scepticism among some Aboriginal South Australians about the ability of government and industry to deliver on future commitments. This concern is founded on past failures.[52] For any engagement process to achieve a fair result, the government and project proponent must ensure that any discussions regarding risks and opportunities are realistic and that commitments made are kept, through, for example, binding agreements with appropriate mechanisms to address ongoing compliance and deal with disputes.[53]

103. As part of a community engagement process, there are established and sophisticated frameworks that have supported deliberation on complex issues in the past, through which Aboriginal communities in South Australia should be approached.

South Australia has 20 years' experience with the native title framework, which has been used successfully by communities and proponents to facilitate negotiation and decision-making processes about developments.[54] Structures in this framework include native title representative organisations, prescribed bodies corporate, Indigenous land use agreements and native title management committees. These structures have processes through which information is presented to and discussed and debated in Aboriginal communities.

Regional authorities are an emerging representative structure for Aboriginal nations[55] and South Australia's natural resources management boards are an additional mechanism through which Aboriginal communities could be engaged. The Alinytjara Wilurara Natural Resources Management Board, for example, has developed successful engagement programs and partnerships between development proponents and communities that have recognised, respected and enhanced the interests and values of all parties to an agreement within the native title framework.[56]

Numerous organisations represent South Australia's Aboriginal communities across a range of functions and interests. A project proponent should take care that, if an organisation has been given responsibility for making a decision in a community, it is the one that the community views as legitimate to make such a decision relevant to that particular issue. Depending on the location, an appropriate combination of mechanisms for engagement with land- and rights-holding structures may be required.

104. Principles for engagement with Aboriginal communities in many cases apply equally to the urban, regional and remote communities of which they are an integral part. In addition to principles for community engagement set out at Finding 100, the Commission recommends, based on feedback from Aboriginal communities, that the following principles apply:

a. any progress towards an activity is based on a principle of negotiation in good faith and on equal terms

It is essential that the process of engagement with Aboriginal communities empowers people to participate on equal terms in discussions about a proposal.[57] This would require appropriate resourcing of communities, including providing information, expert advice, translation services and staff to manage the learning and engagement process, as discussed at Finding 100.[58] The process would need to allow sufficient time to ensure that Aboriginal people understand the full extent of any potential impacts that may result from the proposed activity and reach informed decisions according to their own processes.[59]

b. there is a common and realistic understanding as to both the risks and opportunities of the proposed activity—it is essential that benefits are not oversold and risks are not underestimated

Aboriginal communities would need to be provided with transparent and objective information about the risks and opportunities that may arise from an activity over time.[60] This may include providing some information in graphics[61], using appropriately trained translators[62], providing funding for independent expert advisors[63], or taking community representatives on tours of similar sites.[64] The communities would also need to understand and agree to the distribution and future use of any benefits arising from the project. It should also be acknowledged that for Aboriginal communities, cultural values will underpin the balancing and weighting of risk against benefit and guide decisions on 'acceptable risk'.

c. there is early engagement with representative organisations and the local community about a proposed activity, including preparing a framework for further engagement

Taking time to establish relationships with community members and their representatives at the outset of a proposal can deliver better outcomes in the later phase of the process.[65] Early and sustained engagement with Aboriginal communities should start with developing an agreed approach to consultation, with the nature of the engagement process to be determined by the participating communities.[66] Given community willingness to recognise and respect traditional knowledge in South Australia[67], a project proponent should be open to using such local knowledge to inform facility designs and make siting decisions, as has occurred overseas.[68] A genuine recognition of cultural knowledge and an opportunity for knowledge sharing with other aspects of project planning and design have the potential to enhance overall project outcomes.

d. the proposals place particular emphasis on long-term risks and opportunities

Many community groups and individuals have expressed concerns about long-terms risks of nuclear development and their potential effect on future generations.[69] If specific nuclear facilities were to be proposed for South Australia, the long-term social, environmental, cultural and economic risks and opportunities and how they would be managed would need to be clearly addressed.[70] It would be important for the project proponent to be able to demonstrate there would be a net positive impact arising from the proposed activity.[71]

e. the communication process is practical, genuine and agreed by the community

Communication between stakeholders should be face-to-face where possible[72], conducted in accordance with a process devised by the community[73], and continuous.[74] Resources should be allocated so that stakeholders can meet face-to-face.[75] This will be understood by a community to be genuine if the proponent and other stakeholders do what they say they will do. That process is assisted if outcomes are agreed and can then be seen to be implemented.

f. realistic, and potentially longer than usual, timeframes are set for the community engagement process and decision making

Engagement and decision-making processes will need to proceed at a pace that is acceptable to the affected community so that it can receive, learn about, assess and act on information according to its own needs, values and interests.[76] Accordingly, longer timeframes may be required for free and informed decisions to be reached collectively by communities.[77] Any requirement to build additional community capacity so that it could participate in the learning and decision-making processes on equal terms would need to be factored into the timeframe.[78]

g. the community is supported to make its own decision, whether yes or no, free from the influence or pressure of the proponent or lobby groups with their own agendas

Communities participating in discussions about a proposal must be able to learn, deliberate and make decisions free from external pressure, influence, coercion, intimidation or manipulation.[79] Care should be taken to ensure that any misinformation is quickly corrected and that information provided is objective and independently verified.[80]

Aboriginal communities in particular can be vulnerable to criticism from external sources if they engage in a process to learn about a nuclear activity. This has occurred in the Northern Territory and Western Australia.[81] Communities that volunteer to partake in a process would need to be supported to cope with such criticism.[82] It would also be important that those communities and individuals who do not support a particular proposal are treated with respect.[83]

Success should not be measured in terms of a community providing consent to a particular activity or development.[84] Instead, it should be measured by a community making a free and informed decision—regardless of whether that is yes or no. Communicating this at the outset of a proposal would increase the legitimacy of the community engagement processes.[85]

LAND, HERITAGE AND RESPECTING RIGHTS

105. To the extent that any project would be proposed on land in which there are Aboriginal rights and interests, including native title rights and interests, they must be respected.

While suggesting suitable sites for any new facility is beyond the scope of the Commission's inquiry, it also must be acknowledged that the range of Aboriginal rights and interests in South Australian land is widespread and diverse. These include those recognised and protected under the *Native Title Act 1993* (Cth) and the *Aboriginal Heritage Act 1988* (SA), through mechanisms such as the right to negotiate and Indigenous land use agreements[86], as well as rights and interests in Aboriginal freehold land established under specific legislation.[87] A proponent of a nuclear development would need to understand and adhere to the frameworks that protect Aboriginal rights and interests.

While existing legal and regulatory regimes provide some protection and guidance, more than bare observance of legal requirements would be required. Early and meaningful engagement by a proponent would be fundamental to demonstrating genuine respect for rights and interest holders.[88]

106. The deep connection that Aboriginal people have with the land and their responsibility for its care must be understood and respected by any nuclear project proponent.

For many Aboriginal people, identities are defined in terms of their relationship to their lands, as the following quotation attests:

> *Native title rights and interests are integrally linked to the health of country, with rights and interests including the right to hunt, gather, camp, conduct ceremonies, teach younger generations and conduct cultural activities. These depend on a healthy environment, and without a healthy environment, cultural practices are put at risk.*[89]

As evidenced by submissions to the Commission, many Aboriginal people view nuclear activities as dangerous acts that bring harm to the land and, therefore, harm to themselves, their ancestors and their descendants.[90] This extends to a belief in the need to proactively protect land and heritage. These views reinforce the need for a project proponent to exercise great care and consideration in the way it engages with and seeks to inform a community about any proposal to avoid social harm. In demonstrating understanding of and respect for Aboriginal people's connection to the land and their desire to continue to practise their living tradition, proponents would need to engage with Aboriginal communities according to the principles outlined at Finding 100, ensuring that cultural and land rights and interests are respected and protected.

107. There are existing regulatory mechanisms for the protection and preservation of Aboriginal heritage, which would, with some qualifications, apply to any future nuclear developments in South Australia.

The Aboriginal Heritage Act establishes the key framework for protecting Aboriginal heritage in South Australia. Under this Act, it would be an offence for a proponent embarking on a new nuclear development to damage, disturb or interfere with Aboriginal sites, objects and remains.[91] Under this framework, proponents should gather as much information as possible about heritage sites by working closely with local Aboriginal groups.[92] Proponents may apply to the Minister for Aboriginal Affairs and Reconciliation for authorisation to undertake an activity that would disturb a heritage site.[93] In determining whether to authorise such an activity, the Minister is required by the Aboriginal Heritage Act to consult with interested Aboriginal organisations and individuals, and traditional owners.[94] Aboriginal heritage can also be protected through binding agreements and Aboriginal cultural heritage management plans.[95]

The exception to this framework is the Olympic Dam mine. In the event of expanded operations as a result of the *Roxby Downs (Indenture Ratification) Act 1982* (SA), the predecessor to the Aboriginal Heritage Act, the *Aboriginal Heritage Act 1979* (SA) applies with some qualification.[96] However, heritage issues are addressed under the Olympic Dam Agreement between the mine owner BHP Billiton and the Barngarla, Kokatha and Kuyani Aboriginal groups. This agreement contains a Heritage Management Protocol that places further obligations on BHP Billiton for Aboriginal heritage protection and management.[97]

Although a systematic analysis was beyond the scope of the Commission, it has heard criticisms of the heritage protection framework, particularly the consultative provisions.[98] It has also heard of both positive and negative experiences concerning respect for the views of Aboriginal communities. A consistent theme is that it is critical to the satisfaction of a community that a project proponent does not seek to aggressively pursue a minimum legal compliance approach to Aboriginal heritage management.

Additional mechanisms for protecting Aboriginal heritage exist within the native title framework. Aboriginal heritage is among the wide range of matters that can be addressed in binding Indigenous land use agreements and in agreements made under the *Mining Act 1971* (SA).[99]

In relation to exploration and mining, specific regulatory requirements including programs for environment protection and rehabilitation (PEPRs) and conditions imposed on mining licences are to ensure that the protection and management of Aboriginal heritage is addressed before the start and during operation of a mine.[100]

The Aboriginal Heritage Act has recently been amended to clarify and preserve the rights and interests of a 'Recognised Aboriginal Representative Body', which may correspond with the registered native title body corporate in respect of any area.[101] The amendments recognise that it is desirable for a project proponent to negotiate a local heritage agreement with such a representative body before seeking the Minister's authorisation. Assuming these amendments will enter into effect, a proponent should ensure that it plans and implements any project by working closely and genuinely with the relevant Aboriginal communities and in accordance with the practical guidance set out in this chapter.

108. From a practical standpoint, bearing in mind the concerns expressed in many submissions about potential risks to heritage and culture posed by developments, there are important principles that any nuclear proponent should observe.

While compliance with regulatory frameworks is essential for any proponent wanting to progress a proposal, it is equally critical that a proponent ensures that:

a. those with knowledge and responsibility for heritage in a community clearly understand the nature and extent of a proposal

b. processes are established that exhaustively identify what must be protected

c. negotiations about proposals accommodate concerns about heritage

d. what is agreed as a result of negotiation is legally binding

e. mechanisms exist to monitor ongoing compliance with agreed commitments and address disputes arising between parties.

Early engagement with a community about these protections would be essential to building the type of trusting and sustainable relationship required for any project to progress.

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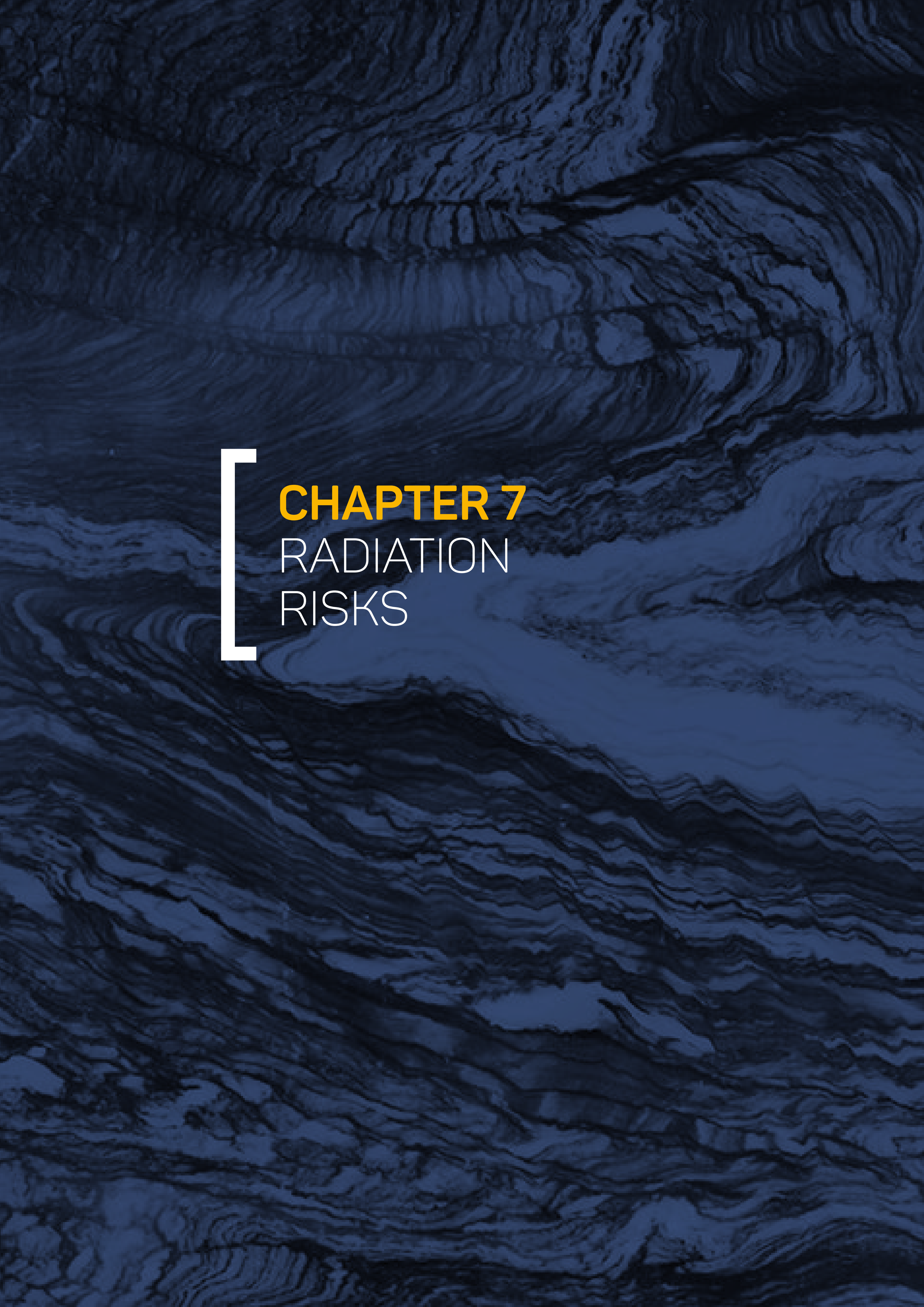

CHAPTER 7

RADIATION RISKS

CHAPTER 7: RADIATION RISKS

109. Australia's annual limits on the amount of ionising radiation (in 'doses') that can be absorbed for the public, workers and the environment are set on a precautionary basis. As people and the environment are constantly exposed to natural background radiation, the limits seek to minimise exposure to additional radiation from artificial sources.

All people are continuously exposed to ionising radiation from natural sources, or 'natural background radiation', throughout their lives.[1] Natural background radiation arises from a variety of sources, including rocks and soil (terrestrial radiation) and matter in outer space (cosmic radiation). People are exposed to the natural radiation present in their bodies, in the food they eat and in the radon gas they inhale, which comes from the ground.[2]

The level of natural background radiation that people will be exposed to depends on their location and the combination of radioactive sources present at that location.[3] On a worldwide basis, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has estimated that an individual's average annual exposure from natural background radiation is 2.4 millisieverts (mSv).[4] In Australia, the public is exposed to between 1.69 mSv and 3.79 mSv of natural background radiation per year.[5]

Figure 7.1 compares the additional doses that the public receives from artificial sources of radiation from medicine with the range of expected doses that the public in Australia and the United Kingdom receive from natural background radiation, and from nuclear facilities in the United Kingdom and Spain. In all cases, the additional doses to the public from nuclear fuel cycle facilities are many times lower than the annual regulatory limit fixed for those doses. It is also evident that doses from these facilities are much lower than natural background radiation and medical procedures.

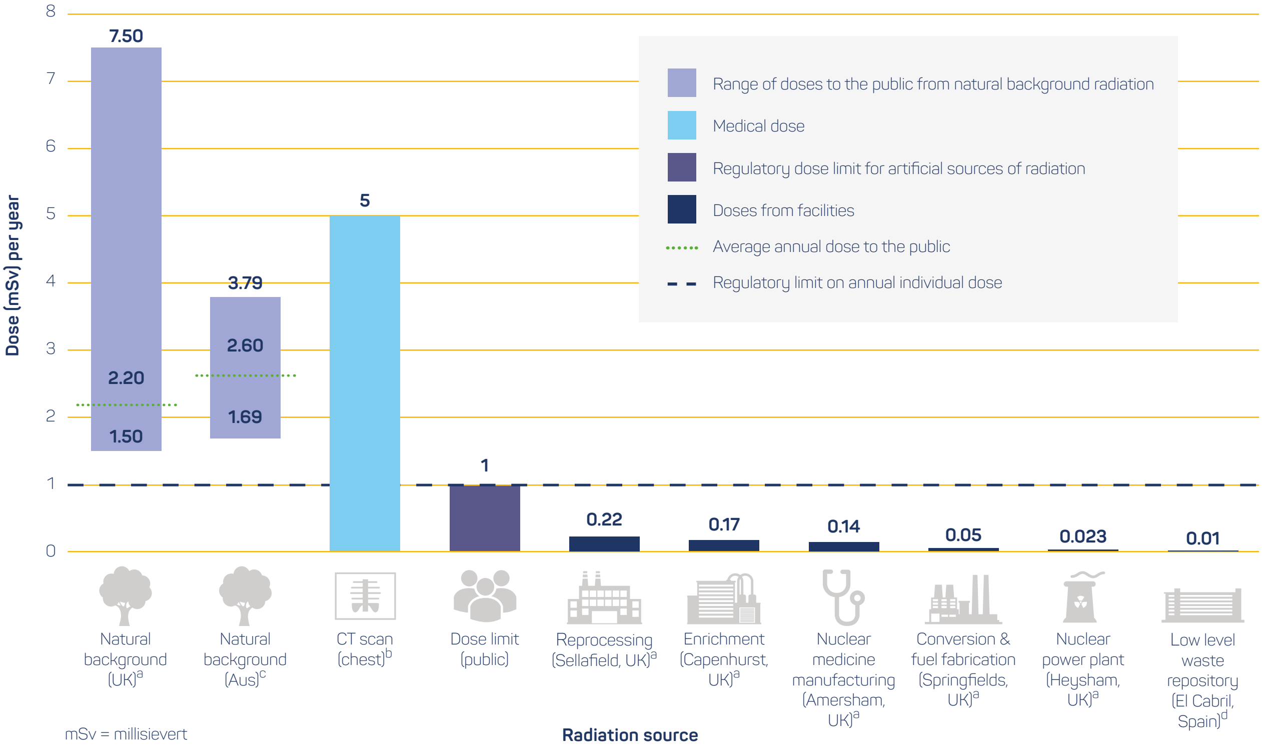

Figure 7.1: Expected radiation doses to the public from natural background radiation, medical sources and international nuclear fuel cycle facilities, and regulatory limit for doses of radiation to the public additional to natural background sources and medical procedures

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Radiation exposure often takes place for diagnostic or therapeutic purposes in medicine. For example, a computed tomography (CT) scan of the chest would give the recipient a radiation dose of 5 mSv, although CT scans can result in higher doses of up to about 10 mSv.[6]

In Australia, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) develops national standards for protecting the public, workers and the environment from the harmful effects of radiation based on international requirements.[7] These standards are uniformly applied in the states and territories. ARPANSA develops these standards in accordance with the principles of[8]:

- justification, which requires that the individual or society more generally receives a sufficient net benefit to offset the possible radiation harm caused by an exposure
- optimisation, which requires that all reasonable measures are taken to minimise the likelihood of exposures taking place, the number of people who are exposed and the magnitude of any exposures, including in accidents
- limitation, which requires that no individual is exposed to excessive radiation by reason of any radiation safety measures implemented to address risks to the broader community, unless the individual is receiving medical treatment.

In its application of these principles, ARPANSA sets limits on the permissible doses of radiation which the public and workers can receive from manmade sources, which are additional to natural background radiation.

For the public, the limits are significantly lower than what an average Australian might expect to receive from natural sources in any year. ARPANSA has specified that the effective dose limit for members of the public is 1 mSv a year.[9] This limit does not apply to radiation exposure in occupational or medical settings, where doses may exceed 1 mSv a year.

Although the limits are higher for workers, the principles that apply to public exposure also apply to minimise occupational exposure. For radiation workers, the limit is generally 20 mSv a year, averaged over five consecutive years, and no more than 50 mSv in any one year.[10] Radiation doses to workers are discussed in more detail later in this chapter.

In the case of the environment, operators of facilities that release radiation are required to optimise environmental radiation exposure. This involves determining an appropriate 'environmental reference level' (ERL) at which releases of radiation (above natural background radiation) would create little risk to the environment. Unlike dose limits for the public and workers, ERLs are calculated for specific projects to account for the diversity of flora and fauna present in nature.[11]

110. At very high levels of radiation exposure, adverse health impacts can be directly observed or inferred from statistical analysis; however, at low levels (in the range of ordinary exposures from natural background sources) there is ongoing scientific debate on the extent of any health risk. Despite this uncertainty, it is appropriate to apply a precautionary approach to radiation safety, even at low levels of exposure.

Over the past century, there has been extensive research into the effects of radiation on the human body. (See Appendix K: Radiation concepts, for more detailed information about the different types of ionising radiation and their biological effects on humans.)

While there is scientific consensus that human exposure to high doses of radiation will cause adverse health effects[12], there is disagreement about the health effects of radiation at low doses. It has been argued that any dose of radiation is unsafe and adverse health effects can result from natural background radiation alone[13], although no evidence was presented to the Commission that definitively supported these claims. Conversely, some studies have suggested that low doses of radiation could have positive health effects.[14]

This debate cannot be readily resolved. The health impacts of low levels of radiation are obscured as people are continuously exposed to natural background radiation and make other lifestyle choices that have adverse health effects. This makes it difficult to isolate the causes of those impacts with any certainty using current scientific methodologies.[15] Further, although it is known that radiation exposure can potentially cause cancer and other diseases, it is impossible to unequivocally attribute this to radiation or any other possible cause in an individual.[16]

Given these issues, the most conservative approach to managing radiation risks is to assume that any increase in radiation exposure will lead to a corresponding increase in risk to human health. That approach is known as the linear non-threshold (LNT) assumption and, in light of the ongoing debate, is the most prudent way to manage health risks from radiation exposure.[17] This is consistent with statements made by UNSCEAR and guidance by the International Commission on Radiological Protection.[18]

111. Any new nuclear facilities in South Australia would need to be designed and operated to ensure regulatory limits are not exceeded. The greater the radiation risk, the greater the level of engineered barriers, automation of processes and protective work practices required.

Australia's radiation safety regime adopts an approach in accordance with the LNT assumption.[19] Consequently, all facilities where radioactive substances are handled or produced must implement appropriate controls to ensure that doses of radiation are as low as reasonably achievable.[20] To that end, engineered control measures are designed and built into modern facilities before they begin operations. These measures include shielding to ensure there are low radiation areas and additional barriers to separate people from processes involving the greatest potential for radiation exposure.[21]

When planning a project to mine or mill uranium in South Australia, proponents are required to formulate a radiation management plan (RMP) and a radioactive waste management plan (RWMP), which outline the measures that would be in place to protect the public, workers and the environment from radiation during project operation and in managing wastes that are produced. Assessments must be undertaken of the potential pathways for radiation exposure, the controls that would apply to each pathway and how the effectiveness of those controls would be monitored.[22] The South Australian Environment Protection Authority (EPA) reviews and approves RMPs and RWMPs before any mining or milling operations start and, during operations, carries out quarterly inspections to ensure the plans are properly implemented.[23] It would be appropriate to undertake similar assessments in relation to any new nuclear facilities in South Australia.

112. Data from modern nuclear fuel cycle facilities demonstrates they operate well within the applicable regulatory limits for workers, the public and the environment. Doses of radiation to the local community from any new nuclear facilities in South Australia could be expected to be in the range of those estimated from the international nuclear facilities set out in Figure 7.1.

Internationally, operators and regulators of nuclear facilities undertake studies on radiation exposure to the public. For example, in the United Kingdom the various environmental and food safety regulators monitor radiation levels in food, and in land and marine environments near nuclear facilities. Radiation is released into the environment from nuclear facilities in the form of gaseous, liquid or particulate discharges. Some gamma radiation may also be released directly from the facility.[24] To assess the dose of radiation that the public might receive from a facility, regulators develop a 'representative person', who performs activities that could result in exposure to radiation from the facility, such as eating locally produced food and attending the local area for work or other purposes. These habits are determined on the basis of local survey data, with the representative person performing the activities that could cause exposure more frequently than the average person.[25] The estimated doses in Figure 7.1 relate to a representative person who carries out all the activities that have been identified as leading to radiation exposure.[26]

As Figure 7.1 indicates, the levels of radiation exposure to the public from international nuclear fuel cycle facilities are lower than what might be expected from natural background radiation. Keeping in mind the regulatory framework already in place, it is reasonable to envisage that any new nuclear facilities constructed in South Australia would be expected to give rise to doses in the range of those assessed at international facilities. Indeed, at the Open Pool Australian Lightwater (OPAL) research reactor operated by the Australian Nuclear Science and Technology Organisation (ANSTO) in New South Wales, the maximum potential dose to nearby residents from the facility's airborne emissions in 2014–15 was 0.0026 mSv, or less than 0.3 per cent of the 1 mSv annual dose limit for the public.[27]

113. The likely dose of radiation that members of the public would receive from a deep geological disposal facility has been estimated in assessments by overseas regulators. Even for the most conservative assumptions about future site conditions, radiation doses to the public are well below applicable regulatory limits.

The potential doses of radiation to the public from deep geological disposal facilities are estimated in 'safety cases' which are assessed by regulatory authorities. Estimates are made for both operations and after closure. Safety cases are discussed in more detail in Chapter 5 at Finding 69, with particular reference to long term safety.

With respect to operational safety at a disposal facility, the risks are similar to those that arise when loading dry casks at reactor sites. However, at the point at which used fuel is ready for disposal, though still highly hazardous, radiation levels are significantly lower than when dry storage of the used fuel began. The principal risk in used fuel storage and disposal operations is a used fuel assembly being physically damaged during on-site handling.

Once containers of used fuel have been placed in the disposal facility, it is closed by backfilling the tunnels to place it in a passively safe state. Assessments in Finland and Sweden are based on known characteristics of the materials throughout the first 10 000 years after closure. In the reference scenario, the used fuel containers will remain integral.[28] Despite the use of high-quality welding techniques, the reference scenario for Finland has conservatively assessed the consequences of a container with a small hole being emplaced.[29] Even in that unlikely scenario, the potential annual dose to the most exposed person will be less than 0.000001 mSv, which is a tiny fraction of the annual dose from natural background radiation.[30]

For other baseline scenarios, additional assessments have been made that take into account changes in groundwater conditions, container corrosion rates and the effects of climate change.[31] For these scenarios, potential annual doses to the most exposed person are still significantly less than 0.001 mSv.[32]

As geological disposal sites have not yet been identified in Belgium and Switzerland, their safety cases are at a more preliminary stage. Nevertheless, their reference scenarios show that annual doses during the first 10 000 years after closure will be significantly less than 0.0001 mSv.[33]

The safety cases also assess the potential doses that could arise from unlikely events, such as inadvertent intrusion after the facility's closure. Siting the facility at an appropriate depth, away from natural resources, and preserving records

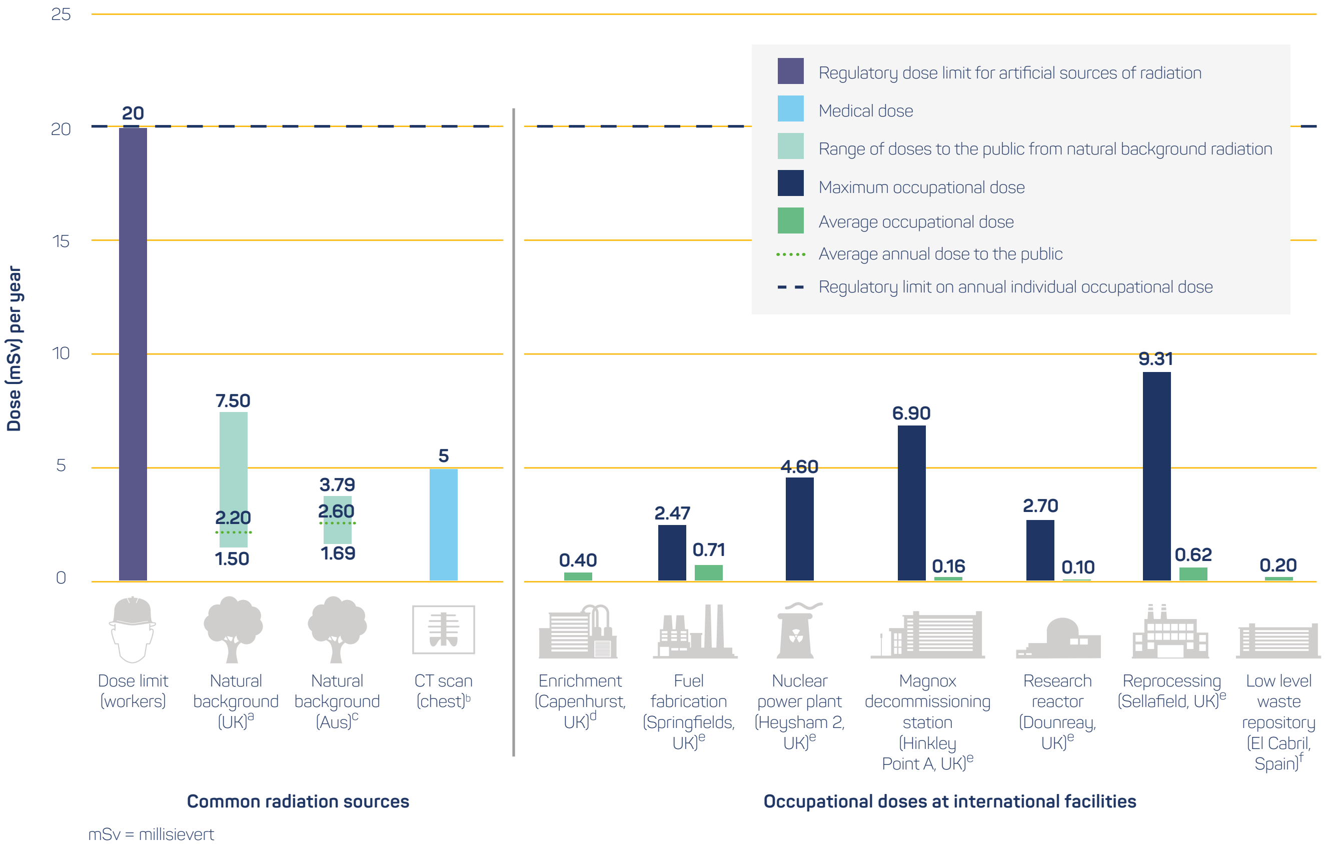
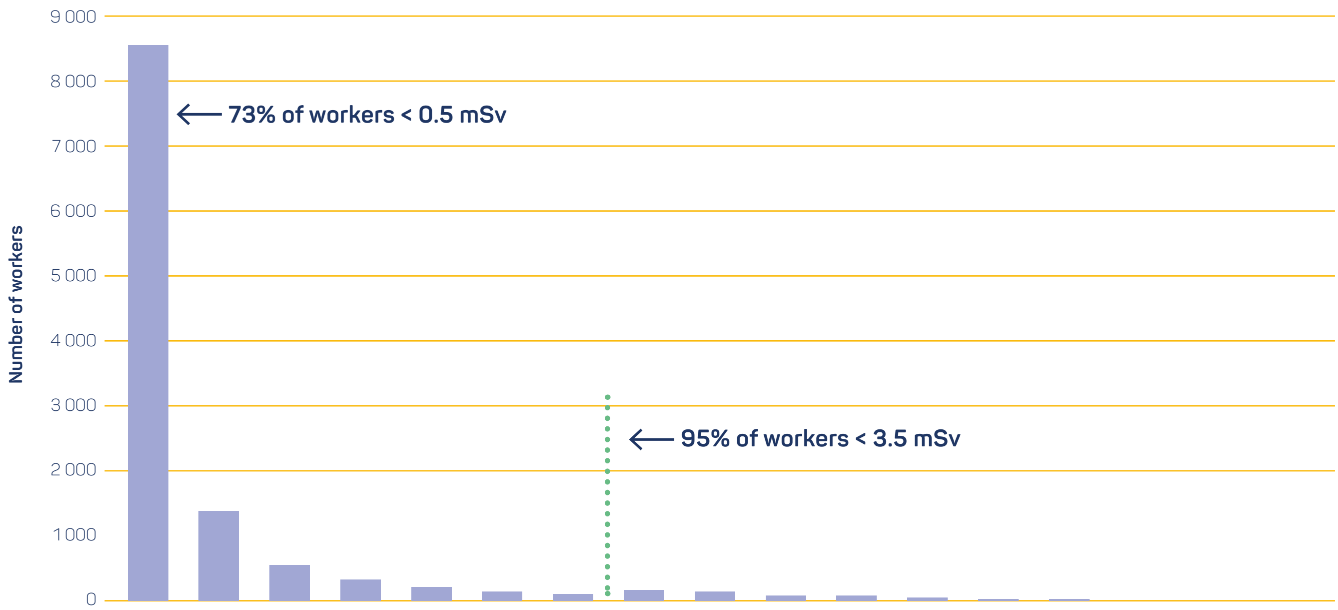


Figure 7.2: Expected radiation doses to workers from common sources, measured occupational doses at international nuclear fuel cycle facilities and regulatory occupational limit for doses of radiation additional to natural background sources

a. Cefas, *Radioactivity in food and environment*, p. 19
b. ARPANSA, *Ionising radiation and health*
c. Muston, 'Spatial variability of background radiation', p. 38
d. URENCO, *Sustainability report 2014*, URENCO Ltd, United Kingdom, 2015
e. Transcript: Fisher, p. 1789 and accompanying slides
f. E Neri (ENRESA), letter to the Nuclear Fuel Cycle Royal Commission, 21 December 2015



Effective dose (mSv)	0–0.5	0.5 –1	1–1.5	1.5–2	2–2.5	2.5–3	3–3.5	3.5–4	4–4.5	4.5–5	5–5.5	5.5–6	6–6.5	6.5–7	7–7.5	7.5–8	8–8.5
No. of workers	8 505	1 361	529	324	201	123	111	174	131	97	50	42	32	18	7	2	0

Figure 7.3: Annual dose distribution for all Australian uranium workers in 2014

Data sourced from ARPANSA, 'Analysis of ARPANSA data', *ANRDR in Review*, Issue 2, July 2015, p.5

of the site reduces the likelihood that this could occur while the used fuel presents a safety hazard.[34] The greatest potential doses from these unlikely scenarios would arise from drilling into a container of used fuel.[35] If that occurred soon after closure and parts of the fuel were brought to the surface, the driller would receive a significant radiation dose.[36] In addition, the most exposed member of the public could receive doses of a few tenths of a mSv a year, which is less than typical regulatory limits of 0.1 mSv per year for disposal facilities.[37]

Appendix I: Safety cases for geological disposal facilities provides a more detailed description of assessments of long term safety of geological disposal facilities.

114. For workers at nuclear facilities, the annual dose of radiation received varies depending on the nature of the tasks performed. The range of occupational exposures that might arise in South Australia from nuclear fuel cycle activities could be expected to be in the range of those recorded at the international nuclear facilities set out in Figure 7.2.

Given the implementation of the radiation management practices discussed earlier, exposures to workers at nuclear facilities could be expected to be in the ranges depicted in Figure 7.2. It can be seen that the average occupational dose received by workers is only a fraction of natural background radiation, and the maximum occupational dose received by any worker recently at those facilities is less than half of the annual occupational regulatory limit of 20 mSv.

At uranium mines in South Australia, radiation safety is already regulated by the EPA. It does so in accordance with ARPANSA's Radiation Protection Series, thereby maintaining national uniformity in radiation safety standards.[38] Operators of uranium mines are required to monitor the doses that workers receive to ensure that regulatory limits are not exceeded.[39]

Radiation exposure at uranium mines has not always been addressed in the way it is today. For example, at the Radium Hill mine, which operated from 1952 to 1961 in eastern South Australia, control measures for radiation safety were minimal and, at times, may even have been absent.[40] There is evidence that the lack of priority placed on radiation safety and the consequent exposure of miners to radiation led to an increased risk of developing lung cancer, although it is not known what impact smoking may have had.[41]

Modern uranium mines are required to be operated in accordance with the radiation safety principles outlined earlier, and operators need to demonstrate their ability to do this before receiving approval to proceed. Operators are required to provide information on worker radiation exposure to the Australian National Radiation Dose Register (ANRDR), which is a consolidated source of worker dose data administered by ARPANSA. A central source allows trends in occupational radiation exposure to be monitored, although the actual doses received by workers are likely to be lower than recorded as the data does not take into account the effect of protective equipment.[42] As the ANRDR data in Figure 7.3 shows, 73 per cent of workers in Australian uranium mines during 2014 received an annual dose of radiation of less than 0.5 mSv.[43] This is significantly less than the radiation doses received by miners in the past.[44]

115. The more significant radiation risks are created in the event of an uncontrolled release of nuclear or radioactive material during an accident at a nuclear power plant. The severity of those risks can vary depending on the extent of any such release. Authoritative international organisations have extensively evaluated the independent and peer-reviewed epidemiological data obtained by medical doctors and other scientists into the health effects of each accident. The credibility of these organisations and their findings is not open to doubt.

Other than the survivors of the Nagasaki and Hiroshima atomic bombs, the populations affected by the nuclear power plant accident at Chernobyl in 1986 have been the subject of the most extensive studies into radiation health effects. The most prominent is the study undertaken by the 'Chernobyl Forum', a joint study involving eight United Nations (UN) organisations and the governments of Belarus, the Russian Federation and Ukraine, which released its reports in 2006.[45] The most recent and comprehensive assessment of the available evidence, including the Chernobyl Forum reports, was published by UNSCEAR in 2011. Research into the effects of the Chernobyl accident is ongoing and society's understanding of its impacts will further improve.

The circumstances surrounding the nuclear accident at Fukushima Daiichi in 2011 are markedly different to those at Chernobyl. This difference led to very different levels of radiation release. The Fukushima accident, its causes and the measures taken in response, are discussed in more detail in Appendix F: The Fukushima Daiichi accident.

In its findings into the Fukushima accident, published in 2014, UNSCEAR estimated that the atmospheric release of the radioactive elements iodine-131 and caesium-137 (which contribute most to the radiation exposure to the public and the environment) were respectively about 10 per cent and 20 per cent of the levels released from the Chernobyl accident.[46] Further, the total dose of radiation to the Japanese public was about 10–15 per cent of the comparable dose to the European populations affected by radiation from Chernobyl.[47]

Despite its extensive studies into both accidents, UNSCEAR's standing as an authoritative source has been questioned. Claims were made in oral evidence to the Commission that the experts in UNSCEAR were not appropriately qualified and its investigations used data which was either incomplete or of poor quality, thereby excluding significant radiological impacts from its findings.[48] In addition, it was asserted that the World Health Organization (WHO) was prohibited by the International Atomic Energy Agency (IAEA) from undertaking its investigations appropriately and it did not physically examine the health effects of the Chernobyl or Fukushima accidents.[49]

UNSCEAR comprises 27 member states, including Australia, and its investigations are performed by teams of experts nominated by those states. In the case of the study into the Fukushima accident, a cohort of more than 80 scientific experts (including medical doctors) was assembled from specialists in 18 countries. They were organised into various expert groups which undertook independent investigations and reviewed data collected and provided by Japanese government agencies, UN member states, international organisations such as the Food and Agriculture Organization of the UN, and WHO, and non-governmental organisations.[50]

The WHO is the peak UN authority responsible for assessing current international health issues, including those arising in emergencies, and providing guidance about the appropriate management response. Its guidance, on topics including radiation, is developed independently of the IAEA.[51] Having led the comprehensive Chernobyl Forum studies in the past, it was directly involved in the assessment of health risks resulting from the earthquake, tsunami and nuclear power plant accident at Fukushima. After doing so over the course of two years, it produced a Health Risk Assessment in 2013 which estimated the future health impact of the accident on affected populations based on the available data at the time and using widely accepted methodologies and conservative assumptions.[52]

Both UNSCEAR and WHO draw similar conclusions from their independent investigations. Given their role, composition and the comprehensive nature of the investigations, they should be accepted.

116. The most serious consequences for human health caused by the radiation releases following the Chernobyl and Fukushima Daiichi accidents are well understood, although sometimes misreported. Given the latency of some less serious but potential consequences, ongoing health monitoring of affected areas and populations will continue. This will enhance understanding of health impacts of exposure. The detriment to mental health of persons affected by each accident and evacuation must also be acknowledged, particularly in future emergency response planning.

Despite the depth of research into the Chernobyl accident, there are very different views about the estimated health impacts asserted to be attributable to the radiation released. A paper by Yablokov, Nesterenko and Nesterenko concluded that 'the overall mortality rate for the period from April 1986 to the end of 2004 from the Chernobyl catastrophe was estimated at 985,000 additional deaths'.[53] That conclusion was reached using overly simplistic methodologies to analyse cause and effect, and without considering extraneous factors such as socioeconomic conditions and the impact of increased screening.[54] Such methodologies are known to give rise to erroneous conclusions and, given the additional difficulties in attributing health effects to low levels of radiation exposure, have been recommended against by UNSCEAR.[55] The publication, including its methodologies and conclusions, has been specifically criticised in the scientific literature.[56]

With respect to the presence of radioactive materials in the environment at Chernobyl, it has been claimed that the radioactivity in some places will increase over time.[57] Certain radioactive elements, known as 'hot particles', were released during the accident and the levels of one of those elements—americium-241—are increasing as it is a product of the decay of other radionuclides.[58] However, because these hot particles are 'heavier' than other elements, they do not travel far from the nuclear power plant site in the event of an accident.[59] Although these elements will remain radioactive in the long term, they will only be present in trace quantities.[60] Those quantities will not materially add to radiation from background sources.

UNSCEAR has identified several areas where uncertainties affect its ability to draw conclusions from the available evidence about the health effects of Chernobyl. As cancer and other stochastic effects are difficult to attribute to radiation given they have other potential causes, it is only possible to determine a probability that the effect was wholly or partly caused by radiation exposure. Each effect must be examined on its own merits and in light of other relevant factors. These limitations are even more pronounced in the populations that received low doses of radiation from the Chernobyl accident given the presence of natural background radiation.[61]

Bearing these uncertainties in mind, UNSCEAR made the following conclusions[62]:

- Of the plant staff and emergency workers who received very high doses of radiation, 134 people developed acute radiation syndrome (ARS), which caused the deaths of 28 of those people. Two other workers died in the immediate aftermath of the accident from causes unrelated to radiation exposure.
- Of the ARS survivors, a further 19 had died by 2006 (two decades later), although their deaths were not directly attributable to radiation exposure. The remaining ARS survivors experience skin injuries, cataracts and ulceration as a result of radiation exposure, the severity of which is consistent with the dose of radiation received. No other health conditions experienced by the ARS survivors have been attributable to radiation exposure.
- Among the public, who received much lower doses of radiation than the plant staff and emergency workers, there were no cases of ARS or associated fatalities. A significant increase in thyroid cancers was observed in members of the local population who were children or adolescents at the time of the accident. Doses of radiation to the thyroid were caused by the contamination of milk with radioactive iodine in the immediate days after the accident. Radiation is considered to have contributed to a large proportion of the 6848 cases of thyroid cancer reported between 1991 and 2005. Fifteen of these proved fatal.
- While those who received high doses of radioactive iodine or were exposed as children or adolescents are at increased risk of developing radiation-related conditions, it has not been possible to confirm whether any further health impacts were attributable to radiation. As the public were generally exposed to doses of radiation in the range of those from natural background sources, it is unlikely that any identifiable health impacts will be attributable to radiation released as a result of the accident.

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In its assessment of the health impacts from radiation released at Fukushima, UNSCEAR reached the following conclusions[63]:

- No plant staff, emergency worker or member of the public died or developed acute health effects (such as ARS) as a result of radiation exposure. A small proportion of workers received higher doses during the accident and in the immediate clean-up period; however, these doses are understood to be a long way below the threshold for acute effects.
- In estimating potential health risks, including solid cancers, thyroid cancer, leukaemia, breast cancer and diseases associated with prenatal exposure, UNSCEAR considered the extent to which radiation exposure would affect the natural incidence of these diseases in the exposed populations. In general, it was concluded that it would not be possible to discern an increase in these diseases from that baseline level of risk.
- There may be an increased risk of cancer, particularly of the thyroid, and hypothyroidism in more vulnerable groups, including the 173 workers who received effective doses of 100 mSv or more, and infants and children in the evacuation zone. However, any such increase would be difficult to attribute to the accident, given the understood levels of exposure.

UNSCEAR stated that its findings do not preclude the possibility that health effects attributable to radiation from the Fukushima accident might be identified in future.[64] To that end, it has implemented a process of ongoing review of new information about radiation effects from Fukushima.[65] In the first of these reviews, in 2015, UNSCEAR concluded that its findings on the health implications for workers and the public 'remain valid and are largely unaffected by new information that has been published so far'.[66]

The health of the people exposed to radiation from the Fukushima and Chernobyl accidents will continue to be monitored by local authorities and the international community over the coming decades. Given the increase in thyroid examinations in Fukushima, it is expected that thyroid abnormalities not necessarily attributable to radiation will be identified that would not have been detected otherwise.[67] Further study since UNSCEAR's report has supported this view.[68] In the case of Chernobyl, the Chernobyl Tissue Bank has been established as a central data repository to assist in understanding how radiation induces cancers.[69]

Following the accidents at Chernobyl and Fukushima, evacuations and other response measures reduced the risk that radiation presented to local populations. However, these measures in themselves gave rise to other health implications.[70] Studies have found increased levels of depression and anxiety in populations affected by the Chernobyl accident.[71] In Japan, the comprehensive Mental Health and Lifestyle Survey indicated the presence of severe traumatic problems in adults from the Fukushima evacuation zone.[72] Mental conditions are also likely to lead to negative health effects and will have significant implications for public health.[73]

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CHAPTER 8

NON-PROLIFERATION AND SECURITY

CHAPTER 8: NON-PROLIFERATION AND SECURITY

117. Australia has sound non-proliferation and nuclear security credentials developed over many decades. Maintaining that reputation would be critical in contemplating participation in new nuclear fuel cycle activities.

In considering the nuclear proliferation and security risks associated with new nuclear activities in South Australia, the focus should be on Australia's policies and international reputation in relation to these issues and the relevant geopolitical environment. Any further nuclear activities in South Australia would be subject to the current international and domestic regulatory regime that is concerned with nuclear proliferation and security. It follows that the proliferation and security risks associated with further nuclear activities must be considered in the South Australian context, rather than circumstances which apply to other countries or which existed in the past.

The Commission's attention has been drawn to Australia's more supportive attitude towards nuclear weapons in the past. It was said there is no guarantee it would not revert to this policy position given the right circumstances.[1] That argument fails to consider the significant changes since the peak of the Cold War era, primarily the establishment and adoption of the international legal regime for non-proliferation. In light of the following, the Commission does not accept that it is credible to suggest Australia has nuclear weapons ambitions.

Underpinning the non-proliferation framework is the Treaty on the Non-proliferation of Nuclear Weapons (NPT), which seeks to constrain the number of countries that possess nuclear weapons by prohibiting their development or acquisition (Article II) and mandating the implementation of measures known as safeguards to verify compliance with that prohibition (Article III). Australia has been a party to the NPT since 1970 and ratified its requirements in 1973, legally committing to the international community not to develop or acquire nuclear weapons.

Since that time, Australia has developed a strong reputation in non-proliferation because of its active involvement in strengthening the international safeguards system and by undertaking measures to facilitate global non-proliferation efforts in addition to the minimum requirements of the NPT.[2] Australia is a party to the South Pacific Nuclear Free Zone Treaty through which it relinquishes any potential decision to acquire or possess nuclear weapons (Article 3) and commits to preventing the stationing (Article 5) or testing (Article 6) of any nuclear weapon in its territory by others. It is also a member of the Nuclear Suppliers Group, a collective of countries that supply nuclear materials and technologies only in accordance with guidelines that are complementary to the NPT arrangements.[3] Australia has a longstanding history of supporting strengthened International Atomic Energy Agency (IAEA) safeguards, including through its chairing of the IAEA's Standing Advisory Group on Safeguards Implementation, facilitating field trials for new safeguards technologies and procedures, and being the first country to conclude an Additional Protocol to its safeguards agreement with the IAEA.[4]

Regarding nuclear security, Australia has demonstrated a successful approach to managing security risks at its existing nuclear fuel cycle facilities. It is involved in several international measures to promote the importance of nuclear security, including as a founding member of the Global Initiative to Combat Nuclear Terrorism, a member of numerous IAEA bodies concerned with nuclear security and a regular contributor to the IAEA Nuclear Security Fund.[5] Recently, the Nuclear Threat Initiative ranked Australia as first in the world based on the security measures in place to protect its nuclear materials and facilities.[6]

Australia's compliance with the NPT is verified through its application of IAEA safeguards to all nuclear activities.

118. Any nuclear fuel cycle facility to be built in South Australia would need to be constructed and operated in accordance with the strengthened international safeguards system, thereby assuring other countries that the facility is used solely for peaceful purposes.

In addressing international non-proliferation objectives, it is important for countries to not only act in accordance with global norms directed towards that end, but also to be seen as doing so by other nations. Concerns have been expressed that, in some circumstances, a nation's entry into or expanded involvement in the nuclear fuel cycle could create an impression in other countries that such actions might be taken for non-peaceful purposes.[7] The issue is said to arise particularly where nuclear fuel cycle activities are undertaken in the absence of any clear economic rationale, potentially creating the impression that national security considerations are driving their development.[8]

Generally, the separation between civil and military uses of nuclear technology and materials is well understood by countries.[9] However, the precise international policy implications associated with the development of new nuclear activities can differ based on the specific activity contemplated. Activities involving uranium mining, uranium conversion and fuel fabrication, power generation using nuclear fuels, and nuclear waste storage and disposal are unlikely to raise international concerns about Australia's intentions.[10]

In the context of uranium mining, different views have been expressed regarding the recently concluded bilateral agreement to export Australian uranium to India. The reservations are largely founded on India's non-membership of the NPT and Comprehensive Nuclear-Test-Ban Treaty (CTBT), and the potential for the supply of uranium to create surplus capacity in a customer's domestic stocks for use in weapons production.[11]

While these are legitimate concerns to hold, it is important for countries such as Australia to engage in diplomacy as a way of expanding the reach of global non-proliferation norms.[12] The Parliament of Australia's Joint Standing Committee on Treaties (JSCOT) recognised this issue in its appraisal of the proposed agreement with India.[13] In its response to that appraisal, the Australian Government indicated that it is already engaged in dialogue with India consistent with JSCOT's recommendations in this regard.[14]

The position would be more complex if uranium enrichment or used fuel reprocessing operations were established in Australia, especially without economic justification.[15] It might be difficult in that case to convince other countries that these capabilities were being developed exclusively for peaceful purposes, even though that would be true in Australia. There is also a risk that doing so might set an international precedent and lead others to consider doing the same for national security reasons.[16] For this reason, if enrichment or reprocessing activities were to be undertaken in the future, they should take place on a multilateral basis as discussed further in Finding 121.

If Australia were to widen its involvement in nuclear activities, it would need to be proactive in assuring other countries that it remains committed to its international and domestic non-proliferation obligations. Several means of doing so are already in train. Australia is active in supporting the development of verification infrastructure to promote the CTBT's entry into force.[17] In addition, Australia was central to establishing the Asia-Pacific Safeguards Network (APSN). Consisting primarily of regional organisations involved in nuclear safeguards, APSN seeks to promote greater quality in safeguards implementation through training and information sharing in collaboration with the IAEA.[18]

119. The potential for proliferation risks from nuclear fuel cycle activities is greatest for enrichment or reprocessing because those facilities can produce highly enriched uranium or separated plutonium capable of use in nuclear weapons.

The extent to which each nuclear fuel cycle activity gives rise to proliferation risks is closely associated with the potential production of weapons-usable material during the activity.

Nuclear weapons require either highly enriched uranium (HEU), which comprises about 90 per cent of the uranium-235 isotope, or plutonium, which, in the context of weapons, should be made up of primarily plutonium-239.[19] Enriched uranium and separated plutonium are produced using technologies for, respectively, uranium enrichment and used fuel reprocessing. Ordinarily, nuclear fuel cycle activities undertaken for the purpose of power generation do not produce HEU or plutonium with the ideal isotopic composition for use in nuclear weapons. However, uranium enrichment and used fuel reprocessing provide at least the basic capability to acquire these materials and are therefore of greatest concern to the non-proliferation regime.[20]

International bodies, national governments and industry recognise that these processing activities are most sensitive to proliferation risks, therefore the technologies' use is subject to a range of measures that seek to limit those risks. International transfers of nuclear material and technologies are performed in accordance with bilateral agreements executed between the governments of the countries involved in the transactions.[21] Australia already has bilateral arrangements with every nation to which it exports UOC. These agreements impose numerous conditions on the recipient nation, including the acceptance of IAEA safeguards on the material and establishment of administrative arrangements to account for the material to the Australian Safeguards and Non-Proliferation Office (ASNO).[22]

The Nuclear Suppliers Group has issued Guidelines which set out detailed conditions for the supply of enrichment technology, such as measures against replication of the technology and alternative arrangements to the establishment of national facilities including supplier involvement and appropriate multinational participation.[23] Consistent with this, the existing enrichment technology providers, namely URENCO and TENEX, do so on a 'black box' basis, whereby critical design information relating to the technology is withheld as a barrier to its replication.[24] Although black box arrangements are not impregnable,[25] they are an additional barrier to improper application of the technology, increasing the number of measures in place to minimise proliferation risks.[26]

Other stages of the nuclear fuel cycle can give rise to proliferation concerns, but to a far lesser degree than uranium enrichment and used fuel reprocessing. They include[27]:

- uranium mining and conversion, the products of which are unusable in a nuclear weapon without enrichment or, if already incorporated into used fuel, reprocessing
- the storage and disposal of low and intermediate level wastes, being either contaminated materials or wastes immobilised in glass, ceramic or concrete. Even if some wastes contain trace amounts of enriched uranium or separated plutonium, they are practically irrecoverable for weapons use
- the storage and disposal of high level wastes, which do not contain materials readily recoverable for use in weapons
- the storage and disposal of used fuel. Although it contains plutonium, used fuel would require the further step of reprocessing before the plutonium could be used in a weapon
- nuclear power plants. Although such plants produce plutonium in uranium fuel, that plutonium is not usable in weapons unless it is separated through reprocessing.

120. Engagement in new nuclear fuel cycle activities would require further regulation in Australia. Models of regulation addressing proliferation from other jurisdictions could be applied to an Australian context for any potential new activity.

The proliferation risks associated with the nuclear fuel cycle are managed through a combination of technical and regulatory means. Where a Comprehensive Safeguards Agreement (CSA) has been concluded with the IAEA, a country is required to accept IAEA safeguards on all nuclear material within the nation's control and used for peaceful purposes.[28]

Safeguards allow nuclear material flows to be tracked such that any diversion for non-peaceful purposes would be detected. The IAEA implements safeguards using the state-level concept: a means by which it is able to allocate safeguards efficiently by considering a country's entire nuclear fuel cycle.[29] In practice, safeguards require the nation state to provide information to the IAEA about nuclear material flows, which is subsequently audited based on the IAEA's own field observations (incorporating various surveillance, containment and process monitoring techniques) and information it receives from other sources.[30]

Claims have been made that the utility of IAEA safeguards is adversely affected by countries providing limited information.[31] However, limits placed on the information provided to the IAEA, whether resulting from commercial confidentiality or national security reasons, are unlikely to be a barrier to nuclear materials accounting. Arrangements can be devised that balance the need for effective verification with the need for maintaining the confidentiality of sensitive technological aspects.[32]

It is also said that material accounting discrepancies (known as material unaccounted for, or MUF) are commonplace.[33] The concept of MUF relates to the variation between the estimated and measured samples of nuclear materials that are being processed during a nuclear fuel cycle activity at a given time. The variance could be positive or negative and does not necessarily indicate that any nuclear material is absent.[34] Further, nuclear materials accounting is complemented by containment and surveillance measures, such as cameras, portal monitors and radiation monitors, to provide assurance that nuclear material has not been removed.[35]

A CSA (including an Additional Protocol) has been implemented in Australia for many years. The arrangements under the agreement are managed by ASNO, which monitors the production and movement of nuclear materials to, from and within all Australian states.[36] An expansion of South Australia's involvement in the nuclear fuel cycle would have implications for both the IAEA's and ASNO's roles in managing the associated proliferation risks, commensurate with the level of risk associated with the specific activity.[37] Other nation states, such as Japan, already manage proliferation risks in the context of a more comprehensive nuclear fuel cycle. Australia would be able to draw on that experience should a decision be made to proceed in that direction.[38]

121. In the event that a fuel leasing arrangement provided the basis to establish enrichment facilities, that activity should be carried out under an appropriate multilateral arrangement with partner countries.

A nation's engagement in domestic enrichment activities can cause other countries to question whether those activities are for exclusively peaceful purposes. In the absence of appropriate assurances, such a scenario is likely to have a negative impact on regional diplomatic relations.[39] If South Australia sought to establish enrichment capabilities in future, the ideal pathway would be through a multilateral approach with partner countries. The participation of other countries in those activities provides an additional level of assurance that enrichment capabilities will not be used for non-peaceful purposes.[40]

Internationally, numerous multilateral approaches have been considered in the past, particularly in the context of enrichment services.[41] There are examples of enrichment service providers currently operating through a multinational model, particularly URENCO (established through treaties between Germany, the Netherlands and the United Kingdom). The International Uranium Enrichment Centre in Angarsk, Siberia also has multilateral participation. The advantages of multilateral approaches generally include[42]:

- minimising the spread of enrichment technology to facilities in multiple countries
- making the potential for any one participating country to withdraw from the NPT more difficult, particularly if that country seeks to do so without arousing suspicion at an early stage
- reducing the potential for HEU to be produced or diverted in secret
- allowing for the efficient application of safeguards to a centralised facility by the IAEA, especially if the multilateral arrangement incorporates IAEA oversight
- reassuring the international community that the development of enrichment capabilities is for exclusively peaceful purposes.

It is argued that the future establishment of multilateral arrangements (short of incorporating all existing domestic facilities into those arrangements) is unlikely to have any positive impact on non-proliferation efforts. As evidenced by the Pakistani nuclear scientist AQ Khan's ability to steal and distribute enrichment technology from URENCO in the past, the concept can present some risks.[43]

The practical implementation of a viable multilateral arrangement would not be simple and would need to address any vulnerabilities that have been exploited in the past. For a proposal of this nature to be attractive to customer countries who would otherwise develop domestic enrichment capabilities, a reliable supply of nuclear fuel would need to be assured without discrimination.[44] However, it is also true that a multilateral arrangement manages proliferation risks much more effectively than domestic arrangements.[45]

122. Nuclear fuel cycle activities give rise to security risks, which are comparatively lower in Australia than in other parts of the world. They are already managed at nuclear fuel cycle facilities in accordance with a mature international framework.

Security at nuclear fuel cycle facilities is broadly concerned with the risks of:

- unauthorised removal of nuclear materials
- the theft of proliferation-sensitive technology
- the sabotage of facilities.

In guarding against unauthorised removal of materials, the primary consideration is the extent to which the material could be used in a nuclear explosive device. This dictates how attractive the material might be to people seeking to construct such a device. Given that Australia possesses minimal quantities of attractive material (HEU or plutonium) and has a small number of nuclear sites, the level of security risk is much lower than in many other countries.[46] The likelihood of the material being removed for radiological dispersal is also a significant consideration.

In the case of technology theft, the concern is directed towards preventing the dissemination of enrichment and reprocessing technologies.[47] For sabotage, the main issue is the radiological consequences that could result from a malicious act directed at the nuclear facility.[48]

The international community places great emphasis on addressing threats to nuclear security, having created standards for that purpose and guidance for their implementation. The Convention on the Physical Protection of Nuclear Material (and its 2005 Amendment) and the International Convention for the Suppression of Acts of Nuclear Terrorism place obligations on nations to have a regulatory structure in place that effectively deters, resists and reprimands attempts to breach security at nuclear fuel cycle facilities and during domestic and international transport of nuclear materials.

The IAEA also has developed principles for assessing the magnitude of security risks and the appropriate response measures that should be implemented.[49] Most recently, the United States held the fourth in a series of Nuclear Security Summits, which was attended by more than 50 nations that reaffirmed their commitment to further strengthen the relevant international architecture and, in doing so, maintain international cooperation.[50]

New nuclear facilities are designed, constructed and operated in a manner that supports the effective management of security risks. For example, current nuclear reactor designs, given they are at higher risk of sabotage due to their inherent driving force for radiation dispersal, are developed to be able to withstand the impact of an aircraft collision.[51] Nuclear power plant operators also have stationed on-site teams that are highly trained in counter-terrorism operations to respond to security threats.[52]

In Australia, security risks are already managed in accordance with international guidance. In consultation with ASNO, the Australian Nuclear Science and Technology Organisation has developed a security plan for its nuclear reactor at Lucas Heights, to address credible hostile scenarios formulated on the basis of advice from national intelligence agencies.[53]

Security plans rely on the concept of defence in depth, which employs multiple layers of security to protect a facility from becoming vulnerable should a single barrier be overcome. The security layers incorporate physical barriers to restrict access, technological means including area surveillance, and measures to prevent cyber attack. Security plans are tested in exercises designed to simulate realistic threats. Current Australian arrangements were peer-reviewed in 2013 by the IAEA-led International Physical Protection Advisory Service, with positive feedback provided and recommendations made as to how they might be further strengthened.[54]

123. The development of a proposal to receive used fuel would require the construction of a new secured port and railway. However, the risk of intentional interference or misuse of used fuel is greatly limited by the characteristics of the fuel and the casks in which it is stored and transported.

There are numerous facilities around the world covering all aspects of the nuclear fuel cycle where security risks are managed in accordance with international standards and guidance. Measures in place at these facilities employ the principles discussed earlier to meet security threats by employing multiple barriers. The practical security arrangements, comprising physical, technological and procedural facets, are tailored to the relative sabotage and other threat risks presented by a specific facility.

In the context of used fuel storage and disposal facilities, used fuel incorporates barriers to potential security risks, particularly its inherent radiological properties and the nature of the casks in which it is transported and stored. The difficulties in physically removing the used fuel, followed by the need for reprocessing capabilities to recover any plutonium for use in a weapon, reduce its potential attractiveness for theft.

Used fuel is highly radioactive and needs to be isolated from people and the environment to ensure that its harmful effects are contained.[55] This is achieved during transport and storage, primarily through the use of purpose-designed casks, which are handled remotely as a further means of radiation safety. Casks containing used fuel are sealed and require specialist equipment to open them.[56] During storage, used fuel is contained in large casks made of steel, concrete or a combination of both.[57] The casks are stored in an area protected by multiple physical barriers and equipped with technological means to detect unauthorised access or intrusion.[58] The analysis undertaken by Jacobs for the Commission included financial provision for security barriers, security systems to complement them and contractors to provide security services.[59]

Attempts could conceivably be made to steal a cask during transport or to sabotage a consignment of used fuel. In an extreme case, sabotage could be attempted using heavy weapons, such as armour-piercing rockets.[60]

The risk of used fuel being stolen during transport is limited by the difficulty associated with moving the casks. The transport package incorporates extensive shielding to contain radiation and its structure is reinforced to withstand a wide range of accident conditions. Each package is about four to five metres long and weighs more than 100 tonnes.[61] Consequently, their transport requires heavy vehicles and their movement from one mode of carriage to another requires specialist equipment.[62]

To plan, resource and execute a breach of security would be extremely challenging. Even if an organisation had the physical capabilities to do so, the breach would need to be planned and performed without attracting the attention and subsequent intervention of international and national security agencies. Further, should an attempt at theft or sabotage be made, a transport plan would be in place that would incorporate appropriate emergency response measures, including the assistance of state and federal law enforcement agencies and even the military. Therefore, even in the unlikely event that one of these potential threats materialised, there would be a comprehensive framework in place to respond to the threat and mitigate any consequences arising as a result.[63]

NOTES

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3 Nuclear Suppliers Group, 'About the NSG' and 'Participants', NSG, http://www.nuclearsuppliersgroup.org/en/about-us.

4 Australian Safeguards and Non-Proliferation Office (ASNO), *Annual report 2014–2015*, Australian Government, Australian Capital Territory, 2015, p. 65; International Atomic Energy Agency (IAEA), 'Safeguards legal framework – status of the additional protocol', IAEA, 26 February 2016, https://www.iaea.org/safeguards/safeguards-legal-framework/additional-protocol/status-of-additional-protocol.

5 ASNO, *Annual report 2014–2015*, pp. 107–110.

6 Nuclear Threat Initiative (NTI), *Nuclear security index: Building a framework for assurance, accountability, and action*, 3rd edn, NTI, Washington DC, 2016, pp. 36, 53.

7 Submissions: CCSA, ACF & FoE, pp. 94–95, 101; ICANW, pp. 9, 12; MAPWA & PHAA, pp. 21–22, 46.

8 Transcript: Sokolski, pp. 1474–1475.

9 Transcript: Evans, pp. 1553–1554.

10 ibid., pp. 1554, 1561–1563.

11 Transcripts: Evans, pp. 1554–1555; Sokolski, pp. 1483–1484. Submissions: CCSA, ACF & FoE, p. 107; ICANW, p. 10.

12 Transcript: Evans, p. 1554.

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14 Australian Government, 'Australian Government response to the Joint Standing Committee on Treaties report: Report 151', Canberra, November 2015, pp. 1–2.

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20 Transcript: Floyd, pp. 1491–1492.

21 ibid., p. 1493.

22 ASNO, *Annual report 2014-2015*, pp. 30–31.

23 Nuclear Suppliers Group (NSG), *Guidelines for nuclear transfers*, NSG guidelines, pt 1, NSG, June 2013; NSG, *Guidelines for transfers of nuclear-related dual-use equipment, materials, software and related technology*, NSG guidelines, pt 2, NSG, June 2013.

24 G Evans, T Ogilvie-White & R Thakur, *Nuclear weapons: the state of play 2015*, Centre for Nuclear Non-Proliferation and Disarmament, Canberra, 2015, p. 203.

25 Transcript: Sokolski, p. 1485.

26 Transcripts: Evans, pp. 1559–1560; Floyd, pp. 1506–1507.

27 Transcripts: Evans, pp. 1554, 1561–1563; Floyd, pp. 1491–1492.

28 IAEA Department of Safeguards, 'IAEA Safeguards: Serving Nuclear', p. 9.

29 Transcript: Floyd, pp. 1512–1513. IAEA Department of Safeguards, 'IAEA Safeguards: Serving Nuclear Non-Proliferation', IAEA, Vienna, 2015, pp. 11–13.

30 Transcript: Floyd, p. 1502. IAEA, 'IAEA Safeguards: Serving Nuclear', pp. 9, 13–14.

31 Transcript: Sokolski, pp. 1480–1481. Submission: CCSA, ACF & FoE, pp. 102–103.

32 Transcript: Floyd, pp. 1501–1502.

33 Transcript: Sokolski, pp. 1480–1481. Submission: CCSA, ACF & FoE, pp. 102–103.

34 Transcript: Floyd, pp. 1499–1500.

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40 Transcript: Floyd, p.1495. Submission: Australian Government, p. 10.

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44 G Evans & Y Kawaguchi, *Eliminating nuclear threats*, pp. 144–145.

45 Transcript: Floyd, p. 1497.

46 NTI, *Nuclear Security Index: Building*, p. 36.

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56 Jacobs & MCM, *Safety and risks in the transportation of radioactive materials to and in Australia*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, 31 March 2016, pp. 40–41, http://nuclearrc.sa.gov.au/

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59 Jacobs & MCM, *Radioactive waste storage*, pp. 138, 182.

60 Jacobs & MCM, *Safety and risks*, pp. 40–45.

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Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website:www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

CHAPTER 9

TRANSPORT, REGULATION AND OTHER CHALLENGES

CHAPTER 9: TRANSPORT, REGULATION AND OTHER CHALLENGES

TRANSPORT

124. The international transport of radioactive materials, such as mined uranium, processed uranium for nuclear fuels, nuclear medicine and waste, is routine. Consignments are transported safely by road, rail, sea and air.

Each year, about 20 million consignments of radioactive materials are transported worldwide.[1] Isotopes for nuclear medicine make up most of this global activity, with radioactive materials relating to the nuclear fuel cycle representing about 5 per cent of consignments.[2] Many medical isotopes have short 'half-lives', a limit to their effectiveness that makes the use of air transport necessary to deliver the material promptly.

Of the nuclear fuel cycle radioactive materials, there have been approximately 7000 international shipments of used fuel since 1971, comprising more than 80 000 tonnes of material.[3] This includes high level waste from commercial nuclear power reactors, as well as intermediate level waste from research reactors such as the Australian Nuclear Science and Technology Organisation (ANSTO) facility at Lucas Heights in New South Wales. ANSTO has sent a total of nine shipments for reprocessing overseas.[4]

A large proportion of the shipped material has been for reprocessing, including 40 000 tonnes of used fuel at the La Hague facility in France and more than 30 000 tonnes at the Sellafield facility in the United Kingdom.[5]

There are concerns about the safety of used fuel shipments and the risk that an accident would harm people and the environment through radiation exposure.[6] Accidents have occurred during shipments of used fuel, but none has resulted in either a breach of the packages containing the radioactive material or any harmful effects due to radiation.[7] Packages containing used fuel are specifically designed to withstand serious accidents. Past incidents have proven their ability to do so, including at Fukushima in 2011 when eight casks stored in the plant remained intact despite being hit by the tsunami.[8]

In the context of nuclear medicine, approximately 9600 domestic consignments a year are made from ANSTO to hospitals, radiopharmacies and nuclear medicine practices around Australia.[9] There is an equivalent number of intrastate shipments in Australia each year, made using wide-bodied aircraft and handled by certified personnel. The most significant product in these consignments is molybdenum, which is used in about 80 per cent of the world's diagnostic imaging.[10]

125. Uranium oxide concentrate is routinely exported from Australia. While there have been incidents involving damage to containers or drums, there has never been an accident involving the release of radiation that has adversely affected workers, the public or the environment.

Uranium oxide concentrate (UOC) is transported and exported in powder form, which is also known as yellowcake. It has low radioactivity and remains chemically stable during transport, handling and storage.[11] In South Australia, UOC is transported via rail and road from the mine site where it is produced to Port Adelaide, from where it is shipped overseas. About 11 000 containers of UOC have been exported from Australia in the past 30 years.[12]

The UOC for shipment is packaged at the mine site. It is placed in 200-litre steel drums and sealed with a secured lid. The sealed drums are then stowed in sea freight containers and secured using a Kevlar-based system of straps. The container is clearly labelled and sealed with numbered seals at the mine site, ensuring that the container remains sealed from the mine to the final delivery point. The radioactivity of each consignment is measured before it leaves the mine site.[13]

Consignments are inspected throughout the transport process, with any anomalies or incidents being reported, regardless of how minor. Any damage to containers is reported by the transporter to the consignor and consignee, with certified personnel checking for any radiation-related risks. In Australia, the Australian Safeguards and Non-proliferation Office (ASNO) is also informed of these incidents.[14] Figure 9.1 illustrates examples of the incidents that have occurred during UOC consignments.[15]

Figure 9.1: Damage to UOC shipping and packaging containers

Images courtesy of Frank Boulton, Class 7 International

Despite concerns being raised about safety during UOC transport,[16] there has never been an accident in Australia resulting in the release of UOC to an extent that has adversely affected workers, the public or the environment. Incidents do occur; however, these generally result in minor damage to the packaging without compromising its integrity.[17]

126. The transport of nuclear materials is undertaken in accordance with a mature international regulatory regime, which establishes minimum standards for transport packages, including that they are specifically designed to accommodate the physical, chemical and radiological properties of their contents.

