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CHAPTER 9:

Nuclear Power and Associated Environmental Issues in the Transition of Exploration and Mining on Earth to the Development of Off-World Natural Resources in the 21st Century

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Nuclear Power and Associated Environmental Issues in the Transition of Exploration and Mining on Earth to the Development of Off-World Natural Resources in the 21st Century

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ABSTRACT

Once humans landed on the Moon on July 20, 1969, the goal of space exploration envisioned by United States President John F. Kennedy in 1961 was already being realized. Achievement of this goal depended on

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the development of technologies to turn his vision into reality. One technology that was critical to the success of this goal was the harnessing of nuclear power to run these new systems. Nuclear systems provide power for satellite and deep space exploratory missions. In the future, they will provide propulsion for spacecraft and drive planet-based power systems. The maturation of technologies that underlie these systems ran parallel to an evolving rationale regarding the need to explore our own solar system and beyond. Since the Space Race, forward-looking analysis of our situation on Earth reveals that space exploration will one day provide natural resources that will enable further exploration and will provide new sources for our dwindling resources and offset their increasing prices or scarcity on Earth. Mining is anticipated on the Moon for increasingly valuable commodities, such as helium-, rare earth elements, uranium, etc., and on selected asteroids or other moons as a demonstration of technology at scales never before imagined. In addition, the discovery of helium-3 on the Moon may provide an abundant power source on the Moon and on Earth through nuclear fusion technologies. However, until the physics of fusion is solved, that resource will remain on the shelf and may even be stockpiled on the Moon until needed. It is clear that nuclear power will provide the means necessary to realize these goals while advances in other areas will provide enhanced environmental safeguards in using nuclear power in innovative ways, such as a space elevator or by a ramjet space plane to deliver materials to and from the Earth's surface and personnel and equipment into space and a space gravity tractor to nudge errant asteroids and other bodies out of collision orbits. Nuclear systems will enable humankind to expand beyond the boundaries of Earth, provide new frontiers for exploration, ensure our protection, and renew critical natural resources while advancing spin-off technology on Earth. During the past ten years, China, Japan, India, and other countries have mounted serious missions to explore the Moon and elsewhere. Recent exploration discoveries by Japan on the Moon may mark the beginning of a new race to the Moon and into space to explore for and develop natural resources, including water (from dark craters to make hydrogen for fuel and oxygen, etc.), nuclear minerals (uranium, thorium, and helium-3), rare-earth minerals, and other industrial commodities needed for use in space and on Earth in the decades ahead.

INTRODUCTION

In 2005, the International Atomic Energy Agency (IAEA) (2005a) published a comprehensive review of the history and status of nuclear power used in space exploration. Based on this review and on our research, we will place some perspectives around the function nuclear power will likely have in the future from developing and fueling the technology for use on Earth (Campbell et al., 2009a) to developing the ability to explore for and to recover natural resources that likely await our discovery on the Moon and elsewhere in the solar system (Campbell et al., 2009b). Recently, we described the nature of the occurrence of uranium and thorium deposits on Earth (Campbell et al., 2008), and we suggested that it is likely that certain types of deposits also can be expected to occur elsewhere in our solar system.

Recovering such resources can only be realized via small steps in technology, starting with satellites in orbit and followed by the development of electronics to communicate with humans on Earth. Satellites and their communications equipment are powered by solar energy for low electrical demands and by nuclear energy for missions with heavy load and long-duration requirements. Without nuclear energy, missions to recover resources from elsewhere in the solar system are not possible.