The International Atomic Energy Agency (IAEA) has developed international regulations for the safe transport of radioactive material.[18] These transport regulations are applied to the domestic carriage of radioactive materials within IAEA member states. Further, the IAEA regulations are incorporated into rules established by different modal regulators for safe international carriage, including the International Maritime Organisation for sea transport and the International Civil Aviation Organisation in the case of air transit.[19]

Under the regulatory requirements, different types of radioactive material are to be packaged and transported according to their radioactivity level, whereby greater shielding is incorporated to address higher radioactivity.[20] Radioactivity is measured when the materials are packaged by taking readings at the surface of the package as well as 1 metre from the surface.[21]

The five types of packages according to IAEA regulations are: Excepted, Industrial, and Types A, B and C. Excepted packages are used to transport material that has such extremely low radioactivity that it does not present a hazard to people or the environment.[22] Industrial packages are also used for materials with low radioactivity, including UOC, and do not require any specific shielding to be designed into them.[23] Packages rated to Types A, B and C incorporate shielding to address highly radioactive material and, in the cases of B and C, reinforced components for accident resistance (see figure 9.2).[24]

These international standards have been incorporated into a code coordinated by the Commonwealth radiation safety regulator, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), which is applied to transport throughout Australia by state and territory regulators.[25] ASNO is responsible for reviewing and approving a security plan that is in place during a consignment.[26]

127. Shipments of used fuel are routine. They are undertaken in accordance with international requirements that address the risks associated with the heat and radiation that the fuel produces.

Used nuclear fuel is transported in Type B packages, which are comprehensively engineered products each weighing more than 100 tonnes when filled (see Figure 9.2).[27] As loaded used fuel packages emit some external radiation, their routine transportation results in very small doses of radiation to the public along the route travelled.[28] These doses are some tens to hundreds of thousand times lower than the levels of naturally occurring background radiation.[29]

The transportation packages undergo rigorous testing to ensure they retain their integrity during numerous operational conditions, thereby reducing the potential for any release of their radioactive contents during an accident.[30] The testing standards are set by the IAEA transport regulations and involve:[31]

- dropping the package on to an unyielding surface and a steel vertical bar from a height of 9 metres
- submerging the package under 15 metres of water for eight hours and 200 metres of water for no less than one hour
- subjecting the package to an all-engulfing fire at 800 degrees Celsius for 30 minutes.

Arguments have been advanced that these testing requirements are not sufficiently rigorous and the conditions a package might be exposed to in an accident are potentially more damaging.[32] The testing regime is directed towards ensuring that any given package design is capable of withstanding accident conditions that are reasonably expected to occur.[33] Further, the tests are cumulative and the same package is subjected to each exercise outlined above.[34] Demonstrations have shown that the packages are capable of withstanding actual accidents.[35]

In most accident scenarios that could occur during international shipments of used fuel, it is unlikely that an actual accident would be more severe than the tested conditions.[36] The exception is if a package were lost in deep water. In that event, it is considered unlikely that the package would fail completely, as water ingress would cause the pressure to equalise.[37] Even were a package to be lost in coastal waters and leach radioactive material into the ocean, studies have estimated that the resultant dose to the maximally exposed individual as a result of eating only contaminated seafood, would be 0.00041 millisieverts per year (mSv/a).[38]

The modal standards that apply to ships carrying used nuclear fuel are outlined in the International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code). The code incorporates ratings of INF 1, INF 2 and INF 3, where INF 1 can carry the least amount of material and INF 3 has no limit.[39] Ships meeting the INF 3 rating are specifically engineered for the transport of used nuclear fuel packages. There are at least five small INF 3 ships (1250–2200 tonnes in mass) and four larger, purpose-built INF 3 ships (3800–4900 tonnes in mass) that operate globally.[40]

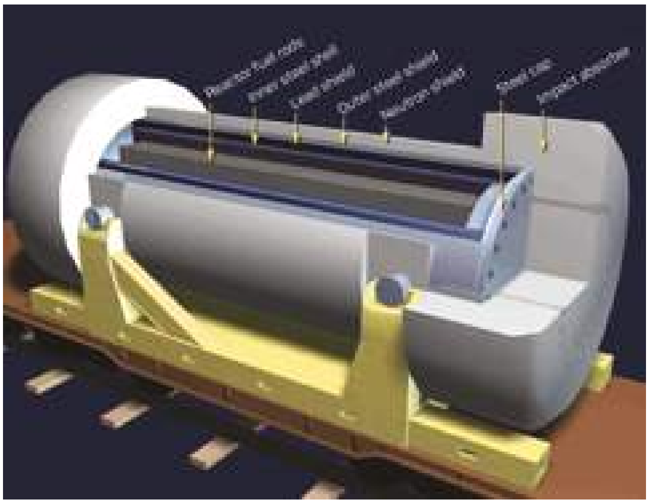

Figure 9.2: A generic Type B transportation cask on a rail bogie

Image courtesy of Nuclear Energy Institute

To be classified as INF 3, ships must meet a range of requirements concerned with safety and security, as illustrated in Figure 9.3. These standards are often exceeded with additional measures to improve a vessel's ability to withstand an accident, such as double hulls.[41] Further procedural measures also are incorporated to address security risks, such as restricting access to the cargo holds and navigating the vessel to avoid known areas of conflict. When the nuclear material being transported presents a greater security risk (such as highly enriched uranium [HEU] or plutonium), armed guards are present throughout the voyage. In any event, theft of the cargo would be extremely difficult, given its weight and the need to use a heavy crane to extract it from the holds.[42]

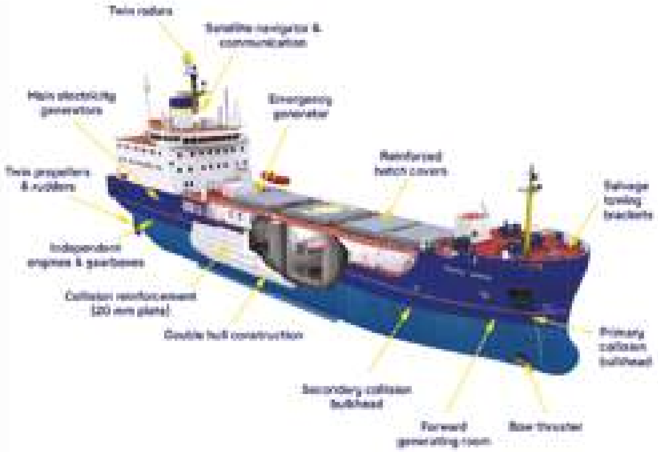

Figure 9.3: A schematic of an INF 3-rated ship, purpose-built to transport used nuclear fuel packages

Image courtesy of Pacific Nuclear Transport Limited

Bilateral arrangements are entered into so that the transport process and responsibilities of the consignor and consignee are well understood. The agreements establish handover protocols between the consignor, the operator of the vessel and the consignee to ensure security is maintained throughout the voyage.[43] Transport plans ensure that approvals are obtained for the use of the embarkation and destination ports before the voyage starts.[44] In addition, transport ships are generally designed to be able to carry their cargoes to their destination via any route without needing to stop.[45]

As a party to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, Australia is required to ensure, during any transboundary movement of used fuel or radioactive waste, that people and the environment are protected from any potential hazards presented by these materials.[46]

If facilities were to be established in South Australia for the storage and disposal of used fuel, a number of accident scenarios could conceivably take place while the spent fuel is being transported. On the basis of extensive international studies and experience in transporting used fuel, and the range of regulatory measures discussed earlier which are directed towards its safe transport, analysis has been undertaken to estimate the likelihood of a range of incidents occurring in the context of South Australian facilities. During normal transport conditions via sea, rail and road, there is a low probability that an accident would occur with the potential to damage the transport package.[47]

In the unlikely event of such an accident, studies demonstrate there is a very low probability that the package would be perforated, causing a release of radioactive material.[48] Studies also show, however, that small amounts of radioactive material could be released in the event of an exceptionally severe, and extremely low probability,[49] impact accident, causing damage to the seals between the cask lid and walls. Such a release could only occur in transport packages that contained directly loaded used fuel (that is, with no inner steel welded canister containing the used fuel rods),[50] unlike the cask depicted in Figure 9.2, which contains an inner steel shell and would likely be the preferred design for any proposed transportation in Australia. In such an event, any resultant radiation exposure to people and the environment would depend on population density proximate to the accident site at the time. If emergency response and radiation protection measures are implemented swiftly following such an accident, exposure to members of the public is likely to be limited.[51]

As it is envisaged that new dedicated port, rail and road infrastructure would need to be established to service any storage and disposal facilities, it would be possible to design and site them in a way that supports the safe transport of used fuel.[52] This would further limit the potential for any serious incidents and their radiological consequences.

REGULATORY OVERSIGHT

128. Effective regulatory oversight of nuclear activities is principally required to:

- **a. protect workers, the public and the environment from the harmful effects of radiation**
- **b. physically secure nuclear material against theft or unlawful use**
- **c. safeguard against the proliferation of nuclear weapons**
- **d. provide public confidence that the activity is properly and safely managed.**

Given that ionising radiation presents particular health and environmental hazards, it is appropriate for government to develop industry-specific policies and laws to ensure safety, including the safe handling, transport and use of radioactive materials.[53] Such laws and policies need to be designed to limit occupational and incidental human exposure to radiation to accepted safe levels, including by preventing the release of radioactive material into the environment, where it can enter the food chain. Because certain types of radioactive material have the potential to be used in the manufacture of nuclear weapons, legal restrictions on the possession, handling and sale of such material are also needed to ensure its use is solely for peaceful purposes.[54]

The extent of policies, laws and other regulatory instruments required would depend on the nature of the activities or facilities in any jurisdiction. Such laws and policies would require transparent and robust implementation and enforcement to encourage compliance by industry, and provide assurance to the general public that the potential hazards are being actively managed.[55] This includes the requirement for approval in advance of the construction and operation of nuclear facilities and transport of radioactive materials, along with ongoing compliance monitoring from an independent and trusted regulatory authority.[56]

129. The existing regulatory framework at state and federal level for the purposes of radiation protection, security and non-proliferation is appropriate for the limited scope of nuclear activities currently undertaken in South Australia.

The activities that require radiation protection measures comprise uranium mining and milling operations, centres for nuclear medicine research and treatment such as universities and hospitals, and some industrial manufacturing using sealed radioactive sources, for example, specialised bulk material analysers.[57] The development and operation of such nuclear facilities, and the associated transport of radioactive materials, are subject to federal and state laws. These Acts comprise the principal legislation at the federal level[58]:

- The *Environment Protection and Biodiversity Conservation Act 1999*, requires the federal Minister for the Environment to approve in advance certain 'nuclear actions', including uranium mining.
- The *Australian Radiation Protection and Nuclear Safety Act 1998* (ARPANS Act) establishes ARPANSA, which develops the national codes of practice for protection from the harmful effects of radiation based on international requirements and promotes their uniform application by state and territory regulators. That Act creates a regulatory regime for the licensing of the possession of certain radioactive materials, and the construction, operation and decommissioning of 'nuclear installations', by or on behalf of the Australian Government.
- The *Nuclear Non-Proliferation (Safeguards) Act 1987*, which creates a regulatory regime of permits for the possession and transport of nuclear materials, and the establishment of nuclear facilities, to ensure that appropriate measures for the safeguarding and security of nuclear materials can be put in place. This regulatory framework is based on internationally recognised standards and fulfils obligations under treaties and conventions that Australia has ratified.

At the state level, the *Radiation Protection and Control Act 1982* (SA), administered by a special team in the South Australian Environment Protection Authority (EPA),[59] applies consistently with the ARPANS Act to ensure that exposure of persons to radiation is kept to as low as reasonably achievable. A bespoke regime for radiation protection applies to uranium mining and milling activities at the Olympic Dam mine pursuant to the *Roxby Downs (Indenture Ratification) Act 1982* (SA).[60]

While the Commission has received a submission and a response to the Tentative Findings that are critical of the existing regulatory regimes,[61] there was no credible evidence to suggest these regulatory regimes were inadequate to appropriately protect workers, the public and the environment from the hazards of ionising radiation presented by the nuclear activities undertaken in South Australia.

The Commission considers that the existing requirements relating to security and non-proliferation are effective in ensuring, as far as possible, the application of Australian radioactive material for peaceful purposes only. For further discussion see Chapter 8: Non-proliferation and security.

130. Regulatory frameworks would need to be developed for new activities that are not presently undertaken in South Australia.

Existing federal and state legislation prohibits the establishment in South Australia of further processing facilities for nuclear fuel, nuclear power plants and international nuclear waste storage and disposal facilities.[62] Depending on the type of facility proposed, legislative amendment at one or both levels of government would be required before a proposal for any such facility could be progressed.[63]

Engagement in such activities would require changes to the existing regulatory frameworks to address specific hazards. In particular, it would be necessary to develop and implement a regulatory framework for the approval in advance of the design, construction and operation of any proposed facility, including the associated transport of radioactive materials.[64] This is typically done by requiring a proponent to obtain a licence from an independent expert regulator before each step.[65]

The regulator and licensing process would require sufficient legislative underpinning to ensure all aspects of the proposal were able to be tested and verified to a standard that would give the public confidence about the safety and security of the proposed facility at each stage of its development.[66]

Such arrangements would need to be in place well in advance of any licence application being contemplated to ensure the regulator is appropriately resourced to manage pre-licensing discussions with potential proponents and any resulting licensing process.[67] Sound working relationships with related government and other stakeholders (for example, customs and emergency services) would also need to be established.[68]

Core competencies of regulatory staff would include technical, organisational, communications and legal expertise.[69] The engagement of a technical support organisation to advise and assist in the initial stages should be considered where appropriate.[70]

131. Effective regulatory oversight of nuclear activities not presently undertaken in South Australia requires the regulator to be:

a. independent of both industry and the executive government

b. transparent and consistent in its decision making

c. committed to safety, and encouraging a safety culture, in all aspects of its operations

d. supported by, and welcoming of, international advice and peer review, including that provided through the International Atomic Energy Agency.

The safe and secure operation of any nuclear facilities would need to be the cornerstone of regulatory decision making.[71] To ensure this, the regulator would need to be able to make judgements and provide independent advice to government, free from political or economic pressures.[72] While regulatory staff would need to be appropriately qualified and experienced, they should not have any interest, direct or indirect, in the activities to be assessed.[73] The actual and perceived independence of the regulator would be essential to maintaining the public's trust and confidence in the regulatory process.[74]

Similarly, the respect and confidence of all stakeholders, including the public, in regulatory decision making would be increased where the regulator's processes are transparent and decisions coherent and consistent.[75] The regulator should be designed, established and operated to encourage scrutiny and informed debate with respect to its activities and decisions, from both its own ranks and external sources. The goal should be continuous improvement, particularly with respect to safety concerns.[76]

As nuclear activities including further processing, power generation and high-level waste storage and disposal would be novel to Australia, any new or expanded regulatory regime would need to draw heavily on international experience.[77] Peer reviews, including as part of the Integrated Regulatory Review Service offered by the IAEA, should be encouraged and acted on by the regulator.[78] Consideration should be given to establishing an international advisory body to provide ongoing review and advice to the regulator.[79]

In relation to high level waste storage and disposal facilities, any regulatory arrangements established would need to provide for an appropriately resourced, trusted and independent regulator. A regulator would need to be capable of assessing in detail the safety of any facility proposal put forward by a project proponent, in order to authorise further activity at particular stages of any project. The role of such a regulator would commence well in advance of any licence being sought, and would involve liaising constructively with the proponent in the development and evolution of a safety case, The role would include providing coherent and reliable information to the community as to the regulatory requirements and project progress. Once a licence was granted, the regulator would be required to monitor facility construction and operation to the level required to ensure safety.[80]

132. The types of nuclear fuel cycle activities proposed would be critical to the division of responsibility between the federal and state governments when expanding the regulatory infrastructure.

As matters of international concern, nuclear safety and security are the subjects of many treaties and international bilateral agreements, to which Australia is a party.[81] The Australian Government therefore has an ongoing role to ensure the standards set out in these international instruments are met.[82]

Were South Australia to host a new nuclear facility, the state government would also have a significant interest in ensuring that safety and security risks are properly managed.

Therefore, it is likely that both federal and state legislation and regulation would be required, as would close coordination between the two spheres of government.[83]

Irrespective of whether a new or expanded regulatory regime is established at federal or state level, or both, the ongoing presence of key regulatory staff in South Australia would be likely to assist in building and maintaining the public's trust and confidence in the regulator's processes and decisions.[84]

133. There are choices in terms of regulatory design.

Different regulatory approaches affect the requirements placed on potential proponents.[85] Outcomes-based approaches establish specific performance goals or outcomes for proponents to attain, but do not specify how they must be attained. In contrast, prescriptive approaches establish specific requirements for proponents and their activities, including proposed technical and other processes for meeting those requirements.[86] Each approach has benefits and difficulties. In practice, and consistent with IAEA requirements,[87] nuclear industry regulators around the world employ a graded range of adapted processes appropriate to the relevant activity and the nature of the associated safety or security risk.[88]

The preferred regulatory approach to creating and enforcing safety requirements would need to be determined following consultation and agreement between relevant state and federal government agencies, to ensure a coordinated approach. Irrespective of the approach chosen, it would need to be established in, or be clearly implicit from, the regulator's founding legislation. This would support consistent and coherent regulatory decision making, creating an environment in which potential proponents, the public and the international community have confidence in the process. This would be essential for any proposed new nuclear facility, both in encouraging investment and maintaining social consent.[89]

134. The regulatory structure should be flexible enough to allow advantage to be taken of credible overseas licensing processes of similar proposals or technologies.

While it is important that overarching policy, foundation legislation and a framework for the preferred regulatory approach be settled early, detailed requirements and guidance for particular activities could be developed by the regulator in parallel with any project proposal contemplating those activities.[90]

The benefit of international experience and expertise should be harnessed as far as possible. For example, relevant aspects of regulatory instruments or decisions from experienced overseas regulators could be adopted where applicable to the contemplated facilities or activities in the South Australian context.[91] The United Arab Emirates (UAE) Federal Office for Nuclear Regulation took this approach as part of the regulatory approval process for its recently established nuclear power program.[92] The UAE's experience shows this approach can be effective and efficient for some technical aspects of facility design and operation, but would have less application to site-specific considerations.[93]

It would be critical that all regulatory decision making relating to safety and security, particularly if based on analysis by overseas authorities, is justifiable and communicated to government and the public.[94]

INVESTMENT

135. There is significant appetite in the private sector investment community to support new Australian infrastructure projects.

136. Securing investment in energy market infrastructure in Australia has been challenged by significant policy uncertainty and a sustained period of falling demand.

Private sector investors consider Australia to have a strong and established infrastructure market, with significant appetite for direct investment in large infrastructure projects.[95] However, projects perceived to be politically sensitive and lacking stable bipartisan support from both federal and state governments would not be attractive to potential investors.[96]

In the absence of such support, securing investment in a nuclear infrastructure project would be challenging, given that it is perceived as being particularly risky due to technical and regulatory complexity combined with potentially long payback periods on a large initial capital outlay.[97]

Further, political and sovereign risk, as evidenced by policy changes affecting previous commitments of governments at the state and federal levels in Australia, remains a primary concern.[98] In deregulated energy markets such as Australia's National Electricity Market, the uncertainty surrounding both long-term wholesale prices and falling demand has made investment in new generation infrastructure particularly challenging.[99] Stable policy and regulatory support, including financial incentives through mechanisms such as the Australian Government's Large-scale Renewable Energy Target or the United Kingdom's Contract for Difference arrangements, have been necessary to stimulate such investment.[100]

Such incentives provide a revenue stream from a credible and accessible market.[101] Where private sector investment would be required to underpin any proposed new nuclear facility in South Australia, consideration should be given to establishing enabling regulatory mechanisms.[102] Such mechanisms should support a credible market-based pathway towards the timely repayment of reliably estimated costs, with a sufficient return.[103]

INSURANCE

137. Insurance for nuclear activities in Australia is provided under a series of specific arrangements, in the absence of a need for a comprehensive nuclear liability regime.

Activities at nuclear facilities present the risk of an accident and the potential for loss and damage to be suffered. The severity and consequence of the accident depend on the type of facility. These can range from catastrophic impacts of major nuclear power plant accidents causing significant releases of radioactive material, to minor accidents during routine transportation of radioactive material causing no harmful radiation releases, such as those discussed at Finding 125. Accordingly, appropriate insurance arrangements to cover potential accidents and their consequences vary, depending on the facility.

The activities undertaken in Australia—the mining, milling and transport of uranium oxide, and the transport of small amounts of sealed radioactive sources for medical, industrial and research purposes—have very limited potential to result in damage from the release of ionising radiation. For that reason, a statutory nuclear liability and insurance regime has not been required.[104]

A site-specific arrangement applies to ANSTO's Open Pool Australian Lightwater (OPAL) research reactor at Lucas Heights in New South Wales, in that the Australian Government has indemnified the organisation and its contractors against any claim for damage allegedly caused by ionising radiation.[105] Such an arrangement would not be appropriate for new commercial nuclear activities such as power generation, particularly where private sector entities are involved.[106]

Any new type of nuclear fuel cycle activity, such as conversion, enrichment, fuel fabrication, power generation or waste storage and disposal, undertaken in South Australia, whether by a private sector or government proponent, would require appropriate arrangements to ensure adequate cover for damage caused in the event of an accident. Before the development of any such facilities, it would be necessary to ensure the international nuclear liability conventions are implemented into a domestic statutory regime.[107]

138. An existing international regulatory framework provides guidance for compensating victims of damage from nuclear processing, power generation, and waste storage and disposal.

139. The amount of commercial insurance cover mandated by the international agreements is apparently inadequate to fully compensate victims and remediate the environment in a catastrophic scenario at a nuclear power plant, although that is not the case with respect to accidents at other nuclear facilities.

A number of longstanding international conventions govern nuclear insurance.[108] Australia has not ratified these conventions.[109] However, in the event of new nuclear activities, ratification and domestic legal implementation of one or more of these conventions would be required to comply with the IAEA recommended regime for nuclear insurance and to provide certainty for potential participants about the applicable insurance arrangements.[110]

To implement the convention principles, any domestic legislation would need to include:

a. a defined scope for the liability regime, in terms of the type of damage that is covered

b. strict and exclusive liability channelled to a designated operator

c. mandatory minimum insurance requirements for designated operators

d. exclusive jurisdiction of the courts of the state in which the incident occurred.[111]

The conventions allow for the liability of designated operators to be capped, which has been controversial as it is perceived as protecting industry to the potential detriment of the broader public. Many countries have chosen not to implement liability caps, theoretically making liability unlimited.[112] In practice, the amount that could be recovered from a designated operator would be limited by the value of its assets and insurance policies.[113] A legislated requirement that a designated operator hold a certain amount of insurance would therefore be critical to public confidence that a meaningful level of compensation would be available if required.

The appropriate minimum level of insurance cover would be a balance between the potential cost of accidents relevant to the particular nuclear activity, and the availability and cost of insurance cover to a particular level.[114]

In the event of a nuclear catastrophe such as occurred at Chernobyl in 1986 and Fukushima Daiichi in 2011, the amount of compensation required would far exceed the minimum insurance limits required under the international conventions, and indeed the amount of insurance cover likely to be available on the commercial market.[115] It is inevitable in such scenarios that the state would pay additional compensation or take responsibility for environmental remediation. Beyond a certain level, therefore, it must be accepted that the consequences of a catastrophic accident at a nuclear power plant are effectively socialised.

That is not the case for an accident at a conversion, enrichment, fuel fabrication, or waste storage and disposal facility, including during transport of radioactive materials associated with these activities. The International Expert Group on Nuclear Liability has concluded that the minimum insurance required under the conventions are likely to be adequate, even in the case of a transport accident involving high level waste.[116] Despite this, it would assist in maintaining public confidence in the management and operation of any such nuclear facilities in this state to understand that a certain amount of any profits derived were quarantined for potential compensation and remediation in the event of an accident, even if not required.

140. A commercial market for insuring nuclear fuel cycle operations is available internationally. This market can be accessed in respect of an Australian facility.

Because most commercial insurers do not cover the risk of a nuclear accident,[117] a specific nuclear insurance industry has developed, which includes a number of insurance pools that would support each other if required to pay out the full amount of cover for any particular facility.[118] It would be possible for a local facility to access insurance that is underpinned by relevant international providers in Europe, particularly the United Kingdom. The necessity to establish a domestic nuclear insurance pool would depend on the scope and scale of any potential expansion of Australia's nuclear industry.[119]

EDUCATION AND SKILLS DEVELOPMENT

141. Building up a sufficient level of local nuclear engineering expertise requires time, commitment and planning. Skills planning, such as has been incorporated into international programs to develop major nuclear projects, would be necessary to ensure an appropriately skilled workforce was available.

Careful planning years in advance of the construction of a nuclear facility would be essential to ensure an appropriately skilled local workforce is available for all stages of the project.[120] The early identification of skills gaps is central to such planning.[121] Extensive skills planning has been integral to international programs for the development of major nuclear projects, most notably for nuclear power where workforce requirements have been analysed (see Figure 9.4).[122] For example, in preparation for expanding the nuclear power program in the United Kingdom, the government established a specific group, the Nuclear Energy Skills Alliance, to closely assess current nuclear skills gaps, future skills needs, and plan for skills delivery across all sections of the nuclear workforce.[123]

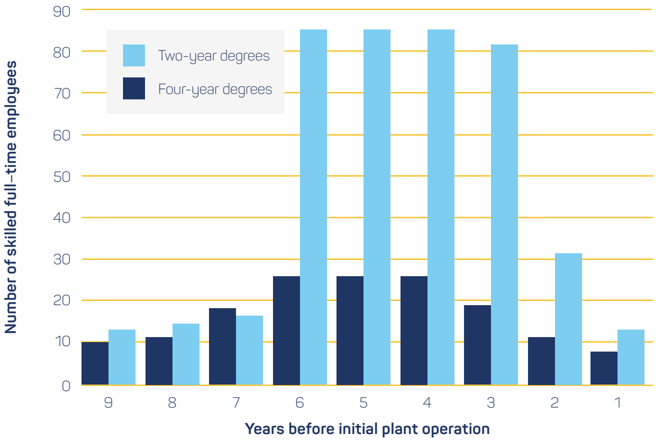

Figure 9.4: Timing of workforce employment before nuclear power plant operation

Data sourced from Nuclear Power Institute, Texas A&M University, 2014

A strong commitment to the project from state and federal governments would be critical to the higher education sector's ability to plan and develop the necessary programs and attract students to the industry.[124]

Due to Australia's limited experience in commercial nuclear activities, it may be necessary during early stages of planning to import a small proportion of specialised nuclear skills from jurisdictions with advanced nuclear industries while the local workforce develops the necessary competencies.[125] Skills planning should also take into account the time required for enhancement of local skills through practical training at overseas nuclear facilities.[126]

142. With some additional skilling, Australia's engineering and technical workforce would be a sound base for the construction of new nuclear fuel cycle facilities. Additional skilling would be necessary to meet the more exacting standards of the nuclear industry.

Australia has an established workforce with a range of skills applicable to the planning, construction and operation of large, complex industrial projects.[127] Many existing competencies are applicable to the construction of any new nuclear facilities in South Australia.[128]

Were South Australia to embark on a new nuclear development, further education and training of Australia's existing workforce would be necessary to ensure higher nuclear standards were met.[129] The installation of new nuclear facilities requires more exacting standards of safety,[130] quality and transparency than those required for large infrastructure projects in other industries, such as oil and gas.[131] Heightened attention to detail and quality is a particular imperative in the planning, construction and operation of nuclear power plants due to the specific safety risks inherent in the generation of electricity from nuclear fuel.[132]

The nature of the nuclear competencies required, and the associated extent of upskilling, would depend on the type of nuclear facility planned.[133] Some facilities similar to other advanced manufacturing and industrial processes already in Australia would require less extensive additional education in nuclear science than,[134] for example, nuclear power reactors, which require more specialised skills.[135]

The existing platform for upskilling includes trade skills such as concreting, electrical, carpentry and welding; broad engineering capabilities, particularly from within the electricity generation and oil and gas industries; and high-level project management and regulatory skills in various technologically complex and hazardous industries such as oil and gas, and aerospace.[136]

Relevant lessons on accessing and building necessary capabilities locally can be drawn from ANSTO's construction of the OPAL research reactor. That experience demonstrated that sections of Australia's existing workforce are capable of filling key roles in the construction of a nuclear reactor, and also highlighted the necessity to ensure the local workforce is trained in accordance with, and able to deliver, the highest standards of quality required for nuclear new builds.[137]

143. Australia's existing base of nuclear engineering capability would need to be enhanced should additional nuclear activities be pursued.

While technical and trade-based personnel would make up a significant proportion of the workforce during the construction phase of a nuclear project, a contingent of nuclear engineers with specialised knowledge and experience would need to be available early in the process. Such nuclear-educated professionals would serve a critical role from the outset by ensuring safety and quality of design, construction and operation, in addition to ongoing complementary research and development.[138] Australia has a relatively modest base of nuclear science and engineering expertise, primarily associated with the activities of ANSTO.[139] This base would need to be expanded and tailored to the particular facility under development through further education and training programs.[140]

The two university-level postgraduate nuclear engineering and science-based programs offered in Australia, which presently accommodate limited student numbers and are relatively broad in content,[141] could provide platforms to support the expansion of the nuclear engineering skill base.[142] There may also be scope for other Australian universities to offer further nuclear education programs, depending on demand.[143]

A partnering program with international universities that offer high quality nuclear engineering courses could augment existing Australian courses to deliver the specialised content required and ensure that local courses address contemporary international developments in the nuclear industry.[144] Such partnerships would be most beneficial when established with the overseas institutions that have leading expertise and practical experience in development and operation of the particular facility contemplated. Several Australian universities already have experience developing such international connections in nuclear education programs.[145]

Establishing educational networks or consortiums between higher education and research institutions at the national, and potentially regional or international levels, would enable high-quality specialised nuclear education to be delivered by a number of institutions coordinated under the one program. Under this model, students would have the benefit of access to a wider range of educational resources from multiple universities or institutions. The effectiveness of the network or consortium approach to address future nuclear skills needs has been demonstrated in several countries, including the United Kingdom, Canada and Belgium.[146]

Research and development capabilities would also need to be enhanced through centres of excellence to support innovation and continuous learning on topics of significance to the planned nuclear facility.[147] Australia has significant experience in, and well established frameworks for, building research and development capacity in scientific areas, particularly those which have been identified by the government as priority.[148] Such centres might also be developed through partnerships or networks abroad.

144. In planning for the development of a geological disposal facility, a proponent would need to engage early with South Australian educational institutions to address the skills required throughout the facility's lifetime. It would be important for South Australian universities, in developing local programs to provide the requisite skills, to collaborate with universities overseas that have strong research capabilities focused on used nuclear fuel management and connections with their national used fuel and high level waste disposal industries.

In light of Findings 80 to 95, were South Australia to develop a geological disposal facility for international used fuel, the proponent would need to plan early, in collaboration with South Australian educational institutions, for the specific skills required throughout the facility's life. Many of those skills, such as community engagement, project management, regulatory and legal, and safety case development, would need to be available from the outset and throughout the life of the project.[149] The project stages and associated capabilities would include:[150]

- legal and organisational aspects—skills required for community engagement, legislative changes, legal and contractual matters, and establishment of a robust regulatory regime for licensing and oversight of the facility throughout its lifetime
- site characterisation—skills in engineering, geology, hydrology, seismology and meteorology for assessing the potential long-term evolution of the site and to establish an underground rock laboratory
- design—engineering and modelling skills for the design of the packaging and disposal concept and development of the safety case for licensing; and knowledge of the behaviour of spent fuel and radiation protection
- waste acceptance—skills in engineering, chemistry and radiochemistry for setting acceptance criteria and designing and testing of packages
- construction—technical and trade skills (including in underground mining) required for site preparation and construction of the facility and associated infrastructure; and nuclear quality assurance and safety skills
- operation—skills required for transport, handling and emplacement of waste packages; maintenance; radiation protection; nuclear security; and nuclear materials accounting[151]
- closure—skills in radiation protection and monitoring for the required period and in interacting with stakeholders, including the community.

As noted, while some of these skills are available in Australia, including in South Australia[152], many of the specialised nuclear skills required for the management and disposal of used nuclear fuel, in particular with respect to the more exacting standards of nuclear safety and radiation protection, would need to be developed.

South Australia's universities could deliver the education programs through a master's-level course capable of providing the nuclear competencies required by the nuclear waste disposal industry. Existing science, technology, engineering and maths-based undergraduate courses would provide sound platforms for developing postgraduate nuclear programs.[153] Collaboration with overseas universities that supply graduates with scientific and research skills to used fuel management and disposal industries would be essential to ensure that courses delivered locally adhere to the highest international standards and latest industry developments.[154] This could facilitate placements or exchange programs to enable South Australian students to gain practical training and experience in developing and operating geological disposal facilities abroad.

IMPACTS ON OTHER SECTORS

145. There is no compelling evidence that the development of nuclear facilities in South Australia would adversely affect other economic sectors, provided those facilities are operated safely and securely.

The risks arising from the normal operation of a nuclear facility, including on other economic sectors, are low and can be managed. However, there are perceptions that any new nuclear developments would pose risks to the tourism, food and wine industries, and to property prices.[155]

South Australia's existing engagement in the nuclear fuel cycle through uranium mining and managing its low level radioactive waste has not been shown to be detrimental to other sectors. However, the Commission has received submissions warning of reputational damage to South Australia's clean, green image from further participation in nuclear activities.[156] This assertion is difficult to accept given the experiences of countries with significant activities at all stages of the nuclear fuel cycle, which have world-leading industries in tourism and agriculture, including aquaculture and viticulture, including France and the USA.[157]

The Commission considers that the state's reputation as a tourist destination and trading partner could be maintained were a new nuclear activity to be developed.

In South Australia, it is the perception of a potential impact that would need to be addressed in the course of a consent-based siting and licensing process should a development be proposed. Targeted, informative and fact-based discussions with potentially affected stakeholders would assist.

A major nuclear accident resulting in the widespread dispersal of radioactive material would have profound regional impacts. However, such catastrophic consequences are conceivable only in the event of a serious accident at a nuclear power plant. With respect to managing radioactive waste in a highly engineered and specifically designed storage and disposal facility, the risks and potential consequences of an accident are different and lower. Facility siting would also take into consideration a wide range of factors, including any potential economic and social impacts. Nevertheless, community perceptions are important. The community must fully understand the nature of the proposed activity and be provided with objective, factual information about the risks involved, in order for community perceptions to move beyond fear-based assumptions that such a facility is a 'dump'.[158]

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CHAPTER 10

RECOMMENDATIONS AND NEXT STEPS

CHAPTER 10: RECOMMENDATIONS AND NEXT STEPS

RECOMMENDATIONS

Based on the findings set out in this report, the Commission recommends that the South Australian Government:

1. pursue the simplification of state and federal mining approval requirements for radioactive ores, to deliver a single assessment and approvals process
2. further enhance the integration and public availability of pre-competitive geophysical data in South Australia
3. undertake further geophysical surveys in priority areas, where mineral prospectivity is high and available data is limited
4. commit to increased, long-term and counter-cyclical investment in programs such as the Plan for Accelerating Exploration (PACE) to encourage and support industry investment in the exploration of greenfield locations
5. ensure the full costs of decommissioning and remediation with respect to radioactive ore mining projects are secured in advance from miners through associated guarantees
6. remove at the state level, and pursue removal of at the federal level, existing prohibitions on the licensing of further processing activities, to enable commercial development of multilateral facilities as part of nuclear fuel leasing arrangements
7. promote and actively support commercialisation strategies for the increased and more efficient use of the cyclotron at the South Australian Health and Medical Research Institute (SAHMRI)
8. pursue removal at the federal level of existing prohibitions on nuclear power generation to allow it to contribute to a low-carbon electricity system, if required
9. promote and collaborate on the development of a comprehensive national energy policy that enables all technologies, including nuclear, to contribute to a reliable, low-carbon electricity network at the lowest possible system cost
10. collaborate with the Australian Government to commission expert monitoring and reporting on the commercialisation of new nuclear reactor designs that may offer economic value for nuclear power generation
11. pursue the opportunity to establish used nuclear fuel and intermediate level waste storage and disposal facilities in South Australia consistent with the process and principles outlined in Chapter 10 of this report
12. remove the legislative constraint in section 13 of the *Nuclear Waste Storage Facility (Prohibition) Act 2000* that would preclude an orderly, detailed and thorough analysis and discussion of the opportunity to establish such facilities in South Australia.

NEXT STEPS

The findings and recommendations in this report represent the beginning of a new series of deliberations that will involve conversations, conclusions and ultimately decisions for the people of South Australia, their institutions and government.

MINING, FURTHER PROCESSING AND ELECTRICITY GENERATION

The expansion of uranium **mining** in South Australia will provide additional benefits to the state. Simplifying the existing regulatory approvals process, and enhancing the further integration and public availability of geophysical data, would help to realise those benefits.

Further processing of radioactive materials would not be viable in South Australia in the next decade. However, fuel leasing based on local used fuel storage and disposal services could create a competitive advantage sufficient to support multilateral entry into some of the global further processing markets in the longer term. Existing prohibitions on the establishment and operation of further processing facilities should be removed, to allow potential fuel leasing opportunities to be explored. This would require action from the Australian Government, which the state government should pursue.

The Commission has found that commercial **electricity generation** from nuclear fuels is not viable in South Australia under current market rules. However, it has found that nuclear energy has the potential to contribute to national emissions abatement after 2030. Given the need for significant decarbonisation of our electricity sector to meet future emissions reduction goals, the Commission has recommended the development of a comprehensive national energy policy, which enables all technologies, including nuclear, to contribute to a reliable, low-carbon electricity network at the lowest possible system cost.

MANAGEMENT, STORAGE AND DISPOSAL OF WASTE

The Commission's findings with respect to radioactive **waste storage and disposal** identify a substantial economic opportunity. If it is to be pursued, it calls for immediate action.

The Commission's key findings are that the disposal of used fuel and intermediate level waste (ILW) could be undertaken safely in a permanent geological disposal facility in South Australia. This would have the potential to deliver significant inter-generational economic benefits to the community. The key recommendation in this regard is that the South Australian Government pursue the opportunity to establish used nuclear fuel and ILW storage and disposal facilities in South Australia consistent with the processes and principles outlined in this chapter.

The Commission appreciates that this is a complex task. It has learned of many failed attempts internationally to progress domestic used fuel disposal projects. The Commission has therefore outlined the steps it considers would need to be taken, both immediately and in the future, should the state government accept its recommendations.

The most important next step would be to engage with the South Australian community to establish whether it wants the government to develop a firm proposal for the storage and disposal of used fuel and ILW. Some South Australians will already have strong opposing or supportive views, which need to be respected. However, many others would require more information before they were able to form a view. This would involve a balanced discussion and debate, based on the understood facts with respect to risks and opportunities.

In setting out the following processes and principles, the Commission recognises, based on experiences overseas, that adaptability of the process is crucial. The importance of allowing the views of the affected community to be heard, to influence and to be reflected in any process cannot be overstated. The next steps are not prescriptions, but principled guidance that the Commission considers would be required at a minimum for progress to be made.

The immediate steps are for the state government to:

1. make public the Commission's report in full as soon as possible
2. define a concept, in broad terms, for the storage and disposal of international used fuel and ILW in South Australia, on which the views of the South Australian community be sought
3. establish a dedicated agency, overseen by an advisory board, to undertake community engagement to assess whether there is social consent to proceed
4. in addition, task that agency to
   a. prepare a draft framework for the further development of the concept, including initial siting criteria
   b. seek the support and cooperation of the Australian Government
   c. determine whether and on what basis potential client nations would be willing to commit to participation.

The future steps, assuming the immediate steps lead the state government to proceed further, are for the government to:

1. pass legislation to facilitate and regulate the development of international used fuel and ILW storage and disposal facilities in South Australia
2. support the community development of a detailed project proposal, including a consent-based process for facility siting.

Each of these steps is discussed in more detail below.

APPLICATION OF THE NUCLEAR WASTE STORAGE FACILITY (PROHIBITION) ACT 2000

The *Nuclear Waste Storage Facility (Prohibition) Act 2000* contains, in section 13, a broadly worded prohibition on the expending of public money 'for the purpose of encouraging or financing any activity associated with the construction or operation of a nuclear waste storage facility' in South Australia.

Amendments recently made to section 13 introduce an exception that allows the use of public money 'for the purpose of encouraging or financing community consultation or debate on the desirability or otherwise of constructing or operating a nuclear waste storage facility' in South Australia.

That exception does not become law unless a recommendation is made by the Commission to conduct public consultation. In recommending the government pursue the opportunity to establish a disposal facility through a process of public consultation, it is anticipated that the exception will apply.

The Commission considers that the immediate steps outlined in this chapter are connected to fostering effective and informed community consultation and debate. In following the Commission's recommendations, the government may at some point be accused of acting beyond the exception. The government quite properly may want to seek further information or greater detail about matters considered by the Commission in order to satisfy itself. It may also want to seek information in anticipation of a community request. It should not have to answer a legal question on each occasion as to whether its activity is 'for the purpose of community consultation or debate' or whether it otherwise falls outside section 13.

It would be preferable for the immediate steps to be undertaken free from any debate about whether expenditure of public money is lawful, through the repeal of section 13.

The prohibitions on the construction or operation of a nuclear waste storage facility (section 8) and on the importation of nuclear waste (section 9) would remain in force while the proposed immediate steps are undertaken.

IMMEDIATE STEPS

1. Make public the Commission's report in full as soon as possible

Many people in the community will be interested in and seeking information on the Commission's findings. There is a vast array of information and misinformation available publicly on matters relevant to its Terms of Reference.

The report of the Commission is intended to make a significant contribution to this body of knowledge from a broad range of reputable and reliable sources, including the integration and analysis of evidence specific to South Australia. It is also important that it be made public in its entirety as part of a continued commitment to transparency in decision-making. Such action would be critical for maintaining respectful community engagement based on the ready exchange of information.

2. Define a concept, in broad terms, for the storage and disposal of international used fuel and ILW in South Australia, on which the views of the South Australian community be sought

Following the submission of this report, it is for the government to decide whether and what further action it would want to take.

If it determines to proceed, the government would need to be clear with the community on what is proposed for any engagement to be meaningful, focused and substantive. It would allow the community to ask and have answered, in broad terms, questions about risks and opportunities.

Defining the concept does not mean there is a need to design or site any facility. Examples of the type of facilities and arrangements to allow the activity to be properly understood would be sufficient. For example, the concept could be based on, or draw elements from, the integrated storage and disposal facility addressed in Chapter 5: Management, storage and disposal of nuclear and radioactive waste.

In releasing the concept for further investigation and discussion, the government must explain its intent in seeking social consent. It should be prepared to provide information about the concept and its plans. It can explain its views of the systems and processes that it would establish in the event it had public support. It should also be prepared to correct misinformation about any of those matters. This does not mean the government would need to commit to developing a storage and disposal facility. The point of the release of a concept is to stimulate and facilitate discussion on that concept, which in turn could be changed by the ensuing deliberations.

3. Establish a dedicated agency overseen by an advisory board to undertake community engagement to assess whether there is social consent to proceed.

As the community engagement process to assess whether such social consent exists would be complex, it would benefit from being led by an independent advisory board, supported by a dedicated, multi-disciplinary agency.

The advisory board would set the strategic direction of the activities to be undertaken. Its independence would be critical if the process and outcomes were to withstand multiple election cycles. The board should be comprised of independent, trusted South Australian community leaders who, given the long-term nature of any development, must be (and be perceived to be) balanced and non-partisan. Its members also should have experience and skill in direct engagement with South Australia's diverse community. The board would need to maintain a culture of transparency and uphold the highest order of careful, measured and ethical conduct.

It would need to be supported by a dedicated agency of experts and administrators from relevant fields of nuclear safety, public health (particularly radiation), engineering, law, environmental science, commerce and economics, and community engagement. Not all of this technical expertise would be required on a full-time basis, and the composition of the agency would need to evolve over time. It would be assisted by the transfer of research information and knowledge from the Commission on technical, social and economic matters. The continuing focus of both the board and agency would be on the public communication of complex issues.

Task and functions

The primary task of the board and agency would be to conduct the process concerned with social consent.

The issue to be considered in the process of community engagement is whether used fuel storage and disposal should be engaged in and, if so, the principles that should govern its future development. The question for consideration is not, as the Commission has sometimes heard, whether the state should instead pursue this or a different economic opportunity. On the basis outlined in this report, used fuel storage and disposal would be economically self-sustaining. It does not present a choice between mutually exclusive options. In fact, the Commission's view is that the proceeds from the activity could support investment in other economic, social and environmental areas.

Assessing social consent should not be viewed in terms of shaping ideas or influencing opinion. The significant challenge exists in establishing the facts in relation to the concept, to the extent that the community and its government are able to make an informed judgement. This challenge arises due to:

- the extent to which people have the time needed to learn about and carefully consider such matters
- the need to build trust and confidence in the provision of information
- the existence of misconceptions, fuelled by misinformation, that influence public understanding and awareness.

Taking the above into account, the dedicated agency should assess the level and sustainability of social consent to proceed by undertaking the following approach.

Task 1: Prepare and publicise a framework that defines the objectives of the assessment process, and how these are proposed to be achieved. This would ensure that the process and purpose of community engagement are understood, and remain consistent.

Task 2: Undertake public engagement by providing information, establishing facts, addressing misinformation and narrowing the scope of discussion to relevant issues. The aim is to facilitate a process of learning for all South Australians, including government, rather than conduct an exercise in advocacy and promotion. This would not prevent it from publicly countering misinformation by challenging those who make unsupported claims.

In later stages, with the facts established, it would be appropriate for representatives of government and other community interests to take more active and public positions either for or against a specific proposition.

Based on the principles discussed in Chapter 6: Social and community consent, public engagement must be:

- face-to-face as far as practicable, with tangible examples or demonstration of concepts
- socially and geographically inclusive. Specific approaches would need to be developed to ensure the engagement of regional, remote and Aboriginal communities. This should occur as early as possible
- transparent, in that each individual's and organisation's involvement or contribution from the start of the engagement process is acknowledged, recorded and, where relevant, responded to
- factual, based on information from appropriately skilled and qualified people

- adaptable. As new and pertinent information is received, it must be incorporated into the community engagement process.

Task 3: Seek feedback from South Australians as to whether, based on the information provided, they would support the government in developing a firm proposal for the storage and disposal of international used fuel and ILW in this state. This step would be likely to evolve from the later stages of Task 2.

As the public engagement process progressed, and the community's and government's understanding and awareness of the risks and opportunities improved (including by incorporation of feedback from the parallel activities contemplated below), issues and principles of importance to South Australians would emerge.

There should be no arbitrary timeframe for the conclusion of the engagement process, although it is feasible that the balance of informed public opinion could start to become clear after six to 18 months of engagement. Given the activity would represent an economic opportunity that South Australia could accept or reject, the process would not need to be unnecessarily prolonged once the balance of opinion appeared clear and likely to be sustained.

4. Further task the dedicated agency to, concurrently:

- **a. prepare a draft framework for the further development of the concept, including initial siting criteria**
- **b. seek the support and cooperation of the Australian Government**
- **c. determine whether and on what basis potential client nations would be willing to commit to participation.**

These activities, further outlined below, would in due course inform the social consent process.

In order to proceed, both the government and the public must understand the nature of the potential infrastructure proposed, the potential scope of operations, and the potential scale of risks and benefits. The government and South Australians would also want to understand how a location for any facilities may be determined, whether the federal government would support and facilitate any proposal, and what may need to occur to obtain greater certainty of commercial viability. This would require further analysis. The activities must be concurrent because their development would be mutually informed. For example, the position of client nations would be informed by the position of the Australian Government; similarly, the position of the Australian Government would likely be informed by the framework for further development and the views of potential client countries. The results of the analysis and other information associated with the three concurrent strands of activity would need to be presented to the community.

a. Prepare a draft framework for the further development of the concept, including initial siting criteria

Social consent needs to be informed by an understanding of the principles and processes that would apply to ensure the safe implementation of a proposal, including initial siting criteria.

Determining the location of any proposed facilities would be a complex and potentially lengthy process, requiring detailed social and technical analysis and community consent. It would not be possible to undertake and conclude that process before broad social consent is achieved. However, it is possible in advance to be clear about the process and principles under which that process would be undertaken.

A draft framework for the further development of the concept, including initial siting criteria, should be prepared and released for comment. It would specify the geoscientific factors that need to be considered to ensure the safety of a geological repository. The initial siting criteria would specify factors in general terms that would be relevant to identifying in a preliminary way a suitable site for a geological disposal facility.

The framework would explain how those factors would be applied as part of a future process for seeking community consent for hosting the facilities contemplated in the proposal, along with a proposed process for undertaking more detailed site investigations.

The preparation of a draft implementation framework for further public discussion needs to be clearly distinguished from a process to seek consent to construct facilities at particular sites.

Such a framework, including initial siting criteria, have been developed in other countries that are seeking to progress domestic geological disposal facilities, including Canada[1], the United Kingdom[2] and the United States.[3] Siting criteria may include a location that:

a. has sufficient land area to accommodate the facilities

b. is outside protected or sensitive environments or places

c. at the depth of the facility, does not contain known groundwater resources suitable for drinking, agriculture or industrial uses

d. does not contain economically exploitable natural resources

e. is not in areas with known seismic, geological and hydrogeological characteristics that would prevent the site from being safe, given the safety factors for a facility

This list is not intended to be exhaustive. The international approaches would provide a useful basis for developing criteria applicable to the South Australian context for consideration and discussion with the community.

b. Seek the support and cooperation of the Australian Government

The continued assistance of the Australian Government in a number of areas would be necessary to further explore the feasibility of international used fuel storage and disposal in South Australia. That assistance would be an extension of the facilitation and assistance the federal government has already provided to the Commission. It would be critical in sustaining an environment in the South Australian community where risks and benefits can be freely and fully discussed.

Given the Australian Government's international responsibilities with respect to non-proliferation, nuclear safety and nuclear security, such support would also be important to both Australian citizens and the international community. Federal assistance and support would be required to facilitate discussions between the South Australian Government and relevant nations and international organisations, including the International Atomic Energy Agency.

In addition, the public engagement process in South Australia would need to include information about the potential nature and form of regulatory arrangements for any proposed facilities. Some preliminary analysis is necessary on potential options for regulatory regime design, including consideration of safety regulation, environmental protection, transport safety and security, customs requirements, non-proliferation assurance and taxation implications. This would traverse both state and federal jurisdiction, and require active participation from and cooperation between authorities at both levels of government.

This support and commitment must be long term and sufficient to endure leadership changes and election cycles.

c. Determine whether and on what basis potential client nations would be willing to commit to participation.

A preliminary indication should be sought from potential client countries as to their interest in further discussions on their potential participation, along with identification of what they would require to be able to make a firm commitment.

The Commission has assessed the potential participation of client nations based on known and future inventories of used fuel and, in the absence of a market, on available proxies of potential willingness to pay. In the absence of either a firm proposal or social consent, the Commission could not expect countries to indicate their commitment. Nonetheless, during its visits the Commission was informed that countries would be interested in further discussions on this issue.

To provide the South Australian community with more detailed information regarding economic viability and potential benefits, it is necessary to determine with more confidence whether potential client nations would be willing to use an international used fuel storage and disposal facility in South Australia. In doing so, it would be necessary to identify what will be important to such client nations before making an initial commitment.

What is needed at this point is an expression of interest in more detailed discussion. No party can or should be asked to make a commitment at this initial stage. The development of trust and openness is critical to the ongoing relationship that must be established with potential client nations. To the greatest extent possible within diplomatic constraints, formal expressions of interest should be able to be made available to the South Australian community, to inform the public engagement process.

FUTURE STEPS

If, following the activities contemplated above, the South Australian Government determines there is sufficient social consent to proceed further, the following future steps are likely to be required.

1. Introduce legislation to facilitate and regulate the development of international used fuel and ILW storage and disposal facilities in South Australia

The ultimate authority for the activity would come in the form of the approval by the South Australian Parliament of facilitative legislation. Such legislation would need to remain in place without substantive amendment beyond electoral cycles in order to provide the necessary certainty and stability for the safe and efficient development of viable international used fuel storage and disposal facilities in this state.

A significant first step would be the establishment of an independent, government-owned statutory authority to initially develop, and potentially implement, a proposal for an international used fuel storage and disposal facility. The powers and functions, constitution, decision-making process and oversight of the authority would need to be made clear. Consideration should be given to the establishment of an expert board to oversee and provide strategic direction to the authority.

Legislation also would be required with provisions that:

- repeal existing prohibitions to the activity being undertaken, or other provisions that inhibit both a proposal being developed
- identify the principles necessary to guide the development of a proposal, which ought reflect the results of the public engagement process undertaken as part of assessing social consent
- establish initial frameworks for regulation of the development and implementation of a proposal, without addressing the detail of regulation necessary for later stages of any project. This would reflect the results of the joint Commonwealth–State cooperative analysis contemplated above
- identify the principles applicable to the protection and future use of any profits received from the operation of those facilities through, for example, a State Wealth Fund. While any profits would not be realised for many years, the establishment of guiding principles within legislation would be likely to assist in maintaining public support for the project.

2. Support the community development of a detailed project proposal, including a consent-based process for facility siting:

a. The authority should seek to identify communities with an interest in learning more about hosting a facility

b. The authority would continue to visit interested communities to provide further information

c. Interested communities should organise their desired decision-making framework

d. The authority and a community may commence negotiations

The development of a proposal would require significant and detailed geological, engineering, commercial, legal, and regulatory analysis, as with any large infrastructure project. However, based on international experience, the area of most complexity is likely to be identifying appropriate sites for the facilities and their associated infrastructure. This aspect differentiates the development of projects related to the storage and disposal of nuclear waste from other infrastructure projects, and is therefore addressed in some detail here.

Interested groups within communities must be able to seek information related to hosting a facility, without any obligation or commitment to proceed, and at an agreed pace. The authority must be suitably resourced and prepared to engage with communities at this pace, including if a community wants to proceed quickly. Given the diversity of South Australian communities and their specific circumstances, the community consent process must evolve over time for each community. Although thresholds for continued investment can be developed, the process should be undertaken without the imposition of arbitrary timeframes or fixed criteria.

An appropriate community consent process would be influenced by the outcome of the proposed immediate steps outlined previously. It is therefore inappropriate to attempt at this point to suggest a precise course of action. However, based on the findings and discussion in Chapter 6: Social and community consent, the following steps might be contemplated and modified in the particular circumstances.

a. The authority should seek to identify communities with an interest in learning more about hosting a facility

The authority should initially provide information (including through public meetings) to all South Australian regions on the siting and community consent process. In doing so, the authority may also meet with local organisations or individuals with an interest in learning more. Consideration should be given to establishing a visitor centre in a central location to allow interested members of the public to access information and ask questions.

Engagement at this early stage should focus on information associated with the process that would be undertaken to determine community consent, and key considerations for the siting of infrastructure (including generic or, if appropriate, host-rock-specific siting criteria), approaches to management of risks and principles for community benefits.

In addition to being provided with information on the community consent process, communities would be invited to consider whether they wanted to learn more about hosting a facility. There should be no criteria for accepting such an invitation: one or more individuals or organisations in a community could ask to learn more. Such a request would not be binding on any community, and would not take the form of any prescriptive registration of interest or nomination.

b. The authority would continue to visit interested communities to provide further information

The authority would commence a longer-term engagement with all those people or organisations interested in learning more about hosting a facility, taking into account the principles discussed in Chapter 6. The way in which this information would be provided could be determined in consultation with the individuals or organisations, which could involve a meeting with one or more individuals or organisations at one time. These may be requested in the context of an existing organisation's business or operations, and as such not be public meetings. This may apply similarly to individuals.

Taking this into account, all materials and information provided during this stage must also be made publicly available on a readily accessible platform (website or similar) to maintain transparency of this process.

At this time, it would be appropriate to undertake a preliminary assessment of site suitability. This would assess the location against the initial siting criteria, and therefore indicate whether it might proceed to be assessed in more detail. Such action should only be undertaken in close consultation with all local community interests engaged in the process.

c. Interested communities should organise their desired decision-making framework

In time, a community may want to start planning how it could organise itself to begin the process of considering consent, and how a proposed project might apply to their specific circumstances. A community would need to consider not only risks and opportunities associated with hosting a nuclear facility, but also how it might make decisions in relation to these. No arbitrary criteria or limitations should be placed on communities in their contemplation of how they might organise themselves to begin a process of discussing consent.

These processes are critically important, involve complex considerations, and must evolve over time. It is also possible that some communities may have trusted and functional pre-existing structures that allow these processes to proceed more quickly. While some elements can only be undertaken by that community, there is a role for the statutory authority to understand the nature and progress of such discussions. It is possible that elements of this process may require resources and other support, for example, assistance with hiring venues to host community discussions or the provision of skilled facilitators to help resolve difficult matters. The authority would be responsible for providing this support, on the basis there was some level of support in that community to take these next steps.

d. The authority and a community may commence negotiations

A community may reach a point where it is sufficiently organised and informed that it wants to commence more formal negotiations regarding the siting of infrastructure and associated matters of risk management and benefit. This would include, as a start, allowing the authority to undertake more detailed technical investigations of a particular site to better understand whether it has the geological, hydrogeological, chemical and mechanical characteristics necessary to ensure safety.

It is important that the authority does not start negotiating until communities are ready to do so. While there are varied and complex matters of risk and potential opportunities associated with a project to consider, there are equally important and complex considerations related to how a particular community is represented, how information is provided and disseminated, who from the community makes decisions, and how decisions are made.

However, neither should the process be unnecessarily prolonged. The establishment of a nuclear waste storage facility is a matter of choice for a community. To this end, it is reasonable for the authority to determine thresholds for continued investment. These thresholds should be explained to the community.

It would be an important first step for both parties (the authority and the community, through their nominated representatives) to agree on principles for the negotiation process. This would include fundamental aspects of how meetings would be conducted and outcomes recorded and disseminated, but would also consider potential options for mediation should negotiations stall, the basis on which the community representatives are authorised to negotiate and make decisions, and how the final agreement, if reached, would be recorded and enacted.

At the appropriate time, a package of benefits would need to be negotiated with a potential host community in exchange for hosting a site. From the outset it should be acknowledged that there would be a substantial package of community benefits. These negotiations must incorporate the ability for a community to influence how the project is developed, to take account of local knowledge, needs, circumstances and aspirations.

A community deciding to undertake such a negotiation would need to be suitably resourced to do so. This support could include coordination and administration, independent scientific advice to assess matters related to siting and associated project risks and management, advice related to developing an appropriate package of benefits, and assistance in disseminating information in the community. Such resourcing is potentially significant. Before providing resources, the authority would need to be satisfied that there is a suitable commitment to consider hosting a facility, and a level of genuine local community support.

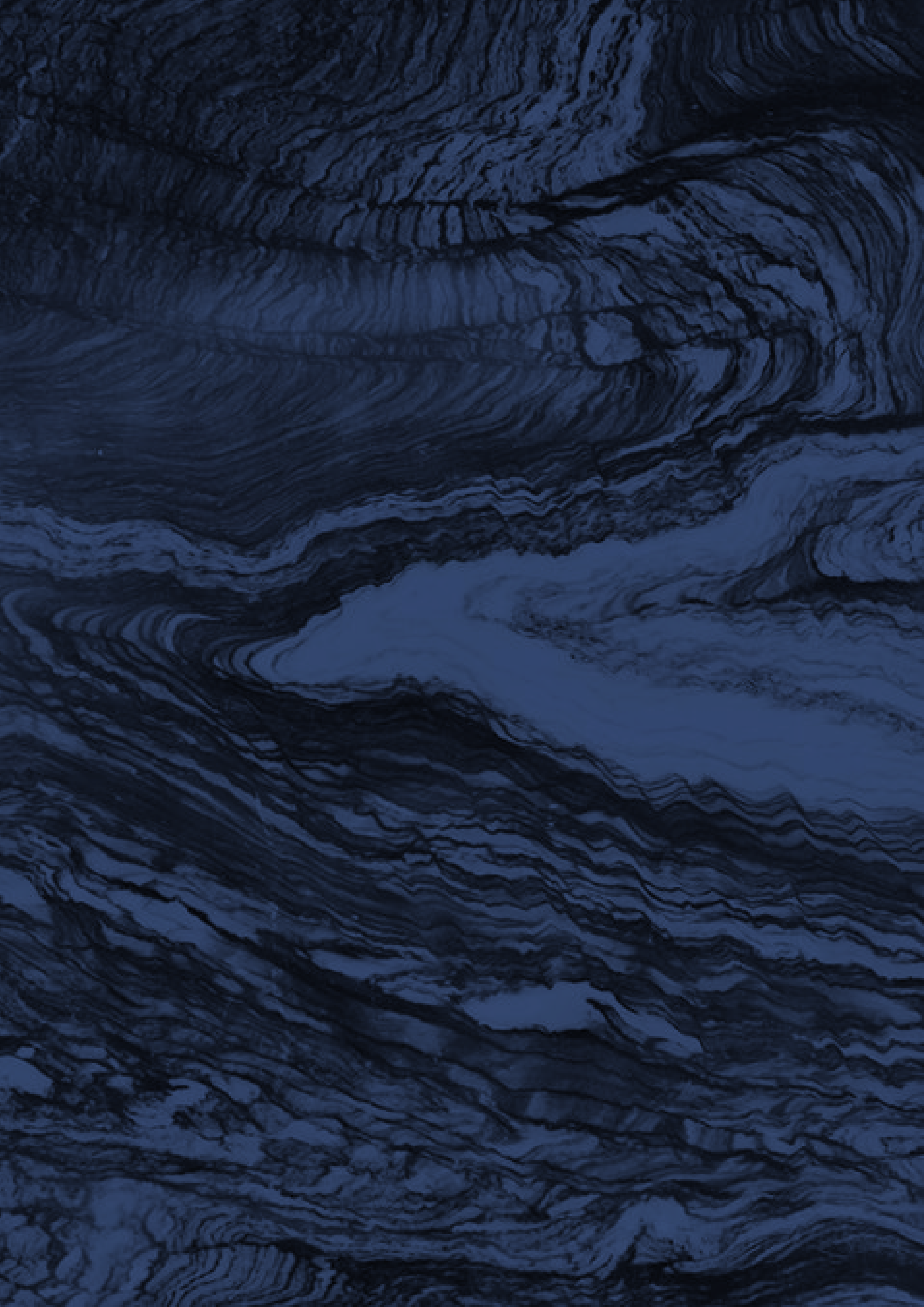
It is possible that the authority might, in time, be negotiating with more than one community and be at different stages of negotiations with each as it does so. It is also possible that the negotiation process would not identify a location with appropriate geotechnical characteristics or a local community willing to host the proposed infrastructure. This must be understood and acknowledged by all parties throughout the process.

CONCLUSION

Unlike nations with domestic nuclear power industries, Australia need not find a solution for the safe, long-term management of used nuclear fuel. Australia has no immediate or future domestic requirement for used fuel storage and disposal facilities. The immediate issue facing South Australians is whether, on balance, it considers the potential opportunities to be of sufficient benefit, and the potential risks to be manageable, so as to support the further and more serious investigation of the commercial development of such a project in this state. The Commission's firm conclusion is that this opportunity should be actively pursued, and as soon as possible.

NOTES

1. National Waste Management Organization, *Moving forward together: Process for selecting a site for Canada's deep geological repository for used nuclear fuel*, NWMO, May 2010, https://www.nwmo.ca/
2. Department for Environment, Food and Rural Affairs et al. (Defra), *Managing radioactive waste safely: A framework for implementing geological disposal*, A White Paper by Defra, BERR and the devolved administrators for Wales and Northern Ireland, Defra, June 2008.
3. US Department of Energy (DoE), *General guidelines for the preliminary screening of potential sites for a nuclear waste repository*, 10 Code of Federal Regulations Part 960, 2003.



APPENDICES

APPENDIX A: TERMS OF REFERENCE

The Commission is to inquire into and report upon the following matters:

EXPLORATION, EXTRACTION AND MILLING

1. The feasibility of expanding the current level of exploration, extraction and milling of minerals containing radioactive materials in South Australia, the circumstances necessary for such an increase to occur and to be viable, the risks and opportunities created by expanding the level of exploration, extraction and milling, and the measures that might be required to facilitate and regulate that increase in activity.

FURTHER PROCESSING AND MANUFACTURE

2. The feasibility of further processing minerals, and processing and manufacturing materials containing radioactive and nuclear substances (but not for, or from, military uses), including conversion, enrichment, fabrication or re-processing in South Australia, the circumstances necessary for processing or manufacture to be viable, the risks and opportunities associated with establishing and undertaking that processing or manufacture, and the measures that might be required to facilitate and regulate the establishment and carrying out of processing or manufacture.

ELECTRICITY GENERATION

3. The feasibility of establishing and operating facilities to generate electricity from nuclear fuels in South Australia, the circumstances necessary for that to occur and to be viable, the relative advantages and disadvantages of generating electricity from nuclear fuels as opposed to other sources (including greenhouse gas emissions), the risks and opportunities associated with that activity (including its impact on renewable sources and the electricity market), and the measures that might be required to facilitate and regulate their establishment and operation.

MANAGEMENT, STORAGE AND DISPOSAL OF WASTE

4. The feasibility of establishing facilities in South Australia for the management, storage and disposal of nuclear and radioactive waste from the use of nuclear and radioactive materials in power generation, industry, research and medicine (but not from military uses), the circumstances necessary for those facilities to be established and to be viable, the risks and opportunities associated with establishing and operating those facilities, and the measures that might be required to facilitate and regulate their establishment and operation.

In inquiring into the risks and opportunities associated with the above activities, consideration should be given, as appropriate, to their future impact upon the South Australian:

a. economy (including the potential for the development of related sectors and adverse impact on other sectors);

b. environment (including considering lessons learned from past South Australian extraction, milling and processing practices); and

c. community (incorporating regional, remote and Aboriginal communities) including potential impacts on health and safety.

APPENDIX B: THE COMMISSION

INTRODUCTION

The Nuclear Fuel Cycle Royal Commission was established by the South Australian Government on 19 March 2015 to undertake an independent and comprehensive investigation into the potential for increasing South Australia's participation in the nuclear fuel cycle. It was required to report to the Governor of South Australia by 6 May 2016.

The Commission's task was to prepare a considered report to government to inform future decision making.

The Commission determined that its process would be:

- evidence-based—meaning that it was concerned with facts and identifying the basis for claims made, rather than seeking views
- open and transparent—enabling interested parties to provide evidence, watch evidence being given, consider and comment on the Commission's tentative findings, and scrutinise the basis for its findings
- independent—forming its views independent of government, industry and lobby groups.

EVIDENCE-BASED

The Commission collected evidence from four sources: written submissions, oral evidence in public sessions, its own research including overseas site visits, and commissioned studies. It carefully considered the reliability and credibility of the evidence it received, and was particularly concerned to understand the basis for many claims made in relation to the issues it considered. This report identifies the evidence the Commission considered to be the most cogent from reliable and credible sources.

Although the Commission considered all the evidence it received, it has not addressed in this report every issue raised in the evidence. Nor has it identified where it has expressly accepted or rejected evidence.

WRITTEN SUBMISSIONS ON OATH

In May 2015, the Commission released four issues papers (focused on exploration and mining, further processing, electricity generation, and storage and disposal of waste), which provided background information related to its Terms of Reference, and invited interested persons to respond to questions. People and organisations were given three months to make written submissions on oath as evidence for the Commission to consider.

The Commission received more than 250 submissions from the community, organisations, industry and government.

Anyone who contacted the Commission seeking help to comply with its process was assisted. At the outset the Commission made public that it would, by arrangement, receive submissions by other means. As a result, it took several oral submissions.

ORAL EVIDENCE IN PUBLIC SESSIONS

The Commission held a series of public sessions from September to December 2015, and in April 2016, on topics of interest to it. In those sessions it received oral evidence on oath from persons with relevant experience and expertise.

The public sessions were conducted informally, with a view to encouraging discussion with witnesses on central topics to draw out information of particular relevance. Witnesses gave evidence to the Commissioner on the basis of questions from Counsel Assisting. Most public sessions were conducted in the Commission's session room in Adelaide, and all sessions were streamed live on the Commission's website. Transcripts and videos were later made available to be downloaded from the website.

Over 37 sitting days, the Commission heard from 132 witnesses from Australia and overseas, including from Belgium, Canada, Finland, Germany, South Korea, Spain, Switzerland, the United Kingdom and the United States of America.

COMMISSION RESEARCH, INCLUDING VISITS TO FACILITIES OVERSEAS AND IN AUSTRALIA

The Commission spoke to representatives from governments, regulators, industry proponents and opponents during visits to Austria, Belgium, Canada, Finland, France, Japan, South Korea, Switzerland, Taiwan, the United Arab Emirates, the United Kingdom and the United States (see Figure B.1). A significant part of the visit to Japan was to the Fukushima district and the Fukushima Daiichi plant to witness firsthand the devastation of the 2011 tsunami and nuclear accident.

COMMISSIONED STUDIES

The Commission engaged organisations with expertise to undertake detailed assessments of the potential commercial viability of establishing nuclear facilities in South Australia to undertake further processing, to generate electricity, and to store and dispose of used fuel and nuclear waste. It also sought an analysis that considered the wider economic effects of investments made in developing those facilities.

It commissioned expert assessments in relation to fuel leasing, the risks of transporting used fuel, how safety cases are undertaken for geological disposal facilities, and skills requirements for the development of nuclear facilities.

The views expressed in these reports are the professional views of the organisations and individuals that prepared them. As such, the Commission treated these reports in the same way as evidence—and the extent to which they have been accepted and relied on is identified in the findings and the reasoning in support of those findings.

OPEN AND TRANSPARENT

The Commission conducted its process with the objective of engaging all South Australians, to encourage feedback, scrutiny and informed debate on the facts and the evidence.

Throughout the process, it published on its website the written submissions it received, information about its international visits, the oral evidence and transcripts, and its tentative findings. It provided information about its key staff and advisors, and disclosed any of their relevant interests.

The Commission held two series of metropolitan and regional information sessions around South Australia, first to inform the public about the role and scope of the Commission's inquiry and the submissions process, and subsequently to explain its tentative findings and invite responses. A wide range of community information sessions were held in metropolitan and regional areas throughout the state (see Figure B.2).

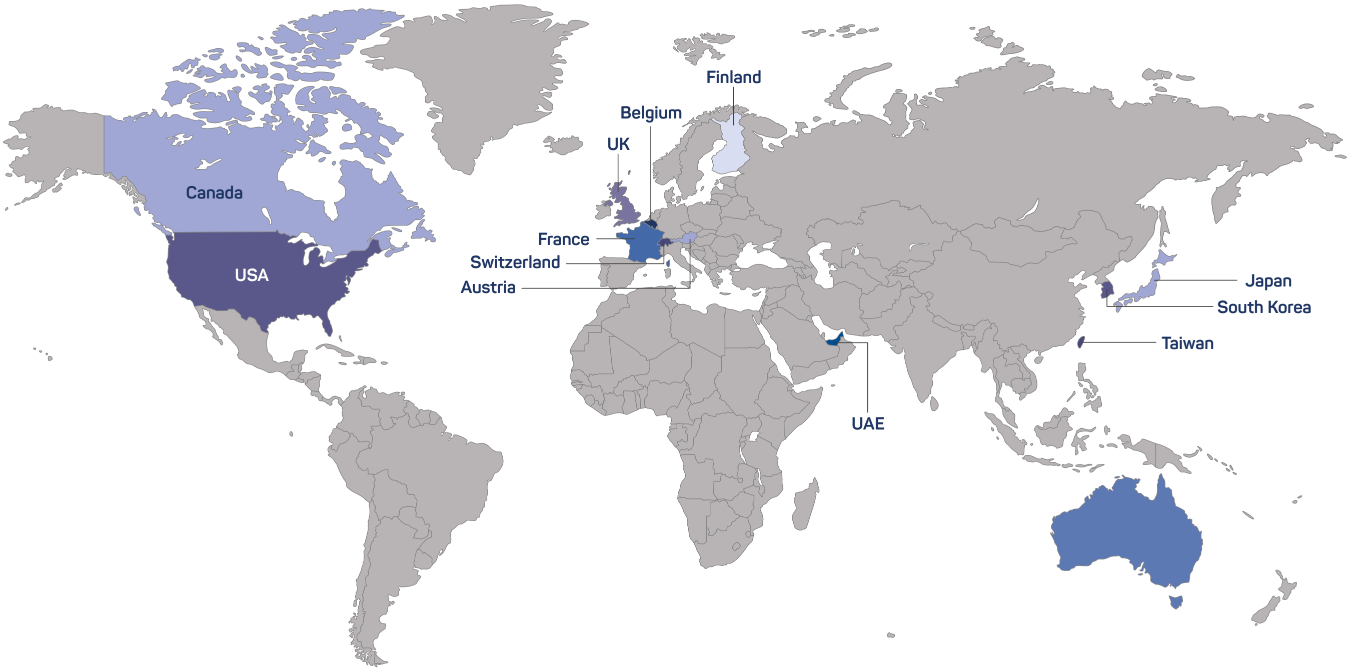


Figure B.1: Countries visited by the Commission

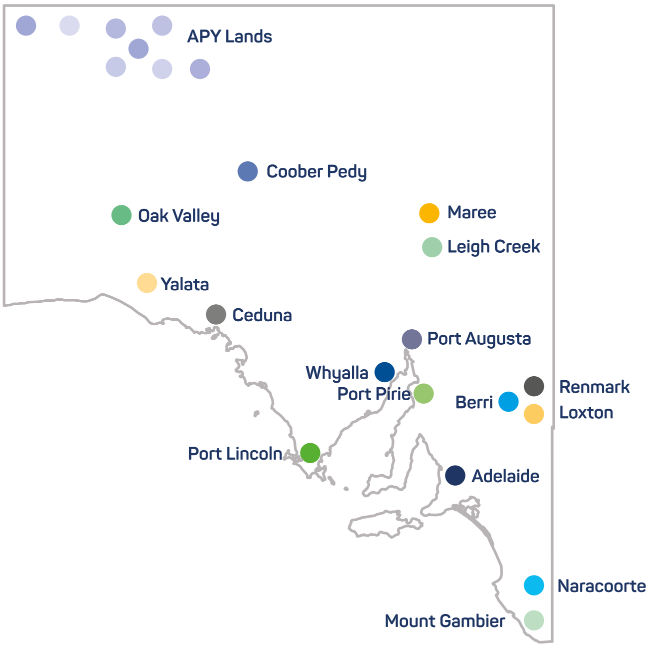


Figure B.2: South Australian locations visited by the Commission

The release of the Tentative Findings on 15 February 2016 shared with the community the Commission's preliminary thinking on issues it considered important, based on evidence. The Commission sought scrutiny by inviting public responses within five weeks. It received more than 170 direct responses. The Commission read all responses and they informed the structure and range of issues addressed in the final report.

The Commission engaged regularly with Aboriginal communities, including through public information sessions. It financially supported the convening of two meetings of the South Australian Native Title Congress (in Port Augusta and Adelaide) to discuss issues relating to the Commission. The Commission also met with the State Aboriginal Heritage Committee and other representative groups and individuals.

During its many visits to Aboriginal communities, the Commission provided an interpreter and written materials in Pitjantjatjara to assist with the communication process.

INDEPENDENT

The Commission had its own staff and engaged its own experts.

COMMISSION STAFF

The Commission had a range of technical, legal support and administrative staff led by Commissioner, Rear Admiral the Honourable Kevin Scarce AC CSC RAN (Rtd).

Chief of Staff

Greg Ward

Legal

Chad Jacobi, Counsel Assisting
Lucinda Byers, Solicitor Assisting
Bonnie Russell, Solicitor
Wesley Taylor, Solicitor

Technical

Dr Julian Kelly, Team Leader

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Dr Christiaan Ridings
David Scroggs

Administration and communications

Jon Bok, Regional Engagement Manager
Helen O'Brien, Business and Information Manager
Lyn Pobke, Executive Assistant
Jenny Turner, Senior Communications Manager
Brittany Mara, Administration Officer
Jacque Mullen, Records Officer

Editor

Rowena Austin

ADVISORY COMMITTEES

The Commission was supported by advisory committees, which provided valuable technical advice on issues of concern to the Commission.

Expert Advisory Committee

An Expert Advisory Committee was established to advise and guide the Commission on a broad range of topics throughout its inquiry. The committee provided comment on drafts of the issues papers, the tentative findings and this report. Its members were:

- Professor Barry Brook, Chair of Environmental Sustainability, University of Tasmania
- Mr John Carlson AM, former Director-General of the Australian Safeguards and Non-proliferation Office
- Professor Ian Lowe AO, past President of the Australian Conservation Foundation and Emeritus Professor of Science, Technology and Society, Griffith University
- Dr Timothy Stone CBE, Visiting Professor at University College London
- Dr Leanna Read, South Australia's Chief Scientist and expert in biotechnology.

Socioeconomic Modelling Advisory Committee

A Socioeconomic Modelling Advisory Committee was established to advise on the development of the economic assessments and their interpretation. Its members were:

- Professor Ken Baldwin, Director of the Energy Change Institute and Deputy Director of the Research School of Physics and Engineering, Australian National University
- Professor Quentin Grafton, Chairholder of the UNESCO Chair in Water Economics and Transboundary Water Governance, Australian National University
- Professor Paul Kerin, Professor and Head of School of Economics, University of Adelaide
- Professor Sue Richardson, Matthew Flinders Distinguished Professor, Flinders University
- Professor Mike Young, Professor, Faculty of Professions, University of Adelaide.

Radiation Medical Advisory Committee

The Commission also engaged medical experts as a Radiation Medical Advisory Committee to advise on current research and knowledge on the health effects of radiation, and the interpretation of medical evidence received by the Commission. Its members were:

- Professor Roger Allison, Executive Director, Cancer Care Services, Royal Brisbane and Women's Hospital
- Professor Dorothy Keefe, Professor of Cancer Medicine, University of Adelaide; Medical Oncologist, Royal Adelaide Hospital Cancer Centre; and Clinical Ambassador, Transforming Health, SA Health
- Dr Leanna Read, South Australia's Chief Scientist and expert in biotechnology
- Professor Daniel Roos, Professor, School of Medicine, University of Adelaide; Senior Radiation Oncologist, Royal Adelaide Hospital.

ACKNOWLEDGEMENTS

Preparing a relevant, detailed and evidence-based report on a topic that may affect all South Australians, including future generations, was an important task. The Commission's staff understood its magnitude and worked with determination and integrity to meet the report deadline. The Commission acknowledges the valuable contributions of its staff and advisors to allow that to occur.

The Commission acknowledges the contributions of its consultants, contractors and the numerous individuals who provided valuable assistance to the Commission.

The Commission extends its gratitude to the many experts who generously provided their time to assist it to both gather and understand a vast amount of information on a range of complex and technical topics.

WITNESSES AT PUBLIC SESSIONS

TOPIC 1: CLIMATE CHANGE AND ENERGY POLICY

9, 14 and 23 September 2015; 23 October 2015; 2 and 10 December 2015

Professor Ross Garnaut AO
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Professor John Quiggin
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Associate Professor Mark Diesendorf
Professor Graham Nathan and Dr Robert Dickinson
Professor David Karoly
Professor Tom Wigley
Professor Ken Baldwin
Professor John Fletcher

TOPIC 2: THE NATIONAL ELECTRICITY MARKET

18 September 2015

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Mr Rainer Korte, Mr Hugo Klingenberg and Mr Brad Harrison
Mr Craig Oakeshott
Mr Mark Vincent

TOPIC 3: GEOLOGY AND HYDROGEOLOGY OF SOUTH AUSTRALIA

22 and 23 September 2015

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TOPIC 4: LOW-CARBON ENERGY GENERATION OPTIONS

29 September 2015; 1, 7 and 30 October 2015; 5 November 2015

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Dr Keung Koo Kim and Dr Kyun S Zee
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TOPIC 5: ESTIMATING COSTS AND BENEFITS OF NUCLEAR ACTIVITIES

6 October 2015

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TOPIC 6: ENVIRONMENTAL IMPACTS: LESSONS LEARNED FROM PAST MINING AND MILLING PRACTICES IN SOUTH AUSTRALIA (CASE STUDIES: PORT PIRIE RARE EARTHS TREATMENT FACILITY AND RADIUM HILL)

8 October 2015

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Dr Paul Ashley

TOPIC 7: EXPANSION OF EXPLORATION AND MINING

14 October 2015; 10 November 2015

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Dr Vanessa Guthrie
Dr Ted Tyne and Mr Greg Marshall

TOPIC 8: ADDING VALUE TO SOUTH AUSTRALIAN RADIOACTIVE MATERIALS

15 October 2015

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Mr James Voss
Dr Michael Goldsworthy
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TOPIC 9: NUCLEAR REACTOR SAFETY AND REGULATION

21 October 2015

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TOPIC 10: NUCLEAR ACCIDENT: FUKUSHIMA DAIICHI

22 October 2015

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Dr Mike Weightman

TOPIC 11: EFFECTS AND THREATS OF RADIATION

27 October 2015; 15 December 2015

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TOPIC 12: INSURING AGAINST NUCLEAR ACCIDENT

5 November 2015

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TOPIC 13: COMMUNITY ENGAGEMENT AND NUCLEAR FACILITIES – GENERAL PRINCIPLES

9 November 2015

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Ms Barbara Campany

TOPIC 13: COMMUNITY ENGAGEMENT AND NUCLEAR FACILITIES–ENGAGEMENT WITH ABORIGINAL COMMUNITIES

12 and 16 November 2015

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17 November 2015

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TOPIC 15: LOW AND INTERMEDIATE LEVEL WASTE STORAGE AND DISPOSAL

18 November 2015

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TOPIC 16: HIGH LEVEL WASTE STORAGE AND DISPOSAL

23, 24 and 25 November 2015; 4, 5 and 6 April 2016

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TOPIC 17: SECURITY AND NON-PROLIFERATION RISKS

25 November 2015; 2 December 2015

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TOPIC 18: FINANCING AND INVESTMENT IN NUCLEAR FACILITIES

30 November 2015; 2 and 10 December 2015

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TOPIC 19: OPPORTUNITIES IN NUCLEAR MEDICINE

3 December 2015

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TOPIC 20: NUCLEAR EDUCATION AND SKILLS DEVELOPMENT

3, 4 and 10 December 2015

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TOPIC 21: REGULATORY OVERSIGHT

11 December 2015

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PUBLISHED SUBMISSIONS

Abbott, James

Aboriginal Congress of South Australia

Adelaide Hills Climate Action Group

Alchemides Pty Ltd

Alinytjara Wilurara Natural Resources Management Board

Askin, Henry

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Australian Nuclear Science and Technology Organisation (ANSTO)

AREVA Resources Australia Pty Ltd

Arius Association

Australian Radiation Protection Society SA

Australian Academy of Technological Sciences and Engineering (ATSE)

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The Australian Government

The Australian Industry Group

The Australia Institute

Australian ITER Forum

Australian Nuclear Association

Australian Nuclear Free Alliance

Australian Workers Union

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Friends of the Earth Australia, the Australian Conservation Foundation, and the Conservation Council of SA

Gale, Luke

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GE Hitachi Nuclear Energy

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Gladstone Uniting Church

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Golder Associates

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Heck, Ulrike

Higson, Donald

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Illert, Chris

International Campaign to Abolish Nuclear Weapons (ICAN), Australia

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Josephite SA Reconciliation Circle

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Kaurna Yerta

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Lerc, Loraine

Ludlam, Scott

Luke, Timothy (Catalyst Energy)

Mace Australia

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Medical Association for Prevention of War Australia Inc. and Public Health Association Australia

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Modistach, Ian

Monceaux, Dan

Murphy, Barry

Murphy, Graeme

Newlands, John

Ngarrindjeri Regional Authority Inc.

Ngoppon Together Inc

Nicholson, Martin and Archer, Oscar

Niven, Robert (School of Engineering and Information Technology, UNSW)

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The Outback Communities Authority

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Toro Energy

The University of Adelaide

Upper Spencer Gulf Common Purpose Group (USPCPG) and Pt Augusta Council

Uranium Council

Uranium Free NSW

VTT Technical Research Centre

Waite, Charles

Wakelin Associates Pty Ltd

Waldon, Gregory Paul

The Warren Centre for Advanced Engineering

Wauchope, Noel

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Women's International League for Peace and Freedom

Woodley Davis, Peter

World Nuclear Association

Wozniczka, Les

Yankunytjatjara Native Title Aboriginal Corporation

Yeeles, Richard

Young, Frank

APPENDIX C: FURTHER PROCESSING METHODS

The uranium oxide (U_3O_8) produced through mining and milling operations must undergo a series of additional processing steps in order to be transformed into a fuel that will generate electricity in a nuclear power plant. The required processes are conversion, enrichment and fuel fabrication.[1] Additionally, used nuclear fuel can be reprocessed to provide new fuel.

URANIUM CONVERSION

The conversion process refines the U_3O_8 and chemically converts it into uranium hexafluoride (UF_6) which readily changes from a solid form to a gas, which is necessary for the enrichment process.[2]

There are two well-established chemical methods for conversion, known as the 'wet' and 'dry' processes. The primary difference between the two techniques is in the way impurities, such as molybdenum and vanadium, are removed. In the wet conversion process they are removed in the second stage using a liquid solvent, and only very pure intermediate products are processed through to the later stages. The dry process does not use liquid solvents but instead removes impurities in the final fluorination stage. Both methods use fluidised bed reactors, employed extensively in chemical process industries, to carry out the chemical reactions that transform U_3O_8 into UF_6.

The final product is pure UF_6, which is transferred into specialised cylinders suitable for storage and transport to an enrichment plant.

WET CONVERSION PROCESS

The key feature of the wet conversion route is that U_3O_8 is pretreated using acid digestion and solvent extraction steps to remove impurity metals and other elements. This yields pure uranium trioxide (UO_3) which is then reacted with hydrogen fluoride (HF) to produce uranium tetrafluoride (UF_4). The final step involves reacting UF_4 with fluorine gas (F_2) in a separate vessel to give UF_6 which is liquefied before transfer into cylinders.[3]

For the production of heavy water reactor fuel, UO_3 is reacted with hydrogen gas (H_2) to produce UO_2 which is suitable for the fabrication of ceramic fuel pellets.

DRY FLUORIDE VOLATILITY PROCESS

In the dry conversion process, U_3O_8 is first heated in H_2 gas to produce UO_2. This compound is physically ground into a uniform size, such that it can be fed into a fluidised bed reactor and reacted with HF to produce UF_4. This compound is fluorinated with F_2 to give UF_6 which is further purified using a distillation process that removes impurities.[4]

ENRICHMENT

In order to be used as a fuel in light water reactors, uranium needs to be enriched in the ^{235}U isotope to between 3 per cent and 5 per cent from its natural abundance of 0.71 per cent. The process of uranium enrichment adjusts the ratio of the three natural uranium isotopes (^{234}U, ^{235}U and ^{238}U) to produce one with an increased proportion of ^{235}U. The remaining portion (commonly called the 'tails') is depleted in ^{235}U and is less radioactive. Uranium enrichment effort is measured and supplied in 'separative work' units. Separative work can be described as the amount of enrichment effort required to increase the concentration of ^{235}U in a set amount of uranium, to a given, higher ^{235}U concentration.[5]

CENTRIFUGES

Commercial enrichment is undertaken using large numbers of interconnected gas centrifuges: highly engineered, fast-rotating cylinders in which the UF_6 is subjected to a large centrifugal force. Heavier ^{238}U molecules move closer to the outer wall of the centrifuge than the lighter ^{235}U molecules. To achieve a high separation factor at each stage, modern centrifuges must rotate at speeds beyond that of sound, and therefore operate in a vacuum. The centrifuge process is difficult to master, since the high rate of rotation requires that the centrifuge be very strong and perfectly balanced, and capable of operating in such a state for many years without maintenance.

The stream that is slightly enriched in ^{235}U is then fed into successively higher stages of centrifuge to progressively enrich the ^{235}U. It requires tens of thousands of centrifuge stages to enrich commercial quantities of uranium. The other stream (the 'tails') is depleted uranium and is recycled back into the next lower stage of centrifuges.

LASER ENRICHMENT

Laser enrichment is based on molecular laser separation technology and has shown some promise as a possible commercial uranium enrichment technique. The process uses infrared lasers to selectively excite and ionise ^{235}U atoms in a stream of UF_6 giving high single-stage separation factors.[6] It is currently under development and has not yet been proven commercially, with one company recently discontinuing its efforts.[7]

FUEL FABRICATION

The final process step before uranium can be used as a fuel is fabrication into pellets within fuel 'bundles', either as enriched or natural fuel. Typically this is achieved in two key steps:

- UF_6 gas is chemically converted into a solid uranium dioxide (UO_2) powder
- UO_2 powder is fabricated into pellets which are then assembled into fuel bundles.

The UO_2 powder is pressed, compacted and sintered into dense ceramic pellets which are machined to the exact dimensions required. The pellets are typically loaded into zirconium tubes, which are assembled into the required fuel geometry. Light water reactors use fuel assemblies that are more than 3.5 m long. Heavy water reactors use short 50 cm bundles.

Nuclear fuel assemblies are specifically designed for particular types of reactors and are made to exacting standards. Many thousands of pellets have to go through rigorous quality assurance before being loaded into zirconium tubes. The product quality of the fuel assembly is a key factor for any power plant operation to assure safety and reliability. Fuel manufactured to the appropriate safety and design standards will support the reactor defence-in-depth approach.[8]

USED FUEL REPROCESSING

Used nuclear fuel can be reprocessed to recover fissile and fertile material in order to provide new fuel for existing and future nuclear power plants.

Only recycled uranium and plutonium can be reused in light water reactors as fresh fuel. Fast reactors can use recycled actinide components including uranium, plutonium, neptunium and americium as well as depleted uranium from the enrichment process. The fertile ^{238}U can be transformed into ^{239}Pu which can be burned in a fast reactor.

The reprocessing of used nuclear fuel is difficult. Full remote-handling operations are required, in 'hot cells'—heavily shielded rooms with thick concrete walls and thick lead-glass windows to protect operators. Hot cells have complex manipulator arms that are controlled by operators outside the cell.[9]

AQUEOUS REPROCESSING

Commercial used nuclear fuel reprocessing plants use the proven aqueous PUREX (Plutonium URanium EXtraction) process.[10] Used fuel is chopped into pieces and treated with strong acid. Most of the fuel dissolves and the liquid stream is subjected to multiple solvent extraction and ion exchange stages to partition groups of elements: uranium, plutonium, fission products and 'minor actinides'.

The products from fuel reprocessing can be fabricated into a fuel known as mixed oxide (MOX) fuel in a specialist fabrication facility. MOX fuel is manufactured from plutonium recovered from used reactor fuel, which is mixed with depleted uranium from the uranium enrichment process, at about 7 per cent to 10 per cent plutonium. This mixture is equivalent to approximately 4.5 per cent enriched uranium oxide fuel.[11]

PYROPROCESSING

Used nuclear fuel can also be treated with high temperature 'pyroprocessing' methods to achieve desired chemical separations. One of the main pyroprocessing techniques involves electrochemically treating the used fuel in one or more molten salt baths incorporating electrodes that allow for selectively separating used fuel components through voltage control. This strategy is particularly well suited for treating used metallic fast reactor fuels.

Another strategy is to simply heat used fuel to high temperatures, either alone or with other materials, in order to separate and remove particular components. Pyroprocessing research and development programs have been under way for many years in countries including the US, Japan and Russia. It is being used in the US to treat used fuel from a shut-down pilot fast reactor, but pyroprocessing has not yet been deployed in the commercial nuclear industry.[12]

NOTES

1 Hatch, *Final report: Quantitative analyses and business case for the development of uranium conversion, enrichment and fuel fabrication facilities in South Australia*, report prepared for the Nuclear Fuel Cycle Royal Commission, December 2015, p. 6, http://nuclearrc.sa.gov.au/

2 Tsoulfanidis, *Nuclear energy: selected entries from the encyclopaedia of sustainability science and technology*, Springer Science & Business Media, Berlin, 2012, pp. 233–243.

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4 CE Johnson & J Fischer, *The fluorination of uranium from dried solids and its application to the fluoride volatility process*, Argonne National Laboratory Report (ANL-6117), 1960.

5 World Nuclear Association (WNA), 'Uranium Enrichment', April 2016, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx.

6 ASX ComNews, *Silex Systems Limited: Annual report to shareholders*, October 2014.

7 World Nuclear News, 'GE-Hitachi to exit laser enrichment JV', *World Nuclear News*, 19 April 2016, http://www.world-nuclear-news.org/UF-GE-Hitachi-to-exit-laser-enrichment-JV-1904168.html

8 WNA, 'Nuclear fuel fabrication', April 2016, http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Fuel-Fabrication/.

9 WNA, 'Processing of used nuclear fuel', November 2014, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx.

10 ibid.

11 ibid.

12 ibid.

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

APPENDIX D: FURTHER PROCESSING–ANALYSIS OF VIABILITY AND ECONOMIC IMPACTS

1. ANALYSIS OF VIABILITY—COMMISSIONED STUDY

This study, undertaken by Hatch Pty Ltd, assessed the business case and provides quantitative analyses for establishing facilities in South Australia that provide further processing services—uranium conversion, enrichment and fuel fabrication. These services have been suggested as having potential to add value to the state's exports of uranium oxide concentrates.

The study assessed the potential returns on investment of establishing the facilities in South Australia. It estimated the revenues and lifecycle costs of a range of uranium processing facilities with the capacity to process volumes equal to Australia's uranium production.

ASSUMPTIONS AND INPUTS

Further processing services

The study analysed several different types of uranium conversion, enrichment and fuel fabrication services, either on a standalone basis or in various combinations, including as vertically integrated activities, as shown in Figure D.1.

Facility capacity

As a baseline the analysis used a capacity based upon Australia's current share in the market for uranium oxide concentrate, comprising both its average output and growth to 2030 consistent with an expansion in global nuclear capacity. That growth in capacity is consistent with the commitments made by countries prior to the 2015 Paris Climate Change Conference in their intended nationally determined contributions (INDCs).[1]

Table D.1 compares the capacity of the facilities addressed in the assessment to current global installed capacity and to relevant currently operating facilities. It shows that while the increment to current global capacity would be between 8 per cent and 17 per cent for the light water reactor (LWR) fuel, the increment to the heavy water reactor (HWR) fuel production capacity would be 23 per cent.

Capital and operating costs

Lifecycle costs were estimated for the development of further processing facilities in South Australia, including each of the five project phases—design, construction, commissioning, operation and decommissioning—as well as waste management.[2]

To estimate capital costs for each of the facilities and the combination of facilities, major equipment and material inventories were developed using process flowcharts for each facility type. These components and materials costs were then individually priced using standard chemical engineering plant cost evaluation methods and commercially available material cost databases.[3]

For each of these facilities, detailed cost estimates were also developed for supporting transport infrastructure (access to roads and port facilities) and for accessing electricity and gas distribution networks. These estimates were made for a hypothetical brownfield location that was assumed to be

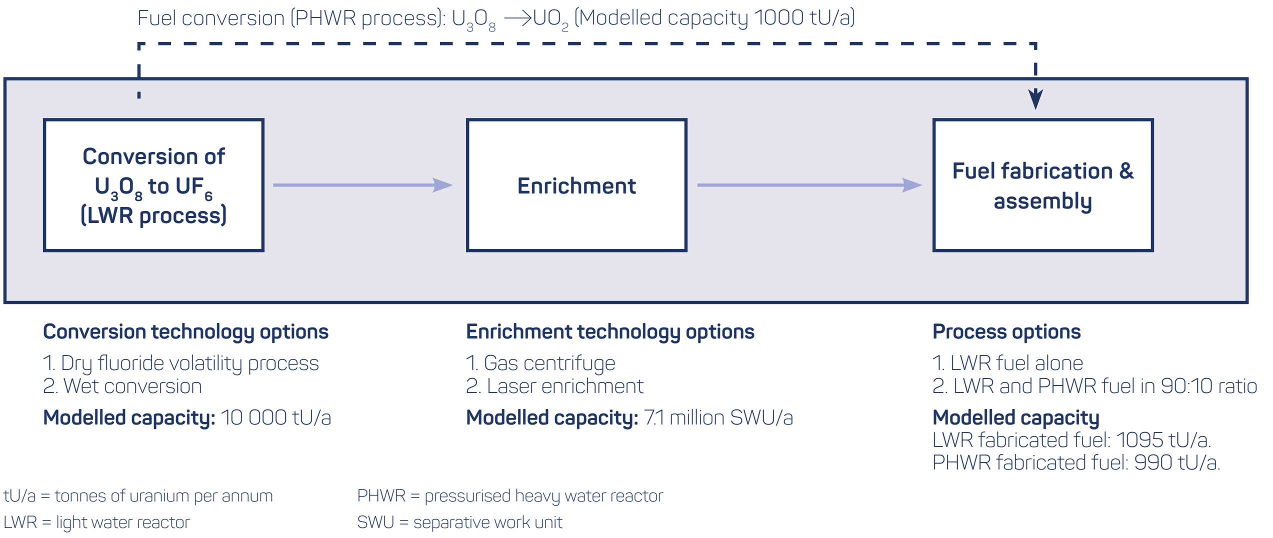

Figure D.1: Conversion, enrichment and fuel fabrication processes and technology assessed

Table D.1: Comparison of modelled facility capacities to current global installed capacity and to capacity of commercially established facilities

Facility	Global installed capacity (2015)	Modelled facility capacity	Increment to current global capacity (%)	Comparable commercially established facilities
Light water reactor process				
Conversion to UF_6	59 100 tU/a	10 000 tU/a	17	Canada: Port Hope, Cameco wet conversion facility (12 500 tU/a) USA: Metropolis, Illinois Converdyn dry conversion facility (17 600 tU/a)
Enrichment	57 million SWU	7.1 million SWU	12	France: Georges Besse II gas centrifuge enrichment facility (7–7.5 million SWU)
Fuel fabrication	13 600 tU/a	1095 tHM/a	8	USA (several): Columbia, Westinghouse facility (1150 tU/a)
Pressurised heavy reactor process (no enrichment)				
Conversion to UO_2	4320 tU/a[a]	1000 tHM/a	23	Canada: Port Hope, Cameco (2800 tU/a)
Fuel fabrication	4320 tU/a	990 tHM/a	23	France: Georges Besse II gas centrifuge enrichment facility (7–7.5 million SWU)

[a] Based on World Nuclear Association 2015 figures
Notes: tHM/a = tonnes of heavy metal per annum, SWU = separative work unit, tU/a = tonnes of uranium per annum
Source: World Nuclear Association

near existing supporting infrastructure and a hypothetical greenfield location that was assumed to be 30–50 km from these facilities. Potential cost synergies from the collocation of further processing facilities were not included, which suggests that further reductions in costs could be achieved.[4]

For operating and other project lifecycle costs, estimates were drawn from technical literature, historical projects, calculations based on process requirement analyses, and financial, environmental and regulatory compliance reports of commercially established facilities.[5]

Estimated capital costs for further processing facilities (base case) are presented in Table D.2. Capital and operating cost estimates were able to be made with greater certainty for the commercially proven wet conversion, gas centrifuge and fuel fabrication processes. The dry conversion technology (with only one operational facility) and laser enrichment technology (not yet commercially proven),[6] have substantial cost uncertainties even though they are estimated to require significantly smaller capital investments than the wet conversion and gas centrifuge processes respectively.

Table D.2: Lifecycle capital and operating costs for LWR processing facilities (2015 A$)

	Wet conversion	Dry conversion	Gas centrifuge enrichment	Laser enrichment	LWR fuel fabrication
Capital costs	$437.4m	$247.2m	$7623.0m	$2616.0m	$977.7m
Operating costs (per year)	$98.0m	$66.0m	$82.0m	$83.0m	$243.0m
Plant design capacity (per year)	10 000 tU	10 000 tU	7.1m SWU	7.1m SWU	1095 tU

Notes: tU = tonnes of uranium, m = million, LWR = light water reactor, SWU = separative work unit
Source: Hatch

Table D.3: Spot and long-term average prices for uranium conversion and enrichment services, 2015

Service	Spot price (A$)	Long-term average price (A$)
Conversion (A$/kgU)	8.4	20.8[a]
Enrichment (A$/SWU)	77.9	182[b]
LWR fuel fabrication (A$/kgHM)	N/A	409
PHWR fuel fabrication (A$/kgHM)	N/A	136

[a] Long-term average price
[b] Over the period 2005–11
Notes: US$1 = A$0.77, kgU = kilograms of uranium, kgHM = kilograms of heavy metal, LWR = light water reactor, PHWR = pressurised heavy water reactor, SWU = separative work unit
Source: Hatch

Revenues

Assessments of viability required determining a range of prices that could be used to estimate revenues that a prospective facility developed in South Australia might secure.

Uranium conversion, enrichment and fuel fabrication services are not traded in meaningful quantities on a commodity exchange.[7] However, prices of actual transactions are available and from them a long-term average price can be determined. Both spot and long-term average prices for conversion and enrichment are presented in Table D.3.

An assessment of viability undertaken on the basis of the long-term average price assumes that either new supply would meet new demand or displace an existing supplier.

In comparison with prices for conversion and enrichment, estimates for fuel fabrication services are more difficult to establish, given that they are based on negotiated long-term contracts and there is no spot market. The analyses undertaken used financial and purchasing reports published by utilities KEPCO (South Korea) and Ontario Power Generation (Canada) to estimate an average price.[8]
The long-term average prices used are set out in Table D.3.

RESULTS OF VIABILITY ANALYSIS

Overall, viewed on a standalone basis, the financial assessments suggested that most further processing facilities were not viable. Those based on currently used and proven technologies were at best marginal investments, and in many cases had negative returns.[9] Positive returns were indicated for facilities that used proprietary or unproven technologies, although that assumed significant investments were made to demonstrate and commercialise those technologies, but no estimate of these investments were made or included as part of the analyses.

Those outcomes are reflected in Figure D.2, which shows facilities assessed to be viable in the upper-right quadrant. They were assessed to be viable if they were profitable with an internal rate of return of 10 per cent—the amount a private investor would expect to receive on an investment.

The relative viability of each of the processing technologies for LWR fuel as standalone facilities is presented in Figure D.2.[10]

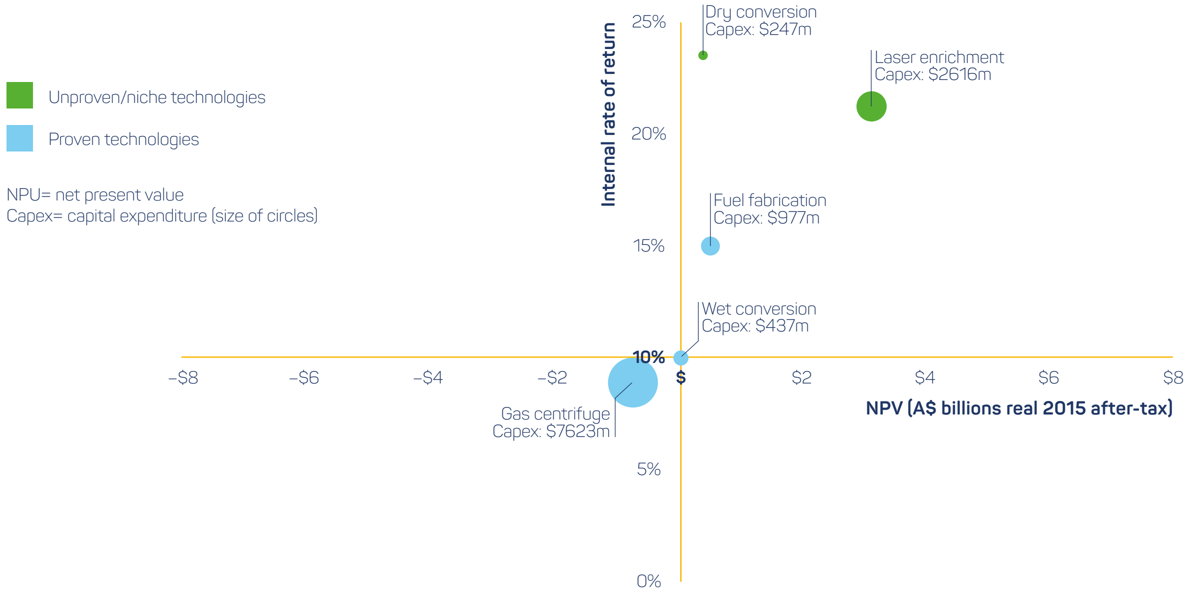

Figure D.2: Commercial viability of standalone facilities

Conversion

While the wet conversion process is marginal but negative, the dry conversion process is very profitable, as shown in Table D.4.

This outcome is in large part a result of the dry conversion process being simpler and requiring fewer processing steps than the wet process—which means that, in the assessments, it has lower capital and operating costs.[11] However, it is important to note that the dry conversion facility carries far greater technical risks.

Table D.4: Project net present value (NPV) for standalone conversion facilities (A$ millions 2015)

Facility	NPV at A$21 per kgU
Wet conversion	-1
Dry conversion	383

Note: kgU = kilograms of uranium
Source: Hatch

Enrichment

Gas centrifuge enrichment is not viable under most realistic future scenarios.[12] In comparison, laser enrichment, if it could be commercially demonstrated at scale, could be highly viable as a disruptive technology. The assessment did not take into account the potentially substantial costs associated with proving commercial feasibility.[13] If it could be, the analysis suggests it would have a substantial competitive advantage over existing producers.[14]

The comparison of the viability of enrichment by gas centrifuge and laser enrichment can be seen in Table D.5.

Table D.5: Project net present value (NPV) for standalone enrichment facilities (A$ millions 2015)

Facility	NPV at A$182 per SWU	NPV at A$78 per SWU
Gas centrifuge enrichment	-709	-5013
Laser enrichment	3114	-1191

Note: SWU = separative work unit
Source: Based on data supplied by Hatch

Fabrication

A fuel fabrication facility manufacturing light water fuel would be viable if contracts could be secured at or above the current estimated prices (approximately US$315 per kilogram of heavy metal (HM)[15]). However, the fabrication of both light and heavy water reactor fuel in a 90:10 ratio in a hybrid facility was found to be less profitable.[16]

SENSITIVITY–VERTICAL INTEGRATION OF TWO OR MORE SERVICES

The analysis was also undertaken on the basis that two or more services might be integrated. That was undertaken for the following reasons:

- Because of the distances involved to export large quantities of uranium concentrate from South Australia to existing uranium conversion suppliers, it is considered uneconomic for the converted product to be returned to the state for enrichment and/or fuel fabrication.
- Standalone fuel fabrication facilities would not be expected to be developed without there being a supplier to a domestic nuclear power plant market, and would therefore—if located in South Australia—need to be associated with conversion and enrichment facilities.[17]

Table D.6 presents a summary of the estimated project returns from investment in various combinations of vertically integrated facilities grouped on the basis of whether they rely on proven technologies (wet conversion and gas centrifuge enrichment) or unproven/niche technologies (dry conversion and laser enrichment). A profitable outcome is shown by a rate of return greater than 10 per cent. A sensitivity analysis was also undertaken to address the risks respectively of significant cost overruns or an adverse market, where the price is significantly lower than the long-term average.

Integrated facilities based on proven technologies that also included fuel fabrication yielded a higher rate of return, than when conversion and enrichment were considered on a standalone basis; however, they were still not viable. Integrated facilities based on unproven or niche technologies, with the qualifications stated above, were viable. It can also be seen that they were less sensitive to adverse market conditions or cost overruns.

Table D.6: Internal rates of return for vertically integrated facilities

Facilities internal rate of return (after tax, real basis)	Conversion, enrichment and fuel fabrication		Conversion and enrichment	
	Proven technologies	Unproven/niche technologies	Proven technologies	Unproven/niche technologies
Baseline scenario: Reference capex estimate, market recovers	9.4%	19.3%	7.8%	20.3%
No market recovery	4.2%	11.3%	1.9%	10.0%
Cost overrun	6.5%	12.0%	5.1%	12.0%
Worst case scenario: Cost overrun, no market recovery	2.2%	6.2%	<1.0%	4.8%

Source: Hatch

2. ANALYSIS OF ECONOMIC IMPACTS —COMMISSIONED STUDY

Economic modelling using a general equilibrium model was undertaken by Ernst and Young to assess the potential effect on the wider South Australian economy of investments being made in further processing facilities. It estimated changes in key measures of economic activity such as gross state income, gross state product, wages and employment.

The modelling undertaken used the transparent, peer-reviewed model maintained by the Victoria University Centre of Policy Studies known as the Victoria University Regional Model (VURM).[18] *This model has been used widely in Australia to assess the effects of investments made in one part of the economy on economic activity more broadly.*

ASSUMPTIONS AND INPUTS

The potential macroeconomic impacts of providing further processing services were assessed by assuming private investment in conversion and enrichment facilities in 2024 for operational commencement in 2030.[19]

It was assumed that a combined investment was made in conversion and enrichment facilities based on proven technologies. Investment in fuel fabrication facilities was not assessed as it was considered that, in the timeframe to 2030, it would not be feasible to establish a sufficiently broad technical skills base to capture market share.

The investment in further processing facilities was assumed to be made in an international market where Australia had implemented a carbon price to meet the abatement targets agreed at the Paris Climate Change Conference.[20]

RESULTS OF ANALYSIS OF ECONOMIC IMPACTS

The combination of conversion and enrichment facilities was estimated to generate annual export revenues for South Australia of A$657m in current terms.

Investment in further processing facilities in South Australia was also estimated to deliver modest but positive outcomes of an additional 0.5 per cent in 2030 for the South Australian economy, as shown in Table D.7.

In the two years prior to commencement of operations, the construction work force would peak at approximately 4000 persons employed on a full time equivalent basis, but this would decline to 1000 persons over the operational phase.[21]

Table D.7: Impact of investment in conversion and enrichment facilities on South Australian economy

	2029–30	2049–50
Gross state income	A$898m (0.65%)	A$794m (0.39%)
Gross state product	A$671m (0.47%)	A$914m (0.45%)
Wages	0.09%	0.02%
Total employment	1013	1000
Direct employment	210	324

Source: Ernst & Young

NOTES

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2 ibid., section 5, http://nuclearrc.sa.gov.au/

3 ibid., pp. vi, section 5, pp. 42–63.

4 ibid., section 7.3, p. 71.

5 ibid., p. vi.

6 ibid., p. vii

7 ibid., section 9.1.2, p. 106.

8 ibid., section 9.1.7, p. 108.

9 ibid., section 9.2, pp. 110–128, section 9.3, pp. 128–131.

10 Nuclear Fuel Cycle Royal Commission internal analysis using Hatch financial model.

11 Hatch, *Final report: Quantitative analyses and business case*, section 4.2.3, pp.34–5.

12 ibid., pp. 111, 115, figure 9.4.

13 ibid., section 4.3.2.1, p.38.

14 ibid., section 9.2.4, p. 115.

15 ibid., section 9.1.7, p. 108.

16 ibid., section 9.2.5, p. 115.

17 ibid., section 2.3.3, p. 11.

18 Ernst & Young, *Computational general equilibrium modelling assessment*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2015, sections 2.3, 2.4, http://nuclearrc.sa.gov.au/

19 ibid., section 4.2.1.

20 ibid., section 3.2, table 7.

21 ibid., section 6.2.2, figure 57.

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

APPENDIX E: NUCLEAR ENERGY—PRESENT AND FUTURE

NUCLEAR POWER PLANT FEATURES

A nuclear power plant produces electricity using heat energy, as do coal and gas fired power plants. The difference for a nuclear power plant lies in the way the heat is created.

Nuclear reactors rely on a controlled process of nuclear fission to produce heat. Nuclear fission is the term applied to an atomic nucleus splitting into smaller elements, releasing neutrons and a large amount of energy.

Nuclear fission produces much more energy than chemical combustion—in the range of 10 000 to 20 000 times more in mass terms. Nuclear fuel is very energy dense: one tonne of uranium fuel yields the same amount of electric power as 20 000 tonnes of black coal or 8.5 million cubic metres of gas. The same nuclear fuel is used in a reactor for up to five years.[1]

In order to safely harness this heat energy and convert it into electricity, special highly engineered pressure vessels, called nuclear reactors, are required.

The key elements of a nuclear reactor are illustrated in Figure E.1.

FUEL ZONE

All nuclear reactors are fuelled by a material that is capable of sustaining nuclear fission. Most commonly this is an isotope of uranium, ^{235}U. The fuel needs to be put into a robust form, such as a ceramic or metal alloy, or encased in graphite, due to the high temperatures of the fuel. Nuclear fuel assemblies are specifically designed for particular types of reactors and are made to exacting standards (refer to Appendix C: Further processing methods).

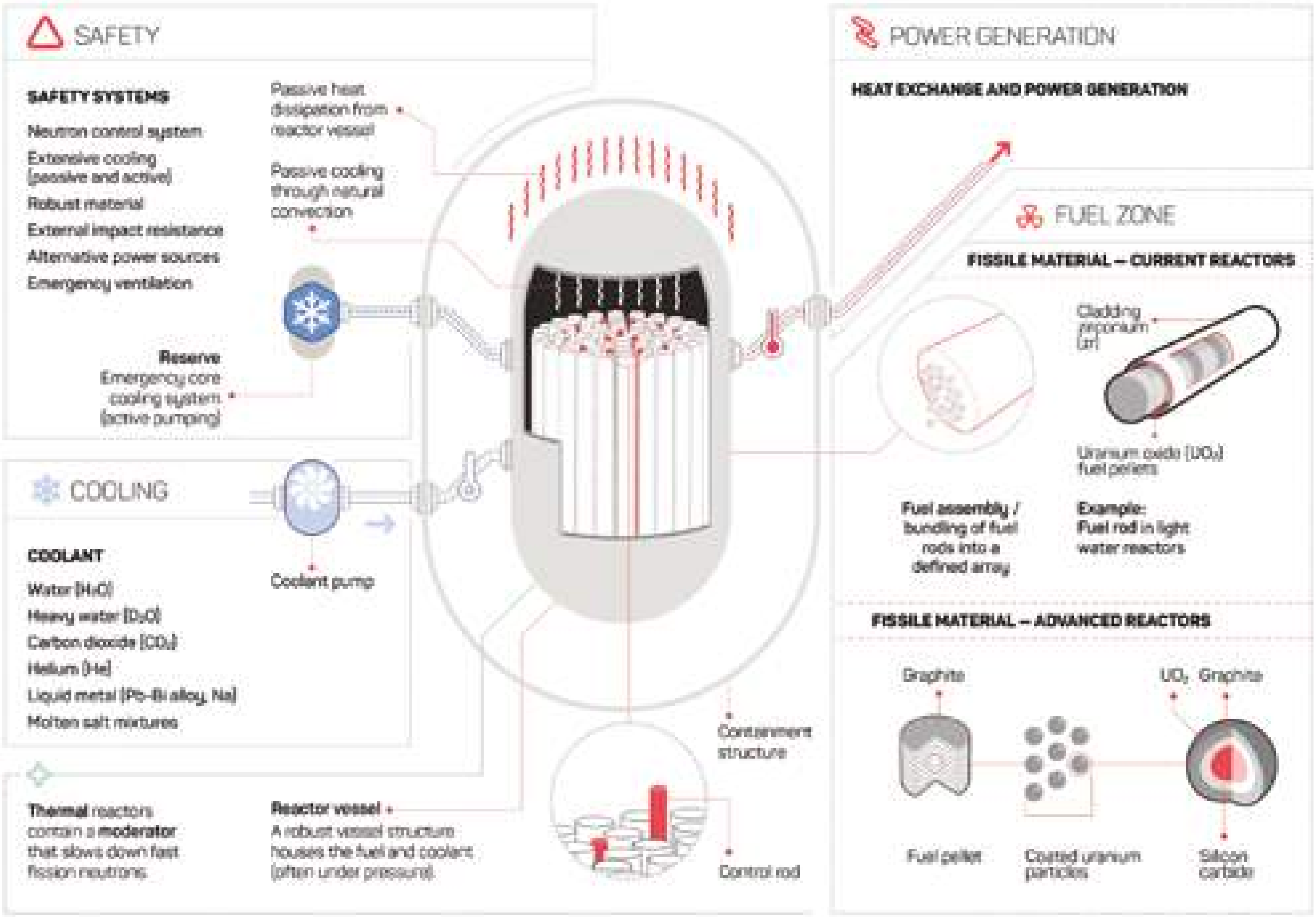

Figure E.1: Key elements of a nuclear reactor

The three main fuel assembly types currently produced are for pressurised water reactors (PWR), boiling water reactors (BWR) and CANDU pressurised heavy water reactors (PHWR). The key elements in a nuclear fuel system and the physical differences in fuel assembly designs are shown in Figure E.2.

COOLANT

Coolants are necessary in a reactor to absorb the heat from the fuel and to transfer that energy to the turbines. Most reactors have multiple cooling circuits and use water, either light or heavy, as the coolant. Some reactors use a gas, such as helium or carbon dioxide. Some advanced reactors use other kinds of coolants, such as liquid metals.[2]

HEAT EXCHANGE AND POWER GENERATION

The heat generated from the fission process in the reactor core is converted into high pressure steam, either directly or in a steam generator, which is fed through conventional steam turbines, similar to those used in coal power plants. The steam expands and causes the turbines to rotate, which in turn drives a generator that produces electricity. Commercial power plants are connected to a high voltage grid to distribute the electricity across a wide geographical area.

LOAD FOLLOWING

Nuclear power plants are typically operated as baseload generators that run continuously at full power. 'Load following' is an operational mode where the electricity output of a power plant is adjusted to reflect the changing electricity demand. Some of the currently operating nuclear plants are configured to have some load following capability; however, it is more economical to run them at full power. Furthermore, operating at full power is less demanding on both the plant equipment and the fuel.[3]

COOLING WATER REQUIREMENTS

Water requirements vary according to features of the particular reactor design, including the operating temperature and the type of cooling system employed.[4] A 'once-through' cooling system involves withdrawing water from a nearby sea, river or major inland water body and circulating large volumes through a condenser(s) in a single pass. The water is then discharged back into the original water source a few degrees warmer without much loss (through evaporation) from the amount initially withdrawn.

Alternatively, cooling may be carried out by 'recirculation': that is, water initially withdrawn from the sea, a river, etc., is recirculated from the condenser to a cooling tower and back to the condenser. A cooling pond works in much the same way.[5] Recirculation is much more efficient in its use of water, compared with the once-through system.

At present, cooling water requirements of nuclear power plants exceed those of fossil fuel power stations by 20–25 per cent on average per m^3/MW hour (Table E.1). This is due to the lower thermal efficiency in most of the existing nuclear power plants, as they operate with lower steam pressures and temperatures. A number of newer nuclear technologies aim to minimise the use of water by, for example, maximising cooling tower concentrations.[6]

COMMON REACTOR TYPES

The two main types of reactor in operation today are the pressurised water reactor (PWR) and the boiling water reactor (BWR) which account for approximately 64 per cent and 18 per cent respectively of operating nuclear power reactors.[8] The key differences between these two types of reactor are:

- The PWR primary coolant is kept under high pressure, which stops it from boiling. A separate secondary circuit, with secondary coolant where steam is generated, is used to drive the turbine.
- In BWRs there is a single circuit in which the water is at lower pressure than in a PWR so that it boils in the core to create steam. This is then used to directly drive the turbines in the absence of a secondary coolant. Since the water in the core becomes contaminated with traces of radionuclides, the turbine is part of the reactor circuit and must be shielded.[9]

Table E.1: Water use for different cooling systems (m^3/MW/hour)

Cooling system	Once-through (withdrawal)	Cooling pond (consumption)	Cooling towers (consumption)
Nuclear	95–230	2–4	3–4
Fossil-fuelled	76–190	1-2	2
Natural gas/oil	29–76	–	1

Source: International Atomic Energy Agency (IAEA)[7]

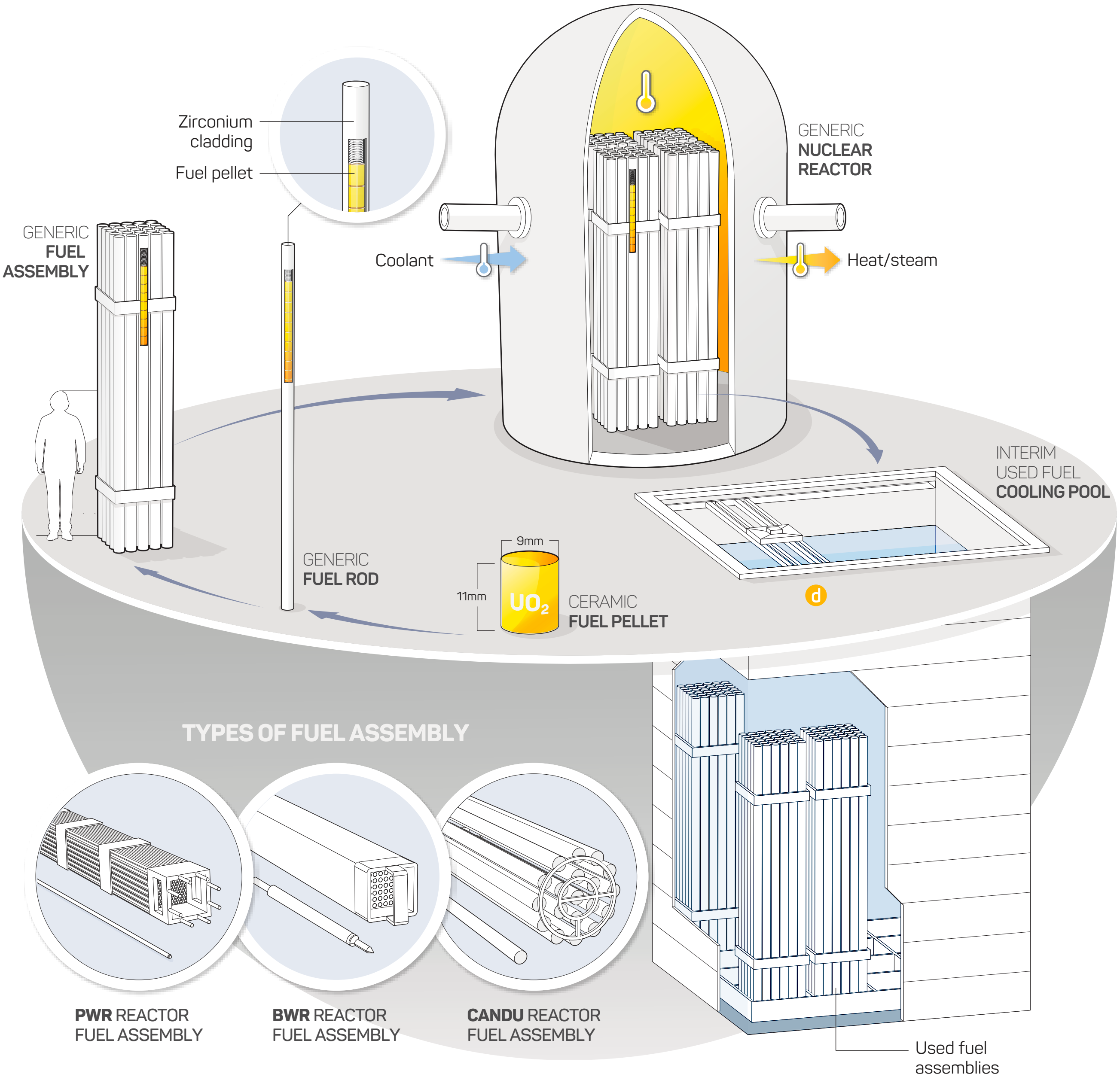

Figure E.2: A nuclear fuel system

NUCLEAR POWER PLANT SAFETY

SHUTTING DOWN A REACTOR AND DISSIPATING HEAT

Shutting down a reactor as part of normal operating procedures or in a fault or emergency situation involves inserting neutron-absorbing material into the core. This rapidly absorbs neutrons and stops the chain reaction and the production of heat from nuclear fission. In all commercial reactors this process is designed to occur automatically and without the need for human intervention.[10]

When the reactor has been shut down and the fission process stopped, it is still necesary to remove residual heat from the core and heat produced from the radioactive decay of the fission products in the fuel. Ongoing cooling is required to effectively remove the heat from the reactor core until the fuel is removed from the reactor.

Most commercial power reactors use water as the primary fuel coolant in closed cycles—those in which the water is recirculated to the reactor core after delivering heat to the turbine/generator system. Given the importance of maintaining adequate cooling for the fuel, reactors are also designed to supply additional coolant in the event of primary coolant loss.

In addition to the systems used for normal operations, all operating reactors are equipped with an emergency *active cooling system*, which makes available large amounts of supplementary water and multiple pumps with independent power supplies.

An emphasis in newer reactor designs is to provide additional fuel cooling using *passive cooling measures*. These rely exclusively on the fundamental physical effects of thermal expansion, gravity and the flow of heat to cooler zones. This can provide core cooling through natural circulation for extended periods without manual or mechanical intervention.[11]

Both active and passive safety systems can provide ongoing fuel and core cooling. However, passive systems to remove heat from the core reduce the dependence on active equipment (e.g. pumps and valves) and operator action in an emergency, and so are an increasingly important design feature for future reactors.

DEFENCE IN DEPTH AND REDUNDANT SYSTEMS

Modern nuclear power plants are designed to incorporate the 'defence in depth' concept. This means that no single human error or equipment failure at one level of defence, nor even a combination of failures at more than one level of defence, can escalate to jeopardise or lead to harm to the public or the environment.[12]

Defence in depth is based on having multiple barriers between radioactive materials and the workforce, the public and the environment, as well as redundancy and diversity of systems. The concept includes measures to protect the barriers themselves and ensures a high level of safety is reliably achieved through:

- high-quality design and construction of nuclear power plant systems
- equipment designed to prevent operational issues or human failures and errors developing into problems
- comprehensive monitoring and regular testing to detect equipment or operator failures
- redundant and diverse systems to control damage to the fuel and prevent significant radioactive releases
- provisions and countermeasures to reduce the effect of severe fuel damage
- improved human performance and a strong safety culture.

IMPACT RESISTANCE OF NUCLEAR REACTORS

Designers of nuclear power plants and the regulators that license plants have considered the potential for impact hazards that could challenge the safety and security of a nuclear power plant, such as terrorist attack and deliberate or accidental aircraft impact.[13]

In 2009 the US Nuclear Regulatory Commission amended its regulations to require applicants for new nuclear power reactors to perform a design-specific assessment of the effects on the facility of the impact of a large commercial aircraft.[14] In Europe, similar regulations are in place to ensure design standards take account of the hazards from impacts.[15]

While differences in detail exist among nuclear reactor types, the fundamental levels of external protection from an impact are:

- the external reinforcement of the outer containment structure
- thick steel construction of the reactor pressure vessel
- fuel and cladding designed to contain radioactive material in the core.

Detailed analysis and modelling has been undertaken on impact events to predict potential damage to the reactor containment.[16] In a postulated aircraft crash, analyses confirmed that concrete walls in the external power plant structure (typically more than one metre thick) are strong enough to protect the fuel from impacts of large commercial aircraft.[17]

Figure E.3, a photo of the Flamanville PWR under construction in France, shows the inner steel containment structure prior to being covered in a thick concrete outer containment. This is typical of a modern light water reactor that is designed to resist and survive large aircraft impacts.

Figure E.4 shows the external containment structure of an existing PWR power plant.

In some newer designs the reactors are recessed into the ground to provide improved protection from impact hazards, as illustrated in Figure E.5. The reactors which are below ground level can be seen on the lower right.

EMERGENCY VENTILATION

In severe accident scenarios hazardous gases may be produced, most notably hydrogen which is potentially explosive. As a result, nuclear power plants also have chemical recombiners to control hydrogen build-up and also, if required, the ability to vent gas into the external reactor building.[18]

Figure E.3: Flamanville PWR plant under construction

Image courtesy of EDF

Figure E.4: External containment of an operating PWR plant

Image courtesy of EDF

Figure E.5: NuScale small modular reactor

Image courtesy of NuScale Inc.

SMALL LIGHT WATER MODULAR REACTORS

Most commercial nuclear plants operating have a generating capacity of about 1 GWe.[19]

A number of firms (see Table E.2) have sought to develop small reactors based on light water designs with generating capacities in the range of 300 MWe or less.[20]

It is thought that such reactors might have the potential to be integrated into a wider range of networks than large plants. Developers of these reactors are aiming to lower the typical construction costs associated with nuclear plants through serial fabrication at an off-site facility, with components brought together at the operational site for final assembly.

This modularisation of components leads such designs to be referred to as small modular reactors (SMRs).[21]

Light water SMR designs using proven light water reactor technology are in various stages of development, with the most advanced being in the licensing process.[22]

There are numerous light water SMR designs being developed, with the most common design features including:

- modular design and small size, lending itself to multiple units on the same site
- smaller output, reducing the level of radioactive inventory in the reactor
- less reliance on active safety systems and pumps to remove heat from the reactor, including during fault or accident conditions
- less cooling water required, so SMRs are more suitable for operating in remote regions and for specific applications such as mining or desalination
- compact design enabling off-site fabrication, if manufactured at a sufficient scale, which can facilitate implementation of higher quality standards and lead to lower construction costs
- below-ground siting of the reactor unit to provide improved protection from natural or external hazards such as aircraft impact
- reduced size of safety exclusion zones
- ability to remove the reactor modules for dismantling and decommissioning at the end of the operational lifetime.

Table E.2: Selected SMR designs under development

SMR type	Vendor/Developer	Country	Description
NuScale	NuScale Power LLC	USA	50 MWe Integral PWR module Deployed with up to 12 modules per plant.
SMART	Korean Atomic Energy Research Institute (KAERI)	South Korea	90 MWe Integral PWR unit Deployed with up to 2 units per plant
mPower	BWX Technologies Inc.	USA	180 MWe Integral PWR unit Deployed with up to 2 units per plant
Westinghouse	Westinghouse Electric Company	USA	225Mwe Integral PWR
ACP100	China National Nuclear Corporation (CNNC)	China	100 MWe PWR
Holtec	SMR LLC (subsidiary of Holtec International)	USA	160 MWe PWR

Source: World Nuclear Association[25]

On the current cost estimates, SMRs require less capital investment prior to producing returns compared with larger scale reactor designs.[23] However, there are no commercially operating examples of light water SMRs that can validate whether the design features listed above can be achieved collectively in a commercial context. In addition, those analysing SMR developments have identified hurdles and uncertainties facing development and commercial deployment including the following[24]:

- SMRs have a relatively small electrical output, yet some costs including staffing may not decrease in proportion to the decreased output.
- SMRs have lower thermal efficiency than large reactors, which generally translates to higher fuel consumption and spent fuel volumes over the life of a reactor.
- SMR-specific safety analyses need to be undertaken to demonstrate their robustness, for example during seismic events.
- It is claimed that much of the SMR plant can be fabricated in a factory environment and transported to site for construction. However, it would be expensive to set up this facility and it would require multiple customers to commit to purchasing SMR plants to justify the investment.
- Reduced safety exclusion zones for small reactors have yet to be confirmed by regulators.
- Timescales and costs associated with the licensing process are still to be established.
- SMR designers need to raise the necessary funds to complete the development before a commercial trial of the developing designs can take place.
- Customers who are willing to take on first-of-a-kind technology risks must be secured.

FAST REACTORS AND REACTORS WITH OTHER INNOVATIVE DESIGNS

Notwithstanding the commercial dominance of LWR designs, work has been undertaken for many decades to improve the sustainability and efficiency of nuclear fuel use in reactors for power production, since current designs utilise less than 1 per cent of the mined uranium. There is also interest in using different nuclear fuel sources such as 'burning' heavy radionuclides and depleted uranium, which are created as byproducts from used fuel reprocessing and fuel enrichment respectively.

For those reasons, different reactor designs have been developed that include:

- fuel forms that can operate at higher temperatures than the current zirconium-clad oxide fuels used in light water reactors
- fuel zones that use higher energy neutrons, the so-called 'fast spectrum'
- coolants that can operate at higher temperatures than water.

Reactors with these design features have operated since the 1960s, but principally as experimental, prototype or demonstration nuclear reactors.[26]

In recognition of the long period and costs involved in their further development, consensus was reached internationally in 2001 that no single country could overcome, in a timely manner, the technical and engineering challenges associated with advanced reactor developments and technologies. Nor could a single country commit the long term resources needed and afford the cost and risks associated with building the next generation of nuclear energy systems.[27]

That consensus led to the establishment of the Generation IV International Forum (Gen IV Forum) to support and manage international cooperation and collaboration on advanced reactor development.[28] Notwithstanding that consensus, some development continues to occur on a national basis.

The Gen IV Forum selected a grouping of six advanced reactor designs updated in January 2014 that are referred to as 'Generation IV' (Gen IV) set out below in Table E.3. The Gen IV Forum has agreed on a common set of high level goals or objectives:

- *Sustainability:* Meets clean air objectives and promotes long term availability of systems and effective fuel, minimising waste volumes and intergenerational burden
- *Economics:* Lifecycle cost advantages over other energy sources, with a comparable level of financial risk
- *Safety and reliability:* Excellence in safety and reliability through a very low likelihood of reactor core damage and removal of the need for an off-site emergency response
- *Proliferation resistance and physical protection:* Least attractive and desirable route for the diversion or theft of weapons-usable materials, and increased physical protection against acts of terrorism.

FAST REACTORS

Many of the Gen IV designs are fast reactors, which utilise fast neutrons rather than the slow or thermal neutrons used by commercial nuclear reactors in operation today. Fast reactors can fission ^{238}U as well as the ^{235}U and this means that more than 60 times more energy can be extracted from the original uranium compared to current reactors. They are also able to use some materials from high level waste as fuel.[30]

Most of the six selected systems employ a closed fuel cycle to increase fuel utilisation and reduce the amount of high-level waste that needs to be sent to a repository for final disposal. High operating temperatures for four of the selected Gen IV Forum systems enable thermochemical hydrogen production, which could prove to be important for future transport fuels.[31]

VERY HIGH TEMPERATURE GAS REACTOR

The very high temperature gas reactor (VHTR), which is one of the systems selected by the Gen IV Forum, is a graphite-moderated, helium-cooled thermal reactor. High outlet temperatures allow thermochemical hydrogen production.[32]

The VHTR has some flexibility in fuel configuration, but no fuel recycling initially. Fuel is in particle form less than a millimetre in diameter, which may be incorporated into billiard ball sized pebbles or prismatic graphite blocks. The VHTR has potential for high fuel burn-up—around three to four times the level of current reactors. VHTR is planned to offer improved passive safety, low operation and maintenance costs, and modular construction features.[33] VHTR can also 'burn' waste actinides if fuel is specially adapted and fabricated for this purpose.[34]

OUTLOOK FOR THE DEPLOYMENT OF FAST REACTORS AND OTHER INNOVATIVE DESIGNS

Presently there are no operational fast reactors or other innovative designs that can be used to validate their potential for commercial deployment.[35] Several countries have research and development programs for improved fast reactors, with some being in place since the 1950s, with significant challenges still to be overcome before commercial operation is achieved.[36]

Today India and Russia regard fast reactors as a priority in their nuclear programs. They also feature in the nuclear energy programs for Japan, China and France. Experimental prototype and demonstration reactor designs are currently in operation in several countries including Russia, China and India.[37]

Prototype and demonstration VHTR designs have previously operated in various countries, although all have been shut down.[38] A twin 105 MWe gas-cooled HTR-PM ('high temperature gas cooled – pebble bed modular') demonstration unit at Shidaowan in China commenced construction in December 2012 and is expected to start operation in late 2017.[39]

Based on the updated technology roadmaps published by the Gen IV Forum in 2014 for Generation IV designs, a reactor demonstration phase is expected to begin in approximately 2021 for the most advanced system.[40] This phase is expected to last at least 10 years and will require funding of several billion US dollars for each system. As a result, based on the published Generation IV planning basis, the earliest timescales for commercial deployment of fast reactors and other innovative designs is reported as 2031.[41]

The proposed Russian BN-1200 design, which is planned as the commercial design developed from the existing BN-800 demonstration sodium cooled fast reactor, may be in operation before then.[42]

In addition, the proposed Chinese twin 600 MWe HTR-PM reactor (which is made up of 6 x 105 MWe modules) at Ruijin city in China's Jiangxi province passed a preliminary feasibility review in early 2015. This design is based on the demonstration HTR-PM reactor, with construction expected to start in 2017 and grid connection expected in 2021.[43]

All the timescales described above are, however, subject to significant project, technical and funding risk, as with any complex technology development.

Table E.3: Reactor designs selected by the Generation IV International Forum

	Neutron spectrum (fast/ thermal)	Coolant	Temperature (°C)	Pressure[a]	Fuel	Fuel cycle	Size(s) (MWe)	Uses
Gas-cooled fast reactors	fast	helium	850	high	^{238}U[b]	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	fast	lead or Pb-B	480–570	low	^{238}U[b]	closed, regional	20–180[c] 300–1200 600–1000	electricity & hydrogen
Molten salt fast reactors	fast	fluoride salts	700–800	low	UF in salt	closed	1000	electricity & hydrogen
Molten salt reactor - Advanced high-temperature reactors	thermal	fluoride salts	750–1000	low	UO^2 particles in prism	open	1000–1500	hydrogen
Sodium-cooled fast reactors	fast	sodium	500–550	low	^{238}U & MOX	closed	50–150 600–1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510–625	very high	UO^2	open (thermal) closed (fast)	300–700 1000–1500	electricity
Very high temperature gas reactors	thermal	helium	900–1000	high	UO^2 prism or pebbles	open	250–300[3]	electricity & hydrogen

[a] high = 7–15 MPa

[b] = with some ^{235}U or ^{239}Pu

[c] 'battery' model with long cassette core life (15–20 years) or replaceable reactor module

Source: World Nuclear Association[29]

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Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

APPENDIX F: THE FUKUSHIMA DAIICHI ACCIDENT

At 2.46pm Japan Standard Time (JST) on Friday 11 March 2011, a magnitude 9.0 earthquake struck 130 km off the north-east coast of Japan's main island of Honshu. The Great East Japan earthquake was caused by 'a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate'.[1] The earthquake lasted for more than two minutes and caused significant damage to infrastructure and property along the east coast of Japan.[2] It also resulted in a 10–20 m horizontal shift of the sea floor and local coastal subsidence of about half a metre.[3]

When the earthquake struck, three of the six reactor units at Tokyo Electric Power Company's (TEPCO) Fukushima Daiichi nuclear power plant were operating at full power. Units 1–3 shut down automatically according to design when plant sensors detected ground vibrations and triggered the reactor protection systems, thereby controlling the reactivity of the nuclear fuel, which is a fundamental safety function.[4] Units 4–6 were in planned shutdown for maintenance and refuelling at the time.[5] Although the earthquake caused no significant damage to the reactor units, it did cut off external AC power supply to the plant.[6] Emergency cooling was maintained as per design by diesel generators located in the basements of the turbine buildings of each reactor unit.[7]

The earthquake caused two tsunamis. Several warnings were issued by the government.[8] The first small tsunami was measured by a wave height meter located 1.5 km off the coast of the Fukushima Daiichi plant at 3.27pm JST.[9] The main tsunami, measuring 14–15 m in run-up height[10], struck the Fukushima Daiichi site at 3.36–3.37pm JST, and ultimately flooded over 500 square kilometres of land.[11] More than 15 000 people were killed and over 6000 injured as a result of the earthquake and tsunami, and around 2500 people were reported to still be missing as of March 2015.[12]

THE IMPACTS OF THE TSUNAMI ON FUKUSHIMA DAIICHI

Units 1–4 of the Fukushima Daiichi plant were built 10 m above sea level, while Units 5 and 6 had elevations of 13 m (see Figure F.1 and Figure F.2).[13] A 4-metre-high sea wall, with a breakwater height of 5.5 m, had been constructed to shield the plant from potential tsunami waves.[14] The sea wall and breakwater protected the site against the small wave, which had a run-up height of 4–5 m.[15] However, the main tsunami wave inundated the Fukushima Daiichi site, flooding and disabling 12 of the plant's 13 emergency diesel AC power generators, located at an elevation of 2 m.[16] This affected the cooling systems of the reactors and spent fuel pools.[17] In addition to disabling the emergency generators, the tsunami flooded the 125 volt DC batteries that supplied power to the instruments for Units 1, 2 and 4, which resulted in the loss of the instruments, controls and lighting for these units.[18]

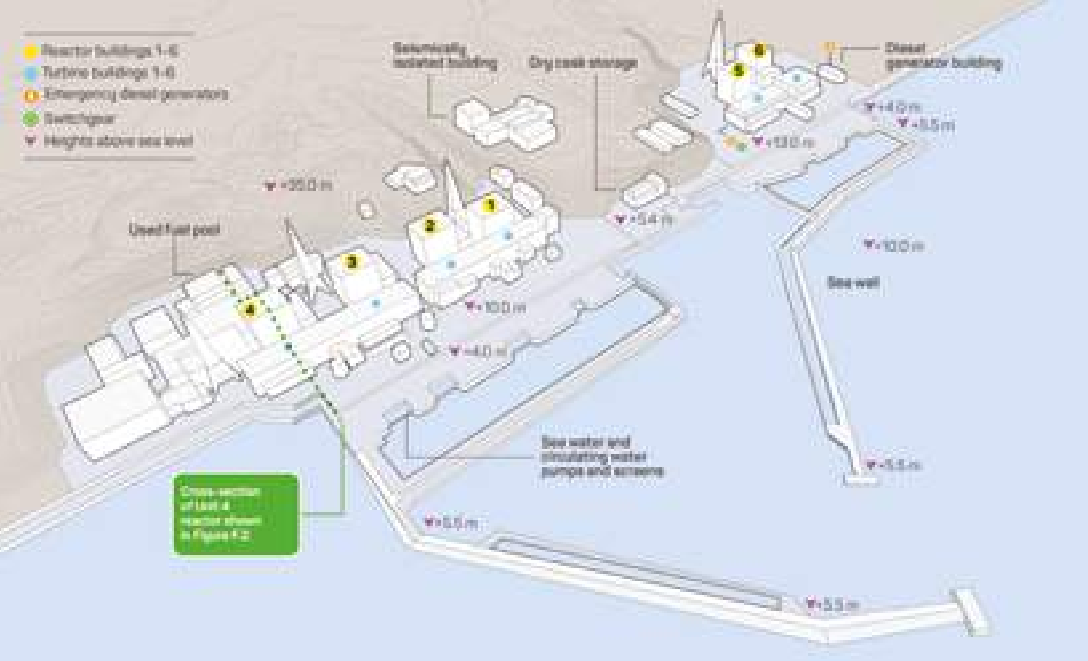

Figure F:1: The elevations and locations of structures and components at the Fukushima Daiichi nuclear power plant

Image adapted from TEPCO data

The widespread destruction caused by the tsunami made it impossible for external electricity supplies to be restored in time to avert melting of the fuel.

Without cooling and water injection, the heat generated by radioactive decay in the fuel caused the water levels in Units 1–3 to drop.[19] The loss of cooling for an extended period of time meant that the nuclear fuel overheated. The high temperatures also caused the exposed zirconium fuel cladding to react with the water vapour in the units resulting in the formation of large quantities of hydrogen gas.[20]

The hydrogen gas leaked from the primary containment vessels, resulting in explosions inside the reactor buildings of Units 1, 3 and 4. In addition, for Units 1, 2 and 3, the extended periods without cooling led to core melting and subsequent damage to the floors of the reactor vessels.[21] Hydrogen gas in Units 1 and 3 migrated from the primary containment vessels and caused explosions on the service floors, which injured workers and damaged the reactor buildings (see Figure F.3).[22] An explosion in the Unit 4 reactor building was caused by the migration of hydrogen gas produced in Unit 3 via a common ventilation system.[23] This destroyed the structure above the service floor and also injured workers.[24] It is thought that there was a containment vessel failure and uncontrolled releases of radioactive materials from Unit 2, though this has not yet been confirmed.[25]

Approximately nine days after the initial loss of power to the plant, AC power was restored to Units 1 and 2.[26] Units 3 and 4 were connected to off-site power approximately one week after Units 1 and 2.[27] Power was restored to Unit 5 through a power line connection to the diesel generators located at Unit 6.[28] On 20 March 2011, Units 5 and 6 were the first to reach a 'cold shutdown state' after the reactor temperatures were brought below 100 °C.[29]

During their response to the nuclear accident, emergency workers attempted to control the escalation of events to limit their impacts. They focused on maintaining cooling in the reactors using the reactor cooling systems[30], but also improvised methods, such as using fire engines to directly inject cooling water into the reactors, and attempted to re-establish temporary AC power.[31] Where damage from the tsunami or hydrogen explosions made this impossible[32], operators tried to prevent or limit the release of radioactive material from the reactor units. Activities included manual venting to depressurise the reactor or containment vessels.[33]

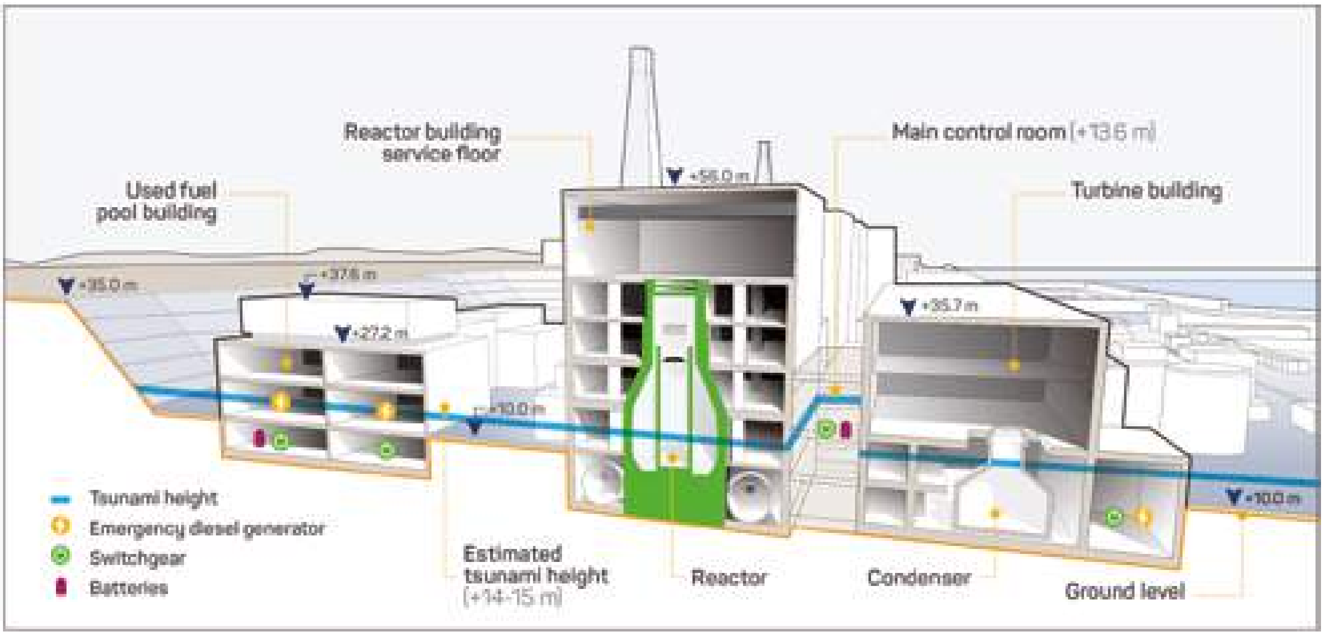

Figure F.2: Cross-section of Unit 4 showing elevations of the plant and the equipment, and the tsunami height

Image adapted from TEPCO data

Figure F.3: Fukushima Daiichi Unit 3 as it appeared on 15 March 2011

Image courtesy of TEPCO

In response to the accident and the potential radiological hazard posed to the surrounding population, the Fukushima Prefecture and, subsequently, the Japanese Government made successive evacuation declarations of increasing radius from the evening of 11 March to 12 March. The Japanese Government also ordered residents within a 20–30 km radial zone to shelter until 25 March.[34] On 16 December 2011, the Japanese Government and TEPCO announced the close of the 'accident phase' of the events at the Fukushima Daiichi plant (see Figure F.4).[35]

There have been no deaths or cases of radiation sickness (of workers, emergency responders and members of the public) attributable to the nuclear accident.[36] However, three workers at the Fukushima Daiichi plant were killed by the earthquake and tsunami.[37] The psychological stress experienced by evacuees as a consequence of the accident and tsunami and the dislocation of evacuees from their communities and livelihoods has had significant health and social impacts.[38]

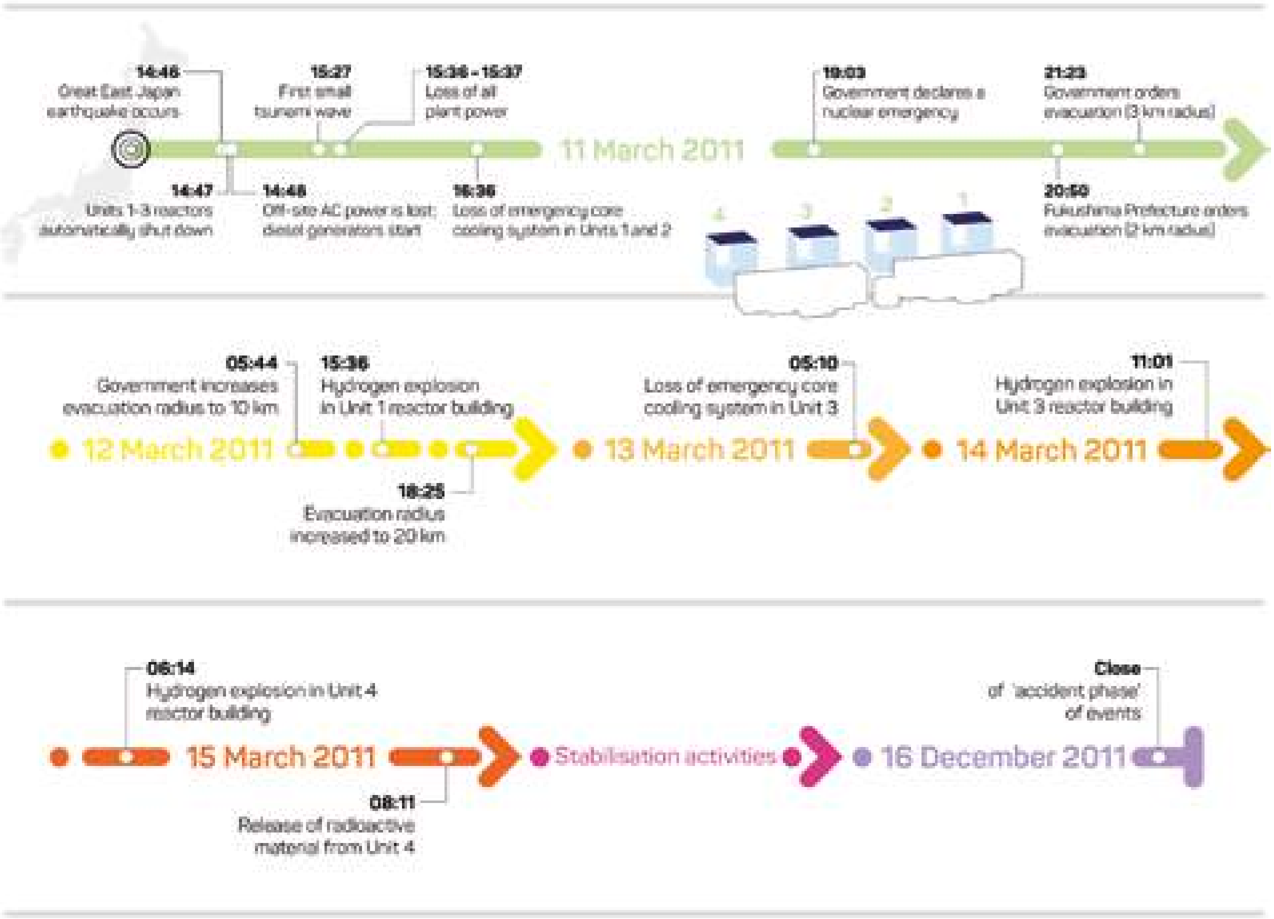

Figure F.4: Timeline of events for 11–15 March 2011, and up to 16 December 2011

Fukushima is an agricultural prefecture, and the economic impacts of the nuclear accident on agricultural production and food consumption, given the radioactive contamination, have been significant. There has also been a wider economic impact in Japan as a consequence of the nuclear accident, as forced reactor shutdowns resulted in a rise in energy imports at significant cost.[39]

The broader impacts of the earthquake and tsunami included damage to or destruction of at least 332 395 buildings, 2126 roads, 56 bridges and 26 railways along the east coast of Honshu. Electricity, gas and water supplies, telecommunications and railway services were also disrupted.[40] The estimated total loss for the Japanese economy caused by the earthquake and tsunami is in the order of US$309 billion.[41]

CAUSES OF THE ACCIDENT

There were a number of deficiencies in the plant design, emergency preparedness, regulatory framework and safety culture in Japan that contributed to the accident and the severity of its impacts.

The Fukushima Daiichi plant was only designed to withstand earthquakes up to magnitude 8.0 and tsunamis up to 5.5 m in height. This design was based on historical seismic records and was not updated to reflect new learning or studies of more recent seismic and tsunami events, nor the experiences of other countries that had faced emergencies at nuclear power plants.[42] Given the magnitude 9.0 earthquake and the 14–15 m tsunami, the events went 'beyond design basis'.[43]

The consequence of the earthquake and tsunami was the simultaneous loss of power to multiple reactor units for an extended period. This revealed several unchallenged design assumptions that:

- nuclear technologies and, particularly, the Fukushima Daiichi plant, were so safe that an accident of the kind experienced was thought to be impossible[44]
- there would never be a loss of power to all units at the same time and any power outage would only be for a short time[45]
- there would not be more than one event to which operators would simultaneously have to respond.[46]

In addition to the design flaws and unchallenged assumptions, workers lacked appropriate training for emergency management, and emergency operational guidelines were inadequate at both the regulatory and corporate levels.[47] Owing to the nature of the emergency, workers were required to improvise solutions, often without appropriate equipment.[48]

Japan's regulatory framework for nuclear power plants was deficient at the time of the accident.[49] The framework was complex, with a number of agencies having overlapping responsibilities.[50] Additionally, regulators were not sufficiently independent of nuclear power companies[51], including TEPCO.[52] The safety culture at the Fukushima Daiichi plant was characterised by complacency, in which operators and stakeholders did not challenge the assumptions.[53] Accordingly, there was no innovation in the safety culture or the regulatory framework.[54]

Tsunami countermeasures plus normal and emergency operating procedures were not aligned with International Atomic Energy Agency (IAEA) guidelines, and periodic safety inspections did not comply with international standards.[55] Despite this, Japan's Nuclear and Industrial Safety Agency permitted the Fukushima Daiichi plant to operate, and did not require improvements to safety and design, including implementing countermeasures for extreme natural events and emergency preparedness.[56]

As reported in Chapter 4, Electricity generation, a number of lessons learned from the Fukushima Daiichi nuclear accident are being applied to existing nuclear power plants and new nuclear developments. The report by the Director General of the IAEA identifies 45 lessons to improve nuclear safety and emergency preparedness in the wake of the Fukushima Daiichi nuclear accident.[57] Other lessons have been reported by TEPCO[58], the United States National Academy of Sciences[59], the United States Nuclear Regulatory Commission[60], the Institute of Nuclear Power Operations[61], and Greenpeace International.[62]

THE STATUS OF DECOMMISSIONING AND REMEDIATION WORKS

Since the Fukushima Daiichi accident, TEPCO and relevant Japanese Government agencies have developed a plan to decommission Units 1–4 and a strategy to remediate the site and surrounding environment.[63] The first phase of the decommissioning plan—removal of fuel from the spent fuel pools—is ongoing.[64] The second phase—removal of fuel debris from the site—is expected to take ten years.[65] Full decommissioning of Units 1–4 is expected to take 30 to 40 years.[66] The remediation strategy aims to reduce the radiation exposure from contaminated land areas by taking direct action on the contaminated areas and limiting exposure pathways to humans.[67] The costs of decommissioning have been estimated at ¥976 billion (A$10.74 billion), while compensation costs are estimated to be ¥6441.2 billion (A$70.88 billion). Combined, the costs amount to approximately ¥7417.2 billion (A$81.62 billion).[68] The true costs will only become known once decommissioning works are complete.

According to one estimate, approximately 135 000 people remain evacuated.[69] This figure includes 75 000 residents evacuated due to the nuclear accident and a further 60 000 evacuated due to the tsunami and earthquake.[70] Some evacuees have now been able to return to their homes.[71] Consistent with the international nuclear liability system, compensation is being paid to evacuees, homeowners and businesses for pain and suffering, loss of property, expenses incurred from evacuation and loss of income or revenue.[72] In September 2011, the Japanese Government established the Nuclear Damage Compensation Facilitation Corporation (renamed the Nuclear Damage Compensation and Decommissioning Facilitation Corporation in August 2014) to oversee decommissioning and remediation works and the compensation scheme.[73]

A significant amount of contaminated water has accumulated on the Fukushima Daiichi site.[74] This water is treated to remove all radionuclides except for tritium, which restricts the ability to release treated water to the sea. Accordingly, the treated water is stored on the site in tanks.[75] Some contaminated water has been released to the sea due to equipment failure and heavy rainfall. More extensive monitoring and mitigation measures have been introduced, but a sustainable solution is yet to be developed.[76]

Research into demonstration-scale technology to remove tritium with a view to full-scale operation is ongoing.[77]

NOTES

1. International Atomic Energy Agency (IAEA), *The Fukushima Daiichi accident: Report by the Director General*, GC(59)/14, IAEA, Vienna, 2015, p. 23.
2. IAEA, *The Fukushima Daiichi accident*, pp. 1, 23.
3. World Nuclear Association (WNA), 'Fukushima accident', March 2016, http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-accident.aspx
4. The safety systems for controlling the reactivity of nuclear fuel in the reactor core are the reactor protection and control rod drive systems. Before the earthquake, Fukushima Daiichi Units 1–3 were operating, while Units 4–6 were shut down for maintenance and refuelling. The reactors in Units 1–3 were automatically shut down by their reactor protection systems, which were activated by the plant's seismic event monitoring equipment. The insertion of control rods by the control rod drive systems stopped the nuclear chain reaction in the nuclear fuel and shutdown the reactors. IAEA, *The Fukushima Daiichi accident*, pp. 5, 24.
5. Eleven reactors at four nuclear power plants were operating in the region when the earthquake occurred and were shut down automatically. In addition to Fukushima Daiichi Units 1–3, TEPCO's Fukushima Daini Units 1–4, Tohoku's Onagawa Units 1–3, and Japco's Tokai reactor were operating. WNA, 'Fukushima accident'; IAEA, *The Fukushima Daiichi accident*, p. 1.
6. WNA, 'Fukushima accident'.
7. IAEA, *The Fukushima Daiichi accident*, p. 24.
8. The first tsunami warning was issued three minutes after the earthquake (2.49pm) and predicted a 3 m wave height. The second tsunami warning was issued at 3.15pm, 29 minutes after the earthquake, and predicted a 6 m wave. A third warning was issued at 3.30pm, 44 minutes after the earthquake, and predicted a wave height greater than 10 m. Committee on Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants, Nuclear and Radiation Studies Board, Division on Earth and Life Studies; National Research Council (Committee on Lessons Learned), *Lessons learned from the Fukushima nuclear accident for improving safety and security of U.S. nuclear plants*, National Academy of Sciences, The National Academies Press (NAP), Washington, D.C., 2014, p. 103.
9. Committee on Lessons Learned, *Lessons learned*, pp. 90–91.
10. Higher run-up (maximum 39 m) and inundation (maximum 33 m) heights were experienced at other locations along the Japanese coast. IAEA, *The Fukushima Daiichi Accident*, p. 30.
11. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources, effects and risks of ionizing radiation*, UNSCEAR 2013 Report to the General Assembly with scientific annexes, vol. 1, Scientific Annex A: Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami, UNSCEAR, UN, New York, 2014, p. 6.
12. IAEA, *The Fukushima Daiichi accident*, p. 1.
13. Elevations are relative to the Onahama Peil (Onahama Port Construction Standard Surface) (OP). Elevations have not been corrected for the ground subsidence that occurred as a result of the earthquake. Committee on Lessons Learned, *Lessons learned*, p. 84.
14. Committee on Lessons Learned, *Lessons learned*, p. 84.
15. IAEA, *The Fukushima Daiichi accident*, pp. 30–31.
16. Committee on Lessons Learned, *Lessons learned*, p. 84.
17. Tokyo Electric Power Company (TEPCO), *The development of lessons from the Fukushima Daiichi nuclear accident*, TEPCO, March 2013, p. 12.
18. IAEA, *The Fukushima Daiichi accident*, p. 32.
19. ibid., pp. 35, 42–43.
20. ibid., p. 57.
21. ibid.
22. ibid., p. 38.
23. ibid., p. 58.
24. ibid., p. 42.
25. ibid., p. 43.

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

26 ibid., pp. 44–47.

27 ibid., p. 47.

28 ibid.

29 The term 'cold shutdown state' was defined by the Japanese Government specifically for the Fukushima Daiichi reactors. Its definition differs from the terminology used by the IAEA. IAEA, *The Fukushima Daiichi accident*, pp. 47–48.

30 IAEA, *The Fukushima Daiichi accident*, p. 26.

31 ibid., pp. 34–44.

32 ibid., pp. 37, 39, 42.

33 ibid., pp. 35–43.

34 ibid., p. 84.

35 ibid., p. 48.

36 UNSCEAR, *Sources, effects and risks*, p. 10.

37 WNA, 'Fukushima accident'.

38 Transcript: Weightman, p. 831. UNSCEAR, *Sources, effects and risks*, pp. 77, 80.

39 Transcript: Weightman, p. 831. V Vivoda & G Graetz, 'Nuclear policy and regulation in Japan after Fukushima: Navigating the crisis', *Journal of Contemporary Asia* 45, no. 3, p. 493.

40 United States Geological Survey (USGS), Earthquake summary, 23 March 2015, http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/#summary

41 USGS, Earthquake summary.

42 Earthquakes in Chile in 1960 and 2010 registered magnitudes of 9.5 and 8.8 respectively, while earthquakes in Alaska (1964) and Sumatra (2004) recorded magnitudes of 9.2; IAEA, *The Fukushima Daiichi accident*, pp. 3–4, 23.

43 Transcript: Caruso, p. 821.

44 Transcript: Caruso, p. 825. IAEA, *The Fukushima Daiichi accident*, foreword.

45 IAEA, *The Fukushima Daiichi accident*, pp. 6, 59.

46 ibid., p. 5.

47 ibid., pp. 4, 59.

48 Transcript: Caruso, p. 822; IAEA, *The Fukushima Daiichi accident*, foreword.

49 Transcript: Weightman, p. 833.

50 ibid., p. 837.

51 ibid., p. 839.

52 Transcript: Caruso, p. 824. Vivoda & Graetz, 'Nuclear policy and regulation', pp. 497–500.

53 Transcript: Caruso, p. 824. IAEA, *The Fukushima Daiichi accident*, Foreword. p. 68.

54 Transcript: Caruso, p. 826.

55 Transcript: Weightman, p. 832.

56 WNA, 'Fukushima accident'.

57 IAEA, *The Fukushima Daiichi accident.*

58 TEPCO, *The development of lessons.*

59 Committee on Lessons Learned, *Lessons learned.*

60 United States Nuclear Regulatory Commission (U.S.NRC), *What are the lessons learned from Fukushima?* U.S.NRC, 17 April 2015, http://www.nrc.gov/reactors/operating/ops-experience/japan-dashboard/priorities.html

61 Institute of Nuclear Power Operations (INPO), *Lessons learned from the nuclear accident at the Fukushima Daiichi nuclear power station*, INPO 11–005, INPO, August 2012.

62 Greenpeace International, *Lessons from Fukushima*, Greenpeace International, Amsterdam, February 2012.

63 IAEA, *The Fukushima Daiichi accident*, pp. 15–16.

64 WNA, 'Fukushima accident'.

65 TEPCO, *The development of lessons*, p. 37.

66 IAEA, *The Fukushima Daiichi accident*, p. 17.

67 ibid., p. 15.

68 T Holloway (Australian Embassy), letter to Nuclear Fuel Cycle Royal Commission on Fukushima Daiichi NPP accident costs, 25 April 2016. Currencies have been converted based on the average 2015 conversion rate – ¥1 = A$0.011.

69 WNA, 'Fukushima accident'.

70 ibid.

71 WNA, 'Fukushima accident'; IAEA, *The Fukushima Daiichi accident*, Foreword.

72 S Matsuura, 'The current progress of relief of victims of nuclear damage caused by the Fukushima Daiichi nuclear power plant accident', in Organisation of Economic Co-operation and Development (OECD) – Nuclear Energy Agency (NEA), *Japan's compensation system for nuclear damage: as related to the TEPCO Fukushima Daiichi nuclear accident*, OECD–NEA, 2012, p. 34.

73 The Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF), *The Nuclear Damage Compensation and Decommissioning Facilitation Corporation*, February 2016, p. 1.

74 IAEA, *The Fukushima Daiichi accident*, p. 149.

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77 World Nuclear News, 'Russia completes design papers for Fukushima tritium removal', 9 July 2015, http://www.world-nuclear-news.org/RS-Russia-completes-design-papers-for-tritium-removal-at-Fukushima-09071501.html

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APPENDIX G: NUCLEAR POWER IN SOUTH AUSTRALIA—ANALYSIS OF VIABILITY AND ECONOMIC IMPACTS

NUCLEAR POWER IN SOUTH AUSTRALIA—ANALYSIS OF VIABILITY AND ECONOMIC IMPACTS

A combination of analyses was undertaken to determine whether nuclear energy would be viable in South Australia in the future.

A study undertaken by WSP/Parsons Brinckerhoff assessed the business case and provides quantitative analyses for developing a nuclear power plant and supporting infrastructure in South Australia.[1]

A separate study undertaken by Ernst & Young evaluated the impact of possible emissions abatement policies consistent with government policy to determine both the future energy generation mix in Australia and associated wholesale electricity prices across the National Electricity Market (NEM). Those outputs were needed to determine the market in which a nuclear power plant would operate.[2]

The outputs of both studies were used in a complementary study undertaken by DGA/Carisway which used the studies' inputs and projections of future electricity demand in South Australia in order to assess the commercial viability of both a large and small nuclear power plant operating in South Australia in 2030 or 2050.[3]

1. ANALYSIS OF VIABILITY—COMMISSIONED STUDY

ASSUMPTIONS AND INPUTS

Nuclear technology options assessed

The financial analysis initially evaluated reactor designs in the Generation III and III+ categories with a generation capacity between 700 MWe and 1600 MWe as well as small modular reactors with a generation capacity less than 300 MWe.[4]

To be further assessed, the reactor technology was required to have:

- been successfully constructed and commissioned elsewhere at least twice by 2022
- cost estimates that were able to be based on realised costs benchmarks or, if they were not available, estimates that could be independently verified.

The analysis considered the most reliable data to be recent, realised benchmarks in project development and construction time frames.

Designs from the following vendors were initially considered[5]:

- light water reactors: Westinghouse AP1000 pressurised water reactor and GE Hitachi economic simplified boiling water reactor
- pressurised heavy water reactors: Atomic Energy of Canada Limited EC6 and ACR-1000
- small modular reactors: NuScale and B&W Bechtel mPower.

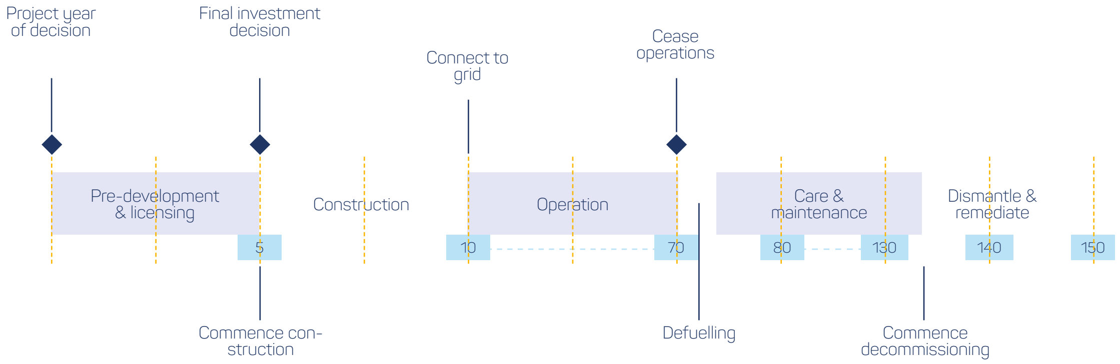
The Westinghouse AP1000 reactor was assessed as being the only advanced pressurised water reactor that met the criteria of having been constructed and commissioned elsewhere at least twice before 2022.[6] This assessment was made on the basis that two units are currently under construction in the USA (Vogtle and VC Summer) and China.[7] Public reporting requirements for the costs of developing these reactors in the USA offered a robust basis for estimating the cost of such a facility in South Australia.[8]

Two boiling water reactor designs were considered. While the advanced boiling water reactor has been constructed in Japan and Taiwan, the economic simplified boiling water reactor that incorporates more passive safety features has received only design certification in the USA but is not being constructed.[9] These reactor designs were not further considered.

The EC6 pressurised heavy water reactor is a new design that has not yet been deployed anywhere in the world; the realistic potential for its deployment before 2030 is not known. The status of the advanced ACR-1000 design based on the CANDU 6 model is also not presently known. These reactor designs were not further considered.[10]

A number of small modular reactor designs are currently at various stages of design, component testing, licensing and commercial development. The two designs included for analysis of viability—NuScale and B&W Bechtel mPower—have received substantial funding from the US Department of Energy and are close to having design submissions that are ready to be reviewed by the US Nuclear Regulatory Commission.[11]

While sufficient design and test work has shown that the design of these reactors is likely to be technically feasible, the extent to which efficiency in factory assembly-line type fabrication will overcome the economies of scale offered by a large nuclear power plant is uncertain.[12]



Development timeline for a large nuclear power plant (in years)

Figure G.1: Development timeline for a large nuclear power plant

Source: WSP/Parsons Brinckerhoff

NON-NUCLEAR OPTIONS ASSESSED

The study also analysed separately two non-nuclear energy generation options that could be operated as part of a low-carbon energy generation system with intermittent renewable technologies. It assessed the viability of installing a commercially proven combined cycle gas turbine system. As an alternative, the gas turbine system was modelled with the unproven carbon capture and storage technology. That analysis provided a baseline against which the viability of nuclear could be measured.

TIMELINE FOR CONSTRUCTION AND OPERATION IN AUSTRALIA

Using the development time frame for a large nuclear power plant in the USA as a basis, an approximate timeline for the development of a large nuclear power plant is presented in Figure G.1.[13] It shows a projected total time frame of approximately 10 years for pre-construction activities including project development, regulatory approval, and licensing and facility construction.

The analysis assumed that project development and licensing time frames for a small modular reactor would be the same as that for a pressurised water reactor. It assumed a short construction time frame of three years on the basis of the pre-fabricated design of small modular reactors.

SITING

Due to costs associated with construction being affected by the presence of existing infrastructure, the viability analysis was undertaken siting the plants on both greenfield or brownfield sites.

A brownfield site was assumed to be very close to or adjacent to established road and electricity transmission infrastructure. A greenfield site, on the other hand, was assumed to be located 50 km from existing supporting infrastructure. For both siting scenarios, a wharf facility was assumed to be developed to support the construction of these facilities and to enable fuel to be transported to and from the nuclear power plant.[14]

CAPITAL AND OPERATING COSTS

Capital cost estimates for the large nuclear power plant were based on realised costs for the Westinghouse AP1000 projects in the USA.[15]

For small modular reactors, cost estimates were based on those of a large scale PWR, with an additional 5 per cent to take account of the absence of benchmark costs.[16]

For both large and small nuclear plants, supporting infrastructure cost estimates were based on realised costs for roads, electrical network infrastructure and wharf facilities in South Australia.[17]

The capital operating and used fuel management costs estimated for the Commission are presented in Table G.1.

For the non-nuclear generating technologies used as a comparison, the capital and operating cost estimates for a combined cycle gas turbine system were drawn from studies published by the Australian Energy Technology Assessment and the Electric Power Research Institute study for the Carbon Dioxide Cooperative Research Centre (CDCRC).

The analysis used the gas price forecast produced for the Australian Energy Market Operator by Acil Allen in December 2014. On this basis, it was assumed that gas prices would vary marginally in the range $9.20–$10.20 per gigajoule between 2030 and 2050.[18]

Table G.1: Life cycle capital and operating costs for two types of small modular reactor and a large nuclear reactor at brownfield and greenfield sites

A$ 2014	Small modular reactor (360 MWe capacity)	Small modular reactor (285 MWe capacity)	Large nuclear reactor (pressurised water reactor – 1125 MWe capacity)
Brownfield site	\$3302m (\$9173/kW)	\$2942m (\$10 323/kW)	\$8962m (\$7966/kW)
Greenfield site	\$3692m (\$10 256/kW)	\$3331m (\$11 689/kW)	\$9323m (\$8287/kW)
Non-fuel operating costs	\$61m	\$48m	\$190m
Fuel costs	\$11.80/MWh	\$11.80/MWh	\$9.90/MWh
Used fuel disposal cost	\$5.80/MWh	\$5.80/MWh	\$4.90/MWh

Source: WSP/Parsons Brinckerhoff

Notes: m = million, MWe = megawatt electrical, MWh = megawatt hour

Table G.2: Assumed level of CO_2-e emissions reduction and corresponding policy mechanisms

Scenario	Current policies	New carbon price	Strong carbon price
Assumed level of emissions reduction	2030: 26–28% reduction in CO_2-e emissions relative to 2005 levels		2030: 65% reduction in CO_2-e emissions relative to 2005 levels
	2050: 80% reduction in CO_2-e emissions relative to 2005 levels		2050: complete decarbonisation
Economic policy	Expansion of emissions reduction fund to 2030 Carbon price implemented beyond 2030	Carbon price policy implemented over the period 2017–2050	Carbon price policy implemented over the period 2017–2050

Source: Ernst & Young

FUTURE TECHNOLOGY MIX

An assessment was undertaken to determine the likely future combination of energy generation technologies comprising solar photovoltaic (PV) and wind generation (both with and without energy storage), battery vehicle to grid with electrical vehicle storage, and open cycle gas turbines.[19] This was analysed as being affected by both abatement policies and the costs of those technologies.

EMISSIONS ABATEMENT POLICY

Three scenarios were developed to reflect a range of realistic and possible emissions abatement targets and policies: see Table G.2. The future carbon price to which each of those policies correspond can be seen in Figure G.2.

FUTURE ENERGY GENERATION COSTS

This analysis required an assessment of the impact of the future costs for renewable energy generation and storage technologies, as well as fossil-fuelled generation and carbon capture and storage.

The analysis relied on the estimates of costs from the Australian power generation technology report (2015)[20], to determine which technologies would be able to offer the lowest overall wholesale electricity prices to meet expected demand in 2030. It took account of expected reductions in cost previously published as part of the Australian Energy Technology Assessment 2013 update, as shown in Figure G.3. The cost reductions in those assessments favour new technologies over mature ones, and assume significant reductions in the cost of wind, solar PV, and carbon capture and storage compared to nuclear and fossil fuel generators.

The costs for nuclear were based on the analysis developed above, but excluding project development and licensing costs. This ensured a consistent comparison with the other technologies in the market model. The costs for nuclear are shown with the costs for other technologies in Figure G.3.[21]

The analysis of profitability, however, included project development and licensing costs.

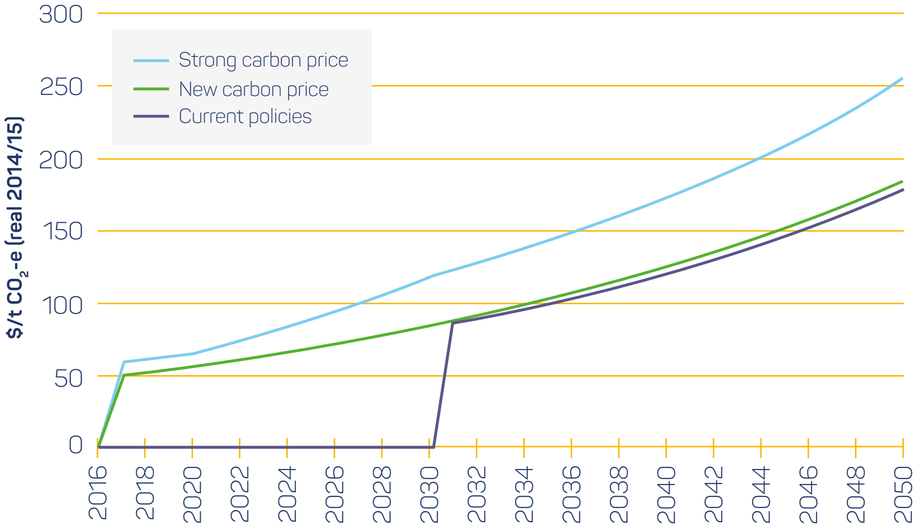


Figure G.2: Assumed carbon prices under the Current Policies, New Carbon Price and Strong Carbon Price scenarios

Source: Ernst & Young

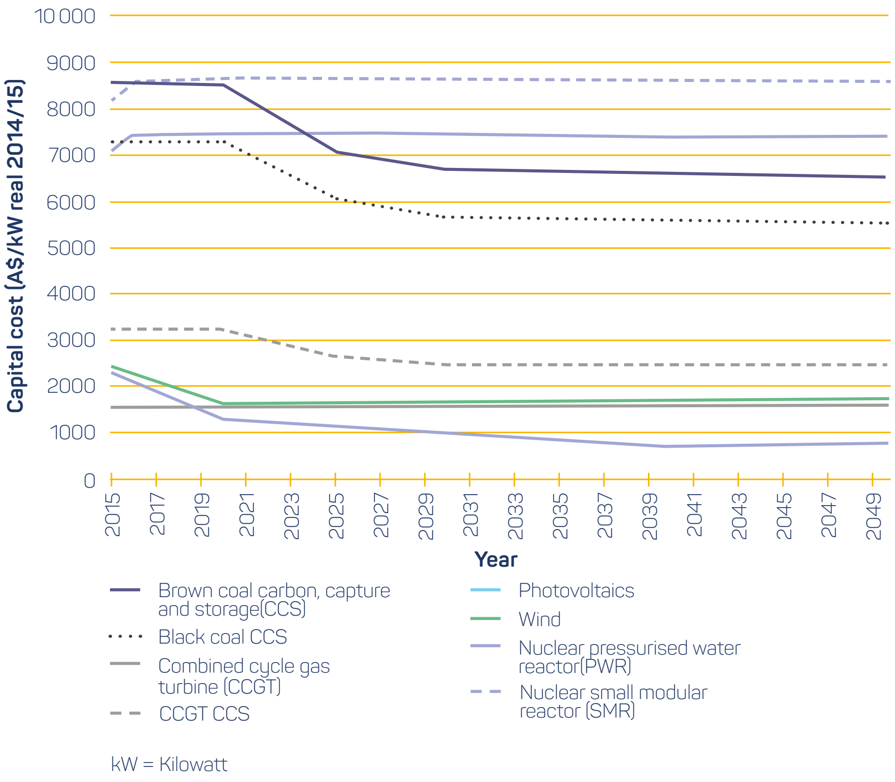


Figure G.3: Estimated capital costs of key technologies to 2050

Source: Ernst & Young

DEMAND

The analysis of demand required views to be reached about the extent to which residential customers would deploy rooftop solar PV and storage technologies and adopt electric vehicles in the future, as each of these affects network demand. However, no independent assessment was made on the returns to the households making those investments. The analysis assumed:

- that saturation capacity for solar PV (75 per cent of suitable dwellings would have installed capacities of 3.5 kW each) would be reached in South Australia by 2028.[22]
- the substantial uptake of storage technologies by half of all households with solar PV systems would lead to battery storage totalling 1.75 GWh by 2030. This is consistent with the assessments of the CSIRO's Future Grid Forum report[23] and a separate 2015 CSIRO assessment of future energy storage trends for the Australian Energy Market Commission[24] on the basis that the costs of these systems would halve by 2030.[25]
- a higher rate of uptake of electric vehicles under the strong carbon price scenario and a lower rate of uptake under the new carbon price scenario that were consistent with those made by ClimateWorks and Future Grid Forum analyses respectively.[26]

A sensitivity study presented in Figure G.4 outlines the effect of these assumptions being different.

The potential for meeting demand from other regions of the NEM was addressed. For the scenarios that included nuclear generation, an interconnector capacity of 2000 MWe was assumed. However, these analyses did not assess the potential viability of undertaking upgrades to the capacity of connection between South Australia and the eastern regions of the NEM because that would require a detailed regulatory investment test to assess net benefits to electricity consumers in different regions of the NEM.[27]

Electricity demand across Australia was estimated using the general equilibrium modelling analysis for the entire Australian economy, which takes into account the wider economic impacts of implementing emissions abatement policies.

The outcomes of these analyses on demand are shown in Figure G.4.

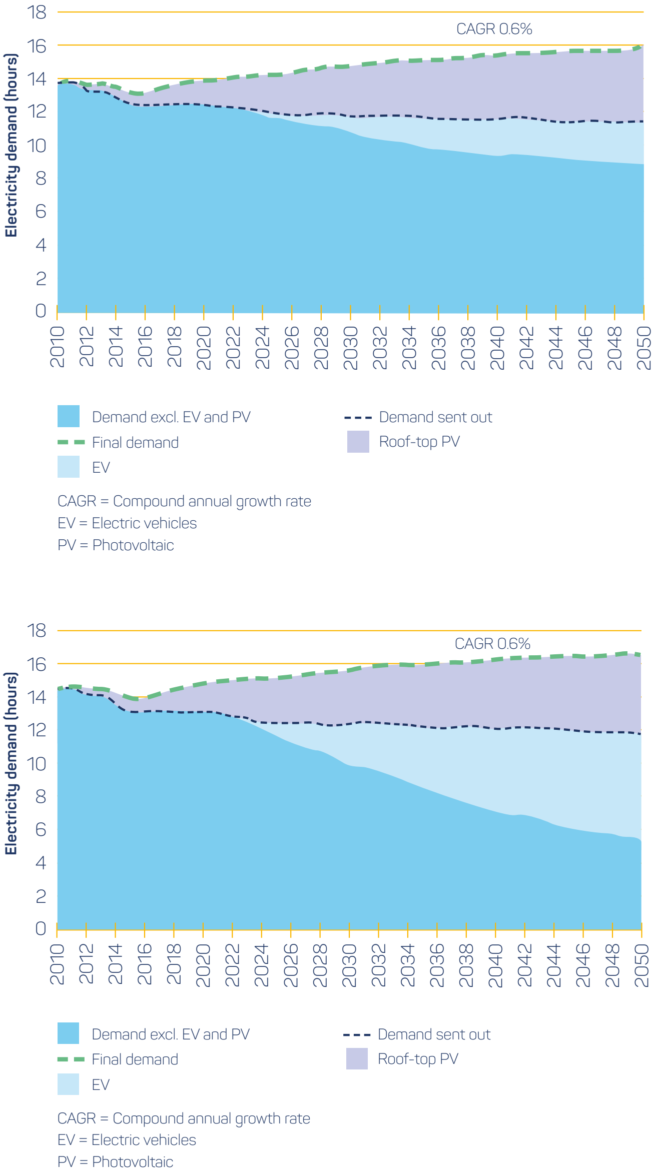


Figure G.4: Electricity demand to 2050 under the New Carbon Price (top) and Strong Carbon Price (bottom) scenarios

Source: Ernst & Young

Notwithstanding projections of a slight increase in total electricity consumption over the next decade in South Australia, the proportion of electricity that would need to be supplied from centralised generation is likely to fall. This is the outcome under either the new carbon price or the strong carbon price scenario.

The electricity demand profile in South Australia was estimated in 2030 and 2050 from data showing network demand at 30-minute intervals in each consumer category: household, business and industry for a full year.[28]

The demand that a nuclear power plant operating as a baseload facility in South Australia could meet was determined on the basis that energy from a nuclear plant would be dispatched after residential solar PV and wind generation.

EXTENT OF DEMAND FOR A NUCLEAR PLANT TO SUPPLY ELECTRICITY IN SOUTH AUSTRALIA

An average operational capacity factor for a large nuclear power plant was estimated to be 92 per cent and for a small modular reactor of 93–95 per cent.[29] That was based upon the capacity factors of modern plants operating in the USA.

Assuming the lowest cost mix of generation and a strong carbon price, the analysis showed:

- half of the annual electricity output of a large nuclear power plant
- 63 per cent of annual electricity output of a small modular reactor[30] would be dispatched within the South Australian region of the NEM.

When there was an excess of supply it was assumed that the balance would be exported to the eastern regions of the NEM through an expanded interconnector of 2000 MW capacity.

RESULTS OF ANALYSIS OF VIABILITY

The introduction of a large nuclear power plant into the South Australian region of the NEM in 2030 as a baseload plant would have an immediate impact by reducing the wholesale regional reference price of electricity in South Australia: see Figure G.5. It would be reduced by about 24 per cent, or $33/MWh, under the strong carbon price scenario.

In comparison, the introduction of a small modular reactor into the South Australian region of the NEM in 2030 would be expected to reduce wholesale prices by approximately 6 per cent, or $8/MWh.

In contrast, the integration of combined cycle gas turbine, or gas turbine with carbon capture and storage, does not have any impact on wholesale prices.

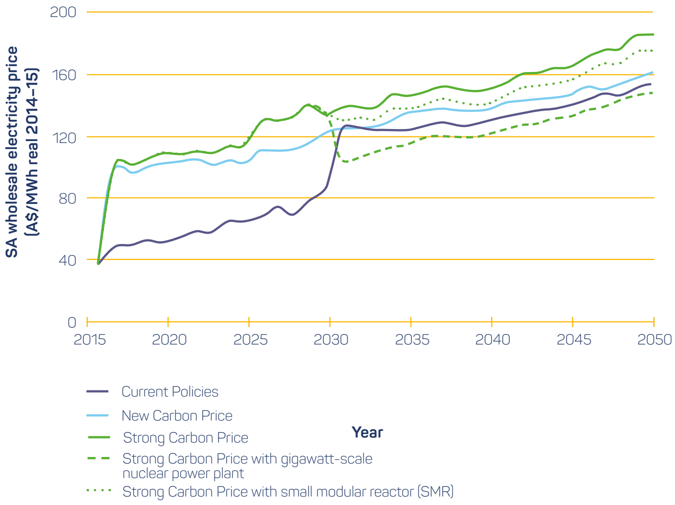


Figure G.5: Annual average real wholesale electricity price in South Australia, 2014/15 prices

Source: Ernst & Young

That is because these generators do not operate in periods of increased supply from renewables or low demand, but only operate when the wholesale price of electricity is greater than their cost of operation.[31]

Based on the annual generation output of both a large and small nuclear plant and the prevailing wholesale price, the revenues of a large and small nuclear plant were estimated. From those revenues and based on the costs discussed earlier, an analysis of profitability showed that both the small modular reactor and large nuclear power plant options consistently deliver strongly negative outcomes under either carbon price scenario on a commercial rate of return of 10 per cent: see Table G.3.[32]

An investment in a combined cycle gas turbine (CCGT) system was found to be viable under all emissions abatement scenarios irrespective of when the facility is commissioned.[33] The viability of installing CCGT with carbon capture and storage was, in comparison, assessed using a different approach that accounted for both the cost and inherent uncertainty associated with proving its feasibility. It was found that it would not be commercially viable due to the significant costs associated with proving the stability of CO$_2$ in underground geological formations.[34] This is discussed in more detail in Box G.1.

Table G.3: Profitability at a commercial rate of return (10%) for large and small nuclear power plants and combined cycle gas turbine plants commissioned in 2030 or 2050 under the new carbon price and strong carbon price scenarios (internal rates of return provided in parentheses for all scenarios)

Net present value (A$ billion 2015)	New carbon price		Strong carbon price	
Year commissioned for operation	**2030**	**2050**	**2030**	**2050**
Small modular reactor (285 MWe)	–2.2 (4.8%)	–1.9 (5.1%)	–1.8 (5.9%)	–1.4 (6.6%)
Large nuclear reactor (1125 MWe)	–7.4 (4.5%)	–6.4 (4.8%)	–6.3 (5.6%)	–4.7 (6.4%)
Combined cycle gas turbine (374 MWe)	0.22 (13%)	0.37 (14%)	0.32 (14%)	0.57 (16%)

Source: DGA Consulting/Carisway

Table G.3 also shows in brackets the internal rate of return that would correspond to the net present value of the investment being equal to zero. These internal rates of return show that a nuclear power plant would be profitable if it received finance at a cost of capital of between 4.5 per cent and 6.6 per cent. While commercial finance is not typically available at this interest rate, if a nuclear power plant were developed as a public project or received a guarantee on debt from a public institution, it might be profitable.

SENSITIVITY ANALYSIS

A sensitivity analysis reflecting a higher cost of meeting abatement goals and a lower consumer uptake of storage was undertaken based upon a higher carbon price (25 per cent higher than the base case) and a lower uptake of residential storage technologies (40 per cent lower than the base case).

This led to a wholesale electricity price (shown in Figure G.6) estimated to be 49 per cent higher in 2050 than under the base strong carbon price scenario.[35]

To assess the potential viability of nuclear power under this scenario, a comparison was made between the levelised cost of electricity of the large nuclear reactor and small reactor options and the levelised price of electricity they would receive over their lifetimes. It was assessed that if the levelised cost of electricity was lower than the levelised price of electricity, a nuclear power plant could be commercially viable in South Australia.

Even with the higher wholesale prices of that scenario, investment in a large nuclear plant would not be viable at present costs. However, as shown in Figure G.7, it might be viable if it were able to be delivered for a cost that is 8 per cent less than the current estimates set out in Table G.1.[36] The same result would prevail, at current costs, if finance could be obtained at 7 per cent: see Figure G.8.

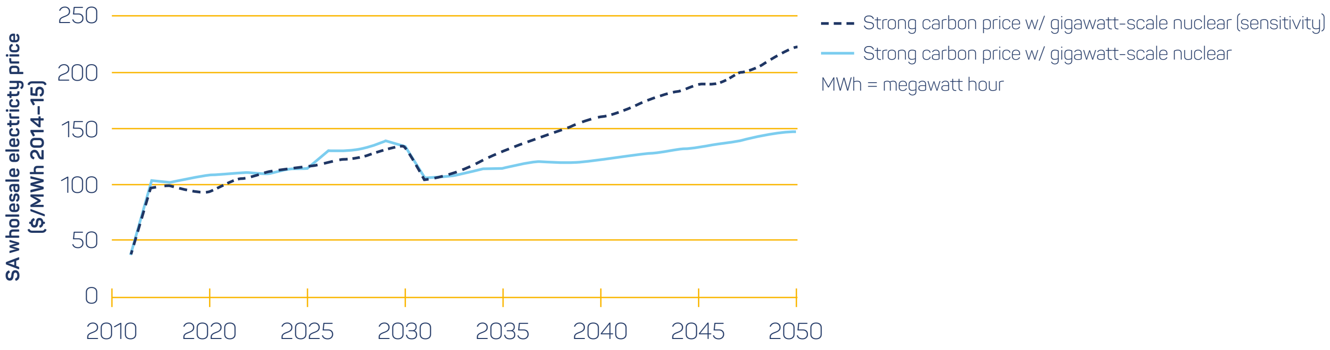


Figure G.6: Annual average real wholesale electricity price in South Australia, 2014/15 prices, Strong Carbon Price sensitivity

Source: WSP/Parsons Brinckerhoff

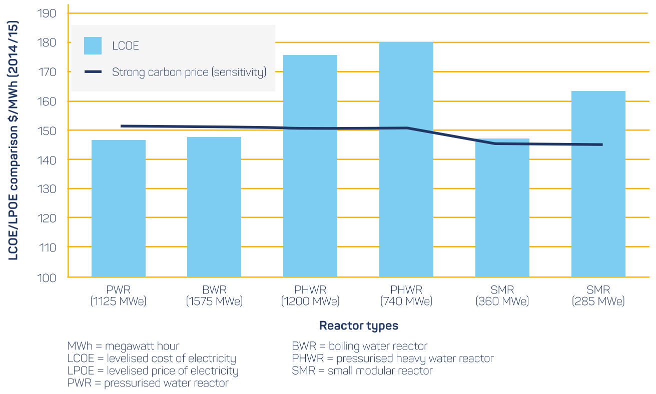


Figure G.7: Low capital cost

Source: WSP/Parsons Brinckerhoff

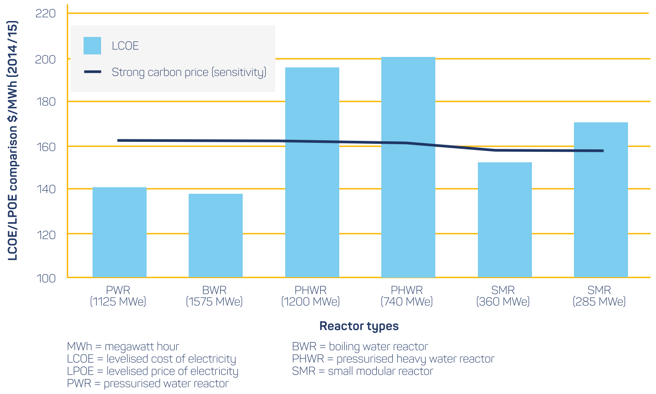


Figure G.8: Low finance cost (7 per cent)

Source: WSP/Parsons Brinckerhoff

2. ANALYSIS OF ECONOMIC IMPACTS —COMMISSIONED STUDY

Economic modelling using a general equilibrium model was undertaken by Ernst & Young to assess the potential effect on the wider South Australian economy of investments being made in either a small or large nuclear power plant. It estimated changes in key measures of economic activity such as gross state income, gross state product, wages and employment.

The modelling undertaken used the transparent, peer-reviewed model maintained by the Victoria University Centre of Policy Studies known as the Victoria University Regional Model (VURM).[41] *This model has been used widely in Australia to assess the effects of investments made in one part of the economy on economic activity more broadly.*

ASSUMPTIONS AND INPUTS

The potential macroeconomic impacts of investing in either a large nuclear power plant or a SMR (285 MWe) were assessed. Given that the business case assessments showed that investment in a nuclear power plant would not deliver a rate of return greater than the commercial benchmark of 10 per cent, for the purposes of the model it was necessary to assume that a substantial subsidy was made to fund its development.[42] It was assumed that this subsidy would only be provided for an investment in either a small or large nuclear power plant under the strong carbon price scenario in response to a government policy decision to meet aggressive emissions reduction targets by 2050.

RESULTS

The modelling analysis showed that investment in either the small or large nuclear power plant would have negative impacts on the South Australian economy between 2030 and 2050, even though there are some positive effects over the construction phase.

This negative economic impact arises because nuclear power does not offer a source of electricity generation that can deliver a commercial rate of return through private investment alone. This outcome is indeed consistent with the business case analyses, which showed that while a nuclear power plant investment does not yield a commercial rate of return under any circumstances, an investment in combined cycle gas turbine does, even under the strong carbon price scenario.[43]

The scale of the impact depends upon the extent to which funds used to develop the nuclear plant impact expenditure on other activities which themselves generate state income.

If an investment in either a large or small plant were funded such that it does not lead to reduced state government expenditure in other areas, it leads to a modest improvement to gross state product and a modest reduction in gross state income in 2049–2050: see Table G.4 and Table G.5.

This outcome arises because a significant decrease in wholesale electricity prices in the SA region of the NEM could lead to significant electricity exports through an expanded interconnector to the eastern region of the NEM: that is, SA could become a net exporter of electricity.

The effect of investment in a large plant if it did lead to reduced state government expenditure in other areas, was estimated to be a substantial decrease in gross state income (–3.6 per cent) and gross state product of (–3 per cent) in 2049–50: see Table G.4.

TECHNOLOGICAL UNCERTAINTY IN PROVING THE VIABILITY OF CARBON CAPTURE AND STORAGE

Carbon capture and storage technologies have been put forward to the Commission as having the potential to reduce the emissions intensity of fossil fuel electricity generation technologies such as combined cycle gas turbine systems. However, while the technologies to capture CO_2 from exhaust gas streams are commercially available, there are substantial uncertainties associated with the capacity of geological reservoirs to store CO_2 and the operational integrity of these reservoirs at high CO_2 injection rates. Substantial investments in research, development and demonstration activities will need to be made to resolve these challenges.[37]

To provide a consistent basis for comparing the viability of energy systems that incorporate carbon capture and storage against technologically mature technologies such as nuclear, the cost associated with demonstrating the feasibility of the technologies must be included. Not only does this assessment need to incorporate the cost of research, development and demonstration (RD&D) activities but also a risk that, even after these investments are made, the technologies remain unproven and the entire investment is lost. To date, most research and development activities in carbon capture and storage have been based on numerical modelling analyses. To validate these numerical modelling analyses there is a need for an investment of $1bn–$2bn in site characterisation, exploration and appraisal activities.[38]

If the costs and uncertainties associated with RD&D activities are incorporated into the model, a combined cycle gas turbine system that incorporates carbon capture and storage is unlikely to yield a commercial rate of return under any scenario. This is because private investors are unlikely to make the substantial investments in RD&D activities that would be necessary to prove the feasibility of this technology. This outcome arose even if a strong carbon price was imposed across the economy.[39]

This means that substantial public investment in RD&D activities would be necessary to support the development of technologies to prove carbon capture and storage for commercial deployment with fossil fuel fired power stations. An assessment of nuclear technologies has to be considered alongside the cost of proving the feasibility of unproven technologies such as carbon capture and storage.

This method of analysis is also applicable to other immature technologies such as energy storage and geothermal energy that will require substantial investment in RD&D to realise expected cost reductions.[40] If these cost reductions are not realised, there is a substantial risk that the cost of achieving emissions reduction outcomes would be higher than has been projected.

Table G.4: Impact of investment in a large nuclear power plant on the South Australian economy in 2030 and 2050 under the Strong Carbon Price scenario

Large nuclear power plant	2029–30	2049–50	2049–50 [a]
Gross state income	$486m (0.36%)	–$7178m (–3.6%)	–$594m (–0.30%)
Gross state product	$524m (0.37%)	–$6000m (–3.0%)	$201m (0.10%)
Wages	0.11%	0.50%	
Total employment	575	620	
Direct employment	330	258	

[a] Economic impact assuming expenditure on developing nuclear power plant does not impact other government expenditure.

Note: m = million

Source: Ernst & Young

Table G.5: Impact of investment in a small nuclear plant on the South Australian economy in 2030 and 2050 under the Strong Carbon Price scenario

Small nuclear power plant	2029–30	2049–50 [a]
Gross state income	$370m (0.27%)	–$68m (–0.03%)
Gross state product	$344m (0.24%)	$107m (0.05%)
Wages	–0.02%	0.14%
Total employment	540	473
Direct employment	167	120

[a] Economic impact assuming expenditure on developing nuclear power plant costs does not impact other government expenditure.

Note: m = million

Source: Ernst & Young

NOTES

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3 DGA Consulting/Carisway, *Final report for the quantitative viability analysis of electricity generation from nuclear fuels*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2016, http://nuclearrc.sa.gov.au

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5 ibid., executive summary, p. x.

6 ibid., section 2.4.1.2.

7 ibid., section 6.2.1.1.

8 ibid., executive summary, p. x.

9 ibid., section 2.4.2.

10 ibid., section 2.4.3.

11 ibid., section 2.5.

12 ibid.

13 ibid., figure 3.1, section 3.2.2, section 6.4.

14 ibid., sections 3.3.2, 3.4, 6.3.

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16 ibid., section 6.2.4.

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27 WSP/Parsons Brinckerhoff, *Establishing a nuclear power plant*, section 7.1.5.

28 DGA Consulting/Carisway, *Electricity generation*, executive summary, p. 9.

29 WSP/Parsons Brinckerhoff, *Establishing a nuclear power plant*, executive summary p. xvii, section 6.8.

30 DGA Consulting/Carisway, *Electricity generation*, section 4.6.

31 Ernst & Young, *CGE modelling assessment*, section 5.9; DGA Consulting/Carisway, *Electricity generation*, sections 5.2.2, 5.7 .

32 DGA Consulting/Carisway, *Electricity generation*, sections 6.1, 6.5.

33 ibid.

34 Ernst & Young, *Analysis of investment risks associated with exploration and site appraisal for carbon capture and storage*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2016.

35 WSP/Parsons Brinckerhoff, *Establishing a nuclear power plant*, section 7.3.3.2, figure 7.21, figure 7.23.

36 ibid.

37 Ernst & Young, *CCS investment risks analysis*, appendix A, p. 23.

38 ibid., p. 11.

39 ibid., p. 15.

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42 ibid., section 6.5

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Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

APPENDIX H: SITING SIGNIFICANT FACILITIES—CASE STUDIES

This appendix presents the findings of six case studies. Five of the studies provide details of the processes used internationally to site new radioactive waste disposal facilities and the relevant aspects of community engagement of each case. The cases are:

- the ONKALO deep geological repository in Finland
- the Konrad deep geological repository in Germany
- the cAt Project surface repository in Belgium
- the CIGEO deep geological repository in France
- the Wolsong surface and geological repository in South Korea.

The final study provides details of the approach used by Energy Resources of Australia in its engagement with Mirarr traditional owners regarding the Ranger uranium mine in Australia's Northern Territory.

Together, these case studies provide valuable lessons on community engagement when siting any future nuclear development in South Australia. The cases show that proponents made mistakes in their early engagement with the affected communities, principally addressing technical issues and paying little attention to community concerns. These initial approaches resulted in either a failure to gain consent or, where the development proceeded, as in the case of the Konrad facility, a rejection of the siting process as illegitimate or unfair by the local community.

In most of the cases, siting approaches were revised to take into consideration the concerns, rights and interests of the affected communities. These changed approaches have resulted in successful facility siting in the Finnish, Belgian, French and South Korean cases.

The case studies support discussion in Chapter 5 and Chapter 6.

CASE STUDY 1

ONKALO DEEP GEOLOGICAL REPOSITORY AT OLKILUOTO, EURAJOKI, FINLAND

ONKALO (see Figure H.1) is expected to be the world's first permanent deep geological repository for spent nuclear fuel. It is being developed in the municipality of Eurajoki, Finland. The proponent company, Posiva, was established in 1995 as the joint initiative of two Finnish electrical energy firms: Teollisuuden Voima Oyj (TVO) (60 per cent) and Fortum Power & Heat Oy (40 per cent). ONKALO is estimated to become operational in 2022–23 and will be closed (permanently sealed) in 2120.[1] Eurajoki, which is an existing nuclear community—home to the Olkiluoto nuclear power plant—provided its consent to locate the facility in the municipality. In December 2000, the Finnish Government issued a 'Decision-in-Principle' in favour of the project.[2] The closest village is 8 km from the facility area.[3] The local economy is supported by industries including agriculture, forestry and tourism.[4] Eurajoki is a popular holiday destination.[5]

Figure H.1: The ONKALO facility (foreground) with the Olkiluoto nuclear power plant above

Image courtesy of Posiva Oy[6]

Development of the project

Construction of the repository will commence in 2016 following receipt of the necessary licence in 2015.[7] The entire project timeline is shown in Figure H.2.

The Nuclear Energy Act 1987 and the Nuclear Energy Decree 1988 govern nuclear developments in Finland, and are set by parliament; other relevant regulatory decrees are set by government. Regulatory oversight is provided by the Radiation and Nuclear Safety Authority (STUK). The licensing procedure is as follows:

1. Application for Decision(s)-in-Principle, both for development approval and final disposal plan; subsequent ratification by parliament
   - environmental impact assessment (EIA) to be conducted in accordance with the Act on the Environmental Impact Assessment Procedure 1994 and the Nuclear Energy Act
   - local municipality vote (veto right)—established in the constitution and the Nuclear Energy Act
   - safety appraisal by STUK (veto right)
2. Application for construction licence—issued by government, Preliminary Safety Analysis Report
3. Application for operating licence—issued by government, Final Safety Analysis Report.[8]

Specific aspects of community engagement

Steps in the community engagement process are shown in Table H.1. Initial consultations with potential host communities commenced in 1987 following a self-selection process, which was preceded by a geological assessment by TVO. Posiva used an environmental impact assessment (EIA) process (1997–99) as a means of ascertaining community sentiment in four volunteer municipalities (Eurajoki, Loviisa, Äänekoski and Kuhmo).[9]

Posiva established proactive stakeholder engagement strategies aimed at promoting the benefits of the project to the municipalities in the knowledge that municipalities had a veto right. Posiva faced opposition from residents, councils and civil society organisations in three municipalities: Loviisa, Äänekoski and Kuhmo. There was no organised opposition in Eurajoki.[10]

Posiva sought to narrow the knowledge gap between nuclear experts and Eurajoki residents. The company linked the development of the repository to the local institutions and culture, in particular the restoration of a local mansion, and to the delivery of employment opportunities, increased tax revenues, and positive health and education impacts.[11]

Posiva was thoughtful in the way it engaged with the community and built trust in the ONKALO project.[12] Several municipal politicians played a role in overturning an earlier ban on the disposal of used fuel in Eurajoki.[13]

The role of STUK was influential in engaging with residents and other citizens, and addressing concerns about risks. 'STUK has been involved in the process from the very beginning and has been at the disposal of the citizens as an independent organisation giving information and being present when required. That has also created some confidence to citizens'.[14]

The 1999 and 2008 EIAs utilised a number of community engagement initiatives (e.g. meetings, a visitor centre, and a travelling exhibition) aimed at generating interaction with the community, soliciting resident input into project design, communicating expert knowledge and reducing misunderstandings about project risks.[16]

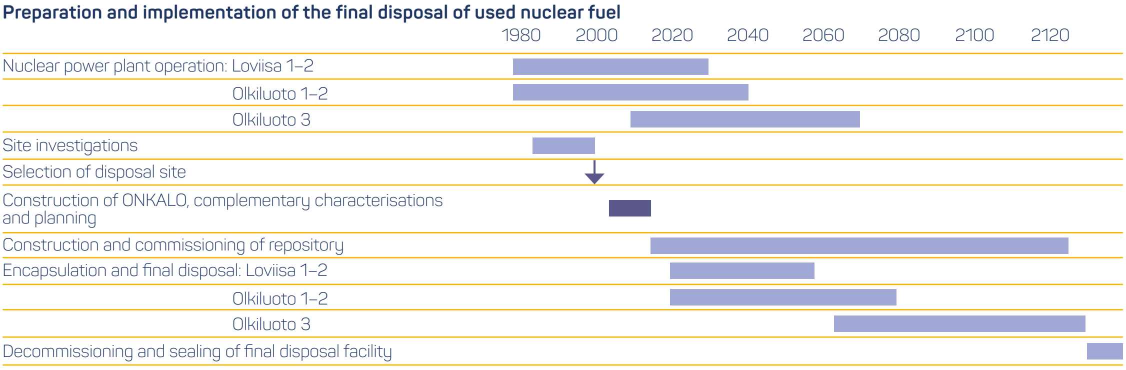

Figure H.2: ONKALO project timeline

Data supplied by Posiva Oy

Table H.1: Points at which community engagement occurred

Date	Event
Late 1980s	Liaison group established by TVO and Eurajoki
1993	Following Eurajoki council elections in 1992, National Coalition Party councillors propose engagement with TVO about hosting a spent nuclear fuel repository
1994-12	Eurajoki overturns previous ban on hosting repository
1996-02	Eurajoki opinion on the repository formed (favourable)
1997–1999	Environmental Impact Assessment process; report delivered 1999
1997-04	Posiva announces that municipal visions will be considered as part of the EIA process
1998-01-22	Vuojoki Working Party established by Eurajoki and TVO/Posiva to negotiate compensation agreement for hosting repository; 21 meetings held between 22 January 1998 and 24 January 2000
1998-12	Eurajoki's Olkiluoto Vision approved by municipal council (20 votes in favour of the repository, 7 against)
1999-05-03	Vuojoki Agreement (compensation agreement) approved by Eurajoki municipal council
1999-05-26	Vuojoki Agreement signed by Posiva and Eurajoki municipal council
Community consent: 2000-01-24	Eurajoki municipal council approves a favourable statement on the Decision-in-Principle (veto right)
2000-12-21	Government approves the Decision-in-Principle
2001-05-18	Parliament ratifies the Decision-in-Principle
2008-03 / 05	Environmental Impact Assessment process (expansion)

Sources: Kojo, Litmanen. [15]

Newsletters were the main medium through which Posiva informed the public on the development of ONKALO.[17]

Perceptions of the Eurajoki municipal council and residents about hosting a repository changed following sustained engagement between TVO (later Posiva) and the community from 1985 to 2000. The project came to be seen as part of, and emerging from within, the community.[18] Working and liaison groups between the companies and municipality contributed to changed perceptions, as did the engagement and communication tools—including language—used by Posiva to describe the development and its associated risks and opportunities.[19] For example, Posiva used the term 'final disposal' instead of 'nuclear waste' or 'spent fuel' in its communication with Eurajoki residents.[20]

Key lessons

Several key lessons emerge for community engagement practice from this case study:

- There is a need to create a sense of shared ownership in order for community consent to be obtained and maintained. Accordingly, a development has to be seen to be built from within the community.
- Public trust in the credibility of the regulatory system was crucial to residents' acceptance of ONKALO.
- Concerns about tourism, other local industries and the natural environment were not impediments to siting ONKALO.
- Due to the set timeframe for project delivery, the community (Eurajoki) was able to exercise its right to veto the development within two years of stating its favourable disposition toward the project. This meant that the community was not left with uncertainty.

Risks were discussed only in the context of assuring residents that the technical experts were competent. Posiva created a 'collective cocoon of safety' around the project.[21]

CASE STUDY 2

KONRAD DEEP GEOLOGICAL REPOSITORY IN SALZGITTER, LOWER SAXONY, GERMANY

Konrad (Figure H.3) is an abandoned iron ore mine in Salzgitter, Lower Saxony, Germany, which is being converted into a low and intermediate level waste (LILW) repository.[22] Disposal will occur in hard rock (coral oolith) at depth below –800 m, under a naturally occurring 400-metre-thick clay barrier.[23] The repository will hold 303 000 cubic metres of radioactive waste at a planned disposal rate of 10 000 cubic metres per year of operation.[24] Konrad was granted a 'plan-approval decision' (licence) in 2002, after many years of legal hurdles and community opposition.[25] In 1984, the German Government awarded German company DBE responsibility for the construction and operation of Konrad.[26] Regulatory oversight is provided by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), while the Federal Office for Radiation Protection (BfS) is the implementing agency for radioactive waste management. The economy of Salzgitter is based on industrial activity, services, culture and history.[27]

Development of the project

The licensing procedure was conducted in several stages (see Table H.2). It required consultation with the public and involvement of local authorities.[28] Technical bodies also were involved at the national and *Länd* (state) level. The licensing procedure in the Konrad case proceeded according to the processes established in a plan-approval application.[29] The German Bundestag passed a new Repository Site Selection Act in 2013, which does not apply to Konrad.[30]

Specific aspects of community engagement

The Konrad mine was first proposed by the local community as a potential site for a disposal facility following a favourable statement on its suitability by the then responsible agency, the Physikalisch-Technische Bundesanstalt.[32] However, for most of the 1970s, '80s and '90s, there was limited engagement with the host community regarding the siting of Konrad.[33]

There has been community opposition to Konrad since the site was first selected.[34] Environmental groups mobilised against Konrad due to concerns about its safety and the site selection process.[35] According to AG Schacht Konrad, a group established to oppose the repository development,

Figure H.3: The Konrad facility in Salzgitter

Image courtesy of the Federal Office for Radiation Protection

Table H.2: Konrad project timeline and points at which community engagement occurred

Date	Event
1976–1982	Konrad is examined for its suitability as a repository for low and intermediate level waste
1982-08-31	Application filed to initiate a plan-approval procedure for disposal by Physikalisch-Technische Bundesanstalt, predecessor of the Federal Office for Radiation Protection; repository plan submitted to 70 authorities and nature conservation organisations for their opinions
1983-05	Information Centre for Nuclear Waste Management opens in Salzgitter
1989	Repository plan submitted to the Lower Saxony Environment Ministry for approval
1991	Germany's Federal Administrative Court issues a directive to force the public display of the plan documents. Application documents are open for public inspection for two months; across Germany, 289,387 objections to the project are submitted
1992-09-25 – 1993-03-06	75-day public hearing on the repository proposal; objections raised by affected residents in their submissions and the statements of civil society organisations are discussed during the hearing
2000-06-14	German Government announces that the plan-approval process is complete
2002-05-22	Lower Saxony Environment Ministry grants approval for Konrad
2002–2006	Eight legal actions lodged against Konrad by communities, rural districts, churches and private individuals
2006-03-08	Lüneburg Higher Administrative Court dismisses actions and does not permit a revision; one claimant appeals to the Federal Administrative Court
2007-03-26	Federal Administrative Court upholds the Lüneburg Court's decision; the plan-approval for Konrad is effective and enforceable
2007-04-03	Federal Administrative Court rejects non-admission complaint; City of Salzgitter begins proceedings against Konrad in Germany's Constitutional Court
2007-05-30	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) commissions BfS to begin construction of the repository; opening date of 2013 announced
2008-02-21	Constitutional Court rejects legal action brought against Konrad by City of Salzgitter
2008	Approval of operating plan
2011-05-27	Announcement of Konrad Repository Foundation: €100 million (A$147.8 million) will be paid to City of Salzgitter over 35 years
2013-05-15	BMUB announces new opening date (2021), with delay due to need for mine site shaft remediation
2013-10	Construction firm DBE announces new estimated costs for Konrad. The new year for completion is announced as 2022. DBE is required to re-engineer the project to correct assumptions that were made about the project in the 1980s and '90s, and to account for scientific and technological advances, as well as amended legislative requirements

Sources: BfS, AG Schacht Konrad[31]

the project still does not have the support of the host community or the City of Salzgitter.[36]

In 2011, the German Government announced that the City of Salzgitter would receive €100 million (A$147.8 million) over 35 years (majority of funds paid by electric utilities) in return for hosting the repository.[37]

Key lessons

Several key lessons emerge from this case study for community engagement practice:

- Local confidence in the agents responsible for the site selection process was diminished following the 'top-down' siting process, which was viewed by the community as being 'unfair'.[38]
- There is a need for a formal site selection procedure, which engages with prospective host communities. Such a procedure has now been developed by Germany for the selection of a future repository site for disposal of high level waste (HLW).
- The community's perceived lack of engagement from project proponents and concerns about the repository's development resulted in legal actions being brought against the project. These actions have caused significant delays in project delivery.

CASE STUDY 3

THE CAT PROJECT SURFACE REPOSITORY IN DESSEL, ANTWERP, BELGIUM

The Belgian program for the disposal of low level radioactive waste (the cAt Project) is an integrated project for surface disposal of Category A waste (low and intermediate level short-lived waste) in Dessel, Belgium (see Figure H.4). The facility is designed to hold 70 500 m^3 of waste, and is expected to be operational in 2022.[39] Disposal will occur over an indicative duration of 50 years, with a nuclear regulatory control phase involving monitoring and surveillance to continue for 250 years after repository closure. The project integrates technical considerations with socioeconomic aspects, and is a consequence of a unique local partnership process involving the proponent, ONDRAF/NIRAS, and the host community of Dessel, which was established by the Belgian Government. Dessel has a long history with nuclear research and industry, including nuclear fuel production (all activities stopped in 2012) and storage facilities for high level, intermediate level and low level waste. Site selection was driven by community support.[40]

Development of the project

ONDRAF/NIRAS is the independent national agency (answerable to the Ministers for Economic Affairs and Energy) responsible for the management of radioactive waste and enriched fissile materials in Belgium.[41] The Federal Agency for Nuclear Control (FANC) is responsible for licensing, control and surveillance of nuclear activities, including waste management and disposal. The licensing procedure for radioactive waste management and disposal facilities is as follows:

1. licence application submitted to FANC. FANC reviews application and seeks advice of the Scientific Council for Ionizing Radiation (a body of 22 experts in nuclear safety, radiological protection and environmental protection)
2. licence application and preliminary safety advice forwarded to municipal authorities for public enquiry and advice
3. application forwarded to provincial authority for advice. International treaty consultations occur at this time

Figure H.4: Artist's impression of the proposed surface repository in Dessel after closure

Image courtesy of ONDRAF/NIRAS

4. Scientific Council for Ionizing Radiation provides final advice to FANC (veto)
5. licence granted by royal decree, countersigned by Minister for Home Affairs.[42]

Table H.3 shows the project timeline and points of community engagement.

Specific aspects of community engagement

Following the failure of site surveys in the 1980s and early 1990s to identify a repository site that had community support[44], the Belgian Government announced in 1998 that it would concentrate its site selection process for a repository on existing nuclear and volunteer communities, and involve these communities in the process.[45]

Local partnerships were established in three volunteer communities (Dessel, Mol and Fleurus-Farciennes); each partnership signed an agreement with ONDRAF/NIRAS.[46] The partnerships were required to develop technical conceptual proposals for final disposal facilities that also addressed socioeconomic considerations. Municipal councils were required to approve or reject the proposals. The Belgian Government decided final site selection based on an assessment of community consent following community council deliberation. The process resulted in the selection of the municipality of Dessel in June 2006, based on the concept developed by STOLA-Dessel.[47]

Partnerships were tasked with:

- evaluating concepts for disposal facilities integrating technical considerations (design, safety, environmental

Table H.3: The cAt Project timeline and points at which community engagement occurred

Date	Event
1998-01-16	Belgian Government announces start of process to identify location for a repository for Category A waste; Minister of the Economy tasks ONDRAF/NIRAS with overseeing this process
1999-09	Municipality of Dessel and ONDRAF/NIRAS establish the local partnership, STOLA-Dessel
2004-11	STOLA-Dessel publicly states support for siting of repository in Dessel and presents concept proposal
Community consent: 2005-01-27	Dessel municipal council unanimously endorses STOLA-Dessel proposal to develop repository
2005-04	STORA, successor organisation to STOLA-Dessel, founded
2006-06-23	Belgian Government selects Dessel, an existing nuclear community, as the location of the surface repository
2007–2011	Detailed site studies conducted
2010-03	cAt Project master plan released
2011–2012	The Organisation for Economic Co-operation and Development - Nuclear Energy Agency (OECD–NEA) reviews key aspects of the safety case at the request of the Belgian Government
2012	Safety case adapted in response to OECD–NEA's peer review questions/comments; these have been addressed by ONDRAF/NIRAS and its technical support organisations
2013-01-31	ONDRAF/NIRAS submits the adapted safety case to the Federal Agency for Nuclear Control (FANC) as part of the request for a licence to build and operate the surface repository
2013–2016	ONDRAF/NIRAS and its technical support organisations carry out additional safety calculations based on FANC's review comments
2017	*Expected date to submit safety case to the Scientific Council for Ionizing Radiation*
2018	*Expected date to obtain nuclear licence for surface disposal*
2022	*Expected date when repository is operational*

Sources: ONDRAF/NIRAS, NIRAS, OECD–NEA, STORA[43] and health) and social aspects (socioeconomic added value and ecological preconditions)

- facilitating radioactive waste management research complementary to ONDRAF/NIRAS' research
- being forums for structured project negotiation and local consultation
- communicating with local residents.[48]

The key features of the partnership process were:

- the partnership methodology was developed by researchers at two universities in consultation with ONDRAF/NIRAS[49]
- each partnership received an annual budget of ~€250 000 (A$370 000) from ONDRAF/NIRAS to cover operational, staffing and logistical costs. A one-off payment of ~€150 000 (A$222 000) was provided to develop the conceptual proposal and to conduct a socioeconomic assessment[50]
- membership of the partnerships was open to any resident, and was voluntary; neighbouring communities could observe the process[51]
- partnerships had two full-time paid staff (drawn from the ~€250 000); they had general assemblies of the membership and boards of directors, and established working groups on topics of importance to partnership members[52]
- ONDRAF/NIRAS staff were members of both the partnerships proper and the individual working groups; the agency had a veto over project safety[53]
- external experts were invited to explain and discuss many different aspects of radioactive waste management (waste characteristics, repository safety, construction, properties of engineered barriers, transport etc.)
- members of the communities could approach the partnerships with questions and they were answered[54]
- the timeframe for partnerships to develop concepts was extended by several years to allow for communities to become sufficiently aware of the proposal
- there were ongoing community engagement programs developed by the successful partnership[55]

Outcomes include:

- a successful social learning process involving knowledge transfer from experts to residents and vice-versa; because of local partnership involvement, the project became technically better and received broad support across the community[56]
- changes to the ONDRAF/NIRAS preliminary technical design proposal to include a stronger engineered control system and ongoing monitoring systems[57]
- voting of the general assembly of the local partnership and the municipal council indicated receipt of community consent. In Dessel, the general assembly of the local partnership and the municipal council expressed unanimous support for the STOLA-Dessel proposal.

The successful municipality, Dessel, established the STOLA-Dessel partnership, which comprised 76 representative members from more than 20 local organisations and ONDRAF/NIRAS. Dessel has 9250 residents, of whom 1600 are employed in the nuclear industry (including waste processing and storage, and nuclear fuel fabrication until 2012) and research (Belgian Nuclear Research Centre SCK·CEN).[58]

STOLA-Dessel's remit expired early in 2005. Recognising the need for ongoing community engagement, in April 2005 a new community–ONDRAF/NIRAS partnership, STORA (Study and Consultation Radioactive Waste Dessel), was established to oversee nuclear issues in Dessel.[59] STORA has a general assembly composed of 20 local social, economic, cultural and political organisations. There is a board of directors and three working groups ('follow-up of the disposal site', 'radioactive waste' and 'communication'). STORA receives its budget from ONDRAF/NIRAS.

In 2010, STORA and ONDRAF/NIRAS released the cAt Project master plan. Key features include:

- continuing partnership between the Dessel community and ONDRAF/NIRAS
- a multifunction community centre and theme park aimed at showcasing Dessel as a nuclear town through interactive exhibitions
- a sustainable development fund (private foundation overseen by a board of directors) with an initial capital value of between €90 million (A$132.9 million) and €110 million (A$162.5 million) to provide finance for community projects
- change to the town's zone classification to allow for housing and employment growth
- the development and long-term maintenance of nuclear knowledge within the community
- continuous environmental, safety and health monitoring, including free annual health check-ups for residents.[60]

Key lessons

This case study demonstrates the following lessons for community engagement practice:

- Local stakeholders can provide knowledge regarding socioeconomic circumstances, interests and community priorities, as well as physical and technical characteristics (e.g. local hydrogeology, monitoring and control systems), as the STOLA-Dessel partnership did when amending the initial conceptual design.[61]
    - » The regulator, FANC, was included in the learning process from the outset of the partnerships, and engaged in an active dialogue with the community. This improved the overall scientific rigour of the safety case, promoted trust among parties involved in developing and reviewing the safety case, and enhanced the effectiveness of the regulatory review process.
    - » To build knowledge and gain confidence in the long-term safety of the proposed repository requires time (from the project start in 1998 until the expected date of receiving the licence to build and operate in 2018).[62]
- The partnership process took an expansive view of the term 'stakeholder', such that neighbouring communities were able to receive information and participate as observers.
- Despite the initial challenges associated with radioactive waste management, local residents can develop highly creative and innovative solutions if a framework has been put in place that allows genuine engagement in the project design and management process.[63]
    - » The repository is being viewed by the community as an opportunity to advance community development for many generations to come.[64]
    - » Substantiating the safety case is central to community consent.[65]
- Partnerships will continue to provide input to some aspects of the broader disposal project, such as the multifunctional community centre and oversight of the sustainable development fund.

CASE STUDY 4

CIGEO DEEP GEOLOGICAL REPOSITORY IN BURE, MEUSE/HAUTE-MARNE, FRANCE

CIGEO (Industrial Centre for Geological Disposal) will be a deep geological repository for the disposal of high level waste (HLW) and intermediate level (ILW) long-lived waste in the vicinity of the village of Bure, eastern France (see Figure H.5). Once operated and closed, the repository will hold 11 000 m^3 of vitrified HLW and 110 000 m^3 of long-lived ILW waste.[66] Disposal will occur at a depth of ~500 m in clay. A key feature of the repository design (specified in law) is the ability to reverse the disposal to retrieve waste packages for up to 100 years.[67] The progressive approach to reversibility was published in a position paper in 2016.[68] The site was selected by the French Government following community consultation on the basis of its geological conditions.[69] Andra, the French National Radioactive Waste Management Agency, is responsible for developing and managing the repository in conjunction with its prime contractor,

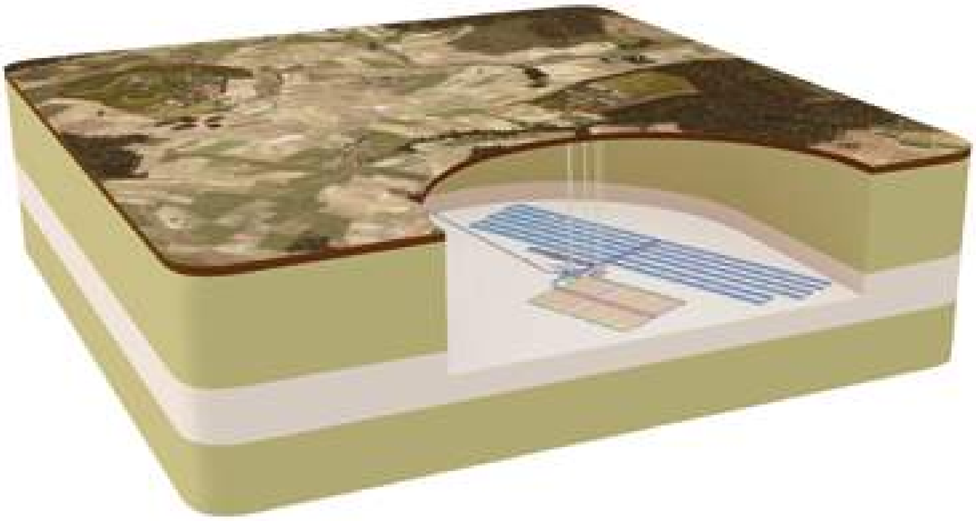

Figure H.5: Model of the CIGEO deep geological repository for disposal of high level and intermediate level long-lived waste at a depth of 500 m

Image courtesy of Andra

Gaiya—a joint venture formed by Technip and Ingerop.[70] The region hosting the facility produces cheese, among which is the world-famous 'Brie de Meaux' cheese.[71]

Development of the project

Licensing of CIGEO is an iterative process involving the regulator, the proponent, the local community and various levels of government. Table H.4 shows the CIGEO project timeline and community engagement points. Stages proceed on the basis of the results of public inquiries and the enactment of specific laws and decrees, which authorise each phase of the development.

The repository will be licensed as a basic nuclear installation (INB).[72] Licensing of INBs is granted within the framework of the decree of 2 November 2007 in application of the Transparency and Security in the Nuclear Field Act 2006 (France). The licensing procedure is as follows:

1. construction licence (authorisation decree)
2. operation licence (commissioning licence)
3. shut-down and decommissioning licences
4. end licences.[73]

Table H.4: CIGEO project timeline and points at which community engagement occurred

Date	Event
1991-12-30	Waste Act 1991 passed by the French parliament, which establishes three fields of research for the management of radioactive waste
1993-01	Siting process starts in 30 volunteer territorial administrative units
1994–1996	Andra carries out geological investigations at four volunteer sites (validated by the French Government) to identify suitable conditions for repository siting
1996-05-10	Decree 96-388 passed requiring public consultation prior to siting of nuclear installations
1997-01-05	Public inquiry into the underground research laboratory (URL) licence application filed by Andra in conjunction with three volunteer host communities
1998-12-09	French Government authorises construction of URL on the Meuse/Haute-Marne site; retrievability of waste is mandated
1999-08-03	Decree of 3 August 1999 authorises Andra to build and operate the URL in the village of Bure
1999	Local Information and Oversight Committee (CLIS) established (structure modified by the 2006 Planning Act)
2001-12	Andra submits safety file to the regulator, the Nuclear Safety Authority (ASN), for review. It was also peer reviewed under the aegis of the Organisation for Economic Co-operation and Development – Nuclear Energy Agency
2005	'Dossier 2005' released. Andra demonstrates to the satisfaction of the ASN that it is feasible and safe to construct a deep geological disposal facility on the Meuse/Haute-Marne site (1 km^2 zone)
2005-09 – 2006-01	Public debate on the management of high level waste, administered by the National Commission on Public Debate (CNDP); 13 public meetings held
2006-06-13	Transparency and Security in the Nuclear Field Act 2006 passed by French parliament
2006-06-28	Planning Act on the Sustainable Management of Radioactive Materials and Waste 2006 passed, which adopts reversible deep geological disposal for the management of HLW and long-lived ILW
2006-12-23	Decree of 23 December 2006 extends Bure URL licence until 31 December 2011
2007	Perennial Observatory of the Environment established on the Meuse/Haute-Marne site to undertake environmental monitoring for at least 100 years
2009-06	Technological Exhibition Facility (in addition to the existing visitor centre) on the Meuse/Haute-Marne site opens to public

Date	Event
2009–2010	French Government approves the 30 km^2 zone of interest proposed by Andra for studying the installation of CIGEO's underground facilities. Site location determined in consultation with community
2011	Industrial design phase for CIGEO starts
2011-12-22	Decree of 22 December 2011 extends Bure URL licence until 31 December 2030
2013-05-15 / 12-15	Second public debate on CIGEO, also administered by the CNDP
2013	Environmental baseline databank established
2013	Industrial design reviewed by ASN and the National Review Board
2015	Preliminary safety file, together with the draft master plan, filed by Andra
2015–2018	*Preliminary safety file to be reviewed by the ASN and an Act passed (before licence is granted) establishing reversibility conditions for CIGEO*
2018	*Licence application for the CIGEO project; third public inquiry to be held prior to delivery of construction licence*
2020–2021	*Construction licence of the INB delivered by the French Government; start of construction*
2025	*CIGEO is expected to be commissioned, subject to approval by the ASN*
2025-2030	*Pilot phase to prove repository design and operation*
2030	*CIGEO to start industrial operation*
2140	*Expected closure*

Sources: Andra, CIGEO, Lebon & Ouzounian, OECD–NEA[74]

Specific aspects of community engagement

Following the failure of an earlier process to identify a repository site, the French parliament in 1991 passed the Waste Act, which specified that there would be no decision on site selection for 15 years.[75] The Act also required that communities be consulted prior to any site investigations.[76]

There is no community right of veto in France. Instead, a public inquiry and debate process results in government decrees, which direct Andra to undertake specified work as agreed by the community during the inquiry process.[77] Two mandated public debates have been held (2005—national level; 2013—district and national level). Following the 2013 public debate, four requirements were added to the project concept:

- development of a pilot plant to prove disposal concept before receipt of an operation licence
- development and regular revision during the operation of the facility of an operational master plan
- schedule changes to allow for the submission of the construction licence in three stages—initial licence application (licence to create) in 2018, then the licence to operate the pilot phase in 2025 and the full licence to operate in 2030
- additional community engagement in the decision-making process[78]

In addition to these changes, the community engagement process has resulted in:

- the requirement that disposal be reversible for up to 100 years, to be clarified via the scheduled 2016 law on the subject
- Andra's plan to connect CIGEO to the national rail network to enable waste packages to be delivered by rail.[79]

A local information and oversight committee (CLIS) to facilitate community engagement was established in the village of Bure in 1999 in accordance with the 1991 Waste Act. However, CLIS is sometimes confused with the proponent, Andra, in community engagement processes.[80]

The nuclear industry in France contributes to the economic development of the Meuse/Haute-Marne districts through two community development funds: Objectif Meuse and GIP (Public Interest Group) Haute-Marne.[81] These two districts with more than 300 townships representing 380 000 residents (2006 figures) are designated as affected and are entitled to receive benefits. However, the operation of the funds is not well understood in the community (including by town mayors) and awareness of nuclear industry-funded projects is low, which has resulted in expressions of concern about the project's value to the community.[82]

Other important aspects of community engagement:

- The strict timeline for project delivery and the associated community engagement process has been criticised by the Meuse General Counsellor (also a CLIS member) for compromising residents' right to information as required by the Aarhus Convention.[83]
- As proposed following the 2013 public debate, Andra proposes to hold periodic reviews and ongoing stakeholder engagement meetings during the operational phase of the repository, according to a master plan for operations.[84]

Key lessons

The following lessons emerged from this case study:

- Proponents need to provide details of what benefits (positive socioeconomic impacts) are funded or facilitated as a result of the development.[85] CLIS and the GIPs have no formal links with each other, which means that benefits arising from the project are not communicated to affected communities.[86]
- A sustained information program is necessary to communicate benefits in order to maintain community consent for the project.[87]
- Reversibility of disposal was not a technical requirement: it emerged as a social requirement through the community engagement process.[88]
- While a strict timetable for project delivery provides for stakeholder certainty, it can also result in lower community confidence if community members believe that the process is rushed and that their voices are not being heard.
- There is a need for clear allocation of responsibilities among the involved parties and various stakeholders.
- Committed involvement of political representatives and decision-makers is required at both the local and national level.
- There is a need for a continuous assessment process for the performance of the system, based on available knowledge (for example, on waste forms and geology), engineering works and safety approaches and assessment.

CASE STUDY 5

WOLSONG LOW AND INTERMEDIATE LEVEL WASTE DISPOSAL CENTER SURFACE AND GEOLOGICAL REPOSITORY IN GYEONGJU CITY, NORTH GYEONGSANG PROVINCE, SOUTH KOREA

The Wolsong Low and Intermediate Level Waste (LILW) Disposal Center (WLDC) is a surface and geological repository located in Gyeongju City, south-east South Korea (see Figure H.6). Construction is occurring in stages: stage one (underground disposal silos at a depth of –80 m to –130 m) started operation in 2014[89]; construction of stage two (near-surface and rock cavern disposal) is ongoing.[90] The repository, which is adjacent to the Wolsong nuclear power plant, is licensed to hold 800 000 barrels (200 L each) or 214 000 m^3.[91] The Korea Radioactive Waste Agency (KORAD) is responsible for developing and managing the WLDC (answerable to the Ministry of Trade, Industry and Energy); the regulator is the Nuclear Safety and Security Commission (NSSC). Gyeongju City is a popular tourism and resort destination, and hosts sites on the World Heritage List.[92] Agriculture, manufacturing and the services industry also contribute significantly to the local economy.[93]

Development of the project

The Minister of Trade, Industry and Energy issues licences for nuclear facilities. The licensing process is as follows:

1. site selection process
2. application for construction permit
   - Korean Institute for Nuclear Safety (KINS) reviews technical files
   - NSSC approves KINS report
3. Minister of Trade, Industry and Energy issues construction permit
4. application for operating licence, which follows above procedure.[94]

Figure H.6: Conceptual model of the Wolsong LILW Disposal Center

Image courtesy of KORAD

Between 1986 and 2004, there was a single site selection process for a repository for high level waste (HLW) and LILW, which resulted in nine failed siting attempts: eight due to community opposition, one due to the discovery of an active fault.[95] However, in 2004, the process was split between the search for a site for disposal of LILW waste and the search for a site for disposal of HLW (the latter process is ongoing and is subject to the Public Engagement Commission on Spent Nuclear Fuel Management).[96]

The Special Act on Support for Areas Hosting the Low and Intermediate Level Radioactive Waste (LILW) Disposal Facility 2005 (South Korea) states that a HLW repository cannot be built in the locality that hosts the LILW repository.[97] The South Korean Government selected Gyeongju City for the WLDC based on the results of a referendum held in four volunteer cities.[98] Table H.5 shows the project timeline and community engagement.

Specific aspects of community engagement

Earlier attempts to site a repository (particularly because of the inclusion of HLW) failed due to inadequate community engagement about the risks and opportunities of the proposed facility.[100] The nine failed siting attempts were 'top-down approaches that did not involve substantial public input and explanation of relative risks and benefits'.[101]

In contrast, in 2005, the South Korean Government changed its site selection strategy. The government 'provided veto power to local residents by introducing a local referendum for the final site selection [LILW] and accepted all local communities that applied for the project as possible candidates'.[102] This raised local residents' perceptions of process fairness and strengthened perceptions about the voluntary nature of the siting procedure.[103]

The South Korean Government additionally offered a package of benefits to the successful host city in order to increase community support for the repository project. The package comprised:

- a special support fund: ₩300 billion (A$352.8 million)
- a local support fee: ₩637 500 (A$749.7) per 200 L drum disposed. A total of 800 000 drums is valued at approximately A$600 million
- community project support: ₩3.2 trillion (A$3.76 billion) to fund 55 local projects
- relocation of the head office of Korean Hydro and Nuclear Power (electric power utility) to Gyeongju City
- a proton accelerator project.[104]

Four cities (comprising the local governments and assemblies, as well as citizen/resident groups) actively campaigned against each other in order to raise resident support to host the repository and to receive the benefits package.[105]

Table H.5: Wolsong project timeline and points at which community engagement occurred

Date	Event
1986–2004	Nine failed attempts at site selection (LILW and HLW)
2004-12	Amendment of the Radioactive Waste Management Policy to separate repository site selection process for disposal of LILW and HLW
2004-12 – 2006-01	Tenth attempt at site selection (LILW); four sites identified through bid solicitation (volunteering)
2005-03	Enactment of the Special Act on Support for Areas Hosting the Low and Intermediate Level Radioactive Waste (LILW) Disposal Facility 2005, which details the package of benefits
2005-03	Organisation of site selection committee (LILW)
2005-06-16	Public notice of new site selection procedure (solicitation application; local referendums; implementation of referendum result; final candidate site selection)
Community consent: 2005-11-02	Referendums held in four cities (Gyeongju City – 89.5%; Gunsan City – 84.4%; Youngdok County – 79.3%; Pohang City – 67.5%)
2006-01-02	South Korean Government selects Gyeongju City as the repository site (LILW) on the basis of the results of the four local referendums
2008-03	South Korean Government enacts Radioactive Waste Management Act 2008
2008-08	Stage one construction and operation licence (LILW); start of construction
2009-01-01	Korea Radioactive Waste Agency (KORAD) established
2012–2019	Stage two construction (LILW)
2014-07	Stage one construction complete
2014-12	Stage one start of operation

Sources: Lee, Leem, Park[99]

Factors leading to the successful site selection and factors leading to failure in the previous attempts are elaborated below.[106]

Success factors:

- separation of LILW and HLW
- enactment of a special law for community benefits package
- free decision of the community as a result of the local referendums
- introduction of a competitive siting process
- trust in the government and regulator.

Failure factors:

- disquiet about long-term safety (risk perception)
- lack of community confidence in the proposed benefits
- lack of community participation in the decision-making process
- lack of transparency in decision making
- lack of trust in the regulator.

Key lessons

Two key lessons emerge from this case study:

- Where the community perceives the benefit from hosting a nuclear development to be greater than its perception of the risks arising from a development, it may provide community consent.[107]
  - » The South Korean Government developed a benefits package to incentivise volunteer communities.

- » The package was developed prior to the site selection process without community consultation and therefore was not viewed as a 'bribe' by volunteer cities.[108]
- The change of site selection strategy (separating LILW from HLW; establishing a community engagement and bid solicitation process) resulted in successful site selection.[109]

CASE STUDY 6

RANGER MINE AT JABIRU, ALLIGATOR RIVERS REGION, NORTHERN TERRITORY

Ranger uranium mine (Figure H.7) is located 260 km south-east of Darwin in the Alligator Rivers Region of the Northern Territory, and started operations in 1980.[110] To date, more than 120 000 tonnes of uranium oxide has been produced from processing ore from Pits 1 and 3.[111] In 2011, Ranger's operator, Energy Resources of Australia (ERA)—a member of the Rio Tinto Group—proposed investigations into the redevelopment of the open cut mine to extract the Ranger 3 Deeps resource (approximately 44 000 tonnes contained uranium oxide) via underground methods.[112] Ranger is surrounded by the World Heritage listed Kakadu National Park. The mine and the previously proposed development of the adjacent Jabiluka uranium deposit have been the focus of anti-nuclear, environmental and Aboriginal land rights campaigns since the 1970s.[113]

Development of the project

The history of Ranger and the associated proposal to mine Jabiluka is important background context to the proposed Ranger 3 Deeps underground mine.[114] Development of Ranger was recommended by the Ranger Uranium Environmental Inquiry ('the Fox report') in 1977. While the Fox report found traditional owners opposed developing Ranger, it also determined the project was in the national interest and, therefore, Aboriginal opposition 'should not be allowed to prevail'.[115] The Mirarr traditional owners were denied the right to veto Ranger under subsection 40(6) of the *Aboriginal Land Rights (Northern Territory) Act 1976*; this right exists for all other Northern Territory traditional owners whose land is subject to the Aboriginal Land Rights Act.[116]

Table H.6 shows the Ranger mine timeline.

Aware that open cut mining at Ranger would finish in 2012, ERA proposed investigations to determine the feasibility of mining Ranger 3 Deeps via underground methods in 2011.[118] ERA approved an exploration decline—a tunnel to aid characterisation of the ore body—in June 2012; this was completed in 2014.[119] ERA conducted a pre-feasibility study during this period.[120] Mirarr did not object to constructing the decline.

Figure H.7: An aerial view of the Ranger uranium mine in the Northern Territory

Image courtesy of Glenn Campbell/Fairfax Syndication

Table H.6: Ranger mine timeline and points at which community engagement occurred

Date	Event
1977	Ranger Uranium Environmental Inquiry recommends construction of the Ranger uranium mine
1978-11-03	Ranger Agreement signed enabling development of Ranger
2000-08	ERA and its owner, North Limited, are acquired by the Rio Tinto Group
2011-08-25	ERA approves $120 million to construct an exploration decline to examine the Ranger 3 Deeps resource
2012-06-14	ERA commits $57 million for a pre-feasibility study of Ranger 3 Deeps
2013-01	ERA submits 'Notice of Intent' and 'Referral' to the Northern Territory Environment Protection Authority and the former Australian Government Department of Sustainability, Environment, Water, Population and Communities
2013-03-13	Australian Government announces that Ranger 3 Deeps is a controlled action and requires assessment under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth)
2013-08	Environmental Impact Statement (EIS) guidelines finalised and issued
2013-12-07	Leach tank failure at the Ranger mine; operations suspended pending regulatory and ERA review
2014-06-05	Regulators approve restart of operations
2014-10-03	ERA submits Draft EIS for public and regulatory review
2014-12-13	Review period on Draft EIS closes
2015-06-11	ERA announces that it will not proceed to a final feasibility study of Ranger 3 Deeps
2015-06-11	Rio Tinto releases media statement withdrawing support for Ranger 3 Deeps
2015-06-12	ERA Board responds to Rio Tinto's media release, reaffirming its commitment to its approach to Ranger 3 Deeps
2015-06-12	GAC announces that Mirarr do not support any extended term of mining at Ranger beyond 2021
2015-06-22	Three independent members of ERA Board resign
2015-10-15	GAC announces that it cannot consider an extension to the Ranger Authority without the support of Rio Tinto
2015-10	ERA commissions strategic review of operations

Note: GAC = Gundjeihmi Aboriginal Corporation

Sources: ERA; Mudd, Kyle, Smith; GAC; Rio Tinto[117]

Regulatory approval for Ranger 3 Deeps was pursued according to the *Environmental Assessment Act* (NT) and the *Environment Protection and Biodiversity Conservation Act* (Cth). This process required ERA to submit an environmental impact statement with a social impact assessment component.[121]

Unlike other mines in Australia, Ranger is not subject to a mineral lease. Instead, it has an Authority to Mine under the *Atomic Energy Act 1953* (Cth). This Authority expires in January 2021, with rehabilitation required to be completed by January 2026.[122] While the initial objective was to execute the proposed Ranger 3 Deeps project within the existing Authority, ERA later commenced a process to seek an extension to the Authority in order to optimise the economics of the project.[123] This would require an amendment to the Atomic Energy Act.[124]

In June 2015, ERA announced that the Ranger 3 Deeps project would not proceed to final feasibility study in the then current operating environment and the infrastructure was placed on care and maintenance.[125] The decision was based on two principal factors: uncertain market conditions and the economics of the project requiring operations beyond the current Ranger Authority.[126] The company stated that it would revisit its economics over time.[127] The June 2015 announcement also advised ERA had commenced discussions with representatives of the traditional owners and the Australian Government regarding a possible extension to the Ranger Authority.

On the same day, Rio Tinto announced that it agreed with the decision not to progress studies on Ranger 3 Deeps and that it did not support any further study or the future development of Ranger 3 Deeps due to the project's economic challenges.[128] Following Rio Tinto's decision to withdraw its support for the Ranger 3 Deeps project, three independent ERA board members (including the chair) resigned due to disagreement with Rio Tinto about the future of the project and the difficulty for ERA to pursue its stated approach without the support of its major shareholder.[129]

In October 2015, the representative body of the Mirarr Aboriginal people—the Gundjeihmi Aboriginal Corporation (GAC)—announced that Mirarr traditional owners would not 'consider any possible extension to the Authority to mine on the Ranger Project area in the absence of support from' Rio Tinto.[130] ERA initiated a strategic review of its operations following communication from the traditional owners; this is due to finish in the March quarter 2016.[131]

Specific aspects of community engagement

The focus of the following discussion is engagement between ERA and Mirarr traditional owners.

The Mirarr traditional owners opposed operations at Ranger when the mine was first proposed in the 1970s.[132] The Aboriginal Land Rights Act specifically excluded the Ranger site from the 'right of veto' provisions contained in that Act. The Australian Government determined that Ranger should proceed as it was in the national interest. The Mirarr felt they had little choice but to agree to the Ranger Agreement, signed in 1978 between the Australian Government and the Northern Land Council[133], which sets out certain terms and conditions for the mine's operations. As a result, for at least the first two decades of Ranger's operational life, relationships between all parties were often characterised by 'acrimony', 'distrust', and 'mutual disengagement'.[134]

Following its acquisition of ERA's owner, North Limited, in 2000, Rio Tinto assumed a majority shareholding in ERA. Rio Tinto applied its community engagement framework to ERA, which has resulted in closer relationships between ERA and traditional owners and their representatives over the last 15 years[135], particularly 2008 to 2013.[136] In this period, ERA and the GAC established new dialogue channels and participated in joint initiatives on environmental and cultural heritage management.[137] ERA entered into a cultural heritage protocol with the GAC in 2006.[138] Such initiatives built trust between traditional owners and ERA, and led to cultural solutions to problems that are also technically sound.[139] ERA continues to provide cultural awareness training for all employees.[140]

Building on the improved relationship, in January 2013 ERA and the GAC signed a new Ranger Agreement. While the terms of the agreement were confidential, it established a 'Relationship Committee' to facilitate dialogue between ERA personnel and traditional owners, and granted more rights and control to the Mirarr over operations at Ranger.[141] The agreement also established the West Arnhem Social Trust, into which ERA undertook to deposit funds to improve Aboriginal social development across the Alligator Rivers Region.[142]

Over the years, ERA has developed an indigenous employment strategy, which includes flexible work arrangements, a mentoring program, workplace literacy and numeracy training, and work experience and school-based apprenticeship support for local students.[143] At 31 December 2015 approximately 13 per cent of ERA's workforce were Aboriginal employees.[144]

The Mirarr have historically refused to participate in periodic social impact assessments (SIAs) due to their belief that to do so would confer legitimacy on ERA's operations.[145] ERA has used its own social assessments (outside regulatory requirements) to identify better ways in which to engage with the community.[146] In 2013, ERA contracted social consultancy Banarra to undertake an SIA (a regulatory requirement) for the proposed Ranger 3 Deeps underground mine. The SIA determined the potential positive social impacts outweighed the negative impacts.[147] GAC Board members were consulted as part of the Ranger 3 Deeps SIA.[148]

A leach tank failure in December 2013 at Ranger set back relationships between ERA and Mirarr. In ERA's 2013 Annual Report, the then chair, Peter McMahon, acknowledged 'the incident re-awakened latent opposition to uranium mining at Ranger, and it has at least interrupted the developing trust between ERA and its community stakeholders, including representatives of the Mirarr people'.[149]

Historically, there have been conflicts within the Alligator Rivers Aboriginal communities (between Mirarr and other groups) regarding the distribution and use of Ranger benefits/royalties and claims about the definition of 'area affected'—those who are entitled to have a say in Ranger's operations and to receive benefits.[150] In 2015, ERA paid $17.9 million in royalties.[151] Despite the economic benefit associated with the Ranger operation, Aboriginal disadvantage is still prevalent in the region.[152]

Key lessons

This case study provides the following lessons:

- There is a need to enshrine community consent provisions at the start of development proposals to avoid ongoing community opposition and potential project failure.
  - » Ranger was constructed without the consent of Mirarr traditional owners.
  - » Engagement with traditional owners throughout the life of a project is essential.
  - » The personal relationships between ERA and GAC personnel, strengthened following Rio Tinto's acquisition of ERA, were crucial to improved project outcomes.
  - » ERA's experience post-2000 shows that community engagement is not a cost, but rather an opportunity.
- Mirarr traditional owners have chosen to engage with ERA through the agency of the GAC. This is not considered 'text book' community engagement practice.[153] However, Mirarr view direct engagement with the company as an unwanted social impact. This again shows that there is no one-size-fits-all approach to community engagement.
  - » Corporate community engagement frameworks do not necessarily align with Aboriginal world views. Proponents need to work with host communities and their representatives to establish culturally appropriate engagement methods.
  - » Engagement with particular community representative groups can precipitate or perpetuate cultural conflicts and disputes about the distribution of benefits.
  - » Determining the community affected and who speaks for that community is difficult and time consuming.
- ERA has found it difficult to effectively communicate the risks and benefits of its operations to traditional owners, such that their sentiment towards Ranger has not substantially changed since the 1970s.
  - » Participation in joint initiatives and adopting cultural solutions to technical problems raised Mirarr traditional owners' trust in ERA.
- There is a need for ongoing social risk and impact monitoring in the same way that environmental and safety risks and impacts are overseen and monitored.

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115 R Fox, *Ranger uranium environmental inquiry*. Second report, Australian Government Publishing Service, Canberra. 1977, p. 9.

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136 Graetz, 'Ranger uranium mine and the Mirarr (Part 2), 2000–2014', p. 144.

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Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

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APPENDIX I: SAFETY CASES FOR GEOLOGICAL DISPOSAL FACILITIES

THE SAFETY OF GEOLOGICAL DISPOSAL

This introduction to safety cases and other concepts used in demonstrating the safety of geological disposal was prepared by N Chapman and C McCombie of MCM International on behalf of the Nuclear Fuel Cycle Royal Commission.

THE GEOLOGICAL DISPOSAL CONCEPT

The concept of using deep geological formations to dispose of high activity radioactive wastes was first advocated in the 1950s by the US National Research Council[1], when a committee of scientists proposed using caverns in rock salt formations. Since then, with 60 years of global research and development, the concept has become mature, with several deep geological disposal facilities (GDFs) in operation or scheduled to begin operation in the next few years.

Geological disposal is regarded as a permanent solution to management of the most highly active and long-lived wastes from nuclear power generation and other applications of nuclear technologies, including medicine and industry.[2] It removes hazardous materials from the immediate human and dynamic, natural surface environment to a stable location where they will remain, protected from disturbance by disruptive natural processes and the activities of people.

After considerable international research, geological disposal is widely favoured by scientists. A 2008 collective statement issued by the OECD–NEA[3] states:

> *A geological disposal system provides a unique level and duration of protection for high activity long-lived radioactive waste. The concept takes advantage of the capabilities of both the local geology and the engineered materials to fulfil specific safety functions in complementary fashion, providing multiple and diverse barrier roles.*
>
> *The overwhelming scientific consensus worldwide is that geological disposal is technically feasible. This is supported by the extensive experimental data accumulated for different geological formations and engineered materials.*
>
> *Ethical aspects, including considerations of fairness to current and future generations, are important for the development of disposal programmes.*

The Council of the European Union observes[4], 'It is broadly accepted at the technical level that, at this time, deep geological disposal represents the safest and most sustainable option as the end point of the management of high-level waste and spent fuel considered as waste'. Geological disposal is the official policy adopted by many nations that have radioactive wastes to be managed.

The geological disposal concept is based on placing solid radioactive wastes in robust, multi-layered engineered packages that are then carefully emplaced in purpose-constructed openings in a GDF and sealed into place. The sophisticated engineering and operation of GDFs is very far indeed from the pejorative term 'nuclear dump' that is often to be found in the media.

Of course, the wastes and other engineered materials that are placed in a GDF will slowly degrade and even the most stable deep geological environments will eventually change with the passage of geological time. However, the hazard potential of the wastes (their capability to cause health impacts) is also decreasing as a result of natural radioactive decay, so the long-term safety of a GDF must be evaluated by detailed assessment of how all these processes are balanced. In a properly sited and constructed GDF, the long containment times and slow movement of any released radionuclides (radioactive isotopes) will ensure that no radioactive material ever enters the biosphere in concentrations that can be harmful to people in the future. This discussion looks at how safety is designed into geological disposal and how it is evaluated and presented.

RADIOACTIVE WASTES BECOME LESS HAZARDOUS WITH TIME

All types of radioactive waste are at their most hazardous at the time when they are emplaced in a GDF and for some hundreds or thousands of years thereafter. Their hazard potential decreases by the process of natural radioactive decay. Figure I.1[5] illustrates the declining hazard potential of used fuel and vitrified high-level waste (HLW) from reprocessing of used fuel (the two most radioactive and long-lived wastes destined for geological disposal) as a function of time.

The hazard potential declines by factors of many thousands over a period of some hundreds to a few thousand years. Providing isolation and containment in the GDF over this period of extremely high hazard potential is paramount and is a critical objective when siting and designing a GDF.

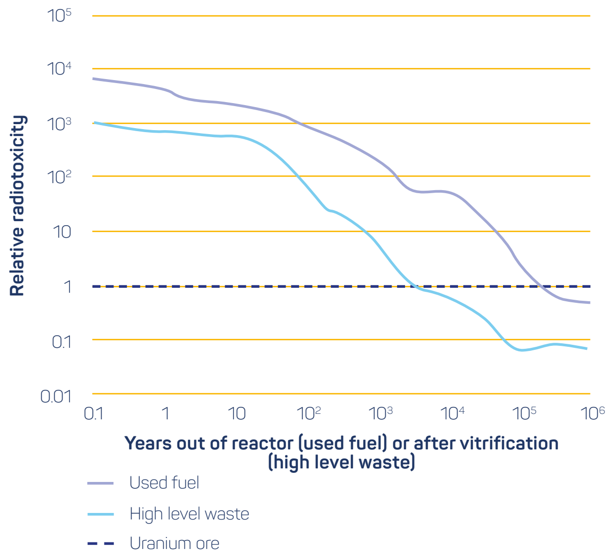


Figure I.1: Declining hazard potential of radioactive wastes over time

Data sourced from Chapman and Hooper

The figure also shows that the hazard potential of both wastes eventually declines to levels similar to natural uranium ore formations over periods from a few hundred to around a hundred thousand years. The enormous reduction in hazard potential that has occurred means that the primary isolation and containment functions of geological disposal have largely been achieved by this time, but we still need to consider the possible impacts of the residual radionuclides on people and the environment, out to around a million years. The safety analyses we discuss later thus continue to calculate risks to people for a long period after isolation and containment have done their main work and have kept the vast bulk of the radionuclides deep within the rock until they have decayed away.

BUT THE TIMESCALES ARE EXTREMELY LONG…

Hazard and safety assessment of industrial facilities is usually carried out for the period over which they are operational—for most industrial activities this would be a few decades. Although we recycle much waste material, many industrial processes leave hazardous residues that need to be collected, stored and eventually disposed of. Even though many hazardous materials do not either decay or become inert with time, radioactive wastes (whose hazard, as we have just seen, does decline with time) have attracted much attention because of the time period over which their hazard is routinely evaluated. Singling them out for such special consideration is partly because the initial hazard potential of the most radioactive wastes is so much higher than many other industrial wastes.

Thus, safety assessments of GDFs commonly look far into the future. As noted above, the engineered barriers in a GDF are designed to contain all of the radioactivity within the waste containers for at least 1000 years. Even this relatively 'short' time in the context of an overall GDF safety evaluation is long in a human perspective.

Because a GDF is no longer managed and is intentionally outside our control after its closure, it progressively becomes part of the natural environment as the engineered barriers decay and degrade by interaction with groundwater and porewater in the rock. This may take many thousands or tens of thousands of years—in some geological environments, or for some materials, even longer. Once water contacts the waste, some radionuclides will dissolve, but the partially degraded engineered barriers will continue to hinder the movement of these small amounts of radioactivity for hundreds of thousands of years. Any radionuclides that migrate into the groundwater system around the GDF will be in minute amounts and will be dispersed during slow movement through the geological environment. The objective of geological disposal is to ensure that, even many thousands of years hence, the presence of any such radioactivity in the groundwater system does not cause unacceptable health risks to future generations. What constitutes 'acceptable risk' can, of course, be a subjective matter, but those concerned with regulating radiological safety typically consider radiation doses that lead to health risks (death, or serious genetic effects) to individuals of less than one in a million per year to be acceptable. Risks less than one in ten million per year are regarded as insignificant and requiring no action to reduce or mitigate them. For comparison, the exposures that we all received from Earth's natural background radioactivity are hundreds or thousands of times greater.

Consequently, safety regulatory authorities require that the processes that occur in a GDF are comprehensively identified, fully understood and their effects then analysed in detail over periods of time out to about one million years. Going beyond the initial period of total containment in the engineered barriers, assessments quantify and model the physical and chemical evolution of the wastes and surrounding rock in considerable detail, out to around 10 000 to 100 000 years. Regulators typically expect to see best estimate calculations of releases that might occur into the biosphere from a GDF and the health impacts if people were to be exposed to the releases in this period. Beyond about 100 000 years, it is recognised that increasing uncertainties over the state of the system and the evolution of the natural environment make it unreasonable to continue with these detailed analyses and regulators often expect then to see broader indicators of the state of the system and how it might affect people and the environment. These different 'indicators' of safety are discussed in a later section, 'How else can we judge the safety provided by a GDF?'.

It can be difficult to grasp the long future timescales discussed above. One way of looking at them is to compare them with what has happened over similar time periods in the past. For example, the period over which the radioactivity of used fuel reduces to levels equivalent to uranium ore is about the same time over which modern humans spread out of their African area of origin to populate the world. A 5000-year design life for a waste container is an equivalent period to the whole of recorded human history. Going back into the past, the length of time it takes for a particular radionuclide to diffuse through just one metre of a clay formation around a GDF would take us back to the time when modern humans first appeared in Europe and the Neanderthals disappeared.

THE SAFETY APPROACH: CONCENTRATE, ISOLATE AND CONTAIN

An overarching principle of geological disposal is that we should collect and bring together highly hazardous materials to improve security and facilitate their safe management. This concentration reflects the long-held conviction that safety is best assured and environmental impacts minimised by *isolating* and *containing* the concentrated materials (see Figure I.2), with these two aims being at the core of safety guidance produced by the International Atomic Energy Agency (IAEA).[6]

A further essential aspect of geological disposal is that a GDF provides protection and safety in a completely passive manner once it has been closed—no further actions are required from people to manage the facility and the wastes, and, over immensely long times, the facility and the wastes become part of the deep, natural environment. Although the system can readily be monitored for as long as might be required, there is no burden placed on future generations to manage a GDF.

GDFs use a multi-barrier safety system, with a series of engineered and natural barriers acting in concert to isolate the wastes and contain the radionuclides present in them. The relative roles of the barriers at different times after closure and sealing of a GDF depend upon GDF design, which itself depends on the geological environment in which it is constructed. Consequently, the multi-barrier system can function in different ways at different times in different disposal concepts. Typical components of a multi-barrier system are illustrated conceptually in Figure I.2.

The manufactured components are referred to as the 'engineered barriers' and the geological formations as the 'natural barrier'.

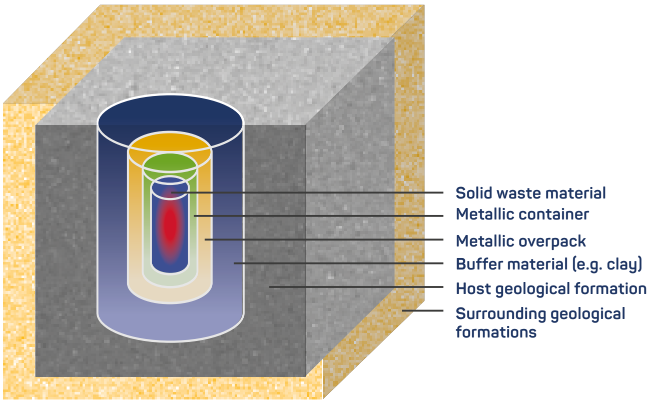


Figure I.2: Typical components of a multi-barrier system

Image courtesy of MCM International

Two principal objectives underpin GDF safety:

- *Isolation:* which ensures that the wastes have no direct contact and interaction with people and the environment. A GDF environment must be deep, inaccessible and stable over many tens of thousands of years. Rapid uplift or erosion and exposure of the waste must not occur. The site should be unlikely to be drilled into during exploration for natural resources in the future.
- *Containment:* which means retaining the radionuclides within the multi-barrier system until natural processes of radioactive decay have reduced the hazard potential considerably. For many radionuclides, GDF designs provide complete containment until radioactive decay reduces their hazard potential to insignificant levels, within or close to the waste package. However, the engineered barriers in a GDF will degrade progressively over thousands of years and lose their ability to provide complete containment. Because some radionuclides decay extremely slowly and/or are mobile in deep groundwaters, their complete containment is not possible. Assessing the safety of geological disposal involves evaluating the fate and impact of these extremely low concentrations of radioactivity that might eventually reach people and the surface environment, even though this may not happen until many thousands of years into the future.

HOW CAN ONE SHOW CONVINCINGLY THAT A GDF IS SAFE?

Proving the safety of a GDF involves understanding and demonstrating the way in which the various barriers in the GDF system provide isolation and containment. The way in which this is done has been developed over many years by the OECD Nuclear Energy Agency and the IAEA, based upon internationally accepted Safety Standards produced by the IAEA.[7] The jargon employed by specialists for the approach used is 'developing a safety case'.

To assess the safety of the GDF, it is necessary to show that the host geological environment and the engineered barriers have been selected and designed to ensure that multiple physical barriers or chemical processes (referred to as safety functions) work together to prevent releases. This provides assurance that, even if one safety function does not perform fully as expected (e.g., owing to an unforeseen process or an unlikely event), others will ensure that overall safety is nevertheless provided.

A safety function can be provided by one of the multi-barrier components of the GDF, such as the waste form, the waste package, the backfill or the host geological formation, or by a chemical property or process, such as the solubility of radionuclides in water, the corrosion rate of containers, or the dissolution rate of waste materials. Safety functions for a barrier or component in the GDF system will vary from one GDF concept to another, from time to time after closure and between different geological environments, meaning that there is not a unique set of safety functions that applies to all GDFs. Once a safety function has been identified for a GDF component, then one can lay down specific requirements on how it must work (these are called quantitative performance targets) in order to assure that it contributes as intended to increasing safety.

In designing a safe system, emphasis is usually placed on system robustness. This can be achieved by keeping the system as simple as possible—avoiding features that are poorly understood or difficult to characterise, and preferring GDF sites and designs that are insensitive to potentially detrimental phenomena (e.g., climate change or geological events).

It is important to be able to demonstrate with confidence that all the safety systems will function as intended. This is done by a mixture of physical tests and experiments, analysing the sensitivity of barrier performance to both natural variability and to uncertainties that cannot be fully removed by measurements, observations on analogous systems that represent larger physical scales, and time periods than can be addressed by testing, and by thorough and transparent scientific review by independent experts.

The arguments and evidence regarding system safety will be refined and strengthened as a GDF project progresses—that is, a safety case has to be developed progressively and elaborated. It is therefore to be expected that a project will have multiple iterations of safety case production, with different levels of formality and detail.

THE CORE OF SAFETY DEMONSTRATION: QUANTITATIVE ANALYSIS OF SYSTEM BEHAVIOUR (SAFETY ASSESSMENT)

Safety assessments are a major component of a safety demonstration. They use mathematical models to frame and describe possible mechanisms that could lead to releases of radioactivity to the biosphere, then calculate their health and environmental consequences.

Because they involve computer modelling and long-term forecasting of consequences, safety assessments are sometimes treated with scepticism. After all, they involve making forecasts of how the GDF and the natural environment could behave over many thousands of years. However, they are not aiming to make precise predictions of the future—only to scope the likely range of outcomes of what are mostly very slow processes that are rather well understood. Most scientists are entirely comfortable with modelling, which is a common method used to interpret observations (e.g., of how natural systems behave) or the results of experiments. All scientists agree, however, that the models must be structured around accepted and testable physical processes, must be built on sufficient quantities of high quality data, and must identify and capture scientific uncertainties transparently, so that we can obtain a proper feeling for the validity of model results and forecasts.

A safety assessment of a GDF will normally begin with modelling a 'reference evolution' of the system—that is, it will assume that most of the physical and chemical processes that could affect future GDF behaviour continue to operate as they do today. This analysis is then complemented by postulating various 'scenarios' of alternative ways the system could evolve:

- *Reference evolution:* This typically consists of the best estimate of scientists about how the engineered barriers, the geological environment and the surface environment will evolve after the GDF is closed. It needs to consider how heat is dispersed in the GDF and the surrounding rock, how water moves from the rock into the engineered barriers, how stresses change in the GDF, how barriers degrade and how radionuclides might be mobilised and start to migrate through the barriers. A central 'reference case' is often defined, with a number of alternatives or 'variants' reflecting different possible behaviour of some component or process. All of the cases tend to be conservative, in that they assume generally pessimistic performance of the barriers, so they would overestimate the potential releases of radionuclides and hence the health impacts of geological disposal.

- *Scenarios:* Owing to the long time periods involved, it is important to consider how the GDF might respond to mainly external or internal processes or events that are regarded as generally of low probability. These typically include natural events such as earthquake faulting, different trajectories for Earth's future climate and the possible impacts of people, who might be unaware of the presence of the GDF in the far future. Highly pessimistic 'what-if' scenarios are often modelled too, to explore how resilient the system would be if one or more of the barriers failed completely for an unknown cause, either locally in part of the GDF, or across the whole facility.

Safety assessments model a large range of conditions and outcomes and then use information generated on releases of radioactivity to evaluate possible health and environmental impacts. These can then be compared to regulatory requirements that are imposed to protect both people and other species. Inevitably, safety assessments and the ways of presenting their results—aimed at other scientists and regulatory authorities—can be extremely complex. Typical safety assessment reports comprise hundreds of pages of analysis, covering numerous variants and cases, and use multiple means of presenting the results.

WHERE DOES THIS INFORMATION COME FROM?

Demonstrating safety in the above manner requires a large amount of information about the properties of the wastes and the engineered materials in a GDF and their long-term behaviour, and about the natural environment in which the GDF is located—in particular, the characteristics of the host rock formation and the surrounding geological formations. Because forecasts are being made far out into the future, information is also required about how the natural environment (e.g., Earth's climate) could change and evolve.

Scientists have been gathering and analysing information on material properties specific to GDFs for more than 50 years by laboratory testing and by experiments carried out in deep underground laboratories in different rock formations around the world. This is supplemented by the enormous database from general materials science studies in other industries. Of course, tests are limited in duration compared to the long times considered in safety evaluations, and the information on physical and chemical processes has to be extrapolated into the future.

To give confidence in these extrapolations, scientists have turned to studies of archaeological materials (such as iron, steel, glass, copper, cement) to identify conditions that favour preservation and to verify their understanding of degradation mechanisms and rates (see the section, 'How else can we judge the safety provided by a GDF?'). Because the engineered barriers in many GDF concepts are conservatively assumed to provide complete containment for only some thousands of years, the condition of archaeological materials of similar age preserved in environmental conditions similar to the deeper underground can provide very useful information.

The second major area of information required for safety demonstration concerns the physical and chemical properties and behaviour of the geological environment. Around the world, there has been a huge effort to characterise the deep geological environment using remote sensing geophysical techniques, drilling, sampling and testing in deep boreholes, and testing and experimentation in underground research laboratories. Scientists need to know how water moves through the rocks, how the rocks respond to the hundreds of years of heat emission from some of the wastes, how excavation of the GDF openings affects the natural properties of the rocks and how contaminants from the waste might interact with the rock and move through it if they escape from the waste packages.

As a result of intensive investigations of several planned or prospective GDF sites around the world in granites, metamorphic rocks, clays and volcanic rocks, there is now a thorough understanding of all these factors, and scientists are confident that safety assessments can be based on sound principles, robust models and credible calculations.

In the same way that archaeological materials provide support to materials science investigations, the natural environment can provide support to estimates of long-term behaviour in the geological surroundings of a GDF, such as the movement of contaminants through the rock. Detailed study of uranium ore deposits, for example, provides direct evidence of the processes whereby uranium (a major component of some wastes) interacts with water in the rock and can migrate through it over millions of years, or be fixed, on or in minerals in the rock. A major international study of this nature took place in the 1980s at the Alligator Rivers uranium ore body in Northern Australia.

Gathering information on the evolution of the geological and surface environments over tens and hundreds of thousands of years, scientists begin with the well-established knowledge of geological history that shows how long the rock formations have been stable at a GDF site. Rates of tectonic processes and erosion can be established by direct observations based on a thorough understanding of the mechanisms involved in shaping Earth's surface. The overall goal is to provide evidence that conditions at depth in the rock will remain more or less as they are today for at least the next one hundred thousand or a million years.

This means that areas that are tectonically active (characterised by active faulting, nearby volcanism or rapid uplift of the rocks) need to be avoided when selecting a GDF site.

To provide the basis for scenarios, scientists will look at the recorded seismic history of a region, observations of ancient faults, and evidence for earth movement and the tectonic stresses to which an area is subjected. This allows them to develop estimates of the frequency with which earthquakes of different magnitudes might occur. Forecasts of Earth's future climate states, which affect surface conditions and might also affect deeper conditions in the rock, tend to be made conservatively, by simulating conditions that have already occurred in the last million years (global cooling during glaciations, long dry or wet, or warm or dry periods, different rainfall patterns etc.) for which evidence of their impacts is preserved in the geological environment.

Overall, there is now considerable experience in several countries in assembling all this information and using it to understand and forecast how the GDF will behave over hundreds of thousands of years and how it might affect the health of people and the environment in the distant future, many generations hence.

WHAT LEVELS OF IMPACT ARE EXPECTED?

The baseline finding of safety assessments is that a well-sited, properly constructed, operated and sealed GDF will have no health impact on people or the environment over the next million years. During that period, it will have become part of the natural environment and, in the more distant future many millions of years from now, a GDF for used fuel might be expected to resemble a deep uranium ore body in many respects.

However, safety evaluations tend to be highly conservative, taking account of all uncertainties and assuming imperfect materials or engineering, or poor properties or behaviour. Effectively, safety assessment scientists tend to focus on the more extreme scenarios in which releases of contaminants into the rock can occur and then assess how those might reach people, and in what concentrations.

The typical output of a safety assessment is thus a calculation of the rate at which each radionuclide or chemical contaminant in the wastes moves through each part of the barrier system and the rate at which those that do escape engineered and geological confinement might reach people in the future. The assumed pathway to people is often chosen to be a water-well in an aquifer above or close by the GDF. It is then possible to make simple assumptions about people's lifestyles and behaviour and calculate the radiation exposures ('doses') they could receive if they used the water from the well. This type of output is useful, because it can be compared directly to regulatory standards, which, internationally, are usually in the form of 'annual dose limits' to hypothetical individual persons who might be exposed to releases from the GDF. The word 'hypothetical' is important, because the times at which releases might be predicted to occur are many hundreds of generations, or tens of thousands of years into the future.

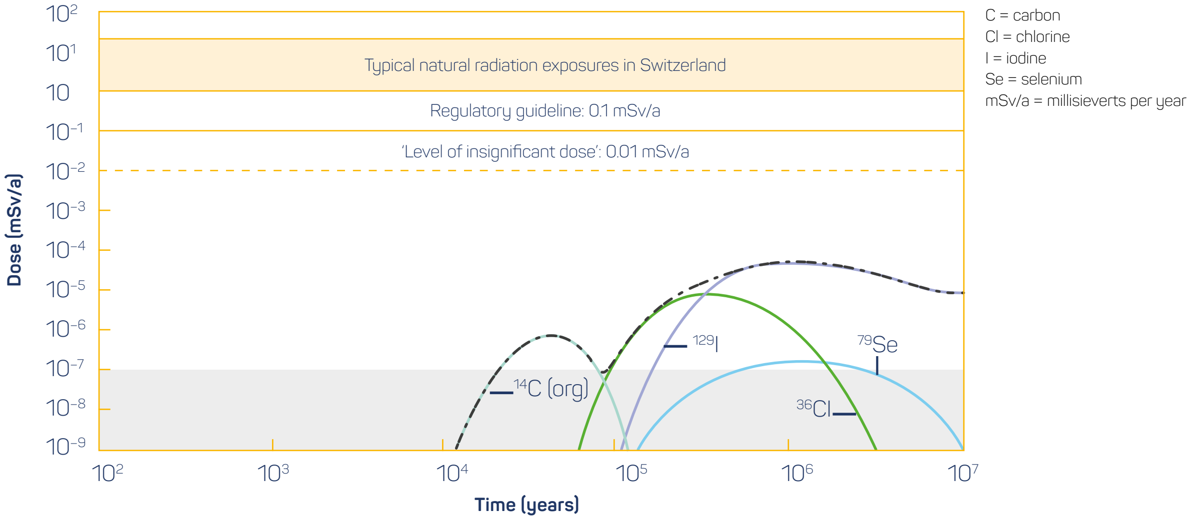


Figure I.3: Typical output of a safety assessment

Data sourced from Nagra

Figure I.3 shows a typical output of this type of safety evaluation—in this case, for the disposal of used fuel in a deep clay formation in Switzerland.[8] It shows estimated radiation doses to a hypothetical person exposed to releases from a GDF as a function of time (years) after closure of the GDF. Note that both the time and the radiation dose scales are logarithmic, meaning that each division shown is ten times larger or smaller than the previous one.

The bottom of the dose axis is a factor of one hundred billion times smaller than the top; the time axis starts at 100 years and goes out to 10 million years.

It can be seen that some releases (for example, of the most mobile radionuclides that might escape from a breached container after the initial period of complete containment) are forecast to occur after several thousand years, but the doses that they might produce are hundreds of thousands of times lower than the Swiss regulatory guideline. Regulatory standards are set so as to protect members of the public exposed to radiation from the nuclear industry and are considered to be quite conservative. For example, the regulatory limit shown on the diagram is tens of times less than the accepted annual radiation exposure limits for people working in the nuclear industry. So, with these dose limits, people are considered to be very well protected and doses very much lower than this (such as those arising from a GDF) are considered to have no impact on health.

There is some lively discussion among scientists on this last point. Some consider that any radiation dose, no matter how small, has a health impact. Others challenge this, considering that either there is a threshold, below which there is no harm, or even that some level of radiation dose has a positive effect on our immune system. In either case, the dose levels estimated to arise from a GDF are acknowledged by all scientists to be so low as to have undetectable health impacts in an exposed population—that is, if there were any impact from these extremely small exposures, we could not see it. Many scientists also point out that we live in a naturally radioactive environment and are constantly exposed to radioactivity. The human species has evolved in a background of natural radioactivity. As can be seen from the diagram, our natural exposures are tens of times (to many hundreds of times, depending on where we live) higher than the dose limits set by regulators for nuclear activities such as a GDF and hundreds, thousands or millions of times higher than doses that are estimated actually to come from a GDF in the far future.

It is easy to see why most scientists are confident that geological disposal in a suitable facility at a well-chosen site will be very safe.

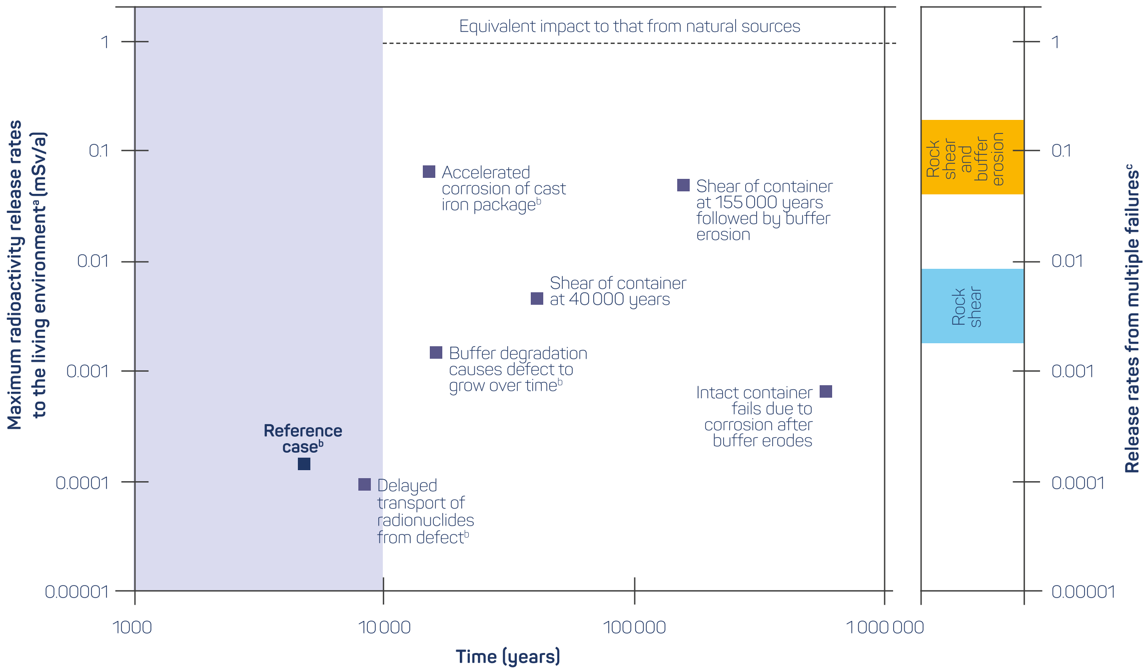
IMPACTS OF LOW PROBABILITY SCENARIOS

As discussed above, evaluating GDF behaviour only for the expected evolution is not sufficient; a safety case will also consider potentially damaging events and processes that have low probabilities of occurrence. The circumstances under which these might occur are described in the form of 'scenarios' and the potential radiological impacts are calculated, just as for the expected evolution of the GDF.

Figure I.4 shows an example of how the results of many different scenario analyses can be presented.[9]
This case is from the safety case that accompanied the construction licensing application for the national GDF for used fuel in Finland, which obtained approval from the regulatory authorities in 2015 and will be the world's first GDF for used fuel.

The diagram is quite complicated, so let's see what can be learned from it. The labelled points show the calculated peak release rates of radioactivity from failure of a single canister of fuel and the times (years into the future) at which they are estimated to occur, for a range of adverse scenarios. It uses the same type of logarithmic presentation as the previous diagram. The scenarios include rock and container shearing in a major earthquake at the GDF site, accelerated corrosion, and base used fuel canisters having undetected defects at the time of emplacement in the GDF, such that they leak immediately.

The diagram also illustrates a point made earlier about regulatory requirements. In Finland, the regulator recognises that calculating doses to hypothetical people entails increasing uncertainty with time, so it requires this detailed analysis only over the first 10 000 years. After this, the regulations are framed in terms of admissible fluxes of radioactivity to the biosphere. The dotted line shows this limit. It can be seen that, apart from the 'initially failed' base scenarios, all the scenarios evaluated have estimated peak releases that occur tens or hundreds of thousands of years into the future. All the scenarios lead to releases of radioactivity that are well below the regulatory constraints.



▨ Period dose is constrained to 0.1 mSv/a by assessment

[a] Normalised to isotope-specific limits in *STUK Guide YVL D.5*

[b] Emplacement of a defective package

[c] Weighted according to probability. Ranges arise due to variation in the number of containers assumed to have been breached by rock shear, as well as the timing of failure

mSv/a = millisieverts per year

Figure I.4: Sample presentation of results of different scenario analyses showing maximum rates of release of radioactivity

Data sourced from Posiva Oy

HOW ELSE CAN WE JUDGE THE SAFETY PROVIDED BY A GDF?

Because radiation exposure calculations focus principally on regulatory standards of dose or risk, a range of other measures has been developed to illustrate more broadly the performance of the difference barriers in a GDF and how they contribute towards safety. Some of these are based on quantitative calculations—others provide more qualitative evidence. Taken together, these 'safety indicators' can provide a fuller picture of how a GDF performs.

COMPARATIVE RADIATION EXPOSURES

The natural radioactivity that surrounds or passes through us all comprises a range of sources: cosmic radiation from beyond the Earth, radioactive gases released from rocks, soils and buildings (our biggest source of exposure) and the food that we eat (for example, coffee and nuts contain higher levels of radioactivity).

Two examples have been widely used to compare the very small calculated doses from a GDF to our natural radiation exposures.

- flying on a holiday or business trip: taking three typical intercontinental jet flights (say, 36 hours of flying) exposes us to around 0.1 mSv of cosmic radiation. This is the same as a typical dose limit we have seen, set by regulators for as the limit for releases from a GDF over a full year, and is hundreds to thousands of times higher than the actual estimated doses we have just seen from a GDF. A few minutes of high altitude flight exceeds the doses that might arise over a whole year from a GDF.
- the 'banana equivalent dose' is a rather whimsical comparison made to the radiation dose that we receive from the radioactive potassium contained in many foodstuffs (also in our own bones), and particularly in bananas. The dose from eating one banana is about 0.001 mSv. Compared with the peak dose levels from

the Swiss GDF, this suggests that the radiation health impacts over a whole year are about the same as those of eating just one banana every ten years.

CONTAINMENT PROVIDED BY EACH BARRIER IN THE GDF SYSTEM

Safety assessments typically find that over tens and hundreds of thousands of years, most of the radioactivity present in the wastes decays without moving outside the degraded waste containers and surrounding engineered barriers, or it is not released because physical and chemical processes trap it, even after the waste material itself may have dissolved and degraded. Those releases that do get into the surrounding rock formations are attenuated by various processes, including trapping in pores and on minerals in the rock, dispersion over large volumes of rock and dilution in deep groundwaters.

One way of showing these various aspects of containment is to look at where radioactivity is to be found in a degrading GDF, far out into the future. An example is shown in Figure I.5[10], for vitrified HLW disposed in a GDF located in a geological environment in which there is no effective groundwater flow in the rock formations 100 m above and below the facility. This would be representative of a thick clay formation or an environment where there are no natural gradients driving deep groundwater movement.

Examination of the diagram, which shows the total radioactivity (here expressed as radiotoxicity) present in different parts of the system at different times in the future (here, out to 100 million years), reveals a number of interesting features. First, the model has assumed that the HLW glass is completely dissolved after about 100 000 years. Before this time, almost all the radioactivity remains in the glass or in mineral precipitates formed in the engineered barriers around it. The remainder is contained with the 100 m 'natural diffusion barrier' provided by the immediately surrounded rock formations. After a few thousand years, this fraction is about a millionth of the total activity in the system—the rest is still in the engineered containment.

Radioactivity does not begin to escape into the overlying rock formations and the biosphere (labelled 'outside' on the diagram) until a million years into the future.

At this time, this partially 'released' fraction is only one ten-billionth of the total radioactivity, most of which is still inside the engineered barriers.

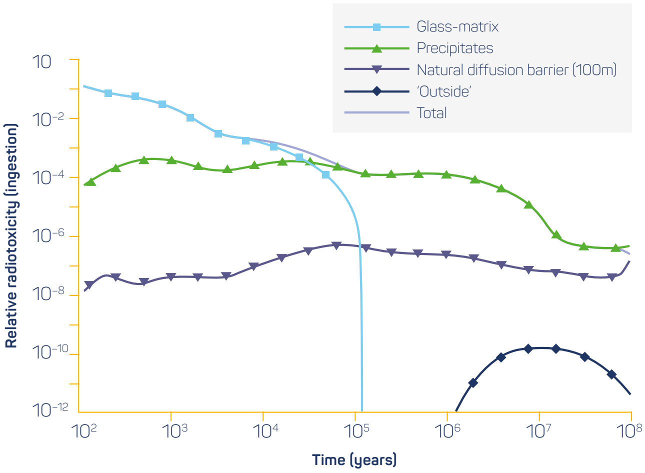


Figure I.5: Example of vitrified HLW in a geological environment free from groundwater flow

Data sourced from Apted, Miller and Smith

MIGRATION TIME COMPARED TO RADIOACTIVE DECAY RATE

As radionuclides move through the degraded engineered barriers and the surrounding rock their radioactivity is decreasing as a result of the natural process of radioactive decay that we have already mentioned. This decay in activity is different for every radionuclide and is characterised for each by a 'half-life'—the time it takes for radioactivity levels to reduce by a half. After one half-life, the original radioactivity will be reduced to a half, after two half-lives have passed, to a quarter and so on. After 10 half-lives have passed the residual radioactivity will be about one thousandth of the original activity and after 20 half-lives have passed, only about one millionth.

Radionuclides have an enormous range of half-lives. Those found in wastes in the GDF typically have half-lives from a few years up to tens of millions of years. If we take a radionuclide with a 30-year half-life (e.g., some isotopes of caesium and strontium, common in many waste types), then during 1200 years of containment in the engineered barriers, around 40 of its half-lives will have passed and natural decay will have reduced the radioactivity to around one billionth of what it was at the time of disposal. This means that the hazard potential of such short-lived radionuclides is to all intents and purposes reduced to insignificance if they can be contained for even a short period in a GDF.
In comparison, iodine has a very long-lived isotope with a half-life of more than 10 million years, so no amount of engineered containment will help to reduce its radioactivity.

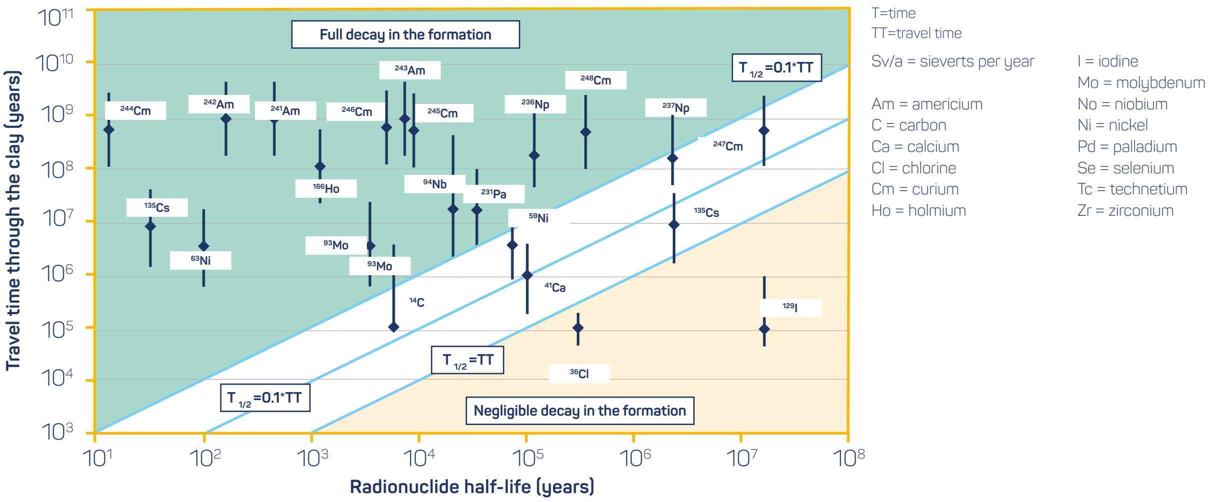


Figure I.6: Effect of containment times on radionuclides that could be found in wastes disposed to a GDF in a clay formation

Data sourced from European Commission PAMINA Project

Figure I.6[11] shows the effect of containment times on some different radionuclides found in wastes that might go to a GDF. It plots half-life against the time it would take the isotopes to diffuse through a clay formation in which a GDF might be located. All those isotopes plotting in the green area are effectively completely contained by the clay and those in the brown area would pass through the clay with largely undiminished activity.

It is clear that safety assessors will then be most interested in what happens to those radionuclides that are not effectively contained. For these radionuclides, numerous analyses have shown that safety is assured because any eventual releases from a GDF at source are initially distributed across long time periods and large spatial scales, and any radionuclides that do migrate out of the GDF are then widely dispersed and diluted by natural processes in the overlying rock formations and the biosphere before they reach people.

This means that concentrations in groundwaters when radionuclides reach the environment would be very low.

RADIOTOXICITY COMPARED TO RADIOACTIVITY IN SUBSTANCES WE USE

Another form of safety indicator is to compare the flux of radioactivity from a GDF to the biosphere with the radioactivity arising from everyday processes in which people are engaged. This is useful, given the inevitable uncertainty about future lifestyles. Figure I.7[12] shows the calculated rate of release of radioactivity from used fuel in a GDF in a clay formation in Belgium (one of the potential targets for the national GDF) as a function of time, again using a logarithmic scale. Here, radioactivity is expressed as 'radiotoxicity', the highly hypothetical radiation dose that would result if a person were to ingest all of a particular radioactive substance released from the GDF in a particular time period. The upper curve shows the total radiotoxicity from all the radioactive substances released into the environment from a GDF for used fuel in the Boom Clay. The contribution to the total made by individual radioactive isotopes (of technetium, chlorine, iodine etc.) is also shown.

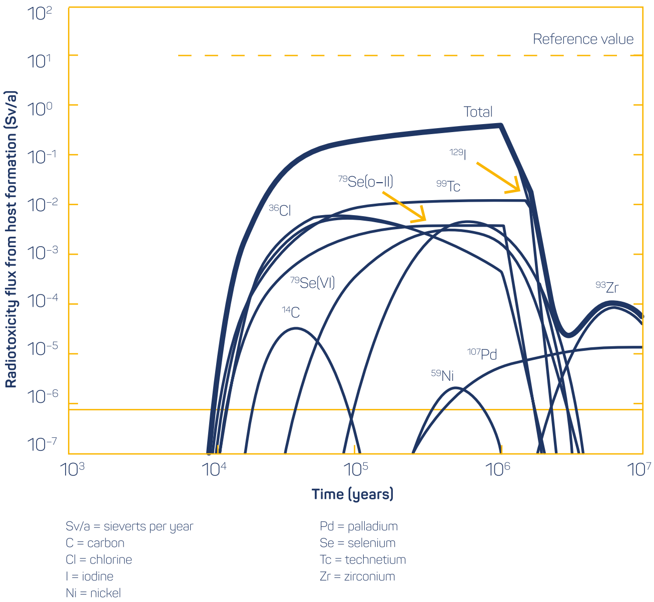


Figure I.7: Calculated rate of release of radioactivity from used fuel in a GDF in a clay formation as a function of time

Data sourced from ONDRAF/NIRAS

The 'reference value' line shows, for comparison, the radiotoxicity of agricultural fertilizers (which are naturally radioactive) that are applied on farmland in the Flanders region of Belgium: about 10 Sv/km^2 per year. A square kilometre is about the size of the GDF, so it can be seen that this is more than ten times higher than the total releases from the GDF.

NATURAL ANALOGUES

Perhaps the most compelling support for the safety case comes from ancient examples of materials that are central to the containment and isolation functions of geological disposal. Analogues of materials and processes from archaeology and from nature have been used for decades to generate quantitative, safety-related information on the nature and rates of processes such as corrosion, alteration and mobility.[13] Much useful scientific information has arisen from studying, for example, how naturally radioactive elements in deep geological systems can be mobilised by groundwater and fixed by interaction with the rock. As noted earlier for example, the Alligator Rivers uranium ore body in the Northern Territory has been extensively studied with this objective.

Another example that has often been used is the Cigar Lake uranium ore body that lies deep under the rocks of the northern Canadian Shield. Figure I.8 shows the geometry of the ore body, which lies at a depth of about 450 m beneath the surface, compared to an early Canadian concept for a GDF for used fuel, which is mineralogically similar to this uranium ore body. Both the ore body and the GDF concept feature a clay 'envelope' around the uranium—in the GDF, as one of the barriers in the system design. The depths of GDFs are also typically around 400 to 1000 m.

Cigar Lake is one of the richest uranium ore bodies known and contains around 100 000 tonnes of uranium (much larger than many national GDFs). The fascinating aspect of this ore body for GDF safety evaluators is that it has been stable for over 1000 million years and represents a potential source of mobile uranium (as does a GDF), yet it exhibits no radiometric signature at the land surface. This gives considerable confidence that, even very far into the future, an ancient GDF would be causing no radiological health impacts to people, even if they were living above it.

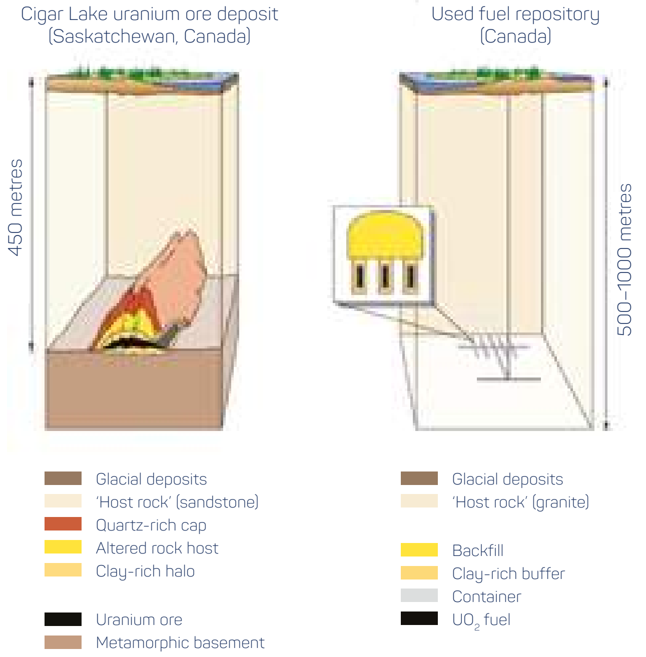


Figure I.8: Cross-section of Cigar Lake uranium ore body, Canada (left), and an early concept for a used fuel GDF (right)

Image sourced from MCM International

Figure I.9: Examples of materials preserved over long periods in conditions similar to a GDF

Photographs courtesy of British Museum, Chapman, Musée du Louvre, Nagra

Figure I.10: Site for Finland's used fuel disposal facility. Support buildings and the tunnel entrance can be seen in the foreground. Nuclear reactors can be seen in the background

Photograph courtesy of Posiva Oy

However, it is perhaps simple physical examples of the longevity of preservation of material properties that can be the most compelling, when it can be shown that the environment in which they have been preserved is analogous to deep underground conditions.[14] Figure I.9 show some examples of materials that have been studied over recent years. They include:

- Iron (the material from which many waste containers and other GDF components are made) in 1900 year-old Roman nails, found among a huge hoard of around 7 tonnes of iron objects, showing very little corrosion in the centre of the mass. In similar wet, anoxic conditions, waste containers are conservatively assumed to have lost their integrity after about 1000 years.
- Glass (analogous to some of the properties of vitrified HLW) in small, intricate, 3500 year-old Egyptian artefacts that have survived in the surface environment of soils, have been useful analogues for disposal of HLW in desert conditions in the USA, where the safety assessment conservatively assumes complete dissolution of massive glass blocks weighing hundreds of kilograms within a thousand years.
- Wood is not, of course, a component of wastes but examples of how clay formations provide excellent preservation environments for materials in a GDF are provided by 'fossil' forests in Italy and Belgium.

  At Dunarobba in Italy, 1.5 million-year-old wood is preserved in close to its natural state in a clay formation—it can still be cut and burned, like modern wood.

SO, HOW SAFE IS A GDF?

Based on the kind of evidence and studies outline in this note, scientists who have looked into the details GDF safety cases would agree that a well sited, constructed and operated GDF provides more than adequate protection of people and the environment for as far into the future as we can make reasonable forecasts.

Perhaps the most compelling argument is that, under every case and scenario analysed, the doses that might affect hypothetical people only occur in the most distant future and are so small that their effects would be undetectable among those of the natural background radiation in which we all live. We could receive considerably higher doses by spending a couple of weeks' holiday in an area with slightly higher background radioactivity or by stepping onto a short aircraft flight to a nearby town—things that we would not think twice about.

SAFETY CASE 1: FUTURE USED FUEL DISPOSAL FACILITY IN FINLAND

One of the key requirements for a 'safety case' is that it should begin with a statement of purpose. This is because safety cases are normally prepared iteratively as a disposal project proceeds through the various phases. In the Finnish case, the most recent full safety case was submitted by the waste management organisation, Posiva Oy, in 2012.

The safety case, entitled TURVA-2012, was submitted in support of the application to construct the disposal facility and in support of the Preliminary Safety Analysis Report.[15] The aim of the safety case was to show that construction could be undertaken safely and to provide a high degree of confidence that future operations and long-term performance of the facility would also be safe. The safety case was found to meet the requirements of the regulator, the Radiation and Nuclear Safety Authority (STUK), who released their own assessment of the proposal in 2015.[16] A further safety case is required in 2020 to provide additional evidence in support of the application to operate the disposal facility and in support of the Final Safety Analysis Report.[17] A safety case will also be required to close the facility once operations cease.

The information in this summary is largely extracted from the TURVA-2012 safety case, STUK's assessment of it and STUK Guide YUL D.S '*Disposal of nuclear waste*'.

OUTLINE OF PROJECT AND DISPOSAL CONCEPT

In Finland, according to law, radioactive wastes must be stored and disposed of domestically.[18] Due to the prohibition on export, any reprocessing would have to be undertaken domestically, with a facility constructed for this purpose.[19] The small volumes of used fuel make reprocessing uneconomical and do not mitigate the need for a geological disposal facility.[20] As a result, Posiva has collaborated with the Swedish waste management organisation (SKB) to develop the KBS-3 multi-barrier solution for the disposal of used fuel in crystalline rock.[21] The crystalline rock that underlies Finland is part of the Fennoscandian Shield, which dates to Precambrian times.[22] This forms the geological barrier in the KBS-3 concept. The other barriers are engineered.

As part of a consent-based siting process, a site at Olkiluoto (Figure I.10) was chosen for the geological disposal facility. The facility will accommodate up to 9000 tonnes of heavy metal (tHM) of used fuel in 4500 containers.[23] This encompasses used fuel from the nuclear power plants as Loviisa and Olkiluoto, as well as foreseen wastes from additional reactors under construction or planned for Olkiluoto.[24]

The KBS-3 multi-barrier system (Figure I.11) involves placing the used fuel in cast iron canisters, which are then placed into larger copper containers.[25] The reference concept for Finland is to emplace the containers into vertical holes drilled in the tunnel floor, surrounded by a buffer of compacted bentonite clay.[26] However, horizontal emplacement is also being considered.[27] The tunnels themselves will be located 400–450 m underground (Figure I.12).[28]

Each of the barriers has its own role in contributing to the long-term safety of the used fuel. These are addressed in Table I.1.

Underground facilities for the disposal of low and intermediate level wastes already operate alongside the nuclear power plants at Loviisa and Olkiluoto. Nevertheless, low and intermediate level wastes that arise from packaging the used fuel will be emplaced in the geological disposal facility, but at a shallower depth.[29] Some 1500 cubic metres of low and intermediate level waste is expected to arise from operating and decommissioning the used fuel packaging plant.[30]

SAFETY CASE REQUIREMENTS

The Finnish regulator (STUK) addresses the need for a safety case in its official guidance on the disposal of radioactive waste—STUK Regulatory Guide YUL D.S, '*Disposal of nuclear waste*'. The guide states that the purpose of the safety case is to demonstrate long-term safety and the suitability of the disposal method and site.[31] The safety case needs to include an analysis of different scenarios, such as those involving any resulting radiation dose and, wherever possible, the probability of unlikely events.[32] The safety analysis will become more comprehensive as the program progresses,

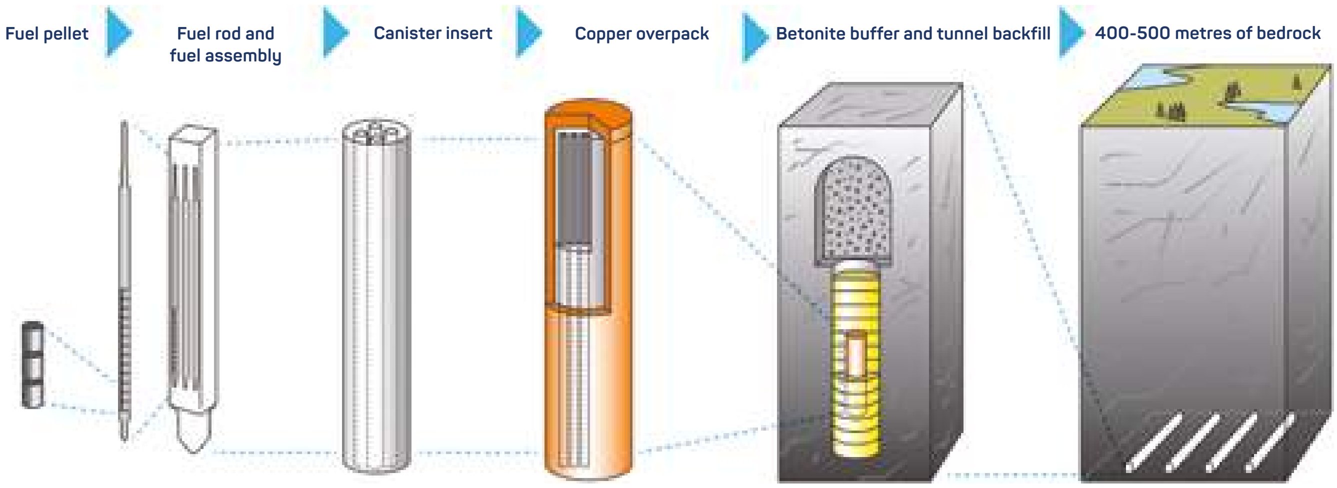


Figure I.11: The KBS-3 concept for the disposal of used fuel in crystalline rock

Image courtesy of Posiva Oy

Table I.1: Safety barrier system for used fuel disposal (reference case)

Barrier	Safety function
Ceramic used fuel in metal cladding	No assigned safety function
Cast iron canister and outer copper container	Containment • Provides mechanical strength and protects the used fuel from pressures in the host rock • Provides high corrosion resistance and delays exposure of the used fuel to groundwater ingress
Buffer of bentonite clay	Containment • Provides conditions that are predictable and favourable to the container • Protects container from corrosive conditions and hinders movement Isolation • Swells on contact with water and provides chemical conditions that limit and retard radionuclide movement in the event of a container breach
Tunnel backfill	Containment • Contributes to the mechanical strength of the rock near the disposal tunnels • Provides conditions that are predictable and favourable to the buffer and container Isolation • Provides conditions that limit and retard radionuclide movement in the event of a container breach
Host rock (geological barrier)	Containment • Provides conditions that are predictable and favourable to the engineered barriers Isolation • Protects against access and distances the waste from surface conditions (including future changes) • Limits and retards any release of radionuclides from the facility
Closure	Containment • Provides conditions that are predictable and favourable to the other engineered barriers by preventing preferential water flow pathways Isolation • Protects against access and distances waste from surface conditions • Limits and retards inflow of water • Limits and retards any release of radionuclides from the facility

Source: Posiva Oy

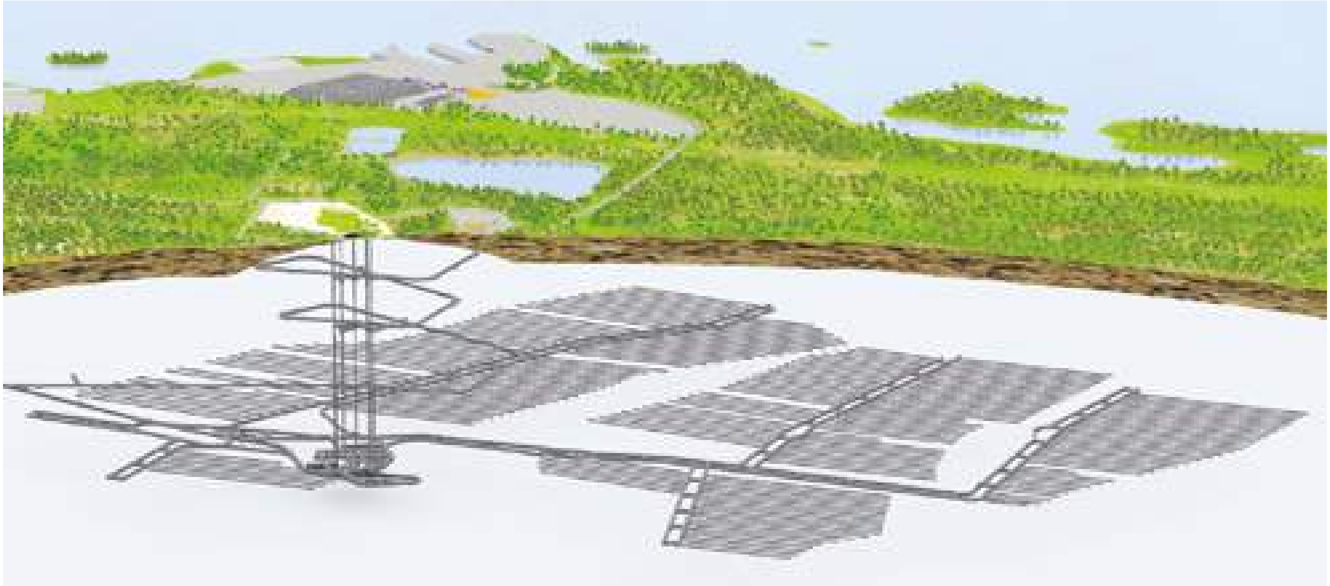


Figure I.12: Illustration of the geological disposal facility

Image courtesy of Posiva Oy

with a preliminary safety analysis report required at the construction licence stage and a final safety analysis report required at the operating licence stage.[33]

The safety analysis must demonstrate that doses to a person in the most exposed group of people, who are self-sustaining and live near the site, would remain below:

- 0.1 millisievert per year (mSv/a) from anticipated operations and from the expected evolution of the disposal facility
- 1 mSv/a in the case of a postulated accident that could occur more frequently than once every thousand years
- 5 mSv/a in the case of a postulated accident that could occur less frequently than once every thousand years.[34]

The dose to other persons must remain insignificantly low, being one to 10 per cent of that for a person in the most exposed group.[35] These constraints apply at least over several millennia.[36] Over the longer term, radiation impacts can only be, at a maximum, equivalent to those arising from natural radioactive materials in the Earth's crust.[37] Constraints for the release of radionuclides from the geosphere (non-living environment) into the biosphere (living environment), whether or not it results in a dose to a person, are specified for this purpose and based on the type of radionuclide.[38] Similarly, the disposal facility must not have a detrimental impact on species of animals or plants.[39]

The regulatory guidance requires that a multi-barrier system be used, so that deficiency in an individual safety function will not cause system failure.[40] It requires consideration of the following safety functions for the geological barrier:

- stability and water tightness
- low groundwater flow and favourable chemistry
- retardation of radionuclide migration
- protection against natural phenomena and human actions, including earthquakes, climate change and borehole drilling.[41]

The following safety functions should be considered for the engineered barriers:

- immobilisation of radionuclides in a waste matrix
- corrosion resistance of the waste container
- mechanical strength of the waste canister
- the ability of the buffer to contain radionuclides and dampen minor rock movement
- the ability to maintain the functionality of other barriers and limit radionuclide migration through excavated regions.[42]

ROLE OF GEOLOGY TO SAFETY

The host geology is located at Olkiluoto, western Finland, in crystalline rock. The site has natural isolating characteristics including[43]:

- a tectonically stable location in the Precambrian Fennoscandian Shield, away from active plate margins
- sparse fractures, low groundwater flows and chemically reducing conditions that will limit the movement of radionuclides—these chemical conditions are not particularly corrosive
- no natural resources, reducing the risk of human intrusion.

The properties of the site have been investigated for more than 25 years.[44] The extensive program of site investigation shows that:

- the crystalline rock is safe for construction and for disposal of used fuel. Various types of crystalline rock, including granite, are present. As a result, its mechanical and thermal properties are not the same in all directions[45]
- although minor seismic activity may occur, large earthquakes leading to broken disposal packages are not expected.[46] Finland is one of the most seismically stable parts of the world.[47] Historical data and measurements show the Olkiluoto site is located in a zone of low seismicity, located between two more seismically active belts.[48] Super blocks, of some several kilometres squared in size, formed in the region a long time ago and move separately from each other.[49] Consequently, the blocks are not susceptible to internal fracture
- low groundwater flows will limit the movement of radionuclides. The flow is naturally slow between fractures at this depth with a hydraulic conductivity of 3×10^{-11} m/s (which equates to 1 mm/a).[50] The chemical reducing conditions, which are not particularly corrosive, will further limit the transport of any radionuclides in the groundwater[51]
- that future climatic and meteorological conditions will not adversely affect the site. Based on investigations of previous glaciations in the area, eight glaciations in the next million years, including one glaciation in the first hundred thousand years, are assumed for the future.[52] Site investigations of previous glaciations show that the frozen zone from the glaciations is highly unlikely to reach the disposal depth.[53]

In addition, complementary evidence has been identified by Posiva to enhance confidence in the performance of the geological barrier. This includes evidence that multiple ore bodies in equivalent geology in the Fennoscandian Shield have been isolated for even longer periods in the past than those required for isolation of used fuel in the geological disposal facility.[54]

ROLE OF ENGINEERED BARRIERS TO SAFETY

The engineered barrier system will use the KBS-3 concept, which was developed in conjunction with the Swedish nuclear waste management organisation, and has features that support containment and isolation, including[55]:

- used fuel, in solid, ceramic form[56]
- a cast iron canister inside a copper container, providing containment over very long time frames—copper is not easily corroded by conditions in the Fennoscandian Shield[57]
- compacted bentonite clay, which surrounds the container.[58] The clay restricts moisture entry by swelling on contact with water.[59] It also makes the local chemistry less conducive to corrosion and the absorption of radionuclides, making them less mobile. The clay can provide isolating properties over geological timeframes[60]
- backfill of underground openings to help restore the site to natural conditions.[61]

The extensive program of research, development and demonstration, which has been conducted over 30 years, shows that[62]:

- radionuclides will be released slowly from the solid used fuel in the event of canister failure; however, no safety functions or performance requirements were assigned to the solid used fuel matrix[63]
- copper containers and inner cast iron canisters can remain intact for a long time.[64] Over the first 10 000 years, the depth of copper corrosion is negligible.[65] More challenging conditions for corrosion may result in wall loss of a few tenths of a millimetre over one million years.[66] The containers will be sealed using a high quality welding technique (friction stir welding) and inspected such that only containers with complying seals will be disposed of[67]
- The buffer of bentonite clay restricts corrosion of the container and can limit the mobility of radionuclides over a very long timeframe.[68] The interaction of bentonite clay with ordinary cement, which is not planned for use, is the main way the buffer's isolating properties can be compromised.[69] Pessimistic assumptions on the density of the emplaced bentonite and groundwater flow have been taken into account.[70] In the event groundwater with unfavourable properties reaches the disposal depth, chemical erosion of the buffer may lead to failure of a few tens of canisters (out of 4500) within a million years.[71]
- Degradation of the hydraulic plugs used to backfill the disposal facility will not lead to the formation of preferential pathways for water migration.[72]

Complementary evidence to enhance confidence in the engineered barrier system includes the observation that copper can contain wastes for hundreds of thousands of years, as copper in the Fennoscandian Shield has retained its elemental (native) form over longer periods in the past.[73] Similarly, archaeological artefacts made of copper and subject to harsher conditions than expected in the disposal facility show that pitting and other localised corrosion mechanisms are not likely to significantly affect the lifetime of the copper containers.[74]

RISK ASSESSMENT UNDER POTENTIAL FUTURE SCENARIOS

The potential future impacts of the disposal facility are assessed under a range of future scenarios, namely:

- the reference scenario, where the multi-barrier system performs as expected
- sensitivity cases, where the impact of different assumptions and uncertainties are tested
- what-if cases that are chosen to represent the impacts of unlikely events
- complementary cases to provide additional confidence in the risk assessments.[75]

Posiva addresses risks using a performance assessment, which evaluates the risk of radionuclides migrating from the geosphere (the non-living environment) into the biosphere (the living environment), as well as from the biosphere to people, plants and animals. If the engineered barriers perform as expected, no radionuclide releases are expected for at least 100 000 years.[76] However, deviations from the expected performance of the barriers may lead to small radionuclide releases.[77]

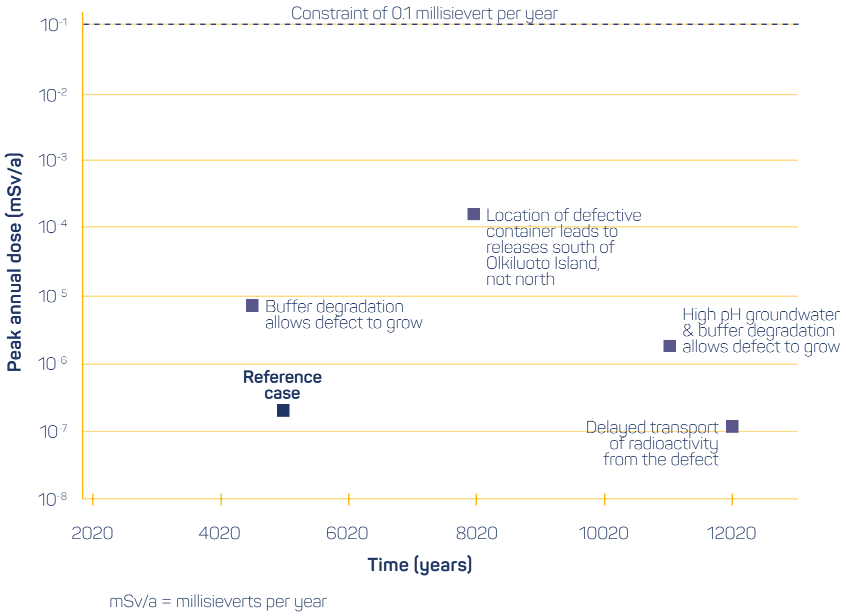


Figure I.13: The annual dose maxima to a representative person within the most exposed group for the scenarios calculated in the synthesis report. The scenario includes the emplacement of a defective canister

Data sourced from Posiva Oy

The overall performance assessment is based on the results of three separate categories: baseline scenarios, variants of the baseline, and disturbance scenarios (Table I.2).

Figure I.4 shows the collective results of radionuclides entering the biosphere under the different scenarios, consistent with regulatory guidance. The worst cases for release of radionuclides from the geosphere into the biosphere arise from accelerated corrosion scenarios, or from a combination of events, namely, where disposal containers are sheared by a seismic event and followed by degradation of the buffer from the ingress of water. It can be seen that peak releases are higher after there has been sufficient time for radionuclides to migrate from the disposal location to the biosphere. These values decrease as radioactive decay takes place, limiting the amount of released radionuclides. In all cases, the releases are below the regulatory constraint by about an order of magnitude or more, suggesting multiple container failures can be tolerated.[78]

Figure I.13 shows the corresponding doses to people in the first 10 000 years based on these release rates. During this time, peak doses arise from variants of the baseline scenario. The data represents a person in the most exposed group of people, who are self-sustaining and consume food from the immediate surroundings of the site.[79]

Table I.2: Scenario categories evaluated in the performance assessment

Most likely lines of evolution	Unlikely events or processes
• *Base scenario–* The performance targets of safety functions are met with incidental deviations from target values • *Variant scenarios–* Substantially declined performance of safety functions	• *Disturbance scenarios–* Long-term safety impaired by unlikely events or processes

Source: Posiva Oy

The highest dose results from emplacement of a defective container in a location with relatively unfavourable conditions compared to other deposition holes, leading to releases south of the present day Olkiluoto Island. In all cases, the annual doses to a person in the most exposed group of people and to others are orders of magnitude below the regulatory constraint of 0.1 mSv/a.[80]

In addition to these cases, the impacts of rock shear leading to container failure(s) 200 years after closure of the facility and of inadvertent intrusion by borehole drilling have been analysed. The dose to a person in the most exposed group from the rock shear is approximately 3 mSv/a.

When taking into account the probability of that occurrence, the dose is below the 0.1 mSv/a regulatory constraint.[81]

The dose to a person in the most exposed group from drilling into a waste container 1000 years after closure of the facility is about 0.003 mSv/a, which is an order of magnitude below the regulatory constraint.[82] An assessment of drilling between 200 and 1000 years after closure has not been undertaken.[83]

The conclusions drawn by the regulator, STUK, in review of the safety case were:

- Based on the review, the safety case is sufficiently reliable at the construction licence stage. However, before the operating licence application can be submitted, the performance and safety analyses require improvement, and the safety case needs to be modified in order to increase reliability.
- In the safety case, Posiva does not always clearly express its position on matters related to safety or justify the choices made. In the future, Posiva must present its conclusions and their rationale more clearly.[84]
- Overall, STUK found there was a high probability that the geosphere release rates and annual doses to people in the future would fall below regulatory constraints.[85]

SAFETY CASE 2: FUTURE USED FUEL DISPOSAL FACILITY IN SWEDEN

One of the key requirements of a 'safety case' is that it should begin with a statement of purpose. This is because safety cases are normally prepared iteratively as a disposal project proceeds through the various phases. In the Swedish case, the most recent full safety case was submitted by the waste management organisation, SKB, in 2011.[86]

The safety case, called a safety report, was submitted in support of the application to construct the disposal facility. The aim of the safety case was to show that construction could be undertaken safely and to provide a high degree of confidence that future operations and long-term performance of the facility would also be safe.

The safety case is being reviewed by the Swedish Radiation Safety Authority (SSM), which is presenting preliminary outcomes as they become available, including that the 'most suitable' site has been chosen based on preconditions for a volunteer municipality.[87] The SSM will present a consolidated interim assessment to the Land and Environmental Court in 2016 and a comprehensive final assessment to government in 2017.[88] The safety case will be updated by SKB prior to construction.[89]

Figure I.14: Aerial photo overlain with artist's impression of the site for Sweden's used fuel disposal facility. The surface facilities will be clustered near the cooling water channel to the nearby nuclear power plant

Image courtesy of SKB

Figure I.15: Sweden's used fuel disposal facility will be located near the nuclear power plant (the white buildings shown in the background)

Image courtesy of SKB

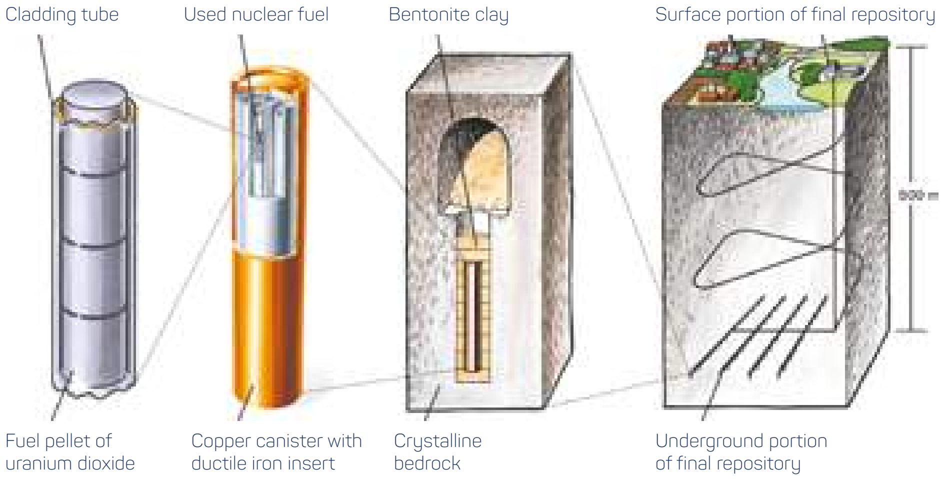


Figure I.16: The KBS-3 concept for the disposal of used fuel in crystalline rock

Image courtesy of SKB

A further safety case is required to provide further confidence in support of the application to operate the disposal facility.[90] A safety case will also be required to close the facility once operations cease.

The information in this summary is largely extracted from the safety case and the accompanying licence application and environmental impact statement.

OUTLINE OF PROJECT AND DISPOSAL CONCEPT

In Sweden, the owners of the nuclear power plants are legally required to safely dispose of their used fuel.[91] The waste must be disposed of domestically, if this can be done safely.[92] Research on a disposal solution for used fuel commenced at the end of the 1970s, leading to the development of the KBS-3 concept in 1983.[93] Finland subsequently adopted the KBS-3 concept for its disposal program and shared in its research and development.[94]

As part of a consent-based siting process, a site at Forsmark was chosen for the geological disposal facility (Figure I.14 and Figure I.15). The crystalline granitic rock that underlies the site is part of the Fennoscandian Shield, which dates back to Precambrian times.[95] This forms the geological barrier in the KBS-3 concept. The other barriers are engineered.

The facility will accommodate up to 12 000 tonnes of heavy metal (tHM) of used fuel in 6000 containers.[96] This encompasses used fuel from the two closed and 10 operating reactors in Sweden.[97] The last of these reactors will cease operating in 2045.[98]

The KBS-3 multi-barrier system (Figure I.16) involves placing the used fuel in cast iron canisters, which are themselves placed into larger copper containers.[99] The reference concept for Sweden is to emplace the containers into vertical holes drilled in the tunnel floor, surrounded by a buffer of compacted bentonite clay.[100] However, as with Finland, horizontal emplacement is also being considered.[101] The tunnels themselves will be located 457–470 m underground (Figure I.17).[102]

Each of the barriers has its own role in contributing to the long-term safety of the used fuel. Although the barriers are the same as for the facility planned for Finland, there are slight differences in how the safety roles have been assigned.[103] The primary function of the barriers is to contain used fuel within the containers, and secondary functions are to retard any potential releases of radionuclides from the geosphere.[104]

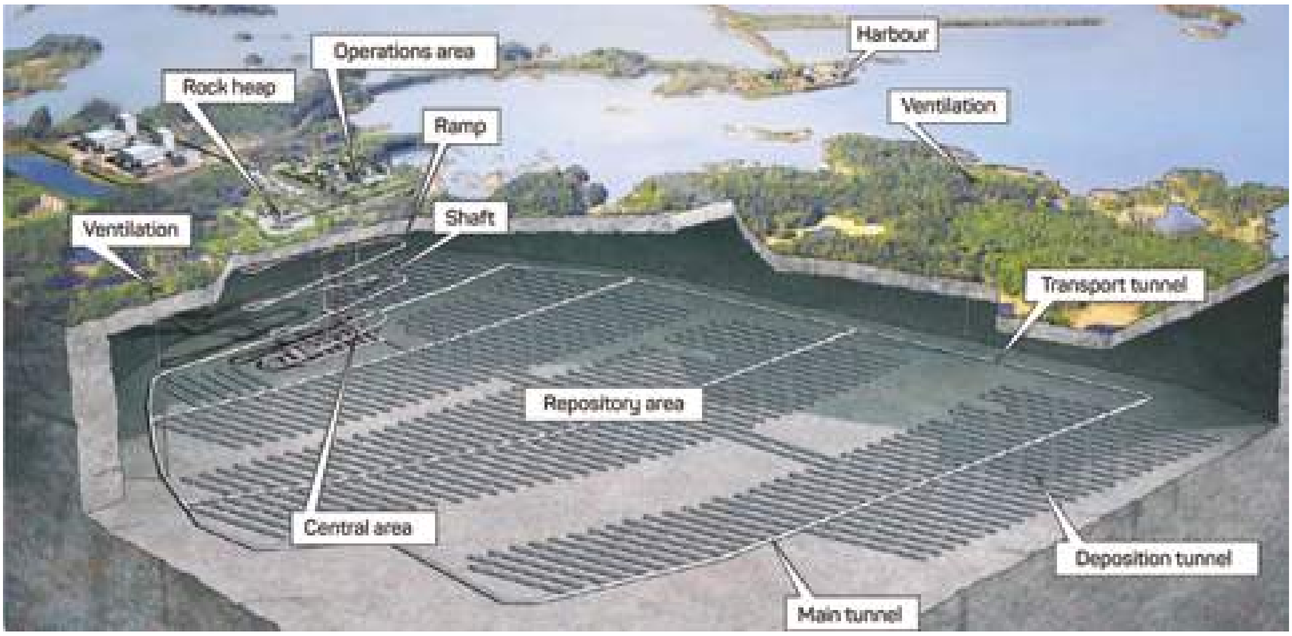


Figure I.17: Illustration of the geological disposal facility

Image courtesy of SKB

The system for used fuel disposal is designed such that it is passively safe and that, after closure, no further action is required.[105]

Unlike the Finnish facility, the collocation of zones for the disposal of low and intermediate level waste is not required at the Swedish used fuel facility. A centralised underground facility for the disposal of short-lived low and intermediate level wastes already operates at Forsmark.[106] Potential interactions between the short-lived waste facility and the used fuel disposal facility have been considered in the safety case.[107] A separate facility is planned for the disposal of long-lived low and intermediate level wastes from Sweden.[108]

SAFETY CASE REQUIREMENTS

Swedish regulations for the safety of used fuel disposal are set out in SSM's regulations concerning safety in final disposal of nuclear waste (SSMFS 2008:21) and its regulations concerning the protection of human health and the environment in connection with the final management of spent nuclear fuel or nuclear waste (SSMFS 2008:37).[109]

Collectively, they require the safety of used fuel disposal to be assessed for one million years using a safety assessment.[110] Risk must be assessed quantitatively for up to 100 000 years, with extra detail required for the first 1000 years.[111] Beyond 100 000 years, the releases from engineered barriers and the geosphere should be shown to be as low as reasonably possible.[112]

To support safety, multiple barriers should be used so that safety is maintained when one barrier's performance is challenged or deficient.[113]

For the quantitative assessment, the risk of harmful effects to a person in the most exposed group should not exceed 10^{-6} (one in a million) per year, which corresponds to a dose of about 0.014 mSv/a.[114] The impact beyond Sweden's borders must not be more severe than those accepted inside Sweden.[115] Nor may the impact lead to a loss in biodiversity of species.[116]

The assessment of safety must take into account the impacts of features, events and processes that could lead to the release of radionuclides after closure.[117] Scenarios should be developed for future sequences of events and conditions that affect the disposal facility, including a main scenario to address the most likely future conditions.[118] Uncertainties in future conditions and barrier performance should also be taken into account in the safety assessment.[119]

As exact risk cannot be known in the distant future, estimates of risk should be evaluated using multiple models or methods, to provide a comprehensive understanding of the possible risks.[120]

ROLE OF GEOLOGY TO SAFETY

The host geology is located at Forsmark, 120 km north of Stockholm, in crystalline granitic rock.[121] The site has natural isolating characteristics, including[122]:

- location in a tectonically stable lens, which is enclosed by regions subject to higher rates of activity
- few water conducting fractures and low groundwater flow rates at depth
- groundwater chemistry that is not conducive to corrosion or degradation of the bentonite clay
- mechanical stability
- no exploitable natural resources.

Site investigation commenced nearly 15 years ago.[123] The extensive program of site investigation shows that:

- the granitic rock is safe for construction and for disposal of used fuel
- although large earthquakes cannot be entirely ruled out, the likelihood that one would damage disposal containers is very low.[124] Historical data and measurements show that the site at Forsmark is far from plate boundaries and tectonically stable.[125] The site geology is less susceptible to internal fracture than the surrounding region, which can fracture when the internal strain is unloaded[126]
- low groundwater flows will limit the movement of radionuclides. There are few open or partly open fractures below a depth of about 300 m, limiting the ability for groundwater flow.[127] At the disposal depth (470 m), the average distance between water conductive fractures is over 100 m.[128] Due to these properties, groundwater will not reach most of the containers for thousands of years.[129] The chemically reducing conditions, which are not particularly corrosive, can support long-term performance of the copper container.[130] The low groundwater salinity will protect correct functioning of the bentonite clay buffer[131]
- future climatic and meteorological conditions will not adversely affect the site. Based on assessment of previous glaciations in the area, another glaciation is expected in the next 120 000 years, with eight glaciations expected in total over the next million years.[132]

In addition, complementary evidence has been identified by SKB to enhance confidence in the performance of the geological barrier. This includes evidence that multiple ore bodies in equivalent geology in the Fennoscandian Shield have been isolated over even longer periods in the past than those required for isolation of used fuel in a geological disposal facility. This includes the uranium ore zone at Lake Palmottu in Finland.[133]

ROLE OF ENGINEERED BARRIERS TO SAFETY

The engineered barrier system will use the KBS-3 concept. This concept, which has been developed in conjunction with Finland, has features that support containment and isolation, including:

- used fuel, in solid, ceramic form[134]
- a cast iron canister inside a larger copper container, providing containment over very long time frames—copper is not easily corroded by conditions in the Fennoscandian Shield[135]
- compacted bentonite clay, which surrounds the container. The clay restricts moisture ingress by swelling on contact with water, giving it a self-sealing capability.[136] It thereby provides low hydraulic conductivity.[137] It also makes the local chemistry less conducive to corrosion and adsorbs radionuclides, making them less mobile. The clay can provide isolating properties over geological timeframes
- the backfilling of underground openings to restrict water flow through underground openings.[138]

The extensive program of research, development and demonstration, which has been conducted over 30 years, shows that[139]:

- copper containers and the inner cast iron canister can remain intact for a long time. Less than 0.5 cm of corrosion, accounting for one-tenth of the thickness of the copper container, is expected in the first one million years.[140] Due to erosional losses in the buffer and pessimistic assumptions about other conditions, a few containers may corrode through during this time period[141]

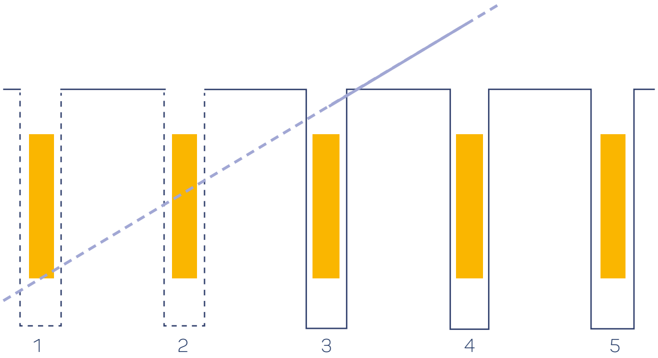


Figure I.18: Disposal containers will not be located in positions that are intersected by fractures, or projected to be intersected by fractures. For a fracture represented by the blue line, positions 1 and 2 would not be suitable for disposal

Image courtesy of SKB

- defects in the welds of the copper containers can be detected with high probability, reducing the likelihood that containers with penetrating defects will be disposed of in the facility. An assessment of detection capability shows that defects of 0.4 cm in size can be detected 90 per cent of the time. Defects of 1 cm size—equating to up to 20 per cent of the container thickness—can be detected nearly 100 per cent of the time.[142]
- failure of the copper containers by rock shear could occur with a rare likelihood over the next one million years, even with a number of pessimistic assumptions regarding performance of the engineered barriers.[143] This is in part because containers will not be located where fractures exist or are projected (Figure I.18), and also because they are designed to withstand shear movements of 5 cm at a velocity of 1 m/s.[144] Locating disposal containers away from these zones further reduces the risk of container shear by seismic activity, as well as by reducing prospective flow rates near the container
- the buffer and backfill can prevent groundwater reaching the containers for thousands of years.[145] While properties of the host geology may lead to some containers being exposed to groundwater in a few tens of years, most of the deposition holes will not be exposed to groundwater for several thousands of years.[146] The buffer of bentonite clay also moderates the impact of seismic shear on the copper containers.

In addition, the following complementary evidence has been identified by SKB to enhance confidence in the performance of the engineered barriers:

- Used uranium oxide fuel can be isolated over the long term in environments with reduced oxygen as the natural fission reactors at Oklo (Gabon) have isolated uranium and many fission products over a long timeframe.[147] The natural fission reactors at Oklo are uranium deposits that naturally supported a chain reaction due to the right geological and groundwater conditions in the past.
- Cast iron canisters can last for thousands of years, as archaeological artefacts have lasted in oxygen-free waterlogged sites and sites with oxygen for thousands of years.[148]
- Copper can contain wastes for hundreds of thousands of years, as native copper in the Fennoscandian Shield has existed over longer periods in the past in conditions similar to those proposed for the Swedish disposal facility.[149]

RISK ASSESSMENT UNDER POTENTIAL FUTURE SCENARIOS

The potential future impacts of the disposal facility are assessed for two reference scenarios where:

- climatic conditions in the next glacial cycle (120 000 years) are similar to those of the last glacial cycle and seven cycles occur over the next million years
- a variant where future conditions have been substantially influenced by human-induced global warming.[150]

Uncertainties regarding conditions that would affect corrosion of the container and that could shear containers through seismic loads were assessed in scenario analysis.[151] Human intrusion scenarios were also assessed.[152]

SKB addresses risks using a safety assessment, which evaluates the risk of radionuclides migrating from the geosphere (the non-living environment) into the biosphere (the living environment), resulting in potential doses to people, plants and animals.[153] The relationship between the safety assessment, the safety case (or safety report), and other key documents is shown in Figure I.19.

If the engineered barriers perform as expected, one out of 6000 containers may fail by corrosion in the first million years.[154] Figure I.20 shows the maximum risk from radionuclides entering the biosphere under the different corrosion and shear scenarios investigated. It can be seen that the maximum risk, including that for the summed case, is below the regulatory limit by more than an order of magnitude.

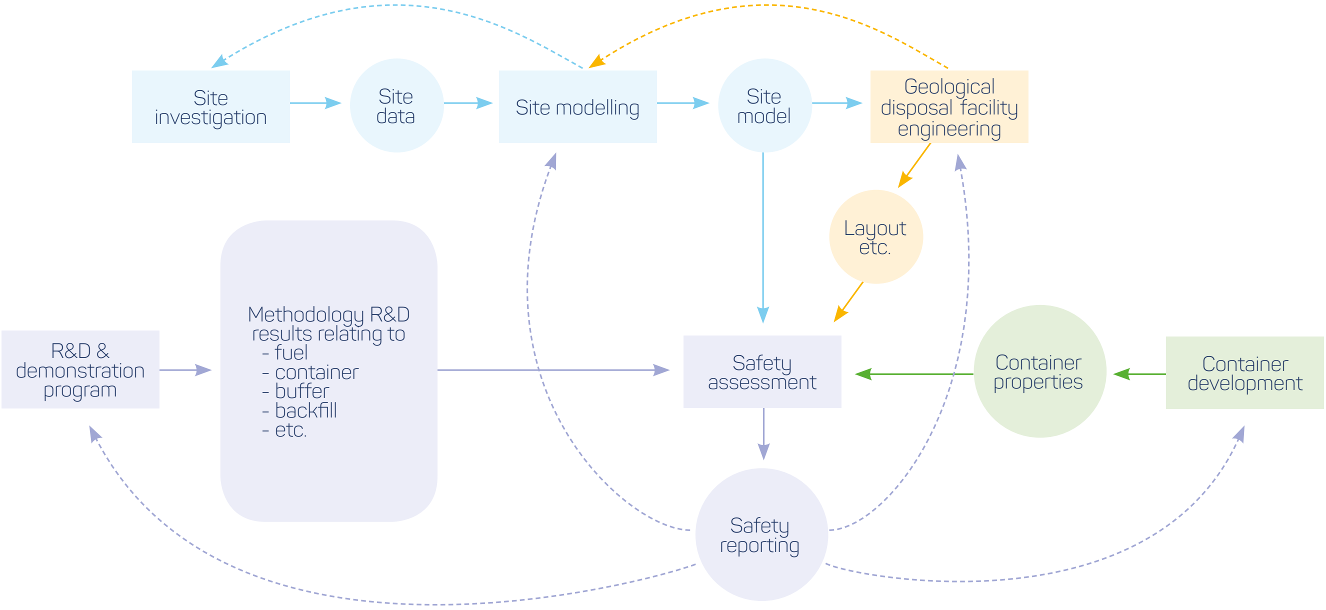


Figure I.19: Relationship between the safety case, safety assessment and other key documents. Activities are shown in boxes, while outputs are shown in circles. Dashed lines represent feedback loops

Data sourced from SKB

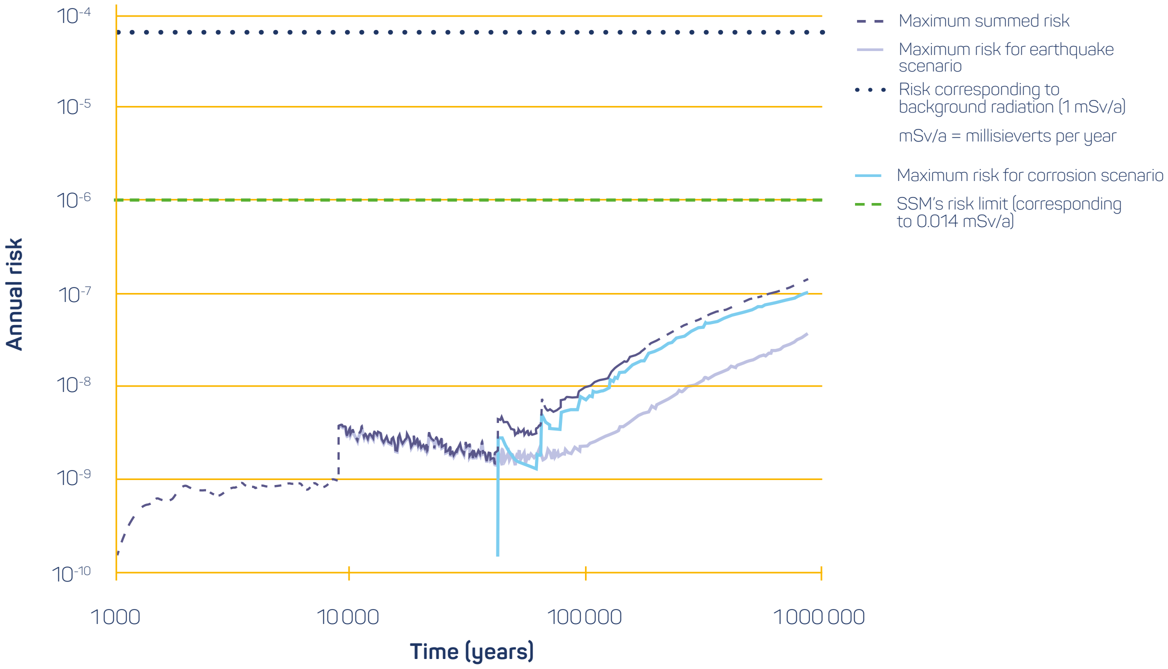


Figure I.20: The overall risk picture from the safety case

Data sourced from SKB

The figure shows the calculation cases that give the highest risk for the earthquake scenario and for the corrosion scenario, plus the sum of these. Since the sum curve lies below the risk limit during the entire million-year period, the conclusion is that SSM's risk criterion is fulfilled for the used fuel disposal facility. The risk limit corresponds to an annual dose of 0.014 mSv and the background radiation risk corresponds to background radiation levels of about 1 mSv/a.[155]

The safety case analysed faster than expected container corrosion rates and found that a recently suggested mechanism for copper corrosion in pure water, for which the scientific basis has been judged weak, has a negligible impact on the overall extent of copper corrosion.[156]

To be conservative, a number of pessimistic assumptions were made regarding the effects of human intrusion after closure of the facility.[157] In the case of inadvertent drilling into a container 300 years after closure, a person in the most exposed group using the borehole for irrigation could receive a dose of 0.031 mSv/a, which is higher than the regulatory limit but lower than the equivalent from background radiation.[158] If parts of the fuel are physically brought to the surface by the drilling, the driller could receive 1000 mSv of radiation in eight hours.[159] That dose is significantly reduced below 1 mSv/h if the inadvertent drilling occurred a few thousand years after closure.[160] The probability of inadvertent drilling resulting in doses to people cannot be known.[161] For this reason, information on, and knowledge of, the facility will be preserved for as long as possible.[162]

The main contaminant to drilling personnel at the 300 year mark is Ag-108m, which is present only in fuel from pressurised water reactors.[163] This accounts for about 25 per cent of the containers that will be disposed of.[164] The probability of rupturing one of these containers from inadvertent drilling is further reduced by locating the disposal zone at a depth substantially lower than that of interest for water supply and away from exploitable natural resources.[165]

In addition to modelling the impacts of potential future conditions for the disposal facility, SKB has modelled stylised 'what-if' cases which show the hypothetical doses that could result from complete loss of barrier function for different combinations of barrier in the multi-barrier system (Figure I.21).

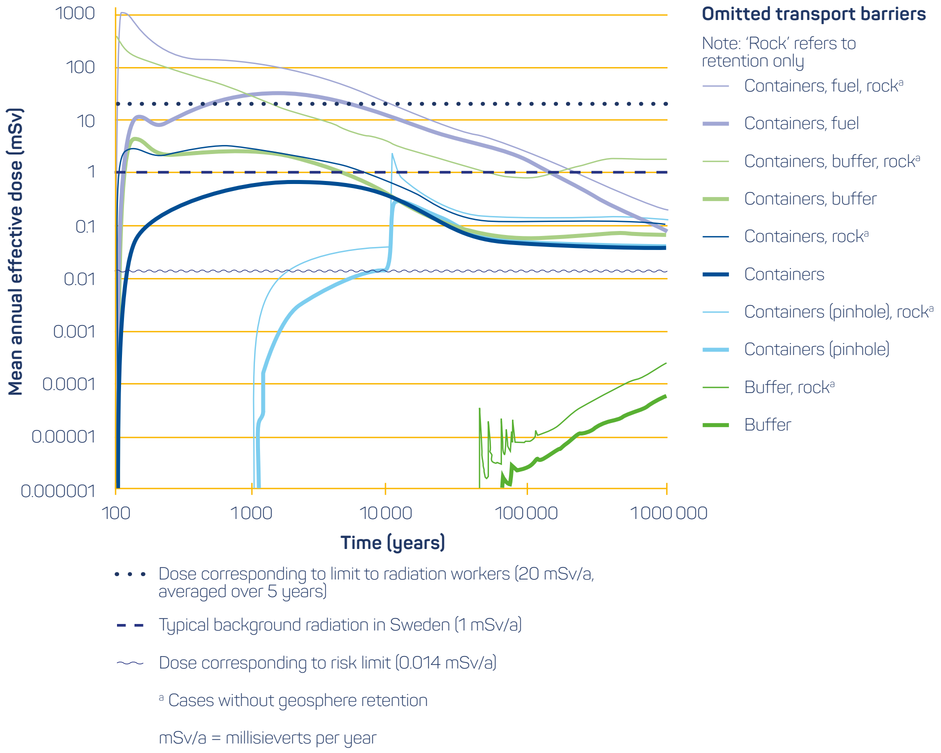


Figure I.21: Results of stylised cases to illustrate doses from complete loss of barrier function, for multiple barriers. Note that an omission of the 'rock' barrier in these cases refers to omission of retention of radionuclides in the rock fractures only, whereas the favourable, low flow rate at disposal depth and the favourable geochemical conditions are still taken into account

Data sourced from SKB

These cases show that members of the public could receive maximum doses above those permitted for radiation workers (20 mSv/a) if:

- all 6000 containers are initially disposed of with large penetrating defects in the copper shell and in the cast iron canister that holds the used fuel, in addition to either:
  - » emplacement of insufficient buffering to allow transport conducive conditions for radionuclides in all 6000 deposition holes, as well as loss of retentive properties in the rock fractures, or
  - » complete dissolution of the fuel and corrosion of metal parts in only 100 years.[166]

Members of the public could receive maximum doses lower than those permitted for radiation workers (20 mSv/a) but more than the typical background radiation in Sweden (1 mSv/a)[167] if:

- all 6000 containers are initially disposed of with the large penetrating defects, in addition to either:
  - » emplacement of insufficient buffering, or
  - » loss of retentive properties in the rock fractures[168]

or if:

- all 6000 containers are emplaced with initial pinhole defects in the copper shell and there is complete loss of retentive properties in the rock fractures.[169]

Lower doses would result from different combinations of barrier failures. The doses arising from variations of future expected conditions are orders of magnitude less than the regulatory limit of 0.014 mSv/a.[170] Chain reactions from the used fuel are not possible for all conceivable future conditions in the disposal facility.[171]

The probability of the extreme cases depicted in Figure I.21 occurring has not been evaluated in light of the licensing process, which requires the proponent to demonstrate that the sealing and emplacement methods can be undertaken to specification and that quality assurance and quality control methods are in place. Furthermore, the presence of an independent regulator and any public oversight body further reduces the likelihood that such gross negligence could occur.

The regulator, SSM, will present a consolidated interim assessment to the Land and Environmental Court in 2016 and a comprehensive final assessment to government in 2017.[172] It has already stated that, based on its ongoing assessment, the 'most suitable' site to host the used fuel disposal facility has been selected under the preconditions for a volunteer municipality.[173]

SAFETY CASE 3: PROPOSED HIGH LEVEL WASTE, USED FUEL AND INTERMEDIATE LEVEL WASTE DISPOSAL FACILITY IN SWITZERLAND

This safety case summary was prepared by C McCombie and N Chapman of MCM on behalf of the Nuclear Fuel Cycle Royal Commission.

One of the key requirements of a 'safety case' is that it should begin with a statement of the purpose. This is because safety cases are normally done iteratively as a disposal project proceeds through the various phases. In the Swiss case, the most recent full safety case was submitted in 2002 fulfilling a requirement of the government to demonstrate the basic feasibility and safety of a geologic disposal facility in Switzerland. Further safety cases are in progress. The updates are aimed at selection of a specific site; thereafter, safety cases will be needed for a general licence, a construction licence, an operation licence and ultimately for a closure licence.

The information in this summary is largely extracted from the documentation prepared by the Swiss implementer, Nagra, and the regulator, ENSI, in the course of preparing and reviewing the safety cases for a deep geological disposal facility for used fuel, high level wastes (HLW) and intermediate level wastes (ILW). The original generic safety case was submitted in 2002. The regulator pronounced it acceptable in 2005 but required certain additional points to be worked on. Nagra responded in 2008 and ENSI commented on this in 2012. Currently Swiss safety case efforts are being devoted to assessments intended to set priorities in the regional siting program for geological disposal facilities; ENSI has produced guidance for this and Nagra is performing safety assessments based on the guidance.

OUTLINE OF PROJECT AND DISPOSAL CONCEPT

All radioactive wastes in Switzerland are intended to be disposed of in a geological disposal facility. Two facilities are foreseen: one for used fuel (HLW and ILW); the other for low-level wastes. Both may be at the same location, however. The 2002 safety case and the ongoing Nagra work are for the former type of disposal facility. The facility is planned to be at the depth of some hundreds of metres in a tight clay formation (Opalinus Clay) which extends over much of northern Switzerland; the Opalinus Clay is the principal geologic barrier. The used fuel and HLW will be encapsulated in long lived, robust steel containers (12–14 cm thick) and emplaced axially in tunnels surrounded by a buffer of bentonite (another type of low permeability clay). The container and buffer constitute the engineered barriers. The ILW is encapsulated in cement and emplaced in larger tunnels backfilled with a special mortar. The disposal system and the safety barriers are illustrated in Figure I.22—Figure I.25.

SAFETY CASE REQUIREMENTS

The official guidelines[174] of the Swiss regulator relating to safety cases for geological disposal facilities (in German) begin by quoting high level requirements stated in the Nuclear Energy Ordinance. This requires that

- geological disposal facilities may lead to only small additional radiation doses to humans or other species
- risks to other countries may not exceed those allowable in Switzerland
- future risks must be no greater than those accepted today
- no further safety measures are needed after closure to assure long-term safety
- long-term safety is to be assured by multiple, passive technical and natural barriers.

ENSI then defines specific criteria for assessing realistic scenarios for future evolution of a disposal facility, requiring that these scenarios be categorised as probable or of low probability:

- For probable scenarios, releases of radionuclides may not lead to individual doses greater than 0.1 mSv/a.
- The low-probability scenarios together should not result in a risk to an individual greater than 10^{-6} per year.

ENSI also sets numerous specific requirements related to the safety case documentation. The most important of these are that:

- safety assessments are needed iteratively up to closure of the disposal facility
- the safety reports must include an assessment of the methodology and the data on which the quantitative results are based
- alternative lines of argumentation, which may include analogue studies, are needed
- all uncertainties are to be identified and their consequences quantified
- a scenario analysis is required and scenarios are to be selected which cover the range of potential impacts
- it should be demonstrated that the dose criteria can be satisfied for up to 1 000 000 years; at later times the levels of natural radiation should not be exceeded. It is noted that the dose calculations are to be regarded as indicators of potential impacts rather than predictions
- human intrusion is to be covered—but only inadvertent intrusion, not deliberate actions; extreme scenarios such as meteorite impact need not be treated
- the potential impacts of changes in the climate and the biosphere are to be examined, but the impacts of radiation on humans is assumed to remain as today (i.e. there is no lower radiation threshold at which damage occurs).

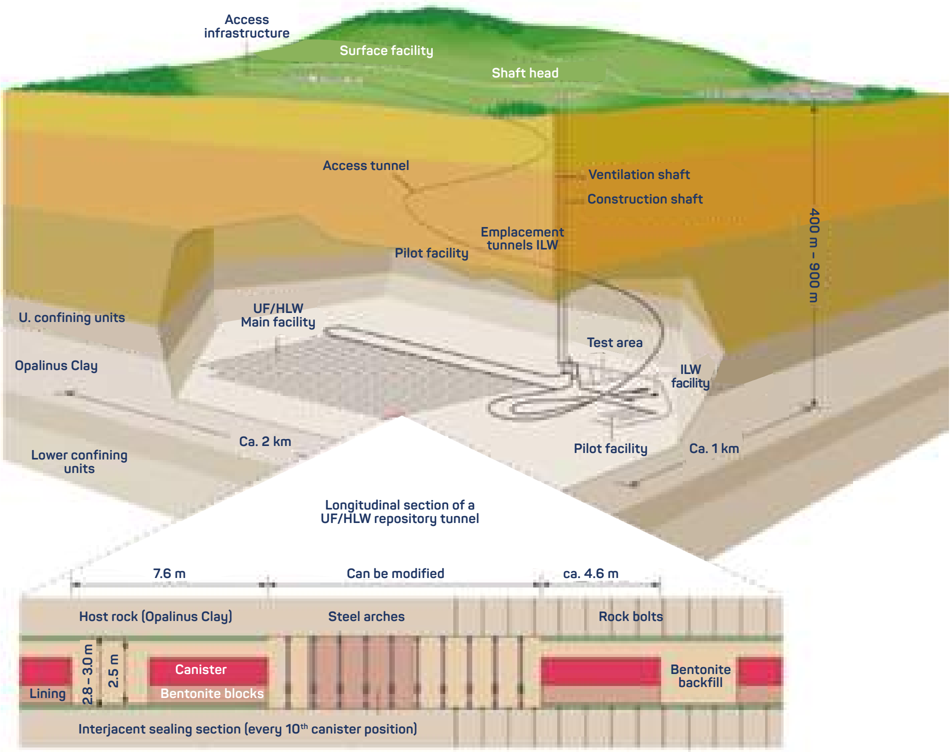
ROLE OF GEOLOGY TO SAFETY

The host geology is Opalinus Clay, which was chosen for the following reasons[175]:

- simplicity—sufficiently homogeneous to allow confident prediction of its behaviour on the time and space scales of interest
- stability—tectonically stable on a timescale of the next few million years
- plasticity/self-sealing capacity
- negligible groundwater
- no resource potential
- geochemical stability and retention capacity
- engineering feasibility.

The geology contributes to safety for a variety of reasons:

- it isolates wastes from the human environment and reduces the likelihood of any undesirable intrusion and misapplication of the materials
- the slowness of groundwater flow and a range of geochemical immobilisation and retardation processes ensure that radionuclides continue to be largely confined within the engineered barrier system and the immediately surrounding geology, so that further radioactive decay takes place
- a number of processes attenuate releases during transport towards the surface environment, and limit the concentrations of radionuclides in that environment. These include radioactive decay during slow transport through the barrier provided by the host rock and the spreading of released radionuclides in time and space by, for example, diffusion, hydrodynamic dispersion and dilution



UF = used fuel
HLW = high level waste
ILW = Intermediate level waste

Figure I.22: The Swiss geological disposal concept

Image courtesy of Nagra

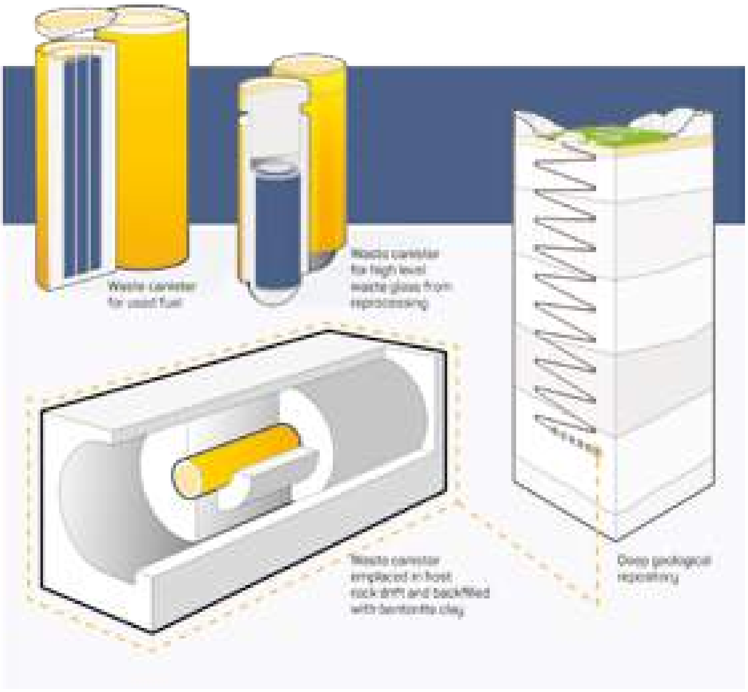
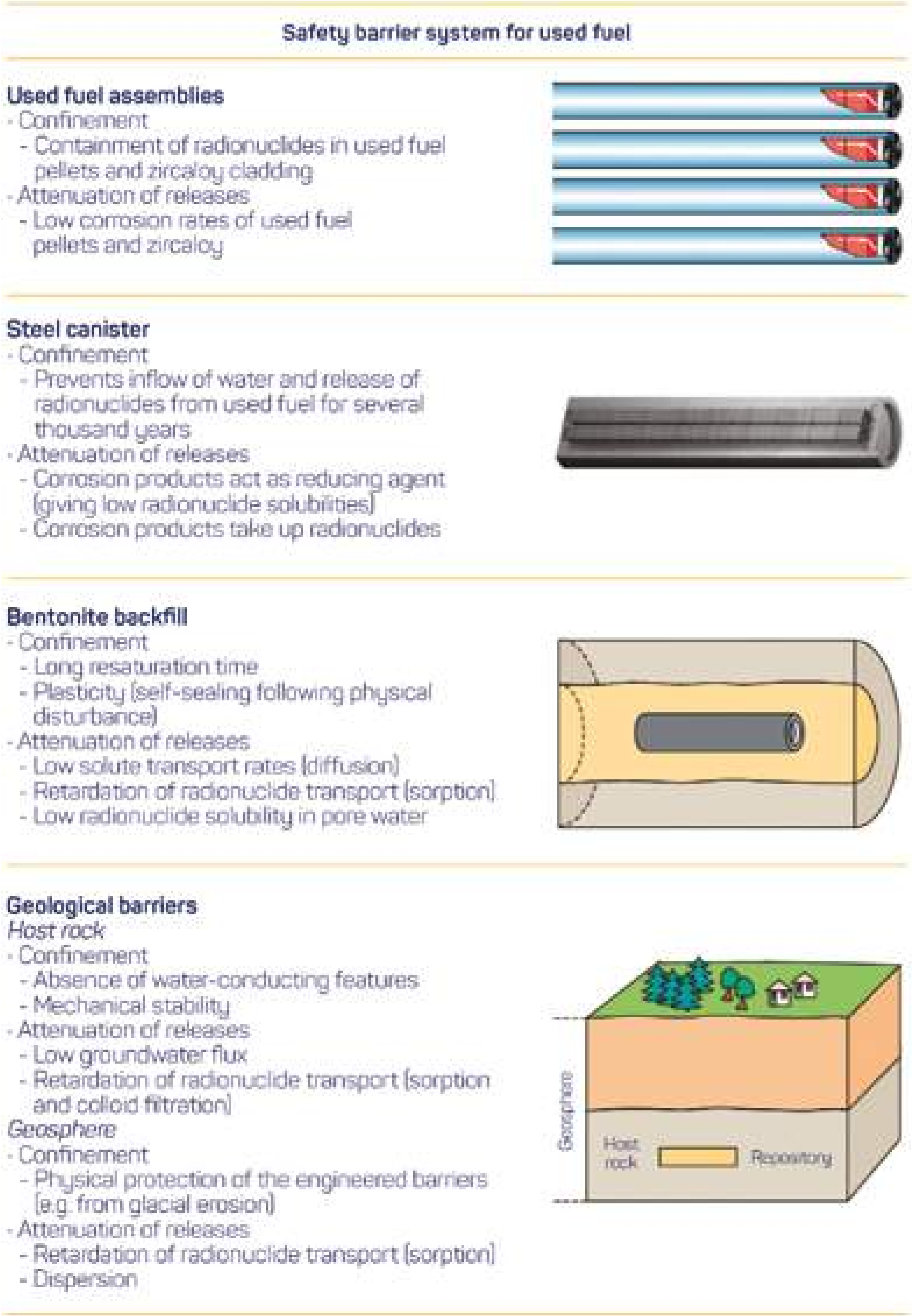


Figure I.23: The Swiss high level waste and used fuel safety barrier system

Image adapted from Nagra



Safety barrier system for used fuel

Used fuel assemblies

- Confinement
  - Containment of radionuclides in used fuel pellets and zircaloy cladding
- Attenuation of releases
  - Low corrosion rates of used fuel pellets and zircaloy

Steel canister

- Confinement
  - Prevents inflow of water and release of radionuclides from used fuel for several thousand years
- Attenuation of releases
  - Corrosion products act as reducing agent (giving low radionuclide solubilities)
  - Corrosion products take up radionuclides

Bentonite backfill

- Confinement
  - Long resaturation time
  - Plasticity (self-sealing following physical disturbance)
- Attenuation of releases
  - Low solute transport rates (diffusion)
  - Retardation of radionuclide transport (sorption)
  - Low radionuclide solubility in pore water

Geological barriers

Host rock

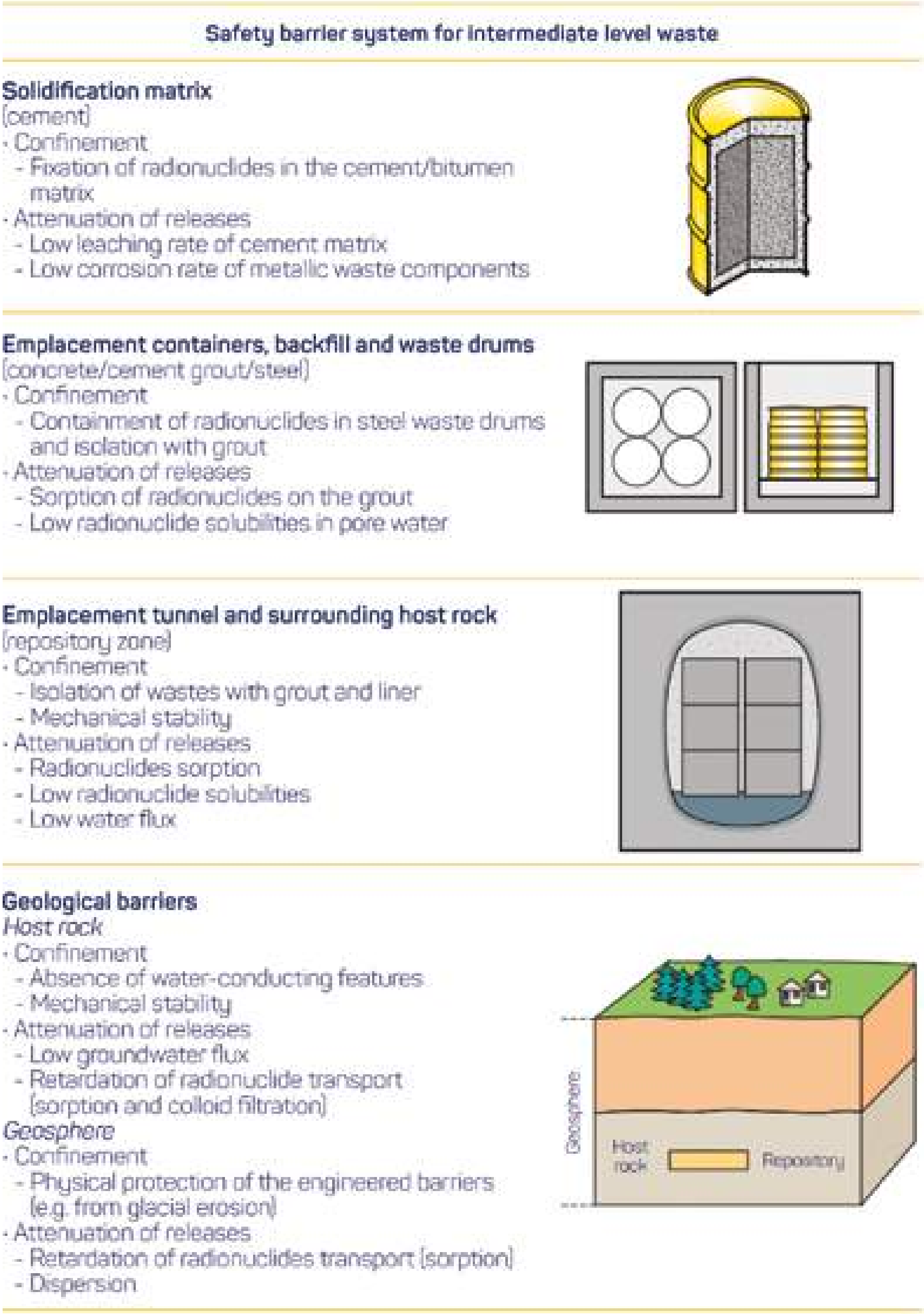
- Confinement
  - Absence of water-conducting features
  - Mechanical stability
- Attenuation of releases
  - Low groundwater flux
  - Retardation of radionuclide transport (sorption and colloid filtration)

Geosphere

- Confinement
  - Physical protection of the engineered barriers (e.g. from glacial erosion)
- Attenuation of releases
  - Retardation of radionuclide transport (sorption)
  - Dispersion

Figure I.24: How the Swiss barrier system for used fuel provides safety

Image courtesy of Nagra



Safety barrier system for intermediate level waste

Solidification matrix
(cement)
- Confinement
  - Fixation of radionuclides in the cement/bitumen matrix
- Attenuation of releases
  - Low leaching rate of cement matrix
  - Low corrosion rate of metallic waste components

Emplacement containers, backfill and waste drums
(concrete/cement grout/steel)
- Confinement
  - Containment of radionuclides in steel waste drums and isolation with grout
- Attenuation of releases
  - Sorption of radionuclides on the grout
  - Low radionuclide solubilities in pore water

Emplacement tunnel and surrounding host rock
(repository zone)
- Confinement
  - Isolation of wastes with grout and liner
  - Mechanical stability
- Attenuation of releases
  - Radionuclides sorption
  - Low radionuclide solubilities
  - Low water flux

Geological barriers
Host rock
- Confinement
  - Absence of water-conducting features
  - Mechanical stability
- Attenuation of releases
  - Low groundwater flux
  - Retardation of radionuclide transport (sorption and colloid filtration)

Geosphere
- Confinement
  - Physical protection of the engineered barriers (e.g. from glacial erosion)
- Attenuation of releases
  - Retardation of radionuclides transport (sorption)
  - Dispersion

Figure I.25: The Swiss ILW safety barrier system

Image courtesy of Nagra

- the chemical environment provides a range of geochemical immobilisation and retardation processes, favours the long-term stability of the engineered barriers, and is itself stable due to a range of chemical buffering reactions.

The last three functions must be understood and quantified in order to carry out the safety assessment calculations that are a key part of the safety case. The proof that they are understood and their numerical characterisation is brought primarily through extensive experiments and measurements in the laboratory (often using radioactive tracers) and in the field (involving comprehensive testing in deep boreholes into the host geology and its surrounding geological formations).

In addition, analogue evidence was put forward by Nagra to enhance confidence in the functioning of the geological barrier. One such example is the behaviour of the rich uranium ore deposit at the 1900 million year old Cigar Lake ore body in Canada, which was discovered only through geophysical surveys since no enhanced radioactivity is seen at the surface. This ore body is surrounded by a low-permeability clay layer which has acted as a powerful migration barrier for the uranium atoms—just as the Swiss safety case presumes will happen for its Opalinus Clay host geology and also its bentonite clay buffer. A further natural example is the unique uranium deposit at Oklo in Gabon which was formed about 2000 million years ago. This is the only known instance of an ore body in which nuclear chain reactions were able to occur naturally over a period of several hundred thousand years because the uranium (which was at that time more highly enriched with fissile ^{235}U) was exposed to particularly pure groundwater that acted as a moderator and allowed a chain reaction to take place. This produced radioactive fission products exactly the same as those in used fuel, and meticulous measurements could demonstrate that there was no major migration of the key radionuclides away from the natural reactor site even over these immense timescales—just as would be predicted by the models used in a safety case.

ROLE OF ENGINEERED BARRIERS TO SAFETY

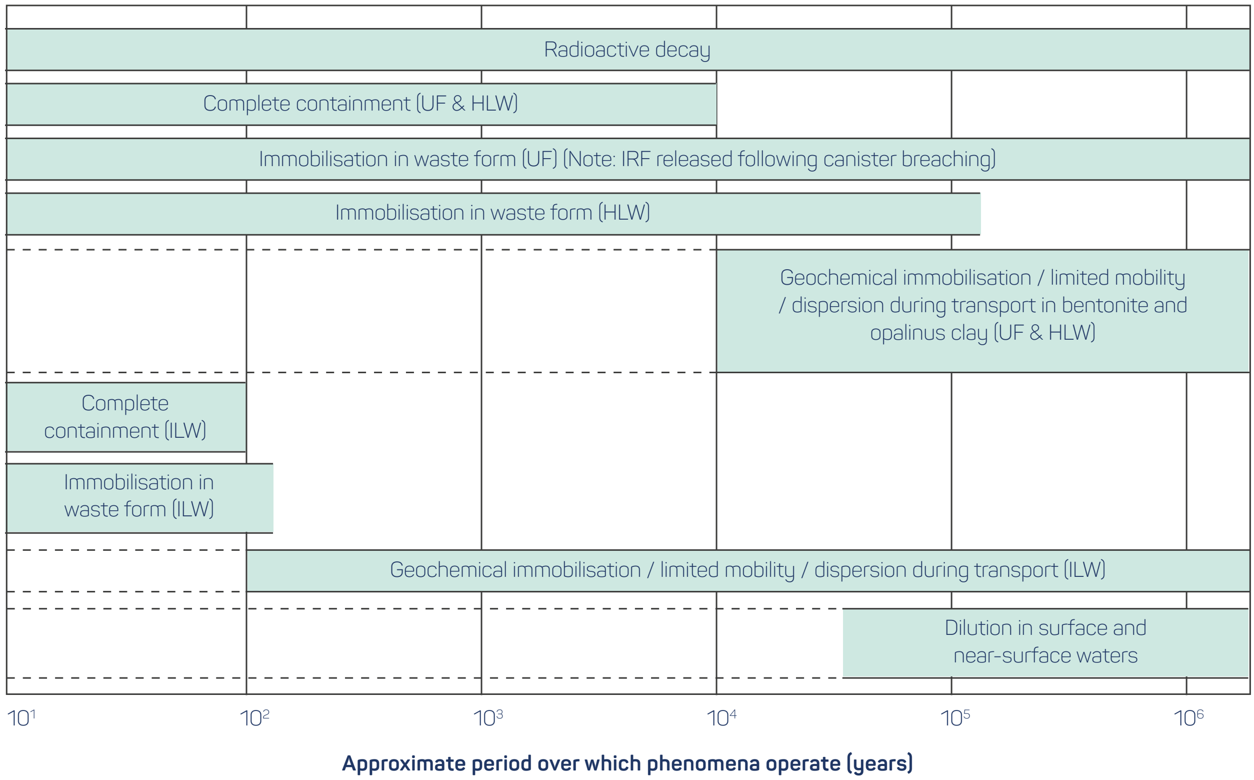
The engineered barrier system in the Swiss concept for used fuel and HLW, as illustrated in Figure I.23–Figure I.25, consists of the waste form, the steel container, and the bentonite buffer. The correct functioning of the engineered barrier system depends upon its emplacement in a suitable geological medium to provide an appropriate hydrogeological and geochemical environment. The used fuel and HLW waste forms are then stable in the expected environment for many thousands of years. The steel containers are mechanically strong and corrosion resistant so that they provide absolute containment for a long time. There is a regulatory requirement of a minimum lifetime of 1000 years, but Nagra proposes a lifetime requirement of 10 000 years to provide a significant margin of safety. The expected corrosion rate, based on present understanding, is 0.001–0.002 mm/a; only about 20 mm of the 120 mm wall thicknesses proposed would be consumed by corrosion within 10 000 years. The bentonite buffer acts as a well-defined interface between the containers and the host geology. The bentonite has similar properties as the host geology, and ensures that the effects of the presence of the emplacement tunnels and the heat-producing waste on the host geology are minimal. It also provides a strong barrier to radionuclide transport and a suitable environment for the containers and the waste forms.

Nagra has a decades-long research program studying the performance of the engineered barriers individually and also in combination. The investigations include small scale laboratory experiments, underground tests in its own laboratories and in international cooperative projects, and analogue studies on archaeological and natural systems. The data obtained are fed into specific models of corrosion, leaching and radionuclide transport. The recent status of modelling is described in NTB 14-09.[176]

The efficiency of the barrier system components has been demonstrated based on the studies and experiments referred to. Some key conclusions are:

- When the used fuel containers and the fuel cladding fail, some radionuclides in the gap are assumed to be released instantaneously but most are released according to the matrix dissolution rates. The best estimate for this rate is 10^{-6} per year[177], implying that it would be 1 000 000 years until all of the included radionuclides could be released into the vicinity of the container. Of course, by then, many will have decayed to negligible concentrations. Some of the important radionuclides are also very poorly soluble in the disposal environment so that they cannot be easily transported away in solution.
- For the estimated dissolution rates, including the effects of cracking, the HLW glasses would dissolve at a rate of ~ 1 part in 10^5 to 1 part in 10^6 per year; again, the release period is up to 1 000 000 years.
- The transport through the clay buffer from the waste to the host geology is then greatly retarded by the physical process of slow diffusion or the chemical retardation processes which have been shown to operate in clays. Most radiotoxicity therefore decays within the used fuel and HLW waste forms and within the surrounding bentonite buffer, or, for ILW, within the cementitious buffer.

The timescales over which the engineered and geological barriers operate are well illustrated in Figure I.26.



UF = used fuel
HLW = high level waste
IRF = instant release fraction
ILW = intermediate level waste

Figure I.26: Features and processes contributing to safety and the timescales over which they operate

Data sourced from Nagra

RISK ASSESSMENT UNDER POTENTIAL FUTURE SCENARIOS

The potential future impacts of the geological disposal facility are assessed under a range of different scenarios. In the reference scenario, the features and processes that contribute to safety are assumed to operate broadly as expected; conservative and realistic assumptions are made on their evolution and on the data. The safety case also looks at 'what if' cases that address phenomena that are outside the range of possibilities supported by scientific evidence but involve assumed perturbations to the key properties of the safety barriers.

Nagra presented the results of its safety analyses in separate categories:

- reference case scenarios
- scenarios with radionuclides released as volatile species
- human actions
- 'what if' scenarios.

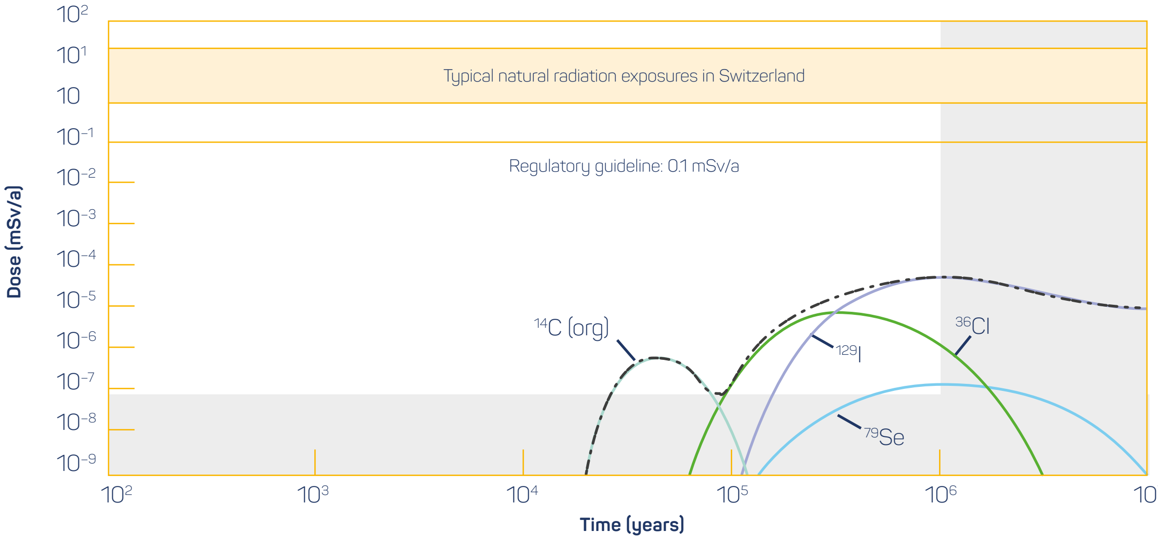
The results for the various cases, including realistic alternative developments and also parameter variations, are presented below. (The results are put into perspective by comparing them with natural background radiation in Switzerland (1–10 mSv/a) and also with the regulatory limit for radiation doses from a disposal facility which is 0.1 mSv/a). The reference case scenarios all lead to calculated doses that are more than 100 times lower than the dose limit, which is itself 10 to 100 times lower than doses from natural radiation. The results of the deterministic calculations which make fixed conservative estimates of all parameters influencing facility performance are expressed as radiation doses to humans; the accepted conversion factor to risk of death is that 0.1 mSv/a equates to a risk of dying of 5 in 1 million per year.

The key results calculated by Nagra and reviewed by ENSI subsequently are summarised and illustrated below. Figure I.27 shows the example of the used fuel base case. It is typical of almost all the calculations in that doses occur only in the very far future and that they are due to exposure to the mobile radionuclides such as ^{135}Cs and ^{129}I, rather than to the heavy elements such as ^{239}Pu which are so strongly retarded that they never appear in non-negligible concentrations in the biosphere.

If all reasonable variations are taken into consideration, there are wider ranges of calculated doses, but a large safety margin relative to the dose limit still results, as the block labelled 'Reference Case including parameter variations' in Figure I.28 illustrates for used fuel, HLW and ILW. The other cases illustrated in Figure I.28 are for plausible alternative assumptions that can be made concerning the system behaviour or evolution. Most of the alternatives lead to results that are even lower than the base case. This is because the base case conservatively does not take credit for some mechanisms that would clearly reduce the release rates of radionuclides, but are not well enough understood or quantified to allow their use in a robust base case. To illustrate this, one can look at the second block, 'solubility limited dissolution'. It is clear that the very low quantities of groundwater around the waste, combined with the known low solubilities of many elements under reducing conditions, can lead to the rate of dissolution being restricted by the inability of the groundwater to transport away radionuclides in solution. This effect is ignored in the base case and introducing it will always result in lower final release and dose estimates. An example with an opposite effect is shown by the final block in Figure I.28: gas-induced release. In this case, for ILW, a scenario in which corrosion gases drive radionuclides out of the geological disposal facility is not included in the base case, and the bar chart shows that, if it were, a dose 10 times higher than the base case (but still well below the regulatory guideline) could result.

In addition to the reference scenarios, alternatives that could plausibly occur were also considered:

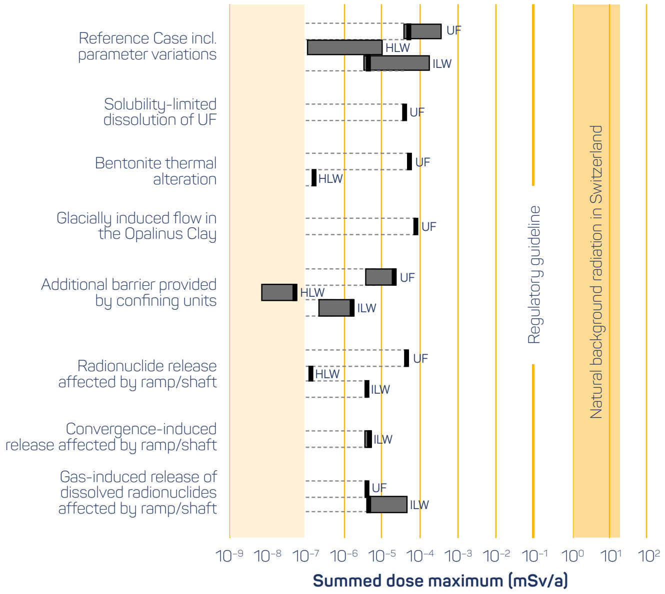
- *Climate effects:* alternative climates following the present interglacial temperate climate were examined; a tundra scenario and full glaciation cycles were considered
- *Alternative engineered barrier system evolution:* bentonite alteration; initial container defects; early container breaching; waste matrix dissolution; redox front propagation in bentonite; increased glass dissolution; gas-induced release of dissolved radionuclides; gaseous release of ^{14}C; convergence-induced release
- *Alternative geological characteristics:* alternative hydraulic conditions; rapid transport of volatile ^{14}C; heterogeneous flow; reduced path length; reduced sorption in Opalinus Clay and bentonite



mSv/a = millisieverts per year
C = carbon
Cl = chlorine
I = iodine
Se = selenium

Figure I.27: Example of calculated doses from the geological disposal facility for used fuel (base case)

Data sourced from Nagra



mSv = millisieverts
UF = used fuel
HLW = high level waste
ILW = intermediate level waste

Figure I.28: Calculated dose maxima and ranges for the various conceptualisations and parameter variations of the reference scenario

Note: Base cases marked by bold lines. Data sourced from Nagra

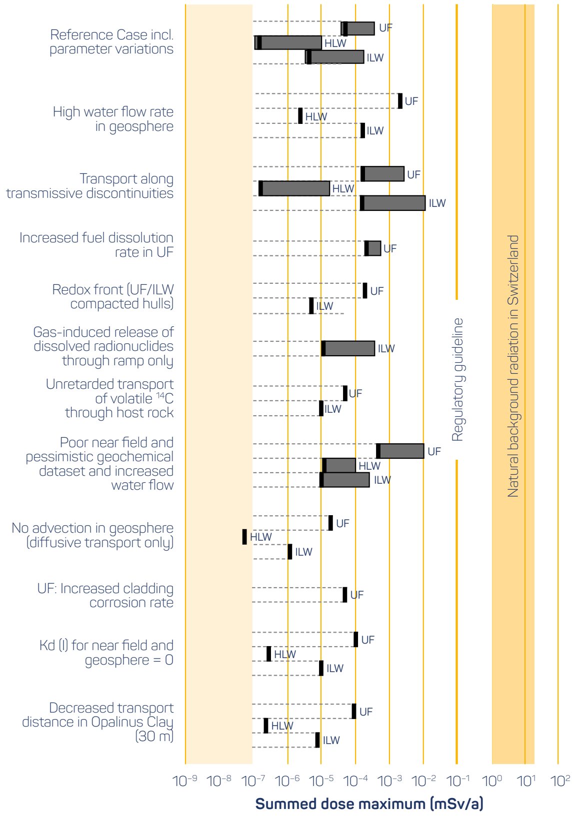
- *Alternative ILW evolution:* gas-induced release of dissolved radionuclides; gaseous release of ^{14}C; convergence-induced release; oxidising conditions
- *Biosphere:* alternative discharge area
- *Human actions:* borehole penetration; deep groundwater extraction; abandonment of the geological disposal facility.

Nagra also studied a range of 'what if' scenarios that are judged to be outside the range of possibilities supported by scientific evidence, but would affect safety if they could occur. These hypothetical assumptions—and the reasons for their implausibility or infeasibility—are:

- high water flow rate in the geosphere (100-fold increase)—despite all measurements and observations
- transport along transmissive discontinuities in the host geology—although such features have not been observed in Opalinus Clay
- redox front penetration within the near field—although there is no plausible mechanism by which this could occur
- increased fuel dissolution (10-fold and 100-fold increase)—despite extensive laboratory measurements
- gas-induced release of dissolved radionuclides from ILW section of the geological disposal facility through the ramp—no good physical model
- only unretarded instantaneous transport of carbon-14—not scientifically credible
- carbon-14 released as volatile species through the host geology—not scientifically credible
- combination of poor near-field performance, pessimistic near-field geochemical dataset, pessimistic geosphere geochemical dataset and enhanced water flow in the geosphere—vanishingly low probability
- no advection in geosphere (diffusive transport only)—this scenario would be more positive than the base case which pessimistically assumes that there would be some advective flow
- increased corrosion of the used fuel cladding—despite laboratory measurements
- zero sorption for iodine in near field and geosphere—despite known scientific data
- decreased transport distance in Opalinus Clay—despite the lack of any mechanism.

All of these scenarios also lead to doses that are at most a tenth of the regulatory limit, as illustrated in Figure I.29.

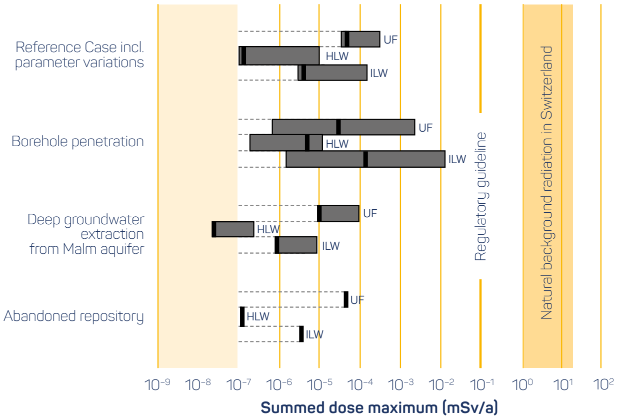
Figure I.30 shows the results for the human intrusion cases. The most commonly discussed case is that of unintentional penetration of the disposal area by a future borehole. The results shown are for doses to the public and not to the single driller who might be exposed by the material brought up the borehole.



mSv = millisieverts
UF = used fuel
HLW = high level waste
ILW = intermediate level waste

Figure I.29: Calculated dose maxima and ranges for the 'what if' scenarios

Note: Base cases marked by bold lines
Data sourced from Nagra



mSv = millisieverts
UF = used fuel
HLW = high level waste
ILW = intermediate level waste

Figure I.30: Calculated dose maxima and ranges for the human intrusion scenarios

Note: Base cases marked by bold lines
Data sourced from Nagra

CONCLUSIONS

The most important conclusions concerning the safety case prepared by any implementer of a geological disposal facility are those that are arrived at by the regulator. In Switzerland, the conclusions drawn by the regulator, ENSI, in its review of the safety case were as follows:

> *Nagra has shown in a manner open to scrutiny that the required long-term protection of humans and the environment can be achieved with the repository system described. The methodology used to demonstrate safety reflects the state-of-the-art internationally. The results of the safety analyses show that no harmful radiological impacts are to be expected from the geological repository.*

In addition to its positive assessment of the Nagra safety case, ENSI did place requirements on Nagra following the regulatory review. These are listed below; they were all judged by ENSI in its 2012 report, ENSI 35/14, to have been fulfilled.

Safety case requirements placed by ENSI on Nagra after NTB 82-05:

- Methodology of safety analysis:
  - » review of the methodology for deriving assessment cases
  - » in-depth analysis of inadvertent human intrusion into the disposal area
  - » analysis of the influence of erosion after very long periods
  - » development of probabilistic methods and codes as well as further development of instruments for sensitivity analyses
  - » ensuring the current state of technology and science for the methodology of the safety analysis
- Derivation of minimum requirements for selected elements of the barrier system:
  - » definition of minimum requirements and design criteria
  - » Biosphere modelling:
  - » in-depth analysis of the effects of geomorphology and climate
  - » in-depth analysis of the development of the concentrations of radionuclides in the various biosphere systems
  - » inclusion of expert knowledge about the biosphere modelling

- Models and data for the analysis of long-term safety:
  - » further development of tools for the safety analysis
  - » staying abreast of current knowledge.

Following are some wider conclusions from Swiss safety cases to date that may provide lessons for other programs:

- The most formal safety case submitted to date was carried out in a specific context, the 'Entsorgungsnachweis' (proof of disposability) project which was designed to assess the technical concept and the achievable safety levels in a particular host geology, Opalinus Clay. When the project was submitted, Nagra also chose to couple it with a formal proposal to narrow down further siting work to the area where the single exploratory borehole had been sunk. The regulator declined to comment on this siting issue since it was outside the scope of the original defined context of the safety case.
- The methodology was state-of-the-art when the project was submitted in 2002; subsequently improvements have been made in modelling capabilities but the basic approach remains the same. This illustrates that, although major methodology developments do not take place in short timescales, a continuing effort is required to stay abreast of progress.
- The review of the safety case by the regulator took several years. It led to a positive result, but also to some additional requirements which again took Nagra several years to fulfil. The time required for passing all regulatory hurdles has been underestimated, not just by Nagra, but by most advanced disposal programs.
- Currently, safety cases with a different goal are in progress—namely, as input to the process of narrowing down the number of potential facility sites. As described in this report, an implementation program for a geological disposal facility will go through a sequence of safety cases.
- Safety cases have rarely if ever been used to give quantitative criteria which can be used to discriminate between potential sites. It is still an open question whether this can be achieved in a reliable manner because of the high margins of predicted safety in well-chosen candidate sites, the achievable accuracy of input data (especially geological parameters) and the precision of the modelling approaches. Final site selections are better based on a wider set of criteria than simply on the numerical results of safety assessment calculations.

SAFETY CASE 4: PROPOSED HIGH LEVEL WASTE AND INTERMEDIATE LEVEL WASTE DISPOSAL FACILITY IN BELGIUM

This safety case summary was prepared by N Chapman and C McCombie of MCM on behalf of the Nuclear Fuel Cycle Royal Commission.

Belgium has a relatively small nuclear power program but has been involved in the development of nuclear energy technologies in Europe since the earliest days, with a sustained program of R&D into disposal of radioactive wastes in deep clay formations since the 1970s. The Belgian program led international R&D on clay-based host formations for many decades. Part of this work has been the development of disposal concepts and associated safety evaluations for used fuel, vitrified HLW and long-lived ILW disposal in the Boom Clay formation and other, related clays. This work is led by the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS) and is supported by R&D carried out by the Belgian Nuclear Research Centre (SCK·CEN), including information from the underground research laboratory at Mol. The most recent comprehensive safety case, called SAFIR 2, was published in 2001 and a broad program of work by ONDRAF/NIRAS is currently aimed at updating this. The final site for the national deep geological disposal facility has not yet been selected. The safe management of radioactive wastes is overseen by the regulatory authority, the Federal Agency for Nuclear Control (FANC/AFCN).

OUTLINE OF PROJECT AND DISPOSAL CONCEPT

As a result of its early involvement in the nuclear industry and associated technologies, Belgium has a complex inventory of historic wastes from developmental and manufacturing facilities, plus those from its nuclear power plants, other reactors, and nuclear research and industrial facilities. It has been involved in the development of geological disposal in Europe since the initiation of joint European Community projects in the 1970s, with a deep underground research facility at Mol in the Boom Clay, one of the target geological formations being considered for the geological disposal facility (GDF). No site is yet selected for the GDF and other clay formations (e.g. the Ypresian clays) may be possible hosts. The Boom and Ypresian clay formations are between about 28 million and 56 million years old.

The wastes destined for geological disposal by 2070 are principally about 10 000–11 000 m^3 of cemented, vitrified and bituminised ILW (a mix of operational, reprocessing and decommissioning wastes, and labelled 'Category B'), plus 600–4500 m^3 of vitrified HLW from reprocessing used nuclear fuel, labelled 'Category C'. The amount of HLW depends on future policy on fuel reprocessing, so there may also be some used fuel (also in Category C) to dispose of in the facility.

The disposal concept involves placing the Category B and C waste containers into massive 'monoliths' and 'supercontainers', respectively (Figure I.31).[178] These containers will be emplaced in tunnels constructed in the deep clay formation and the disposal facility will then be backfilled and sealed. A conceptual illustration is shown in Figure I.32.

SAFETY CASE REQUIREMENTS

ONDRAF/NIRAS has carried out considerable research, development and demonstration (RD&D) since 1974, including several detailed evaluations of the safety of the geological disposal facility. The most recent comprehensive analysis was SAFIR 2, in 2001. In its next stage of work, it will present the FANC with a Safety and Feasibility Case (SFC), a synthesis of evidence, analyses and arguments that quantify and substantiate the ONDRAF/NIRAS claim that the facility can be constructed and be safe after closure, and beyond the time when active control of the facility can be relied upon. At present, FANC is developing the safety regulations that will apply to the Belgian geological disposal facility.

The SFC will become more comprehensive as the program progresses and is a key input to decision making at several steps in facility planning and implementation. In addition to the safety arguments and feasibility specifications, the SFC encompasses environmental policies and their implementation, as well as mechanisms to ensure appropriate public information and participation. The SFC can also be used as a platform for informed discussion, whereby interested parties can assess their own levels of confidence in the project, and issues that may be a cause for concern can be identified for further work.

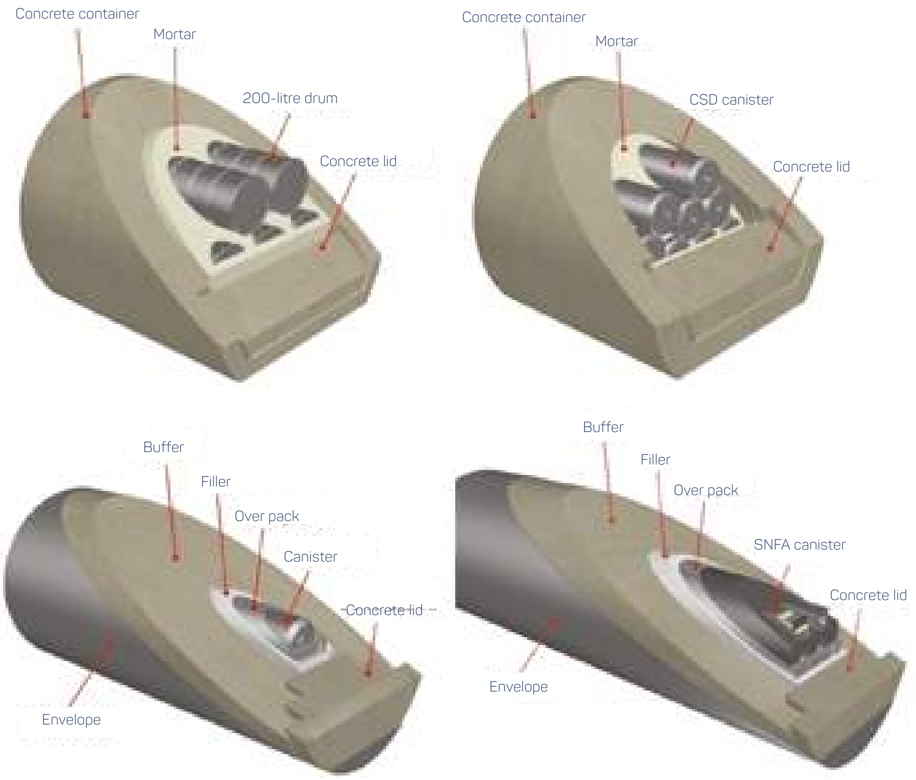


Figure I.31: Monoliths for ILW (top) and supercontainers for HLW and used fuel (bottom)

Image courtesy of ONDRAF/NIRAS

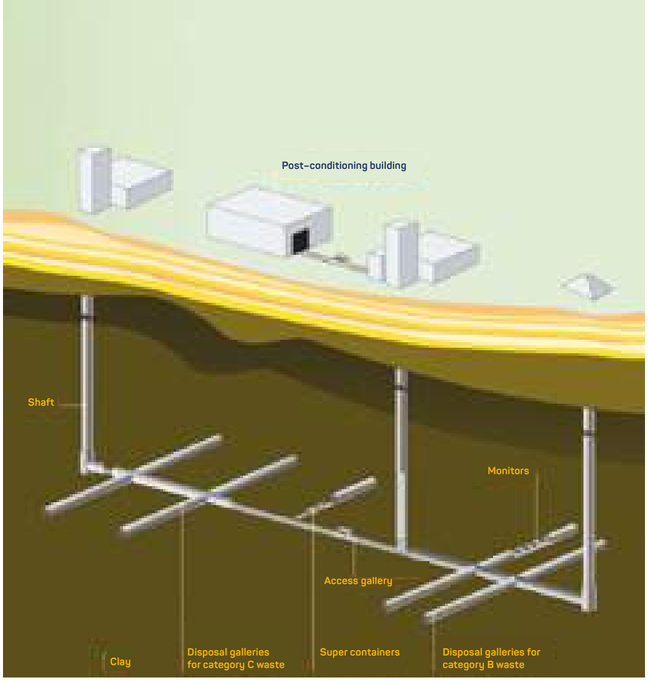


Figure I.32: Detail of the geological disposal concept, showing tunnels in the clay formation for monolith and supercontainer emplacement

Image courtesy of ONDRAF/NIRAS

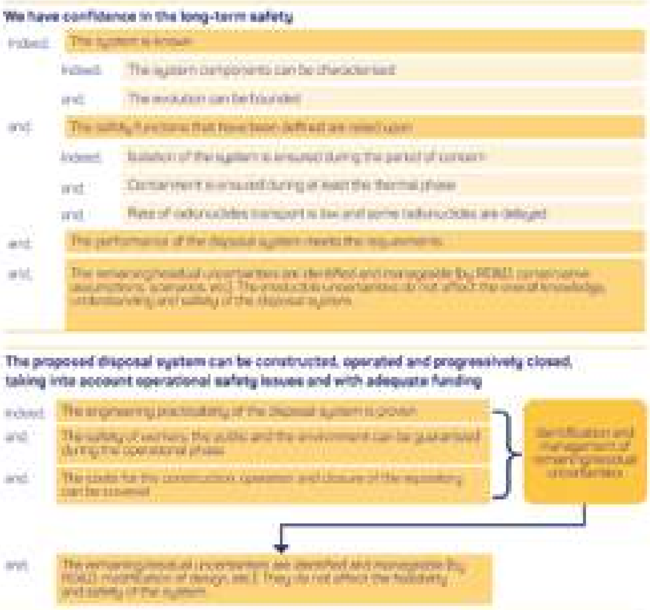


Figure I.33: Hierarchy of statements relating to the safety and feasibility of a geological disposal facility in clay

Image courtesy of ONDRAF/NIRAS

ONDRAF/NIRAS bases its approach on a safety strategy, which uses safety and feasibility statements, in the form of 'trees', containing a hierarchical set of claims that ONDRAF/NIRAS considers to be correct, but which must be substantiated by their RD&D work. The 'Safety Tree' and the 'Feasibility Tree' are illustrated in Figure I.33.

ONDRAF/NIRAS follows the commonly accepted and applied strategy for radioactive waste management of concentration and containment of waste, with isolation from the biosphere. A safe disposal system protects people and the environment now and in the future from the harmful effects of ionising radiation and chemically toxic contaminants associated with the waste. Protection must be provided at all stages over the lifetime of a disposal facility, without imposing undue burdens on future generations.

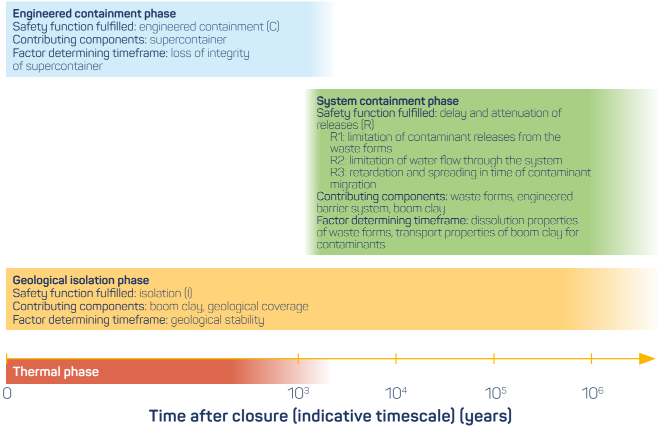
ONDRAF/NIRAS has adopted the following set of safety principles: robustness, demonstrability, passive safety, defence-in-depth, use of best available techniques and optimisation of protection (and safety). These are based on international standards and recommendations by the IAEA.

The safety of the geological disposal facility is characterised by attributing safety functions to the various components of the system, natural and engineered. It can be seen that the components have specific functions, but all the safety functions are dependent to varying extents on the natural (geological) and engineered barriers working together.

Engineered containment (C) (for heat-emitting Category C waste): prevents the release of contaminants from the disposal package during the 'thermal phase' (the first 1000 years or so, during which the facility and immediately surrounding clay formation are significantly heated by the HLW or used fuel) by using one or several engineered barriers. The component contributing to this safety function is the supercontainer (Figure I.31).

Delay and attenuation of releases (R): to retain contaminants within the disposal system. The components contributing to this safety function are the solid waste materials, the engineered barrier system and the host clay formation which, together:

- limit and spread in time any releases of contaminants from the waste packages



C = containment
I = isolation
R = releases

Figure I.34: The time frames over which safety functions of the multi-barrier system operate

Image courtesy of ONDRAF/NIRAS

- limit the flow of water through the disposal system, to prevent or limit transport of contaminants to the environment in flowing groundwaters
- retard and spread in time the migration of contaminants to the environment.

Isolation (I): to isolate the waste from people and the environment by preventing direct access to the waste and protect the GDF from potentially detrimental processes. The host clay formation and overlying geological formations provide this safety function by:

- limiting the likelihood of inadvertent human intrusion and, in case such intrusion does occur, limiting its radiological and chemical impacts on people and the environment
- protecting the waste and the engineered barrier system from natural changes and perturbations in the environment of the disposal facility, such as major climate variations, erosion, uplift, seismic events or rapid changes in chemical and physical conditions.

Figure I.34 shows how these safety functions operate at different times into the far future, from the time of disposal out to more than 1 000 000 years.

Figure I.35: Uniformity of the Boom Clay formation, as seen where it is exposed at ground level

Image courtesy ONDRAF/NIRAS

ROLE OF GEOLOGY TO SAFETY

The Boom Clay is a relatively plastic and highly impermeable formation, which gives it good containment properties. The formation is some tens of metres thick, being present below much of Belgium, dipping gently from the surface in the south-west, down to depths of some hundreds of metres in the north-east. The illustrations below show the uniform structure of the Boom Clay where it is exposed near the surface (Figure I.35) and the general geological structure in which it lies (Figure I.36).[179]

The Boom Clay is an efficient natural barrier to the migration of radionuclides and chemical contaminants towards the surface environment because it has:

- very low permeability, allowing practically no water movement. Movement of contaminants through the clay is thus essentially by the extremely slow process of diffusion
- strong physical and chemical retention capacity for many radionuclides and chemical contaminants, meaning that migration through the clay is considerably delayed
- a capacity for self-sealing: any fractures induced by excavation works seal within weeks.

These properties have been studied and demonstrated in numerous experiments and observations over decades in the laboratory and in the deep underground research

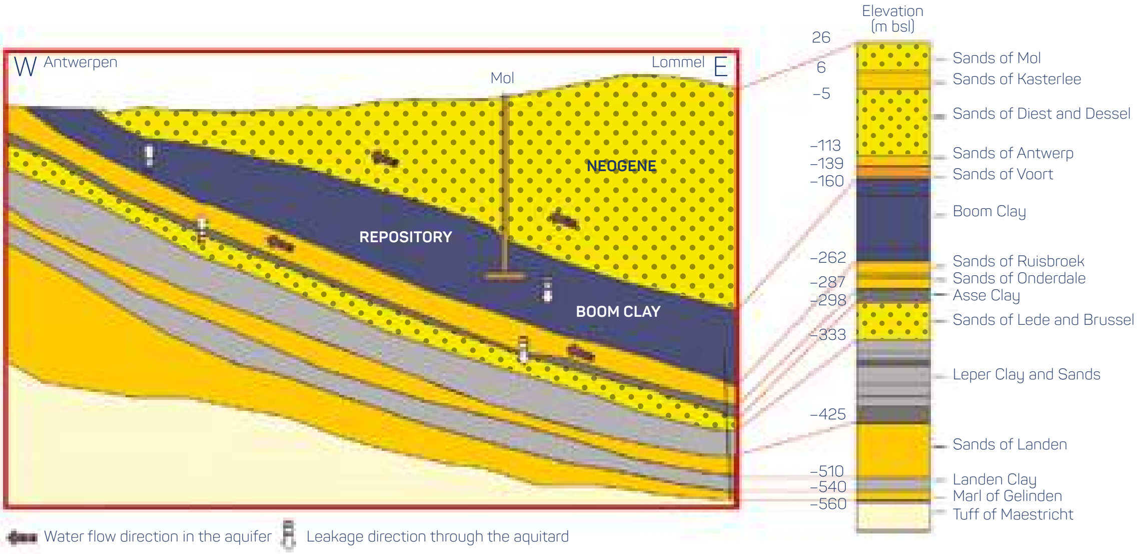


Figure I.36: General geological structure of the Boom Clay formation and surrounding formations

Image courtesy of ONDRAF/NIRAS

laboratory at Mol, where large-scale tests and experiments have been carried out since 1974. In addition, the isolation and containment effectiveness of clay has been shown to protect even biodegradable material such as wood from degradation for millions of years. ONDRAF/NIRAS cite examples such as the 1.5 million year old preserved woods of the Dunarobba 'fossil forest' in Italy and the even older 'fossil' woods of the Entre-Sambre-et-Meuse region.

Overall, a large part of the safety provided by the disposal system comes from the geological barrier, which protects the engineered barriers during the early period after closure so that they can provide their isolation and containment functions, and then continues to isolate and contain the waste far into the future.

ROLE OF ENGINEERED BARRIERS TO SAFETY

The engineered barrier system limits perturbations of the host clay formation by construction, operation and closure of the geological disposal facility and provides complete containment within the facility for Category C waste during the early thermal phase. It also contributes to the delay and attenuation of the releases, as outlined above in 'Safety case requirements'. Backfill and seals in the disposal facility will ensure that, after closure, contaminant movement within the facility will be diffusion-dominated.

After the first 1000 years or so, the engineered barrier system is assumed to become degraded and to have only a limited role in containment and isolation compared to the geological barrier provided by the clay, which dominates the overall safety provided by the disposal system.

The performance of the engineered barrier materials has been tested over many years in laboratory experiments and in situ, in the Mol underground laboratory. Analogues of materials found in nature also provide evidence for the safety case. For example, basaltic volcanic glasses, which have been shown to behave similarly to vitrified HLW glasses, have been found in the Boom Clay, and show no evidence of dissolution, despite being buried for almost 30 million years.

RISK ASSESSMENT UNDER POTENTIAL FUTURE SCENARIOS

Safety assessment in the SFC systematically analyses the hazards associated with the geological disposal facility and its ability to fulfil safety functions and meet requirements from the regulatory body.

Practically, safety assessment evaluates the performance of the disposal system across a large spectrum of scenarios and calculation cases to show that the disposal system will perform safely, if built as intended. It also highlights residual uncertainties and outstanding issues to be tackled as the program moves forward.

In the ONDRAF/NIRAS safety assessment, scenarios include:

- *Reference scenario:* based on a reference case and several alternative cases that make different assumptions. In the reference case, the system is implemented according to the specified design, and the assumptions made tend to be conservative. Alternative cases elucidate the impact of uncertainties or are used to evaluate the impact of different geological disposal facility design options.

- *Altered scenarios:* representing alternative 'futures' of the disposal system that have a lower probability of occurrence than the reference scenario and which result from natural events or processes that might significantly impair one or more safety functions. In the most recent (SAFIR 2) safety evaluation[180], these scenarios included the impacts of future greenhouse or severe glacial climates, poor sealing of the geological disposal facility, the premature failure of an engineered barrier and the possibility of radioactivity being transported by gases produced in the facility.
- *'Human intrusion' scenarios:* represent alternative 'futures' of the disposal system resulting from future human actions. Their probability of occurrence cannot reliably be quantified over the time frame covered by safety assessment, but is kept low by siting and design measures. Human intrusion scenarios will be developed in interaction with the regulators. In the SAFIR 2 safety evaluation, these scenarios included drilling and pumping a water-exploitation well near the geological disposal facility and the drilling of a borehole directly through the emplaced waste.

In the current reference scenario, the Boom Clay is stable and no human or natural events alter the isolation provided by the disposal system. The containment of radioactive and chemical contaminants within the disposal containers lasts until at least the end of the thermal phase (a few thousand years after waste disposal). Water in the clay pore spaces will diffuse slowly into the engineered barrier system and eventually start to corrode the monoliths and supercontainers, and finally the primary waste packages. The waste will begin to dissolve in the pore waters and release contaminants that will diffuse into the host clay formation. The Boom Clay around the facility will have been disturbed by the excavation, construction, operation and post-closure evolution of the geological disposal facility, but the spatial extent of these perturbations is limited. Movement of contaminants is diffusion-dominated and further delayed by retention processes in the clay. After the slow diffusive transport through the Boom Clay formation, during which a large fraction of the radioactivity will have been removed, owing to the natural process of radioactive decay, only a minor fraction will reach groundwater in surrounding geological formations (non-living environment) and the biosphere (living environment).

These processes are evaluated using simulations of radioactivity release and movement. The outcomes of these simulations (called 'safety indicators') are compared with the appropriate limits specified by the regulatory authorities, or with reference values. The most commonly used indicator is the radiation dose rate to hypothetical individuals exposed to releases in the distant future. The uncertainty in dose rate calculations increases with time so additional indicators are used to improve the reliability of the safety assessment. Some indicators are used to explain the functioning of the disposal system by quantifying the contribution of its main barriers or safety functions at different times; such indicators are called 'performance indicators'.

Dose rates to people are mainly calculated by simulating the migration of radioactivity into and through the aquifer in geological formations overlying the geological disposal facility and the Boom Clay host formation. Concentrations of radioactivity in water taken from a well located just above the disposal facility are calculated, along with radioactivity fluxes towards rivers. These concentrations are used to evaluate radiation doses to people using the water for drinking and agricultural purposes.

The results of the safety assessments in SAFIR 2 showed doses below the envisaged regulatory constraint for all wastes considered and for most analysed cases.[181] These assessments showed that the Boom Clay is the dominant contributor to overall safety in the reference scenario and other plausible evolution scenarios. Preparatory safety assessments performed in the frame of the current RD&D program for the SFC confirm these results.

For example, a person living near the disposal facility who takes drinking and irrigation water from a deep well located just above the Boom Clay, where calculations indicate that the highest concentrations of radioactivity would be found, would be exposed to peak radiation doses if they were living there more than 100 000 years in the future.

This is shown in Figure I.37. Note that both the time and the radiation dose scales are logarithmic, meaning that each division shown is 10 times larger or smaller than the previous one.

It can be seen that even the maximum exposure calculated for such a person (if they were living there in about 200 000 years' time) would be 10 to 30 times lower than typical internationally accepted radiation dose limits for geological disposal facilities of 0.1 to 0.3 mSv/a. This calculated maximum radiation dose is extremely low: more than 250 times lower than the radiation dose received annually

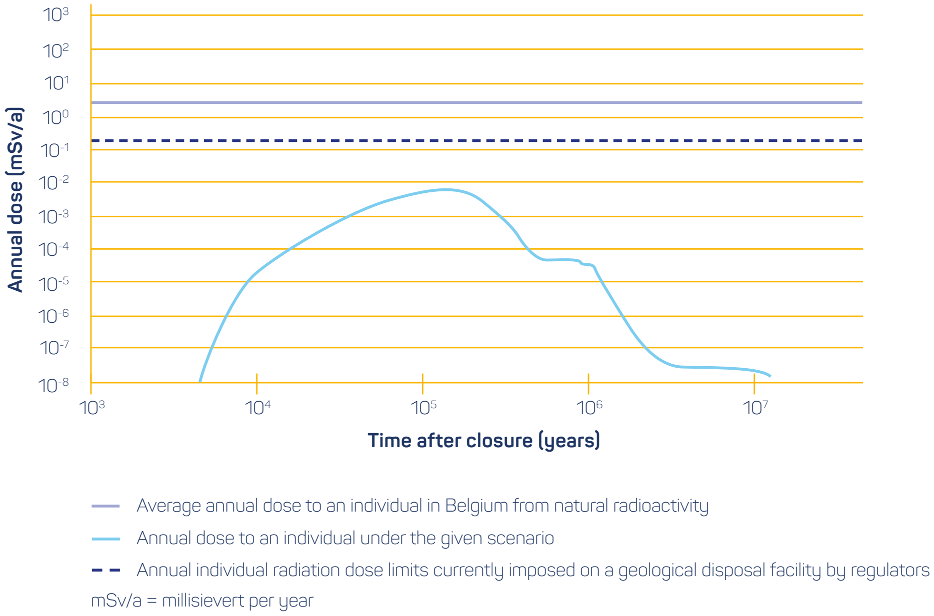


Figure I.37: Reference scenario for a geological disposal facility in Boom Clay

Image courtesy ONDRAF/NIRAS

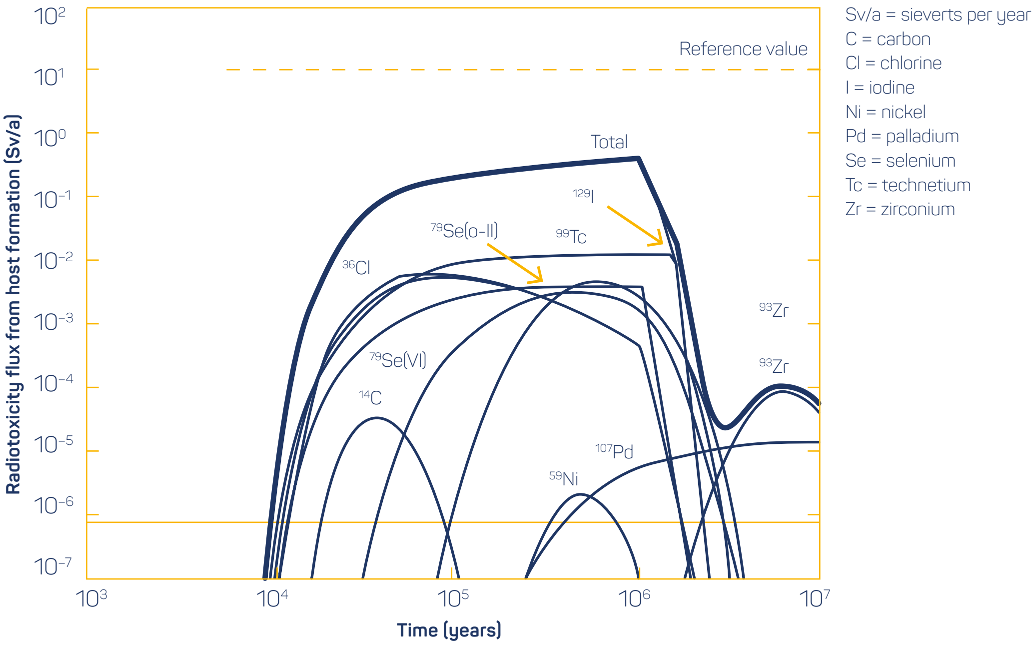


Figure I.38: Comparison of radionuclides released by a geological disposal facility in Boom Clay to those present in agricultural fertilisers, expressed in terms of radiotoxicity

Image courtesy ONDRAF/NIRAS

by a person living in Belgium from the natural radiation background at Earth's surface (about 2.5 mSv/a). The earliest calculated exposures shown on the diagram (after a few thousand years) are hundreds of millions of times lower than this natural background radiation exposure.

Another form of safety indicator is to compare the flux of radioactivity from a disposal facility to the biosphere with the radioactivity arising from everyday processes in which people are engaged. This is useful, given the inevitable uncertainty about future lifestyles. Figure I.38 shows the calculated rate of release of radioactivity from used fuel in a geological disposal facility located in the Boom Clay as a function of time, again using a logarithmic scale.

Here, radioactivity is expressed as 'radiotoxicity', the highly hypothetical radiation dose that would result if a person were to ingest all of a particular radioactive substance released from the disposal facility in a particular time period. The upper curve shows the total radiotoxicity from all the radioactive substances released into the environment from a used fuel disposal facility in the Boom Clay. The contribution to the total made by individual radioactive isotopes (including technetium, chlorine and iodine) is also shown.

The 'reference value' line shows, for comparison, the radiotoxicity of agricultural fertilisers (which are naturally radioactive) that are applied on farmland in the Flanders region: about 10 Sv/km^2 per year. A square kilometre is about the size of the geological disposal facility, so it can be seen that this is more than ten times higher than the total releases from the facility.

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APPENDIX J: WASTE STORAGE AND DISPOSAL—ANALYSIS OF VIABILITY AND ECONOMIC IMPACTS

1. ANALYSIS OF VIABILITY—COMMISSIONED STUDY

This study, undertaken by Jacobs and MCM, assessed the business case and provides quantitative analyses for establishing facilities in South Australia for the storage and disposal of radioactive waste.

The study estimated the whole of life costs of four conceptual waste storage and disposal facilities in a combination of generic stand-alone and collocated scenarios. It assessed the potential returns on investment of establishing those facilities and supporting infrastructure in South Australia.

ASSUMPTIONS AND INPUTS

The assumptions and inputs set out below formed the baseline scenario of the viability analysis.

FACILITY CONFIGURATION SCENARIOS

The study analysed the viability of four facilities in a range of different configurations: see Table J.1. The four facilities were:

- an interim storage facility for above-ground dry cask storage of used nuclear reactor fuel and for storage of intermediate level waste
- a geological disposal facility for disposal of international used fuel
- an intermediate depth repository for international intermediate level waste
- a near-surface low level waste repository for the disposal of low level waste arising from the operation and decommissioning of the interim storage facility, intermediate depth repository and geological disposal facility.

Under the baseline scenario (CS 4 in Table J.1), the intermediate depth repository and geological disposal facility were collocated.

Table J.1: Configuration scenarios modelled

Configuration scenarios (CS)	Coastal location	Inland location	Inland location	Inland location
CS 1: stand-alone facilities	ISF	LLWR	IDR	GDF
CS 2: no ISF		LLWR	IDR	GDF
CS 3: no ISF, collocate GDF & IDR		LLWR	GDF & IDR	
Baseline scenario CS 4: collocate GDF & IDR	ISF	LLWR	GDF & IDR	
CS 5: all facilities at coastal site	All four facilities			
CS 6: collocate IDR and LLWR	ISF	LLWR & IDR		GDF
CS 7: ISF & LLWR collocated, GDF & IDR collocated, 'optimised' case	LLWR & IDR		GDF & IDR	
CS 8: LLWR collocated with GDF & IDR	ISF		GDF, IDR & LLWR	
CS 9: all facilities at inland site			All four facilities	

Notes: GDF = geological disposal facility, IDR = intermediate depth repository, ISF = interim storage facility, LLWR = low level waste repository.
Source: Jacobs & MCM

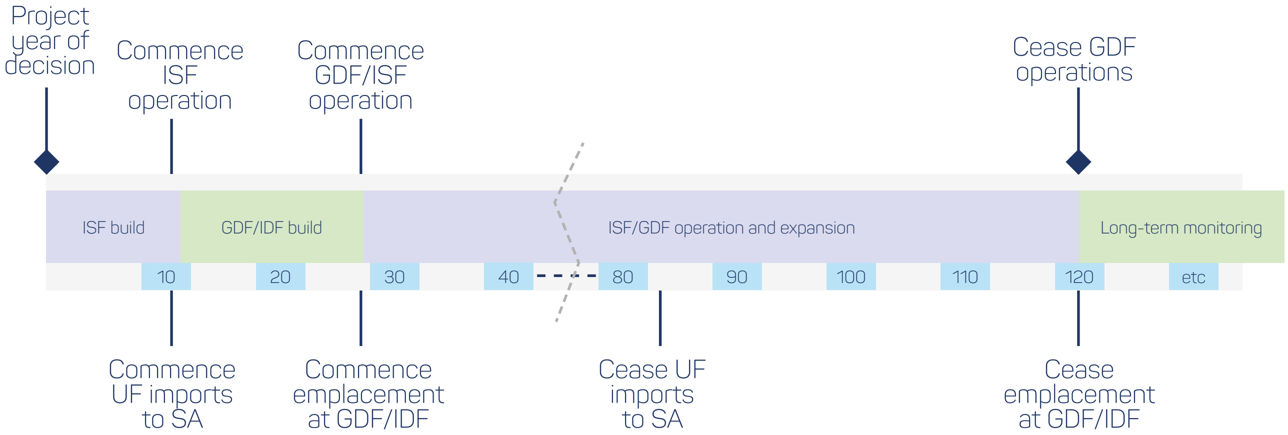


Figure J.1: Assumed facility development and operation timeline (baseline scenario)

Notes: GDF = geological disposal facility, IDR = intermediate depth repository, ISF = interim storage facility, UF = used fuel.
Source: Jacobs & MCM

TIMELINE

The baseline scenario assumes that the interim storage facility would receive used fuel and intermediate level waste in project year 11, after the decision to proceed, siting, licensing and construction were completed. Receipt of used fuel and intermediate level waste would continue at the interim storage facility until project year 83.

Used fuel would be transferred to the geological disposal facility for disposal in project year 28 and continue for 92 years. Intermediate level waste transfers would start in project year 26 and continue for 49 years. The difference in times is primarily due to the need to store used fuel for 40 years before permanent disposal. The timeline for development and operation of the facilities under the baseline scenario is summarised in Figure J.1.

MARKET

The baseline scenario included a conservative assumption about the portion of the total global waste inventory that would constitute an accessible market for South Australian waste storage and disposal services. This required assessment and estimates about historic, current and planned nuclear power programs in countries around the world, and their current strategies and future plans to manage the associated radioactive waste.[1]

There are substantial inventories of used fuel accumulating in countries with nuclear power programs around the world, many of which currently lack solutions for long term management.[2] The total global quantity of used fuel is . currently estimated to be approximately 390 000 tonnes of heavy metal (tHM), and by 2090 this is anticipated to grow to over 1 million tHM.[3]

The assumption about the accessible market excluded countries that are committed to domestic solutions for waste management and disposal, including the USA, France, the UK, Canada, China and India, as well as waste from countries with laws or policies prohibiting export of their waste.[4]

The estimated quantities include waste from existing reactors and those in advanced stages of development that are expected to be operational by 2030, but exclude waste from reactors that become operational after 2030.[5] They also exclude potential waste produced locally if Australia were to develop a civil nuclear power program, although any impact such quantities could have on the baseline scenario is expected to be marginal.[6] Vitrified high level waste as a result of reprocessing spent fuel has been included in this assessment, but forms a small proportion of the total estimated quantities.

The estimated quantities from countries with no domestic solution that could be potential clients for waste storage and disposal services are set out in Table J.2.

The aggregate current and forecast quantities of waste from major potential client countries with no domestic solutions that would comprise the accessible market for South Australia appear in Table J.3.

Table J.2: Current and forecast stockpiles of used fuel and intermediate level waste from existing, operational nuclear reactor fleet

	Used fuel (tHM)		Intermediate level waste (m^3)	
Countries	**Current**	**Cumulative forecast (2080)[a]**	**Current**	**Cumulative forecast (2080)[a]**
Japan	23 126	53 463	85 175	18 0975
Korea	14 199	50 532	25 119	101 732
Germany	15 119	21 786	46 378	67 431
Ukraine	6 205	17 404	24 889	60 246
Spain	5224	9373	15 745	28 849
Belgium	4413	7458	12 749	22 364
Taiwan	3517	8565	10 605	28 490
Argentina	3458	8197	2348	6404
Switzerland	2679	4200	7744	12 547
Romania	2096	10 756	1143	5080

Source: Jacobs & MCM

[a] Based on operation of existing reactor fleet over 60 years

Table J.3: Total current and forecast used fuel and intermediate level waste stockpiles from existing, operational nuclear reactor fleet from nations not committed to a national solution

Total	Current	Forecast (2090)
Used fuel (tHM)	89 979	276 000
Intermediate level waste (m^3)	269 471	782 430

The accessible market estimated for used fuel in Table J.3 represents 26 per cent of the total quantity forecast to have accrued globally by 2090.[7] The estimate for intermediate level waste represents approximately 3 per cent of the total quantity forecast to have accrued globally by 2090.[8]

The proportions of used fuel attributable to current and future nuclear power programs are illustrated in Figure J.2.

Taking into account the possibility that not all countries comprising the potentially accessible market would necessarily use the South Australian storage and disposal services, the baseline scenario assumes that 50 per cent of the accessible quantities of used fuel and intermediate level waste will be stored and disposed of in South Australian facilities: see Table J.4 and Figure J.3. The baseline market capture assumption is compared with higher and lower cases in Table J.4.

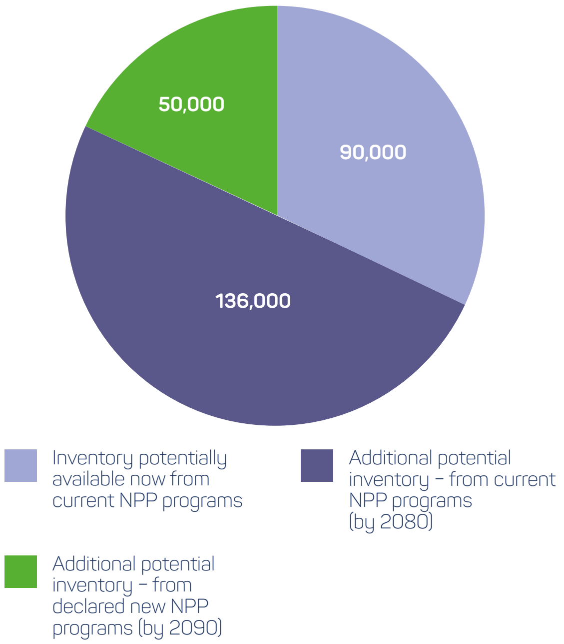


Figure J.2: Potential used fuel inventory (tHM) available to South Australia by 2090

Note: Total 276,000 tHM

Image courtesy of Jacobs and MCM

Table J.4: Potential shares of the accessible market for used fuel and intermediate level waste

Scenario	Used fuel inventory (by 2090)	Intermediate level waste inventory (by 2090)
Upper case (75% of accessible)	207 000 tHM	585 000 m^3
Baseline (50% of accessible)	138 000 tHM	390 000 m^3
Lower case (25% of accessible)	69 000 tHM	195 000 m^3

Note: tHM = tonnes of heavy metal
Source: Jacobs & MCM

Table J.5: Whole of life costs for used fuel disposal in countries with advanced projects

Country	Whole of life disposal costs (A$ million per tHM)
Finland	$0.65
Sweden	$1.13
Switzerland	$2.43

Source: Jacobs & MCM

WILLINGNESS TO PAY AND PRICE TO CHARGE

The estimation of revenues that prospective integrated waste storage and disposal facilities developed in South Australia could secure required the determination of a range of prices that client countries might be willing to pay for the services. The price to charge in the baseline scenario was selected on the basis of a conservative assessment of the range of potential prices identified.

The willingness to pay and price analysis predominantly focused on used fuel, given that it is the most expensive and politically problematic waste type to manage and has the potential to significantly affect the overall viability analysis.[9]

In the absence of a market for international waste storage and disposal services, a potential customer's willingness to pay was inferred from a range of sources including[10]:

- the cost of developing and operating national disposal facilities
- national waste disposal funds
- the cost of reprocessing services

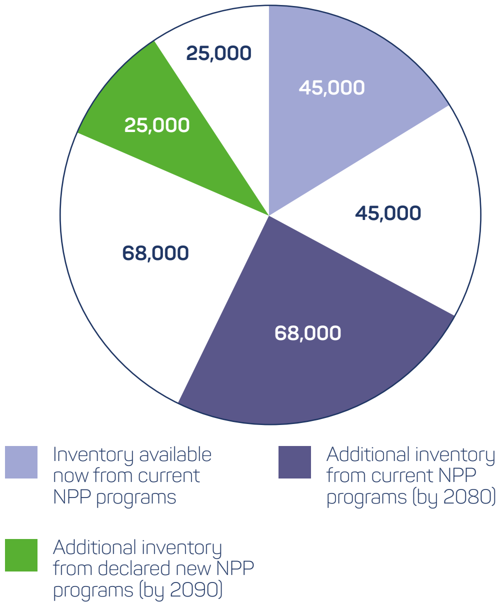


Figure J.3: Baseline assumption–market share of accessible used fuel (tHM) for management and disposal to 2090

Notes: Total 138 000 (50 per cent of Table J.2 total), NPP = nuclear power plant
Image courtesy of Jacobs and MCM

- reductions in the cost of capital from a guaranteed solution for the disposal of waste
- distress payments for plant shutdowns.

A significant aspect of this analysis related to the costs associated with storage and management of used fuel that countries with domestic nuclear power programs might avoid by utilising South Australian services.

Published data and estimates about the costs (per tHM of used fuel) of planning, constructing, operating and closing geological disposal facilities from countries with such facilities in advanced stages of development provided an indication of costs countries might seek to avoid, thus informing willingness to pay (Table J.5). The average cost of A$1.2m per tHM of used fuel provides an illustrative benchmark for costs which might be avoided by utilising South Australia's services.[11]

The cost associated with storage and disposal of used fuel incurred by utilities, which can in turn inform potential willingness to pay, can also be derived from the average levelised cost of electricity (LCOE) of nuclear power plants. From the LCOE, it is possible to identify the proportion that can be attributed to used fuel storage and disposal. This analysis indicated that the cost of storage, transport and disposal of used fuel amounts to about US$1m per tHM or A$1.39m per tHM.[12]

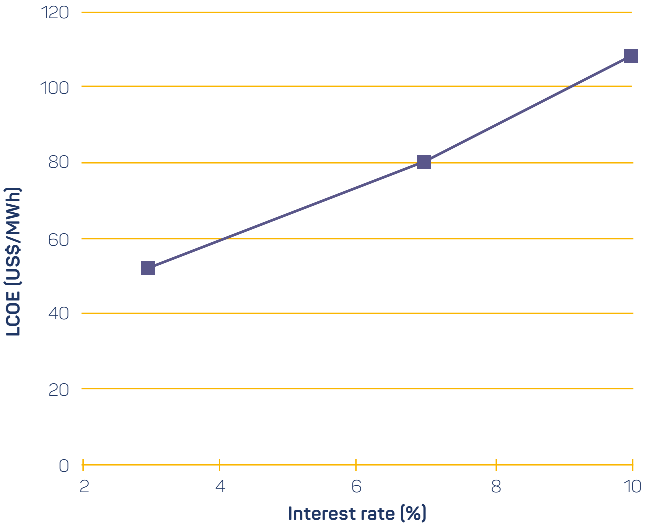


Figure J.4: Variation in nuclear power LCOE with cost of capital

Note: LCOE = levelised cost of electricity
Image courtesy of Jacobs and MCM

The cost of an alternative to storage and final disposal—namely, reprocessing—can indicate willingness to pay. A recent estimate of costs for proposed reprocessing of used fuel from Taiwan suggested a willingness to pay for that service of over US$1m, or A$1.54m per tHM. Given that Taiwan would still receive back after reprocessing vitrified high level waste, which requires further expenditure on a disposal solution, it can be inferred that willingness to pay for combined storage and final disposal services as an alternative to reprocessing might be even higher.[13]

Willingness to pay can also be inferred from potential reductions in the cost of capital for new nuclear power plants that can secure guaranteed back-end solutions. For nuclear power projects with fixed-cost arrangements in place for the used fuel management liability, the project risk is likely to be perceived to be lower, which would assist in securing a lower interest rate on finance. A reduction of 0.5 per cent in the interest rate, attributable to lower project risk, would equate to A$1.9m to A$2.6m per tHM of used fuel. The significant impact of the interest rate on the LCOE of a nuclear power plant is illustrated in Figure J.4.[14]

A further indication of willingness to pay can be drawn from examining the costs that plant operators would incur from unscheduled plant shutdowns due to lack of used fuel storage and the payments they may make to avoid such costs. Table J.6 shows the loss in US dollars that utilities could avoid by utilising an international storage disposal solution.

A baseline willingness to pay estimate (US$1.5m) was derived by taking the mid-point between:

- the average estimated costs of used fuel disposal from countries with geological disposal facilities in advanced stages of development (US$1m), and
- the minimum estimated willingness to pay in countries without a local disposal solution (US$2m).

After subtracting pre-delivery costs incurred by clients in preparing and transporting the waste to South Australia (estimated at US$0.15m per tHM),[15] the baseline scenario assumes a conservative price to charge international clients of A$1.75m per tHM for storage and permanent disposal of used fuel, as shown in Figure J.5. There may be potential to negotiate higher prices under some circumstances.[16]

The potential revenue achieved through storage of intermediate level waste is much lower than for used fuel due to the lower willingness to pay from client countries.[17] Intermediate level waste is considerably less problematic for countries to accrue and store than used fuel. This component of project revenue will have less of an impact on overall viability of the integrated facilities. The baseline scenario assumes a conservative price of A$40 000 per m^3 of intermediate level waste. This figure is based on a proposed appropriate levy on nuclear power plant operators for eventual intermediate level waste disposal in a recent report from the UK Department of Energy and Climate Change. It suggested that a cost of £25 900 per m^3 reflected the anticipated cost of its management, equating to about A$66 000 per m^3.[18]

Table J.6: Loss avoided by availability of international spent fuel transport, storage and disposal

Loss avoided by the availability of fuel storage and transport (US$ per MWh)	Burn-up (GWd/teU)	Thermal efficiency (%)	Output (MWh/teU)	Expected used fuel cost per teU (US$ millions)
80	50	34	408 000	32.64

Notes: GWd = gigawatt day, MWh = megawatt hour, teU = tonne enriched uranium
Source: Jacobs & MCM

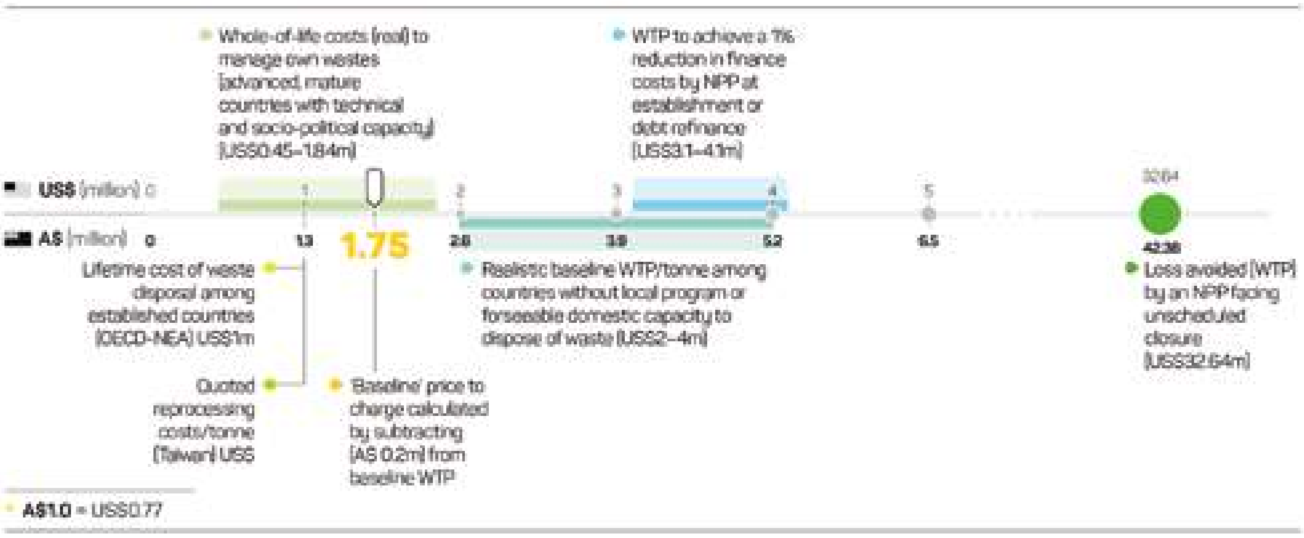


Figure J.5: Summary willingness to pay (US$m and A$m per tHM) based on published data and enhancements

Image adapted from Jacobs & MCM

FACILITY CAPACITIES

The capacities of each facility in the baseline scenario are based on the market capture assumptions discussed above. Under the baseline scenario, the facilities are assumed to have corresponding capacities of:

- 138 000 tHM of used fuel in the geological disposal facility
- 390 000 m^3 of intermediate level waste in the intermediate depth repository (collocated with the geological disposal facility)
- 81 088 m^3 of low level waste in the near surface low level waste repository initially, with the option to expand that capacity on an as-needs basis[19]
- 72 000 tHM of used fuel in above-ground dry casks and 175 000 m^3 of intermediate level waste in the interim storage facility.[20]

CAPITAL AND OPERATING COSTS

Capital and operating cost estimates are based on costs observed and forecast for similar overseas facilities currently in advanced stages of development, converted to Australian dollars and scaled to the projected South Australian scenarios. Cost estimates for supporting infrastructure are based on Australian experience from analogous examples in the resources and other sectors.[21]

The total capital cost for the construction, decommissioning and closure of the baseline facilities is estimated to be about A$41.0 billion, which includes a 25 per cent growth allowance and scope contingency. This sum is inclusive of the costs of developing new port, road, rail, airport and supporting electricity and water infrastructure.[22] Table J.7 shows the capital costs savings achieved by collocating the geological disposal facility and the intermediate depth disposal facility under the baseline scenario due to shared transportation, utility and surface infrastructure costs.[23]

Table J.8 shows the actual or estimated capital costs associated with similar projects overseas.

Total operating costs for the baseline scenario, including labour, contracted services, facility maintenance, equipment lease costs, industrial consumables and utilities, are estimated to be A$877.7 million per annum in the first 40 years, and A$765.2 million after year 40, to take into account the decrease in annual packaging costs at the interim storage facility as packages become available to be reused rather than purchased.[24]

The total combined capital and operating costs are estimated to be A$145.3 billion over the 120-year life of the project.[25] That total includes a significant portion of expenditure allocated to ensuring the safe construction, operation and closure of the facilities, as set out in Table J.9.

Table J.7: Estimated capital costs for the four facilities under the baseline scenario

Facility configuration	Total cost (A$ 2015 m, undiscounted and rounded)	Nominal size of facility (total waste capacity)	Normalised cost per unit (A$ 2015 thousands)
Low level waste disposal facility	820	81 088 m^3	10.1 per m^3
Interim storage facility	2200	72 000 tHM	30.63 per tHM
Intermediate depth disposal facility	14 300	390 000 m^3	36.67 per m^3
Geological disposal facility	33 400	138 000 tHM	242.02 per tHM
Collocated geological disposal facility and Intermediate depth disposal facility	38 000	138 000 tHM, 390 000 m^3	–
Baseline scenario: Low level waste disposal facility, interim storage facility plus collocated geological disposal facility and intermediate depth disposal facility	41 020	N/A	N/A

Source: Jacobs & MCM

Table J.8: Comparison of estimated costs to reference facility costs

Facility	Reference facility/cost database	Cost per stored unit (A$ thousands)	Commission estimated cost as percentage of reference facility
Low level waste disposal facility	El Cabril, ENRESA (2015)	8.9	113%
Interim storage facility	US EPRI, 2009	28	107%
	US DoE, 2013	34	89%
Intermediate depth disposal facility	Forsmark, Sweden (SKB, 2003)	13	277%
	Swiss (NAGRA)	26	139%
Geological disposal facility	Olkiluoto Finland Posiva (2003, 2005, 2012)	176	137%
	Forsmark, Sweden (SKB, 2014)	430	56%
	Swiss Nuclear, 2011	1 300	19%

Source: Jacobs & MCM

Table J.9: Allocated costs for site characterisation, safety case development and geological disposal facility (GDF) design refinement

Phase	Activities relating to demonstrating facility safety	Expenditure allocated (A$ 2015)	Time frame
Siting	1. Undertake initial siting process (including development of any exclusionary criteria and a process to call for and evaluate volunteer sites) 2. Secure permissions for surface-based intrusive site investigations (including deep and shallow drilling, sampling, surface and groundwater studies, in-situ stress measurements at depth, environmental impact studies) 3. Finalise detailed surface investigations, including specific characterization of major site features that will have an impact on GDF design 4. Develop initial safety case—based on naturally isolating characteristics of the host geology and performance targets —in conjunction with initial design of GDF	$938m for GDF $125m for interim storage facility $38m for low level waste repository	Years 1–13
URL-led design refinements	1. Construct access tunnels/shaft and underground research laboratory, including test emplacement gallery 2. Conduct test emplacements and monitor in-situ conditions 3. Refine assumptions underlying performance targets, GDF design and associated safety case to secure licence for construction of disposal galleries for used fuel emplacement	$578m Initial gallery and emplacement cost $250m/a during testing and commissioning phase	Years 19–28
GDF construction	1. Expansion of underground research laboratory: construction of disposal galleries and any additional access tunnels and shafts 2. Conduct additional in-situ testing and monitoring and use data to refine assumptions underlying performance targets, GDF repository design and associated safety case to verify targets in operational license can be met	$250m/a with links to GDF operation phase	Ongoing until no further waste to emplace (see below)
GDF operation	1. Emplace waste (possibly with a pilot phase to begin) 2. Conduct additional in-situ testing and monitoring and use data to validate assumptions to secure licence to close the facility	$205m/a $565m/a if encapsulation costs are included	Years 28–120
Closure and Decommissioning	1. Backfill and plug access tunnel and shafts to put site in a passive state and restore initial conditions—no further safety actions are required 2. Decommission above-ground buildings, interim storage facility and supporting infrastructure	$1150m	Years 83–125
Post-closure	1. Conduct additional surface-based testing and monitoring as per closure licence—this is confirmatory data, not a safety function 2. After the period of testing and monitoring, retain passive institutional controls (such as zoning restrictions as per closure licence) 3. After passive institutional controls are complete, the site is free-released	$0.55–$5.5m/a serviced from income on the reserve fund remaining at the time of closure	Years 125–1125 – ongoing

Notes: GDF = geological disposal facility, URL = underground research laboratory
Source: Jacobs & MCM

RESULTS OF VIABILITY ANALYSIS

The outputs of the analysis demonstrate that the baseline scenario is viable and would generate significant profits for South Australia. The analysis also showed that the development of an interim storage facility along with a geological disposal facility was critical to viability.

The total revenue generated under the baseline scenario would be approximately $257 billion (A$ 2015 real undiscounted) over the 120 year life of the project, with total expenditures of approximately $145 billion (including construction, operating, decommissioning and closure costs, but excluding royalties) over the same period.[26]

Applying a discount rate of 4 per cent, the net present value of profits to the state over the life of the project would amount to $40.4 billion.[27] Applying a commercial pre-tax discount rate of 10 per cent, the net present value of profits to the state would amount to $11.5 billion. These figures exclude the net present value of royalty payments made to the State Wealth Fund.[28]

EMPLOYMENT

The estimates about direct employment were based on an allocation of a reasonable proportion of construction costs to labour requirements. Approximately 1550 direct full-time jobs would be required in South Australia during the 25-year construction phase of the project, with a peak of about 4500 full-time jobs during the geological disposal facility construction phase (in years 21 to 25 of the project). A total ongoing operational workforce in South Australia of approximately 600 full-time direct jobs is anticipated once all facilities are completed.[40]

SENSITIVITY ANALYSIS

Analyses were also undertaken of the impacts on the viability of the baseline scenario if a smaller proportion of the used fuel and intermediate level waste market was captured, if lower prices were charged for services, if there was a delay in the receipt of used fuel and intermediate level waste, and if there were cost overruns. Under these scenarios, the project achieved lower profits than the baseline scenario, but remained highly viable.

MARKET CAPTURE

The impact of higher (75 per cent) and lower (25 per cent) capture of the accessible market of used fuel was analysed and the results illustrated in Figure J.6. That analysis indicates that the project remains viable even where only a quarter of the accessible used fuel market (69 000 tHM) is captured. Figure J.6 also demonstrates the viability of the project in the event of a lower market share at a range of prices below that of A$1.75m per tHM in the baseline scenario.

PRICE

The sensitivity of the baseline scenario's viability to a range of different prices charged for the services, assuming 50 per cent of the accessible market is captured, was analysed, as shown in Figure J.7. The project remains viable at the lowest analysed price of $750 000 tHM. Potential revenues increased significantly depending on the price charged, with higher prices for used fuel having the greater positive impact on profitability than increases in prices for intermediate level waste disposal.[29]

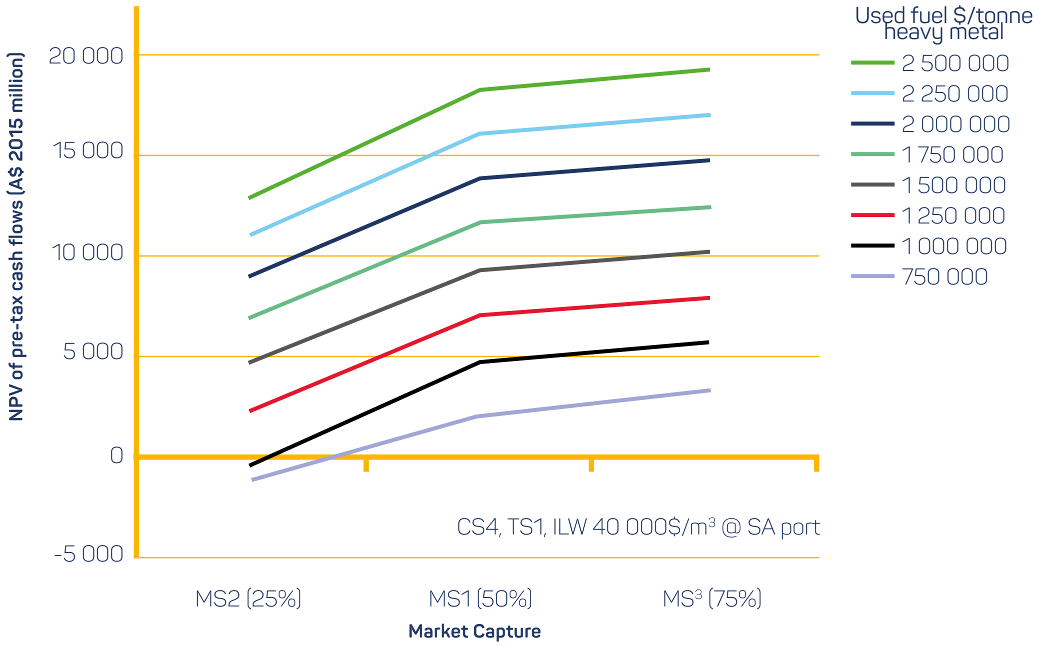


Figure J.6: Sensitivity of baseline scenario viability to lower and higher accessible market capture scenarios (see Table J.4 for details) and to lower and higher prices charged per unit used fuel

Note: CS = configuration scenario, ILW= intermediate level waste, MS = market scenario, NPV = net present value, TS = timing scenario
Source: Jacobs & MCM

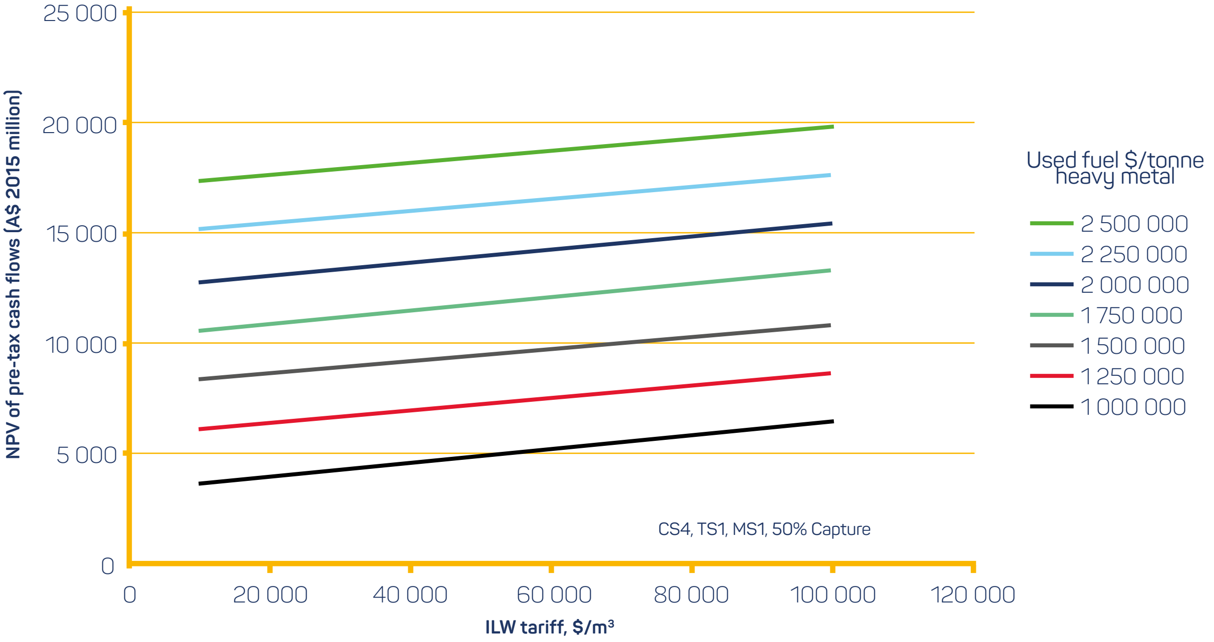


Figure J.7: Sensitivity of baseline scenario viability to price charged per unit of used fuel and intermediate level waste

Note: CS = configuration scenario, ILW= intermediate level waste, MS = market scenario, NPV = net present value, TS = timing scenario
Source: Jacobs & MCM

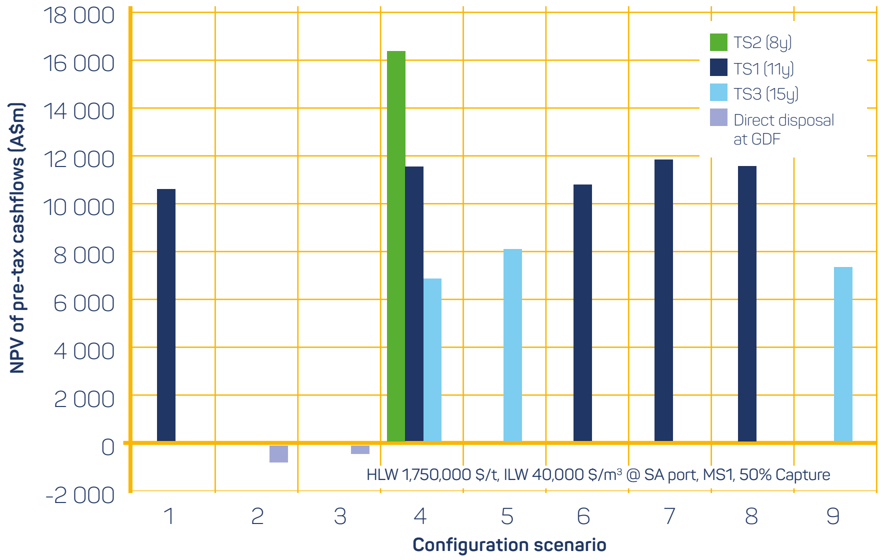


Figure J.8: Comparison of net present value (NPV) in Australian dollars of each of the configuration scenarios (see Table J.1 for details of configuration scenarios)

Notes: HLW = high level waste ILW = intermediate level waste, MS = market scenario, NPV = net present value, TS = timing scenario, GDF = geological disposal facility
Image courtesy of Jacobs & MCM

TIMING OF RECEIPT OF WASTE AND REVENUES

The sensitivity of the baseline scenario's viability to variations in the timeline for receipt of waste from clients was analysed. Figure J.8 illustrates the net present value (at a 10 per cent discount rate) of the baseline configuration scenario (described in Table J.1), when different time scenarios for importation of waste (at 8 years, 11 years and 15 years) are applied. The results indicate that the longer the receipt of waste (and associated revenues) is delayed, the lower the net present value of the project.[30]

Figure J.8 also demonstrates that a facility configuration scenario is viable only with the establishment of a surface interim storage facility capable of accepting used fuel prior to construction of geological disposal facilities.[31] Configurations 3 and 4, which did not include interim storage facilities (see Table J.1), did not generate profits because of the delay in receiving waste and associated revenues. Without a South Australian interim storage facility in which waste is allowed to cool prior to disposal, only used fuel that has already been allowed to cool in its country of origin could be received in South Australia for direct disposal, causing a delay of around 15 years before revenue is generated.

COST OVERRUNS

Analysis of the impact of both capital and operating cost overruns on the baseline scenario demonstrates that the project remains viable, despite a reduction in the overall net present value of the project.[32] Where both capital and operating cost overruns of 50 per cent were applied, the project net present value (at a 10 per cent discount rate) was reduced to A$8.9 billion, compared with A$11.5 billion under the baseline scenario with no such cost overruns applied: see Table J.10.

Table J.10: Sensitivity of project viability to overruns in capital and operating costs, excluding State Wealth Fund net present value

Scenario	Project net present value at 10% discount rate (A$ 2015 billion)
Baseline	11.5
Capital costs + 50%	9.9
Operating costs + 50%	10.5
(Capital and operating costs) + 50%	8.9

Source: Jacobs & MCM

RESERVE FUND

The modelling assumed the establishment of a reserve fund to provide for the costs of decommissioning, remediation of surface facilities, closure, backfill of underground facilities and the ongoing, post-closure monitoring phase.[33]

Given the reserve fund was assumed to be established to meet known liabilities, it was assumed that it would grow over time with a real rate of return equal to 2.4 per cent. This reflects investment of those funds in low risk assets such as government bonds. It is lower than the 4 per cent return assumed for the State Wealth Fund, which is based on more diversified investments.[34]

The modelling for the growth of that fund was undertaken to reflect two alternative approaches, and to provide for their comparison. Both scenarios fully fund all future liabilities.

A baseline scenario assumed that the reserve fund was constituted by drawing funds from operating revenues such that the profitability of the facility was maximised.

In the baseline scenario, the reserve fund was estimated to accumulate funds of A$32 billion (in current dollars), by year 83 of the project. This is sufficient to meet all future liabilities. The profit maximising criteria mean that it would only start to accumulate funds 45 years after the decision to proceed with the project is taken.[35] After year 83, it was assumed that it would be drawn down to meet decommissioning, closure and post-closure expenditures.

An alternative scenario was also considered on a more conservative basis, in which 10 per cent of annual operating profits would be directed to the reserve fund from the first year that used fuel and associated revenues were received. This commences in project year 11.[36] In addition, it did not discount the value of liabilities in the post-closure phase (beyond year 125) and instead assumed they grew at a real rate of one per cent annually.[37]

These assumptions lead to the accumulation of more than A$46 billion in the reserve fund by project year 60–an amount significantly in excess of the estimated decommissioning and closure costs. The effect of such conservative assumptions is that the amount of interest earned on the reserve fund at the time of closure is greater than the annual monitoring costs, i.e. there will be capital available in perpetuity.[38]

This scenario means that the project's overall profitability is reduced by A$1.7 billion to A$9.8 billion on a discount rate of 10 per cent.[39]

2. ANALYSIS OF ECONOMIC IMPACTS—COMMISSIONED STUDY

Economic modelling using a general equilibrium model was undertaken by Ernst & Young to assess the potential effect on the wider South Australian economy of investments being made in an interactive radioactive waste storage and disposal facility in South Australia. It estimated changes in key measures of economic activity such as gross state income, gross state product, wages and employment.

The modelling undertaken used the transparent, peer-reviewed model maintained by the Victoria University Centre of Policy Studies known as the Victoria University Regional Model (VURM).[41] This model has been used widely in Australia to assess the effects of investments made in one part of the economy on economic activity more broadly.

ASSUMPTIONS AND INPUTS

The potential macroeconomic impacts of investing in integrated waste storage and disposal facilities were assessed. The modelling only evaluated the economic impacts of investment in waste storage facilities in the period to 2050, notwithstanding revenues and costs associated with this investment taking place over a much longer timeframe.[42]

In the modelling, it was assumed that a government entity that owns, manages and operates the waste facilities transfers royalty payments and profits derived from revenues to a State Wealth Fund (Figure J.9). The State Wealth Fund was assumed to make investments that enable a real rate of return of 4 per cent per annum based on long term return in similar funds operating in Australia and overseas. It was assumed that half of these returns are transferred annually to the State Government to fund government services.

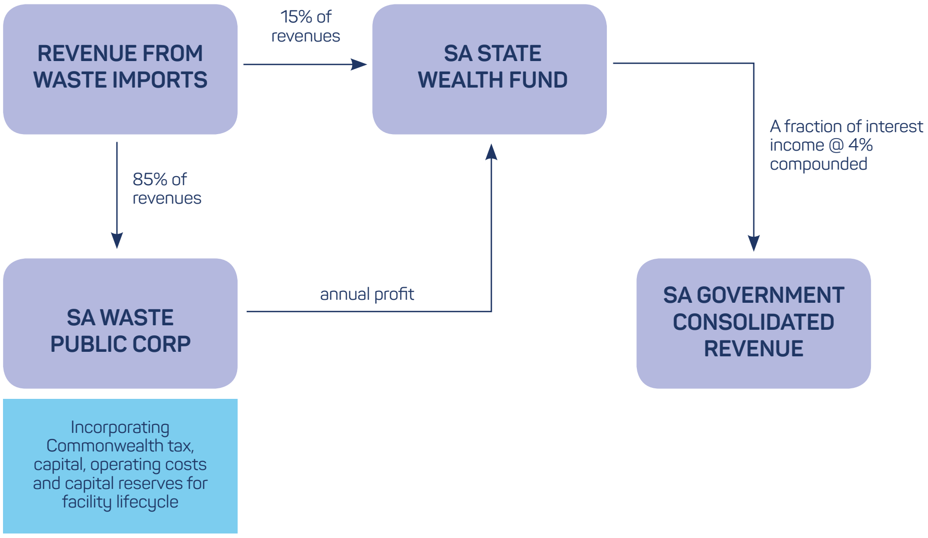


Figure J.9: Assumed revenue transfer model for the integrated waste storage and disposal concept

Image courtesy of Ernst & Young

The modelling also evaluated the economic impact of a combined investment in both the waste storage and disposal facility concept and further processing facilities owned and operated by a private entity providing conversion and enrichment services. The combined investment concept was developed to represent the possible economic outcomes that may emerge under a 'fuel leasing' arrangement.

The model calculated the economic benefits that flow to the state from:

- the combination of investments made in establishing the facilities that comprise the integrated concept
- investments that are made by the State Wealth Fund
- additional expenditure made by the state government.[43]

For the fuel leasing concept, the estimated economic impacts also include the influence of a private, independent investment in a conversion and enrichment facility.

RESULTS OF ECONOMIC IMPACT ANALYSIS

As illustrated in Table J.11, investment in waste storage and disposal facilities alone is expected to improve gross state income and gross state product by about 5 per cent in 2030 and about 3.6 per cent in 2050. It is also expected to generate direct and indirect employment of 9600 in 2030, and 7500 full time positions in 2050.[44]

Table J.11: Impact of investment in integrated waste storage and disposal facilities on the South Australian economy in 2030 and 2050 in a carbon constrained world[45]

Integrated waste storage and disposal facilities	2029–30	2049–50
Gross state income	$6837m (5.0%)	$7290m (3.6%)
Gross state product	$6699m (4.7%)	$7367m (3.6%)
Wages	0.4%	0.1%
Total employment	9603	7544

Source: Ernst & Young

A combined investment in a fuel leasing concept leads to a modest additional improvement to gross state income and gross state product of 0.5 per cent: see Table J.12. However, the present assessment does not consider the potential value of other synergies between the two parts of the fuel cycle discussed in Chapter 5 of the report.

Table J.12: Impact of investment in a fuel leasing arrangement comprised of conversion, enrichment and integrated waste storage and disposal facilities on the South Australian economy in 2030 and 2050

Fuel leasing	2029–30	2049–50
Gross state income (A$)	$7745m (5.6%)	$8106m (4.0%)
Gross state product (A$)	$7370m (5.2%)	$8274m (4.1%)
Wages	0.4%	0.1%
Total employment	11 400	9364

Source: Ernst & Young

SENSITIVITY

Modelling also evaluated the potential impact of revenues generated in South Australia by an integrated waste storage and disposal facility on transfer payments, namely, revenues from the Goods and Services Tax (GST), made by the Australian Government to the South Australian Government.

The states receive a portion of GST revenue from the Australian Government as recommended by the Commonwealth Grants Commission in accordance with instructions provided by the Commonwealth Treasurer. These recommendations are made two to three years in advance. Under these arrangements, while account is taken of other factors, the greater the level of economic activity and associated revenues in a state, the lower that state's share of GST revenue would be expected to be. The determinations about GST revenue are complex and dependent on the arrangements in place at the time between the Australian Government and states (including the agreement on the GST). For that reason, there is no guidance available to project any state's share of GST in the long term.[46]

The modelling undertaken for the Commission assumed that:

- there was no change in the revenue generating capability of any other state
- the current basis for distributing GST revenue would apply
- the revenue generated by the South Australian Government from the development of waste storage and disposal facilities in the years to 2050 was assumed to be the only determinant of South Australia's GST share.

The modelling shows that South Australia's anticipated share of GST revenue (about $1.25 for every dollar of GST revenue generated in the state) would, as a result of the revenues from integrated waste facilities, return to the state's long term average share of GST in 2050. That is because in the next three years, South Australia's share of GST revenue is expected to increase sharply (to about $1.45) as a result of the further decline of manufacturing. The investments and revenues associated with the integrated waste facilities, which on the basis of the financial analysis will commence in about 2030, mean that the state's share of GST revenue will decline again to about their present levels: see Figure J.10.[47]

South Australia's share of GST revenue could be lower still, if industries ancillary to the integrated storage and disposal facilities developed and further enhanced the state's revenue generating capability. However, those effects can be expected to be small. Conversely, South Australia's share could be higher in the event of decline of other industries or if the revenue-generating capabilities of other states improved significantly.

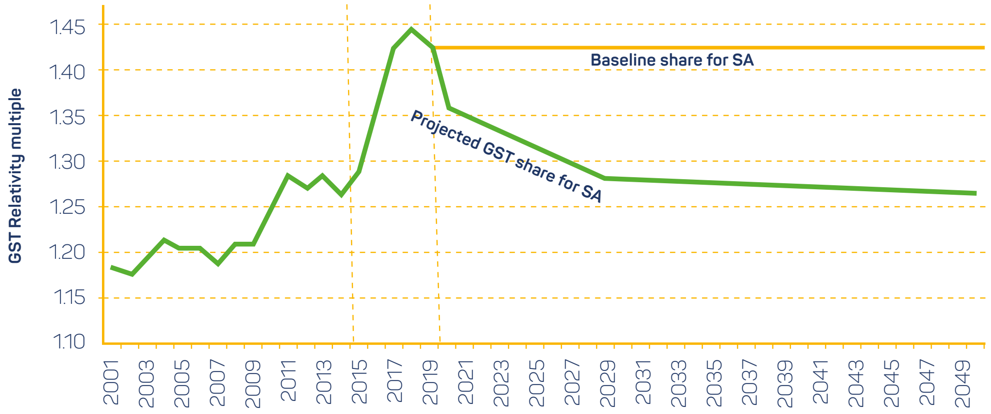


Figure J.10: Projected variation in share of GST revenue received by South Australia from 2019 to 2050 (as a multiple of GST generated in South Australia)

Source: Ernst & Young

NOTES

1 Jacobs & MCM, *Radioactive waste storage and disposal facilities in SA: Quantitative analysis and business case*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2016, paper 2, section 1, http://nuclearrc.sa.gov.au/

2 ibid., p. 3; paper 2, section 2.

3 ibid., p. 3; paper 2, section 2.3.4.

4 ibid., paper 2, section 2.1.

5 ibid., p. 3; paper 2, section 2.3.3.

6 ibid., paper 2, section 2.1.

7 ibid., pp. 3–4.

8 ibid., p. 4.

9 ibid., section 3.

10 ibid., paper 2, section 3.

11 ibid., paper 2, section 3.1.

12 ibid., paper 2, section 3.2.

13 ibid., paper 2, section 3.3.

14 ibid., paper 2, section 3.4.1.

15 ibid., paper 2, section 3.7.1.

16 ibid., paper 2, sections 3.7.1, 3.10.

17 ibid., paper 2, section 3.9.

18 ibid.

19 ibid., paper 3, section 7.

20 ibid., paper 4, sections 2.7.1–2.7.2.

21 ibid., pp. 3–4, paper 3, sections 2.11, 2.13 and 8.

22 ibid., paper 3, section 2.2, section 4.

23 ibid., paper 3, section 7.

24 ibid., paper 4, sections 2.2.0. 2.21, Table 2.14.

25 ibid., p. 1.

26 ibid., paper 5, section 4.1.

27 ibid., paper 5, section 4.10.

28 ibid.

29 ibid., paper 5, section 4.1.

30 ibid.

31 ibid.

32 ibid., paper 5, section 4.3.

33 ibid., paper 5, section 2.4.

34 ibid., paper 5, section 4.7.

35 ibid., paper 5, section 4.6.

36 ibid., paper 5, section 4.7.

37 ibid.

38 ibid., paper 5, section 4.8.

39 ibid., paper 5, section 4.7.

40 ibid., p. 1, paper 3, section 5.12.

41 Ernst & Young, *Computational general equilibrium modelling assessment*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2016, p. 5, sections 2.3, 2.4, http://nuclearrc.sa.gov.au

42 ibid., section 6.3.

43 ibid., section 4.3.4.

44 ibid., section 6.3.1.

45 ibid., sections 6.3, 6.4.

46 ibid., appendix E, box E.1.

47 ibid., section 6.3.4.

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

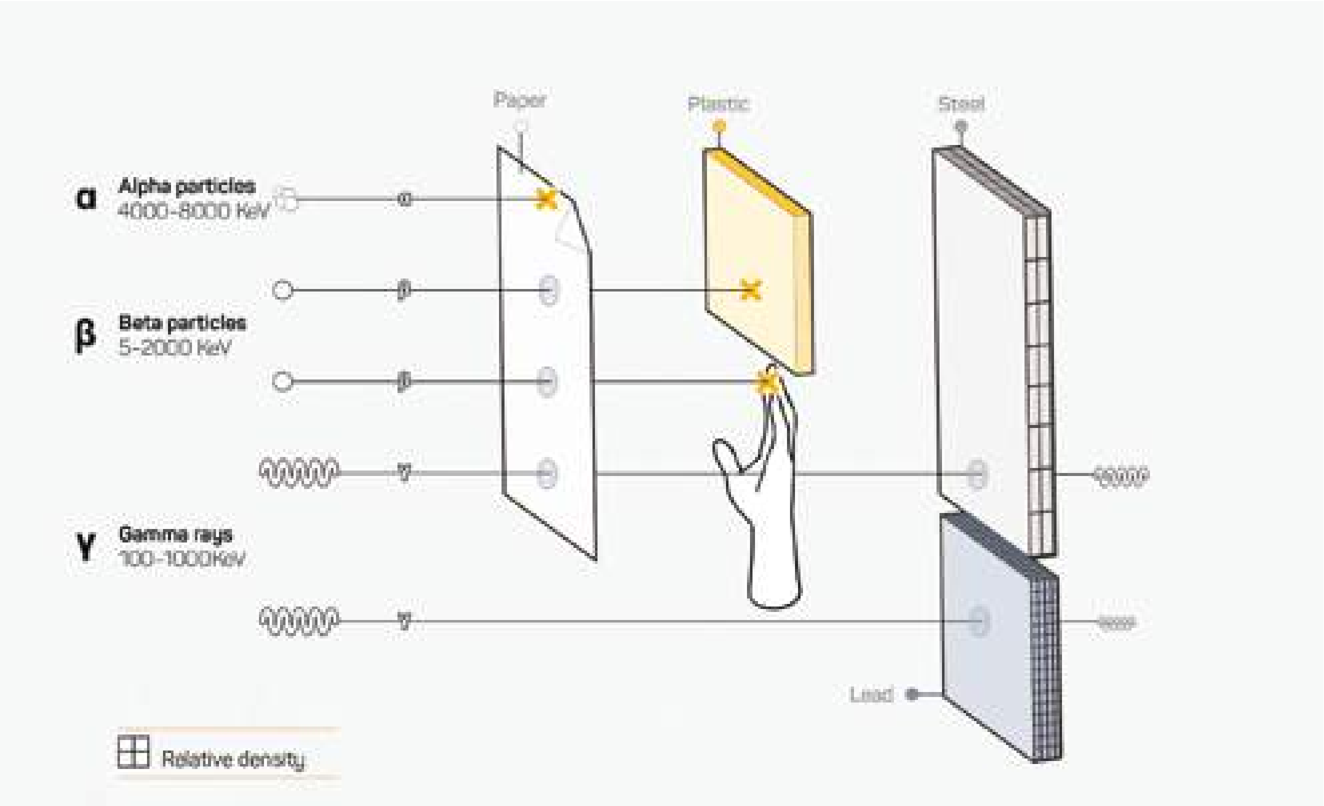
APPENDIX K: RADIATION CONCEPTS

WHAT IS RADIATION?

Radiation comprises particles and electromagnetic waves that have sufficient energy to change the composition of matter, including cells in living creatures.[1] Radiation cannot be seen or heard, and can only be detected and measured accurately and in real time using specialist equipment.

Radiation arises from the radioactive decay of elements on Earth, although it also originates from sources in space.[2] There are three different types of radiation that vary in their physical properties, as seen in Figure K.1. Those types are[3]:

- Alpha radiation: Alpha radiation consists of highly energetic, charged particles that interact with any matter with which they come into contact. As a result, they will not pass through barriers, including human skin, so they are easy to shield against and contain.
- Beta radiation: Beta radiation also consists of highly energetic, charged particles; however, they have a lower charge than alpha particles, do not interact with matter as readily and therefore penetrate further. This makes them more difficult to contain and they require increased shielding.
- Gamma radiation and x-rays: Gamma radiation is naturally occurring but is similar to manufactured x-rays and consists of highly energetic electromagnetic waves. Their high energy enables them to pass through many kinds of materials, including human tissue. Therefore, they are highly penetrative and require a significant amount of shielding.



Source: ARPANSA

Figure K.1: The penetrative ability of different forms of radiation

Neutrons are another common product of radioactive decay.[4] They have a high range of energies and can indirectly damage cells. Neutrons have a similar penetrative ability to gamma radiation.

Radioactive elements that decay can produce one or more types of radiation.[5] This has an impact on the measures that need to be in place to protect people and the environment when radioactive materials are being handled. The duration of the hazard is also affected by the speed of decay. The amount of time it takes for half of the atoms of an isotope to decay is described as a 'half-life'.[6] Some radioactive elements decay quickly—in seconds or fractions of seconds—while others can last for hundreds of thousands of years.[7]

RADIATION DOSE

The concept of a 'dose' is used to quantify the effects of radiation on living things and is the starting point when calculating the effect of radiation on humans. The 'absorbed dose' is a measure of the amount of energy that radiation delivers to a kilogram of material. Doses are measured in units known as gray (Gy).[8]

As previously described, there are a number of different types of radiation, and the impact each type has on living tissue varies. 'Weighting factors' account for the effects of radiation on living tissue when multiplied by the absorbed dose. This is known as the 'equivalent dose' and is measured in sieverts (Sv). To measure low doses, sieverts can be further broken down into millisieverts and microsieverts. One millisievert (mSv) is 0.001 Sv and one microsievert (μSv) is 0.000001 Sv.[9] Low and very low doses of radiation are understood to be below 100 mSv and 10 mSv, respectively.[10]

A weighting factor is used to define the damage caused by radiation exposure to different organs and tissues. Multiplying the tissue weighting factor by the equivalent dose to organs and tissue in humans gives the 'effective dose' to that area, also measured in Sieverts. A total effective dose to a person is the sum of the individual effective doses, which takes into account sensitivities associated with different organs.[11]

RADIOTOXICITY

'Radiotoxicity' describes the toxicity of a particular radionuclide, or combinations of radionuclides, in the event of either ingestion or inhalation. It takes into account both the biochemical (elemental) nature of the nuclide, as well as the type and energy of radiation it emits.[12] Therefore, it addresses how all the individual characteristics (rather than just radioactivity) could harm the human body in postulated scenarios that lead to ingestion or inhalation. For a single radionuclide, the radiotoxicity is obtained by multiplying the amount of the nuclide (measured in Becquerels, or Bq) by established 'dose conversion factors'.[13] For any collection or combination of radionuclides—such as those in used nuclear fuel—the radiotoxicity of the material is the sum of the radiotoxicity of all constituent nuclides. The radiotoxicity, expressed as a dose and measured in millisieverts (mSv), describes the health impact in the event of ingestion or inhalation.

HEALTH EFFECTS OF RADIATION

Exposure to radiation can have a harmful effect on human health. Radiation can damage or cause the death of human cells. Radiation also has the potential to affect the environment and other living organisms through similar mechanisms to human tissue. The effects on fauna can include increased disease, death, or reduced fertility and reproductive success.[14] The types of damage can be defined by two main categories, 'deterministic' and 'stochastic'.

DETERMINISTIC EFFECTS

Deterministic effects occur in cases of very high exposure to radiation, once a certain threshold dose has been exceeded. The severity of the effects increases as the radiation dose increases. Deterministic effects are caused by significant damage to cells or the death of a large population of cells that impact the function of human organs or tissue.[15] These effects develop soon after exposure and may occur within days or weeks of receiving a large dose of radiation. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) defines a high dose of radiation, where acute effects of short term exposures will occur, as more than 1 Sv.[16] The most common effects are associated with bone marrow and its ability to produce blood cells. Other symptoms, such as nausea and vomiting, relate to the gastrointestinal tract.[17] Large doses can cause the central nervous system to fail and, in extreme cases, result in death. A high penetrating dose of radiation in a short period of time can cause acute radiation syndrome.[18] Depending on the dose, this syndrome is characterised by several stages of symptoms including nausea, fever, infection, diarrhoea, bleeding, cardiovascular collapse and respiratory distress, followed by either a period of recovery or death.[18] Delayed deterministic effects can also occur, such as cataracts, which take longer to develop and may not appear for many years following exposure.

STOCHASTIC EFFECTS

Stochastic effects occur as a result of damage to DNA in human cells. Due to this DNA damage, there is the possibility of long-lived mutations in cells, increasing the likelihood of cancerous growths in the future. The higher the dose of radiation received, the greater the likelihood of an effect occurring.[19] There are natural mechanisms that can repair DNA damage, although these are not always effective. Stochastic effects tend to have a longer latency period, from a few years up to tens of years. If reproductive cells are damaged, there is potential to cause hereditary effects, or gene mutations, that can affect the offspring of the exposed person.[20] This effect has been observed in experiments on mammals but no direct evidence has been shown in human populations.[21]

DOSE–RESPONSE RELATIONSHIP

The effects of radiation on biological systems are studied in two ways:

- epidemiological studies, which identify trends and patterns in health effects across a population
- biological studies, which directly observe the effects of radiation on living organisms.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) concludes that it is not presently possible to explicitly attribute a stochastic effect in an individual to radiation exposure. This is because stochastic effects are not distinguishable from other health effects that may arise from different causes.[23] Stochastic effects are not only caused by radiation, but by other lifestyle choices, such as smoking or eating habits, which may bring about the same adverse health effects. Further, the effects may show up in some people and not in others despite their exposure to the same radiation dose. It is only possible to attribute stochastic effects to radiation through epidemiological studies that compare their incidence in an exposed population with a similar one that was not exposed.[24] This is based on the probability that radiation was responsible for an observed increase in the stochastic effects.

These difficulties are even more prominent when studying low radiation doses over long time periods. UNSCEAR recognises that when the dose of radiation decreases to low and very low amounts, the uncertainties in attributing health effects to radiation increase, and the ability to draw conclusions from epidemiological studies is significantly reduced.[25] ARPANSA considers a low dose of radiation to be from 10 to 100 mSv. A very low dose is generally below 10 mSv, which is the range of exposure any member of the public may experience annually.[26] The natural variance in human health, combined with the constant exposure people receive from natural background radiation, means that it has not been possible to establish any significant relationship between health risks and radiation exposure at low doses.

Figure K.2 illustrates the plausible dose–response relationships for health effects (such as cancer) at very low, low, and moderate doses of radiation.

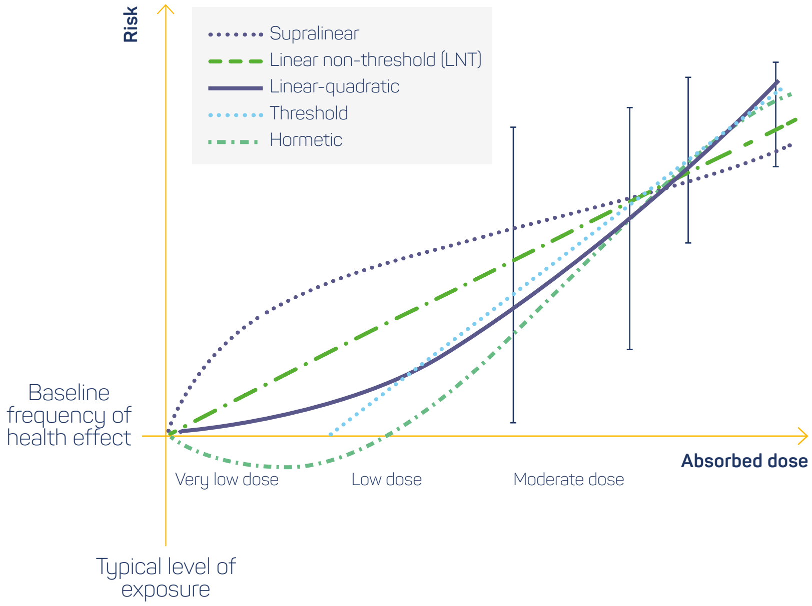


Figure K.2: Schematic plot of possible dose–response relationships (in addition to background exposure) for the risk of health effects in the ranges of very low, low, and moderate doses

Source: UNSCEAR

Given that there are five plausible relationships, there is a large degree of uncertainty in attributing health effects to moderate radiation doses or lower.

At high doses of radiation, the dose–response relationship is far more certain and stochastic effects are much more likely to arise.[27] Very high doses will lead to deterministic effects in addition to an increased risk of cancer.

NOTES

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2 ARPANSA, *Fact sheet: Ionising radiation and health*, September 2015, http://www.arpansa.gov.au/RadiationProtection/Factsheets/is_ionising.cfm; World Health Organization (WHO), *Ionizing radiation, health effects and protective measures*, Fact sheet no. 371, WHO, November 2012, http://www.who.int/mediacentre/factsheets/fs371/en/; United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources, effects and risks of ionizing radiation*, UNSCEAR 2013 Report to the General Assembly with Scientific Annexes, vol. 1, scientific annex A, UNSCEAR, UN, New York, 2014, p. 1.

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4 ARPANSA, 'Other types of radioactive decay', http://www.arpansa.gov.au/radiationprotection/Basics/other.cfm

5 ARPANSA, 'Radiation basics – Radioactivity', http://www.arpansa.gov.au/radiationprotection/Basics/radioactivity.cfm

6 ARPANSA, 'Radiation basics', http://www.arpansa.gov.au/radiationprotection/Basics/glossary.cfm#d1; WHO, *Ionising radiation, health effects and protective measures*.

7 WHO, *Ionising radiation, health effects and protective measures.*

8 ARPANSA, *Fundamentals: Protection*, p. 7.

9 ARPANSA, 'Units of ionising radiation measurement', http://www.arpansa.gov.au/radiationprotection/Basics/units.cfm

10 ARPANSA, *Fundamentals: Protection*, pp. 7–8.

11 ibid.

12 G Kessler, *Sustainable and safe nuclear fission energy: Technology and safety of fast and thermal nuclear reactors*, Springer-Verlag, Berlin & Heidelberg, 2012, p. 243.

13 International Commission on Radiological Protection (ICRP), *Age-dependant doses to members of the public from intake of radionuclides: Part 5 compilation of ingestion and inhalation dose coefficients*, IRCP Publication 72, Annals of the ICRP, 28(4).

14 ARPANSA, *Fundamentals: Protection*, pp. 10–11.

15 UNSCEAR, *Sources, effects and risks of ionizing radiation*, UNSCEAR 2012 Report to the General Assembly with Scientific Annexes, vol. 1, scientific annex A, UNSCEAR, UN, New York, 2012, pp. 23, 29.

16 ARPANSA, *Fundamentals: Protection*, p. 8.

17 UNSCEAR, 'Answers to frequently asked questions (FAQs)', (updated 13 February 2013), http://www.unscear.org/unscear/en/faq.html

18 ARPANSA, *Fundamentals: Protection*, p. 9.

19 ibid., p. 9.

20 ibid., p. 10.

21 ibid.

22 UNSCEAR, *Summary of low-dose radiation effects on health*, 2010 Report to the General Assembly, UN, 2010, p. 11; ARPANSA, *Fundamentals: Protection*, p. 10.

23 UNSCEAR, *Sources, effects and risks*, 2012, scientific annex A, pp. 24–25, 30.

24 ibid., p. 7.

25 ibid., pp. 8, 12, 30.

26 ARPANSA, *Fundamentals: Protection*, p. 8.

27 ibid., p. 8.

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

APPENDIX L: TRANSPORT ANALYSIS

This study, undertaken by Jacobs and MCM, assessed the risks and consequences that would result from possible adverse events during the transport of radioactive materials, both within Australia and internationally. Both potential 'accident' and 'attack' scenarios were considered for transport by road, rail and sea.

The assessment takes into account the engineering of radioactive material packages and the impacts in the event that an accident caused a release of radiation. It also considers the effectiveness of the response measures that would be in place during transport.

ASSUMPTIONS AND INPUTS

METHOD OF ASSESSMENT

The events were assessed considering the probability of an event occurring (using historical data) and, if it did occur, the likely radiological consequences (based on empirical study). In each case, the impact of likely protective measures was also taken into account.[1]

The risk analysis considered the following nine events[2]:

- four 'accident' scenarios involving feasible road, rail and sea transport modes
- four 'attack' scenarios which describe deliberate acts to either capture, or cause the uncontrolled release of, the radioactive material being transported
- one scenario involving low level waste movement on a public road, in an accident scenario and an attack scenario.

LIKELIHOOD OF EVENTS

The likelihood of transport accidents occurring was assessed using statistics both in Australia and around the world:

- for road accidents, one significant (fatal) collision per 18.5 billion tonne kilometres nationally[3]
- for rail accidents, one derailment per 1.04 million kilometres travelled nationally on shared/non-exclusive rail lines[4]
- for accidents at sea—being the longest transport stage in terms of distance and duration—the likelihood of there being a collision or fire is summarised in Figure L.1.

Additionally, in 40 years of low level waste transport in Australia, there have been no road accidents causing a significant release of radiation.[5]

While the likelihood of transport accidents occurring can be confidently estimated due to the existence of extensive transport statistics, the likelihood of deliberate attacks cannot be assessed in the same way. Therefore, the deliberate attack scenarios are assessed on the basis of potential courses of action which might be taken and the likely measures in place to mitigate them.

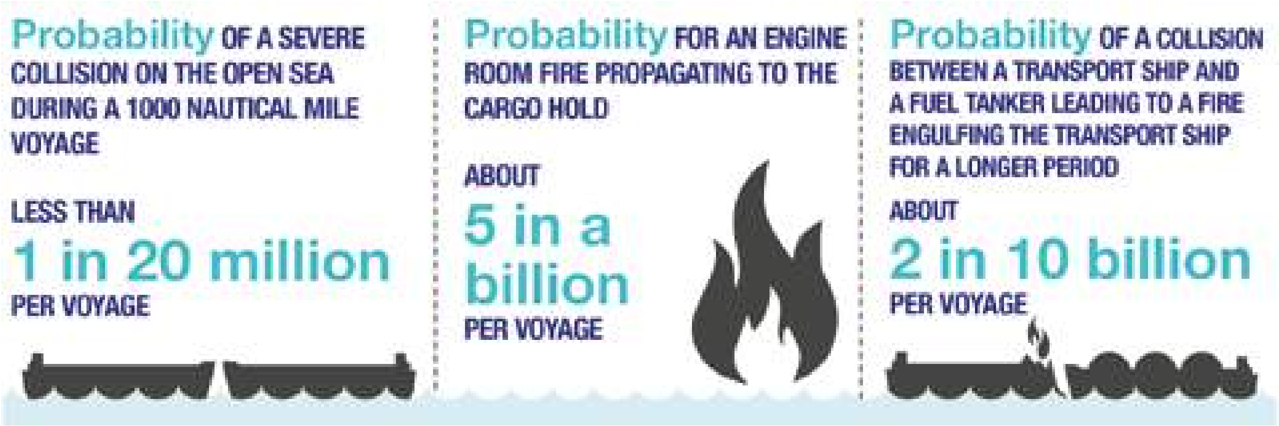

Figure L.1: Probability of accidents involving sea transport

Source: Jacobs & MCM

CONSEQUENCES OF ACCIDENT EVENTS

Casks used to transport used fuel are heavily engineered and undergo a strict testing regime to ensure that no radioactive material is released in the event of a credible accident scenario.[6] They contain solid waste that is physically and chemically stable, and not at risk of explosion.[7] Therefore, the primary consequence of concern is a scenario in which a cask is damaged to an extent where there will be a release of radiation that causes people and the environment to become exposed. The accident events that were analysed gave rise to three types of hazard to the transport casks: severe impacts, fire and immersion in water.[8]

In the context of marine transport, purpose-built vessels are used to transport casks of used fuel. These ships incorporate double reinforced hulls and fire detection and suppression capabilities.[9] It is considered unlikely that a collision or fire on these vessels would damage a cask to the extent that it would fail.[10] Even if a transport vessel was involved in a severe collision that initiated a severe fire while in port, the most exposed person to any possible release of radiation would receive a dose far below natural background levels.[11]

In the hypothetical event of a catastrophic ship collision, it is possible that a cask could be lost at sea. Recovery of the cask would be routine if it were lost within tens of kilometres from shore, with the recovery operation normally taking place before any significant release of radioactivity.[12] The cask is unlikely to be recovered from very deep waters and would eventually corrode to release some radionuclides. Assuming that the radioactivity affected people through the marine food chain, the maximum annual dose expected would be a thousandth to a billionth of natural background levels (depending on how far from shore the cask is lost).[13]

During rail transport of used fuel, the analysis considered hypothetical accidents subjecting a cask to impact damage, fire damage and damage resulting if an elevated portion of a freeway fell directly onto the cask. In all cases, it is highly unlikely that a cask would sustain enough damage to cause a release of radiation.[14] It was considered that a cask would sustain similar conditions in the context of a road accident, thereby also making it highly unlikely that enough damage would be sustained to cause a release of radiation.[15]

Consideration was given to the exposure of emergency workers who would respond to an accident involving a cask of used fuel and would be required to work within close proximity to the cask for an extended period of time. It is estimated that a person working at the accident scene for 10 hours within an average of 5 metres from the cask would receive a dose of around 1 mSv, or 2 per cent of the maximum annual dose limit which applies to radiation workers.[16]

For low level waste transport, data from previous studies indicates that there has not been a road accident which has resulted in significant radiological risks. Where an accident has resulted in a release, contamination has been cleaned up quickly and has not subsequently been found to contribute to natural background radiation at accident sites.[17] The non-radiological risks associated with conventional traffic accidents are much greater, with it being estimated that one or two deaths would occur in road accidents over 70 years of low level waste transport from other causes.[18]

CONSEQUENCES OF ATTACK EVENTS

The attack scenarios considered involved the attempted theft of a cask during sea or road transport or the attempted sabotage of a rail consignment through either damage to the rail line or attack using armour-piercing rocket propelled munitions.

The size and mass of the casks–more than 100 t–means that they cannot be moved without the use of a crane. This makes theft of a cask extremely difficult. In the case of sea transport where the purpose-built vessels have additional security features built into the hatch covers, removal and transfer of the cask at sea is considered technically not feasible.[19]

For rail consignments, the railway line would be designed to minimise the likelihood and consequences of any attempted sabotage. As noted in the context of rail accidents, the robust nature of the cask minimises the potential for damage to it to result in radioactive release. It is considered that an armour piercing rocket has the potential to penetrate the outer wall of a cask and cause a release of radioactivity. However, the successful acquisition and skilled use of such a weapon is extremely unlikely given the range of available risk management measures further discussed below.[20]

MANAGING RISKS

A range of measures are in place during the transport of radioactive materials to reduce the probability of accidents and, should they occur, to minimise the extent of any radiological impact. Risks are managed by three main approaches[21]:

- packaging: the transport casks incorporate a significant amount of engineering to ensure that the contents are protected against the highest credible level of accidental or deliberate events
- further design and engineering: facilities and transport vehicles are designed and maintained to the highest standard to minimise likelihood of accidental or deliberate events occurring
- regulation: high safety standards are adhered to throughout the whole transport chain.

In addition, the likelihood of both accidental and deliberate events can be further minimised by using exclusive transport lines, such as private roads and rail lines between the port and storage facility, as illustrated in Figure L.2.

The safety measures discussed above are also relevant to the protection of consignments against security threats. Further security measures are available to reduce the risk of a deliberate attack being successfully undertaken, including[22]:

- operational measures: operators plan transport routes taking into account information available from intelligence and security services. For transport within Australia, transport plans must be approved by regulators and can incorporate security escorts.
- Australian domestic arrangements: Australian authorities maintain highly developed response and recovery measures. Depending on the circumstances, the South Australian Police or the Australian Defence Force can provide security services and tactical response capabilities.
- international protocols: in the context of sea transport, there are numerous international standards, policies, accreditation requirements and support agencies available to minimise the risk of successful attack on a vessel.

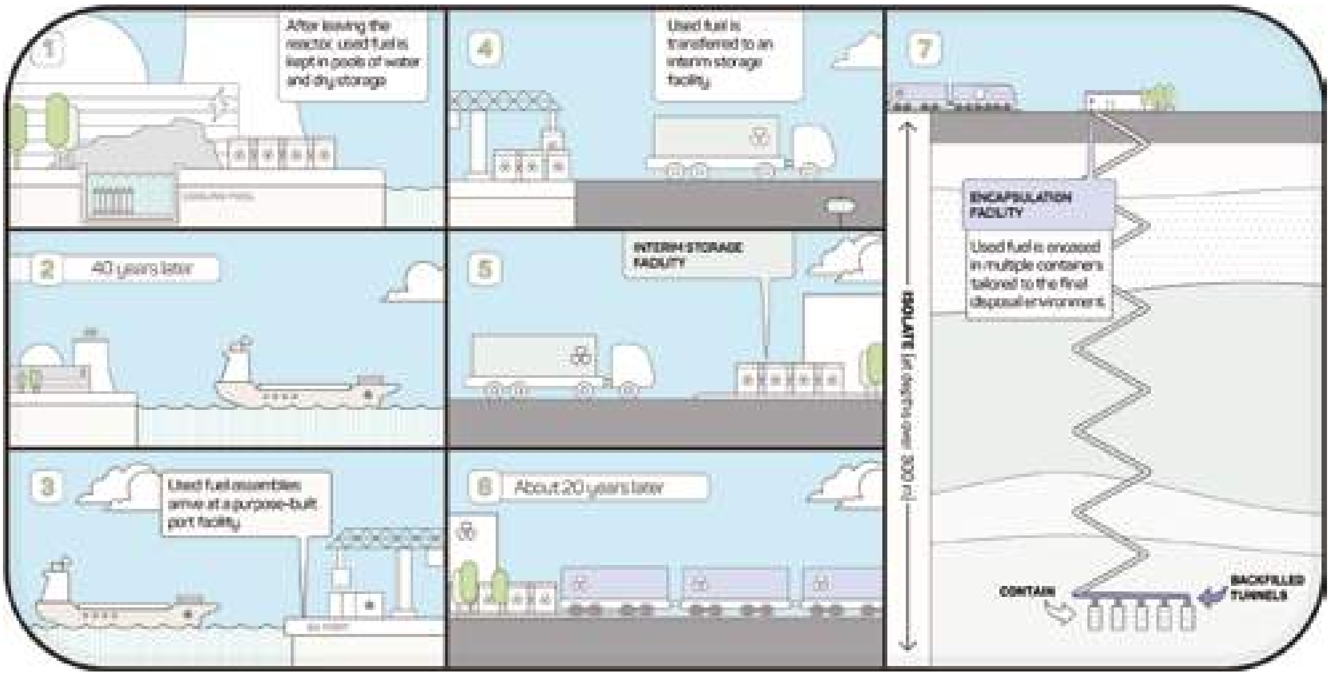

Figure L.2: Steps for importation, storage and final disposal of used nuclear fuel in South Australia

CONCLUSION

The potential risks surrounding the transport of radioactive materials to and in Australia have been assessed factoring in the likelihood of an event occurring and its potential consequences. Possible events have included both accident and attack scenarios during road, rail and sea transport. In all cases, engineering, operational, regulatory and response measures would be in place to minimise the risks.

Given these measures, the risk of an accident occurring that could breach a cask of used fuel and cause radiation to be released is very low. If a cask was lost at sea and was irrecoverable, there is potential for some members of the public consuming locally sourced seafood to receive a very small dose of radiation. However, the maximum annual dose expected would be a thousandth to a billionth of natural background levels.

The attack scenarios that have been analysed are conceivable, although the events that have the greatest potential to cause a release of radiation (namely a rocket attack) are the most logistically challenging. In any case, none of the attack events is likely to be undertaken successfully due to the security measures that would be in place during transport. These include engineering, operational, regulatory and response measures.

NOTES

1 Jacobs & MCM, *Safety and risks in the transportation of radioactive materials to and in Australia*, report prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, 31 March 2016, section 6.2.
2 ibid., executive summary, p. 1.
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4 ibid., p. 13.
5 ibid., p. 38.
6 ibid., pp. 19–21.
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11 ibid., p. 33.
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13 ibid., pp. 32–33.
14 ibid., pp. 34-36.
15 ibid., pp. 36-37.
16 ibid., p. 25.
17 ibid., p. 38.
18 ibid., p. 39.
19 ibid., pp. 40–43.
20 ibid., pp. 41, 43–45.
21 ibid., executive summary, p. 1.
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GLOSSARY

This glossary defines key terms used in this report.

actinides: a series of 15 elements with an atomic number (i.e. the number of protons in the nucleus) between 89 and 103. The actinides include uranium (92), plutonium (94) and americium (95).

activity (nuclear): the number of decays per unit time taking place in a radioactive material. The unit of activity is the becquerel (Bq), equal to one decay per second.

adsorption: the adhesion of atoms or molecules from a gas or liquid as a thin film to a solid or liquid surface.

advanced reactors: reactor designs in which nuclear fission energy is captured and converted more efficiently than in standard water-cooled reactors. They operate at higher temperatures and employ heat-tolerant coolants such as liquid metal or molten salt, and robust fuel materials including graphite.

alpha particle: an energetic positively charged particle emitted from the nucleus of an atom during alpha radioactive decay and consisting of two protons and two neutrons (a helium nucleus).

amortised capital cost: represents the amount of principal (the original amount borrowed) and interest that would need to be paid in each period over a given repayment schedule, such that at the end of the repayment schedule all interest and principal would have been repaid.

aquifer: a body of permeable rock such as sand or gravel through which groundwater moves, and that can store considerable quantities of water, which is underlain by impermeable material.

atom: a particle of matter that cannot be broken up by a chemical process. Atoms have a nucleus containing positively charged protons and uncharged neutrons, and surrounding the nucleus, a cloud of negatively charged electrons.

atomic number: the number of protons in the nucleus of an atom. See also *mass number*.

beta particle: an energetic particle emitted from the nucleus of an atom during beta radioactive decay. Beta particles are electrons with a negative charge or positrons with a positive electric charge.

borehole: a hole drilled into rock to enable an assessment to be made of the characteristics of the rock itself and of the fluids it contains, e.g. groundwater, petroleum, or natural gas.

brownfield: vacant or unused former industrial land with potential for redevelopment.

burn up: the amount of energy generated from a fixed quantity of nuclear fuel, expressed typically as megawatt days per tonne (MWd/tonne).

carbon dioxide equivalent (CO_2-e): a standard measure that allows different greenhouse gases to be compared in terms of their potential contribution to global warming. See *greenhouse gas*.

capacity factor: the percentage of time that a generator is producing electricity.

carbon capture and storage: technologies involving capturing carbon dioxide from exhaust gases produced by power plants and other industrial facilities and injecting it (sequestration) into a sealed underground storage site.

centrifuge enrichment: a uranium enrichment technology comprising cylinders rotating at high speed to physically separate gas molecules of slightly different masses i.e. uranium hexafluoride with ^{238}U and ^{235}U atoms.

combined cycle gas turbine: a gas fired power plant in which the gas turbine cycle is combined with a steam turbine cycle. The hot exhaust gases from the gas turbine are re-circulated and used to boil water (instead of being vented) and generate steam to spin a steam turbine.

carbon price: the cost—imposed by means of a tax, levy, permit or credit—of emitting carbon dioxide into the atmosphere.

containment: a gastight structure around a nuclear reactor made of reinforced concrete designed to prevent the escape of radioactive materials into the environment in the event of an incident.

control rods: moveable rods, plates or tubes containing boron, cadmium or some other strong absorber of neutrons that suppress the rate of the nuclear reaction in a reactor.

craton: a large, coherent domain of Earth's continental crust that has attained and maintained long-term stability, having undergone little internal deformation, except near its margins.

cyclotron: a device which accelerates charged particles to high energies by the application of electromagnetic forces. The accelerated particles may be used to bombard suitable target materials to produce radioisotopes.

decay (radioactive): the spontaneous disintegration of an atomic nucleus resulting in the release of energy in the form of particles (for example, alpha or beta), or gamma radiation, or a combination of these.

depleted uranium: uranium which has less than the natural percentage (0.7%) of the isotope ^{235}U.

discount rate: a rate that is used to convert future costs or revenues to their present value.

dosimeter: a device used to measure the radiation dose a person receives over a period of time.

dose, absorbed: a measure of the amount of energy deposited in a material by ionising radiation. The unit of measure is the gray (Gy).

dose, effective: a measure of the biological effect of radiation on the whole body. It takes into account the equivalent dose and the differing radiosensitivities of body tissues. The unit of measure is the sievert (Sv), but doses are usually measured in millisieverts (mSv) or microsieverts (μSv).

dose, equivalent: a measure of the biological effect of radiation on a tissue or organ that takes into account the type of radiation. The unit is the sievert (Sv), but doses are usually measured in millisieverts (mSv) or microsieverts (μSv).

dose limit: the maximum radiation dose, defined by regulation, that a person may receive over a stated period of time. It excludes doses from natural background radiation and medical sources.

element: a substance that cannot be divided into simpler substances by chemical means.

electron: a light, negatively charged subatomic particle found in all atoms.

Emissions Reduction Fund (ERF): a scheme established by the Australian Government which provides incentives for carbon emissions reduction activities in the Australian economy.

enhanced geothermal system (EGS): a geothermal energy technology that exploits thermal reservoirs found at depths of at least 3–5 km below the surface of the earth, whose permeability is increased (or enhanced) through a process of hydraulic fracturing to capture heat by creating a closed loop circuit of water.

fast reactor: a type of nuclear reactor in which the fission chain reaction is sustained by fast neutrons, in contrast to the slow, moderated neutrons in most thermal reactors. Fast reactors can burn a wider range of nuclides than thermal reactors, including transuranic elements regarded as wastes. They can be configured to produce or 'breed' more fissile material than they consume. Fast reactors generally use liquid metal coolants, such as sodium.

fissile material: any material containing fissile radionuclides capable of undergoing fission by thermal (or slow) neutrons. For example, ^{235}U and ^{239}Pu are fissile radionuclides.

fission (nuclear): the splitting of a heavy atom into smaller fragments, resulting in the release of neutrons, gamma radiation, and a large amount of energy.

fission products: isotopes of lighter elements created through the fission of fissile material. They are most often unstable and undergo radioactive decay, and include ^{134}Cs, ^{137}Cs and ^{129}I and ^{131}I and ^{90}Sr.

fuel assembly: an engineered array of fuel rods (long, sealed metal tubes) that contain pellets of fissionable material that is used in a nuclear reactor to generate thermal power.

gamma radiation: energetic short wavelength electromagnetic radiation of the same physical nature as light, x-rays, radio waves etc.

gigawatt (GW): one gigawatt is equal to one billion (10^9) watts. See *Watt*.

gigawatt hour (GWh): a gigawatt hour (GWh) is a unit of electrical energy equal to one billion (10^9) watt hours. See *Watt hours*.

gray (Gy): a measure of absorbed ionising radiation dose per unit of mass. 1 gray is equal to one joule absorbed into I kilogram of matter.

greenfield: land that has not previously been developed.

greenhouse gas: a gas that traps heat in the Earth's atmosphere by absorbing reflected solar infrared radiation from the earth, thereby causing the greenhouse effect. The main greenhouse gas is carbon dioxide, others include nitrous oxide, methane, fluorinated gases and water vapour.

half-life, radioactive: the period required for half of the atoms in a population of a particular radionuclide to decay. Half-lives vary, according to the isotope, from less than a millionth of a second to more than a billion years.

heavy metal (HM): commonly used in units such as tonnes Heavy Metal (tHM) and refers to the weight of the uranium and plutonium (if present) in nuclear fuel.

heavy by products: actinides produced in the fission of nuclear fuel.

heavy water: water in which both hydrogen atoms have been replaced with deuterium, the isotope of hydrogen containing one proton and one neutron.

heavy water reactor: a type of nuclear reactor which uses heavy water as a both a moderator and coolant.

highly enriched uranium: uranium enriched to at least 20 per cent ^{235}U.

high level waste (HLW): waste containing large concentrations of short- and long-lived radionuclides that generate significant quantities of heat and requires shielding and cooling.

hot particles: particles of nuclear fuel which are dispersed in a nuclear accident. They include radionuclides of strontium, plutonium and americium.

Intergovernmental Panel on Climate Change (IPCC): the international body for assessing the science related to climate change.

intermediate level waste (ILW): radioactive waste that contains some long-lived radionuclides and has higher levels of radioactivity than low-level waste. It requires shielding and does not generate significant quantities of heat.

internal rate of return: the interest rate that makes the net present value of an investment zero when applied to the projected cash flow from an asset, liability, or financial decision. It is used to assess the profitability of potential investments.

Intended Nationally Determined Contributions (INDC): the intended national efforts towards greenhouse gas emission reductions and climate change mitigation that were outlined by the parties to the United Nations Framework Convention on Climate Change (UNFCCC) in the lead up to the Paris Conference (COP21) in 2015.

ion: an atom that has become electrically charged having gained or lost an electron.

ionising radiation: radiation capable of causing ionisation of the matter through which it passes.

ionisation: process by which an atom or molecule gains or loses electrons.

isotope: Nuclides that have the same atomic number (same number of protons) but different mass numbers (different number of neutrons). Different isotopes of the same element have the same chemical properties but different physical properties.

Large Scale Renewable Energy Target (LRET): An Australian Government scheme which creates a financial incentive for the establishment of large scale renewable energy power stations, such as wind and solar farms. It forms part of the broader Renewable Energy Target (RET).

lifecycle analysis: a systematic procedure for compiling and examining the inputs and outputs of materials and energy consumed over the lifetime of an activity.

light water reactor (LWR): reactors that are moderated and cooled by natural water as opposed to heavy water. Types of light water reactors include pressurised water reactors (PWRs) and boiling water reactors (BWRs).

low level waste (LLW): radioactive waste that emits small amounts of gamma radiation, up to regulatory limits, and that can be handled by workers without shielding due to its small associated dose rates. LLW can contain a range of radionuclides, including small amounts of uranium and thorium, and does not produce heat.

mass number: the total number of protons and neutrons in the nucleus of an atom. Different isotopes of the same element will have different numbers of neutrons and therefore different mass numbers e.g. ^{235}U and ^{238}U.

megawatt: a unit of power equal to one million watts. See *watt*.

mixed oxide fuel (MOX): a reactor fuel comprising both uranium and plutonium oxides.

moderator: a material used in a reactor to slow down high speed neutrons, thus increasing the likelihood of further fission. Examples of moderators include normal water, heavy water, beryllium and graphite.

natural uranium: uranium that has not been enriched.

net present value (NPV): the current value of a security or an investment project, arrived at by discounting all present and future receipts and outgoings at an appropriate rate of discount.

neutron: an uncharged subatomic particle found in the nucleus of all atoms, except ordinary hydrogen. Neutrons are the links in a chain reaction in a nuclear reactor.

nuclear reactor: a structure in which a fission chain reaction can be maintained and controlled.

nucleus: the positively charged core of an atom. It contains nearly all of an atom's mass and contains both the protons and neutrons.

open cycle gas turbine: a gas fired power plant that uses a gas turbine engine to create electricity.

ore grade: the concentration of an element of interest in an ore deposit.

plutonium (Pu): a heavy, radioactive, man-made metallic element with an atomic number of 94. It has a number of isotopes produced by neutron irradiation of ^{238}U in a reactor core.

polymetallic deposit: deposit containing economic grades of several metals such as iron, copper, gold and uranium.

positron emission tomography (PET): a nuclear medical three-dimensional imaging technique, based on injected short-lived radionuclides, able to identify diseased tissue with high resolution.

Precambrian: an expression which describes the Hadean, Archaean, and Proterozoic eons, which together comprise the longest period of geologic time beginning with the consolidation of the Earth's crust and ending approximately 4000 million years later with the beginning of the Cambrian Period around 542 million years ago.

proliferation (nuclear): the spread of nuclear weapons, and more generally, the spread of nuclear technology and knowledge that might be put to military use.

proton: a positively charged subatomic particle found in the nucleus of all atoms.

proton therapy: a type of radiotherapy that uses a beam of protons produced by an accelerator, which are capable of penetrating a defined distance into the body.

radioactive waste: material for which no further use is foreseen that contains or is contaminated with radionuclides above regulated limits.

radioactivity: the inherent property of certain nuclides to emit particles or gamma rays during their spontaneous decay into other stable nuclei.

radioisotope: an isotope of an element that is radioactive.

radionuclide: see *radioisotope.*

radiopharmaceutical: a medicine comprising a radioisotope attached to a molecule that targets diseased tissue or physiological function. Radiopharmaceuticals can be used both for diagnostic purposes (imaging) and for therapy (in certain cancer treatments).

radon: a naturally occurring radioactive element with an atomic number of 86, which is the heaviest known gas. It is produced by the radioactive decay of naturally occurring uranium and thorium.

reactor core: the innermost part of a nuclear reactor that contains the fuel, the moderator (in a thermal reactor), and a coolant; where the fission reaction takes place and the level of radiation is highest.

safeguards, nuclear: political and legal mechanisms, including accounting, surveillance and physical inspections, intended to deter the spread of nuclear weapons by early detection of misuse of nuclear material or technology.

separative work unit (SWU): the amount of enrichment effort required to increase the concentration of ^{235}U in a given amount of uranium to a higher concentration.

short-run marginal cost: the additional cost from a unit increase in an activity.

sievert (Sv): a unit of measurement of *equivalent dose* and *effective dose* equivalent to one joule per kilogram of tissue exposed.

spot market: a market for transactions with settlement at a spot date, usually being the normal, earliest date for delivery. The market price for delivery on the spot date is the spot price or spot rate.

stope: a step-like part of a mine where ore is being extracted.

sulphide: a group of minerals in which the element sulphur (S) is in combination with one or more metallic elements.

tails: the depleted uranium stream produced during the enrichment process.

tailings: the ground rock remaining after particular ore minerals (e.g. uranium oxides) are extracted

tectonic plate: one of the large sections or blocks of the Earth's crust. There are seven major plates (the North American, South American, African, Eurasian, Indo-Australian, Pacific, and Antarctic plates) and at least twelve minor plates.

thorium: a naturally occurring radioactive element with atomic number of 90.

tracer: a radioactive isotope used to follow a chemical or biochemical reaction.

transuranic: any elements with an atomic number greater than uranium. They include plutonium and americium.

United Nations Framework Convention on Climate Change (UNFCCC): An international treaty that aims to address climate change through international cooperation. It entered into force in 1994, and has a Secretariat to assist in making the UNFCCC operational.

used fuel: reactor fuel in its assembly following its discharge from a reactor.

uranium: a radioactive element with atomic number 92 with a number of important isotopes, such as naturally occurring ^{235}U and ^{238}U. Uranium is the basic raw material for nuclear energy.

uranium, enriched: uranium in which the content of the fissile isotope ^{235}U has been increased above the ~0.71% natural content. Uranium must be enriched to be used as fuel for light water reactors. Material with 20 per cent or greater enrichment is called high enriched uranium; below 20 per cent is called low enriched uranium.

uranium oxide concentrate (UOC): a commercial product of a uranium mill, usually containing a high proportion (greater than 90%) of uranium oxide (U_3O_8).

watt (W): a unit of power equal to the amount of energy (one joule) that is consumed in a second (J/s). A subscript that is used alongside references to gigawatt (GW) or megawatt (MW) refers to the generation of either electrical (e) or thermal (th) energy. When it is used in association with a power plant, typically in hundreds of MWe, it describes the capacity of that power plant to generate electricity.

watt hour (Wh): a unit of energy equal to a watt of power (thermal or electric) consumed continuously for one hour. A kilowatt hour (kWh) is a unit of electricity that is typically expressed on retail bills to denote the amount of electrical energy that has been consumed.

venturi scrubber: an air pollution control device that uses water or gas flows to remove fine particles from volatile, hazardous, or corrosive gas streams, or from gas streams containing solid materials that are difficult to handle.

vitrification: a technique for the incorporation of radionuclides into glass for storage and disposal.

yellowcake: see *uranium oxide concentrate.*

SHORTENED FORMS

ABWR: advanced boiling water reactor

AEMO: Australian Energy Market Operator

ANRDR: Australian National Radiation Dose Register

ANSTO: Australian Nuclear Science and Technology Organisation

APSN: Asia-Pacific Safeguards Network

ARPANSA: Australian Radiation Protection and Nuclear Safety Agency

ARS: acute radiation syndrome

ASN: Nuclear Safety Authority (France)

ASNO: Australian Safeguards and Non-proliferation Office

AUD or A$: Australian dollar

BMUB: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Germany)

BWR: boiling water reactor

capex: capital expenditure

CCGT: combined cycle gas turbine

CCS: carbon capture and storage

CNNC: China National Nuclear Corporation

CSA: Comprehensive Safeguards Agreement

CSIRO: Commonwealth Scientific and Industrial Research Organisation

CT: computed tomography

CTBT: Comprehensive Nuclear-Test-Ban Treaty

DEWNR: Department of Environment, Water and Natural Resources (South Australia)

DSD: Department of State Development (South Australia)

DU: depleted uranium

EIA: environmental impact assessment

ENSI: Swiss Federal Nuclear Safety Inspectorate

EPA: Environment Protection Authority (South Australia)

EPBC Act: *Environment Protection and Biodiversity Conservation Act 1999* (Cth)

EPRI: Electric Power Research Institute

EPRI/CO_2CRC: Electric Power Research Institute and Carbon Dioxide Cooperative Research Centre

ESBWR: economically simplified boiling water reactor

EUR or €: Euro (currency)

FANC: Federal Agency for Nuclear Control

FAO: Food and Agriculture Organization (United Nations)

FGF: Future Grid Forum

FTE: full-time equivalent

gCO_2-e/kWh: grams carbon dioxide equivalent per kilowatt hour

GDF: geological disposal facility

GJ: gigajoule

GST: goods and services tax (Australian Government)

GWe: gigawatt electrical

Gy: gray, the unit in which a dose of radiation is measured

HEU: highly enriched uranium

HLW: high level waste

HM: heavy metal

HTR-PM: high temperature gas cooled pebble bed modular

HWR: heavy water reactor

IAEA: International Atomic Energy Agency

IDR: intermediate depth repository

IEA: International Energy Agency

ILW: intermediate level waste

INDC: intended nationally determined contribution

INF Code: International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High Level Radioactive Wastes on Board Ships

INLEX: International Expert Group on Nuclear Liability

IPCC: Intergovernmental Panel on Climate Change

ISF: interim storage facility

ISL: in-situ leaching

JSCOT: Joint Standing Committee on Treaties (Parliament of Australia)

KAERI: Korean Atomic Energy Research Institute

kg: kilogram

KINS: Korean Institute for Nuclear Safety

km: kilometre

KORAD: Korea Radioactive Waste Management Corporation

kt: kilotonne

L: litre

LCOE: levelised cost of electricity

LILW: low and intermediate level waste

LLW: low level waste

LNT: linear non-threshold assumption

LOCA: loss-of-coolant accident

LRET: Large-scale Renewable Energy Target (Australian Government)

LWR: light water reactor

m: million

m^3: cubic metre

ML: megalitre

MOX: mixed oxide fuels

mSv: millisievert (0.001 Sv)

mSv/a: millisieverts per year

MtCO$_2$-e: megatonne carbon dioxide equivalent

MUF: material unaccounted for

MWe: megawatts electric

NEA: Nuclear Energy Agency

NEM: National Electricity Market (Australia)

NICNAS: National Industrial Chemicals Notification and Assessment Scheme

NPT: non-proliferation treaty

NPV: net present value

NRC: Nuclear Regulatory Commission (United States)

NSSC: Nuclear Safety and Security Commission (Korea)

OCGT: open cycle gas turbines

OECD: Organisation for Economic Cooperation and Development

OECD–NEA: Organisation for Economic Cooperation and Development–Nuclear Energy Agency

ONDRAF/NIRAS: Agency for Radioactive Waste and Enriched Fissile Materials (Belgium)

OPAL: Open Pool Australian Lightwater

PACE: Plan for Accelerating Exploration (South Australia)

PEPR: Program for Environmental Protection and Rehabilitation (Australia)

PET: positron emission tomography

PHWR: pressurised heavy water reactor

PUREX: plutonium uranium extraction

PV: photovoltaic

PWR: pressurised water reactor

RD&D: research, development and demonstration

RMP: Radiation Management Plan

Rosatom: Rosatom Overseas Inc.

RWMP: Radioactive Waste Management Plan (South Australia)

SAHMRI: South Australian Health and Medical Research Institute

SCK-CEN: Nuclear Research Centre (Belgium)

SKB: Nuclear Fuel and Waste Management Co (Sweden)

SMR: small modular reactor

SPNFZT: South Pacific Nuclear Free Zone Treaty

STEM: science, technology, engineering and maths (based)

STORA: Study and Consultation Radioactive Waste Dessel (Belgium)

STUK: Radiation and Nuclear Safety Authority (Finland)

t: tonnes

TEPCO: Tokyo Electric Power Company

tHM: tonne of heavy metal

THORP: Thermal Oxide Reprocessing Plant

TLD: thermoluminescent dosimeter

tU: metric tonne of uranium

TVO: Teollisuuden Voima Oyj (Finland)

UAE: United Arab Emirates

UN: United Nations

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

URL: underground research laboratory

USD or US$: United States dollar

VHTR: very high temperature gas reactor

VURM: Victoria University Regional Model

WHO: World Health Organization

WIPP: Waste Isolation Pilot Plant (United States)

WLDC: Wolsong LILW Disposal Center (Korea)

WNA: World Nuclear Association

WNN: World Nuclear News

°C: degrees Celsius

μSv: microsievert (0.000001 Sv)

₩: Won (currency)