SATELLITES

In late 1953, United States President Dwight D. Eisenhower proposed in his famous Atoms for Peace address that the United Nations establish an international agency that would promote the peaceful uses of nuclear energy (Engler, 1987). The IAEA had its beginnings in this initiative. Since the time of Sputnik in 1957, artificial satellites have provided communications, digital traffic and satellite photography, and the means for the development of cell phones, television, radio, and other uses. Of necessity, they require their own power source (Aftergood, 1989). For many satellites, this has been provided by solar panels, where electricity is generated by the photovoltaic effect of sunlight on certain substrates, notably forms of silicon and germanium. However, because the intensity of sunlight varies inversely with the square of the distance from the sun, a probe sent off to Jupiter, Saturn, and beyond would only receive a small percentage of the sunlight it would receive were it in Earth orbit. In that case, solar panels would have to be so large that using them would be impractical (Rosen and Schnyer, 1989).

The limitations of solar-power systems in satellites were recognized at the time and prompted the development of the atomic battery, unveiled by President Eisenhower in January 1959. This battery, actually a radioisotope thermoelectric generator, was characterized as part of the Atoms for Peace program. The further development of nuclear power systems arose from the requirements of the particular exploration mission being undertaken.

A space exploration mission requires power at many stages, such as the initial launch of the space vehicle and subsequent maneuvering, to run the instrumentation and communication systems, warming or cooling of vital systems, lighting, various experiments, and many more uses, especially in manned missions. To date, chemical rocket thrusters have been used exclusively for launching spacecraft into orbit and beyond. Many problems would be easier to solve if all power after launch could be supplied by solar energy, but the limitations of solar power forced mission designers to investigate other power systems.

Realization of the limitations of solar power led to the development of alternative sources of power and heating. One alternative involves the use of nuclear power systems (NPSs). These rely on the use of radioisotopes and are generally referred to as radioisotope thermoelectric generators (RTGs), thermoelectric generators (TEGs), and radioisotope heater units. These units have been used on both United States and Soviet/Russian spacecrafts for more than 40 years. Space exploration would not have been possible without the use of RTGs to provide electrical power and to maintain the temperatures of various components within their operational ranges (Bennett, 2006).

The RTGs evolved out of a simple experiment in physics. In 1821, a German scientist named T. J. Seebeck discovered that when two dissimilar wires are and if one junction is kept hot while the other is cold, an electric current will flow in the circuit between them from hot to cold. Such a pair of junctions is called a thermoelectric couple. The required heat can be supplied by one of several radioactive isotopes. The device that converts heat to electricity has no moving parts and is, therefore, very reliable and continues for as long as the radioisotope source produces a useful level of heat. The heat production is, of course, continually decaying, but radioisotopes are chemically customized to fit the intended use of the electricity and for the planned mission duration.

The IAEA (2005b) suggests that nuclear reactors can provide almost limitless power for almost any duration. However, they are not practicable for applications below 10 kW mainly because of the limited duration of available power. The RTGs are best used for continuous supply of low levels (up to 5 kW) of power or in combinations up to many times this value. For this reason, especially for long interplanetary missions, the use of radioisotopes for communications and for powering experiments is preferred. For short durations of up to a few hours, chemical fuels can provide energy of up to 60,000 kW, but for mission durations of a month, use is limited to 1 kW or less. Although solar power is an advanced form of nuclear power, this source of energy diffuses with distance from the Sun and does not provide the commonly needed rapid surges of large amounts of energy. In contrast, solar energy is readily available on the Moon and potentially abundant enough to provide energy on Earth (see Criswell, Chapter 8, this text).

LUNAR SOLAR OR LUNAR NUCLEAR POWER

In the past, solar power was generally considered to be the most efficient source for constant power levels of 10 to 50 kW for as long as sufficient sunlight was available. On the Moon, where sunlight is abundant and constant, higher output could be obtained via a large lunar-solar system, as suggested by Criswell (Chapter 8, this text and 2001, 2004a, b). In addition to supplying the Moon-base requirements for fuel production, habitat maintenance, communications, and research, the excess power could be transferred by large-aperture radar and/or microwave (i.e., power beaming) to Earth for distribution through existing power grids. Missions to the Moon would likely use a combination of power sources, both solar and nuclear, to meet mission objectives. The typical output ranges for the different power sources to supply missions are illustrated in Figure 1.

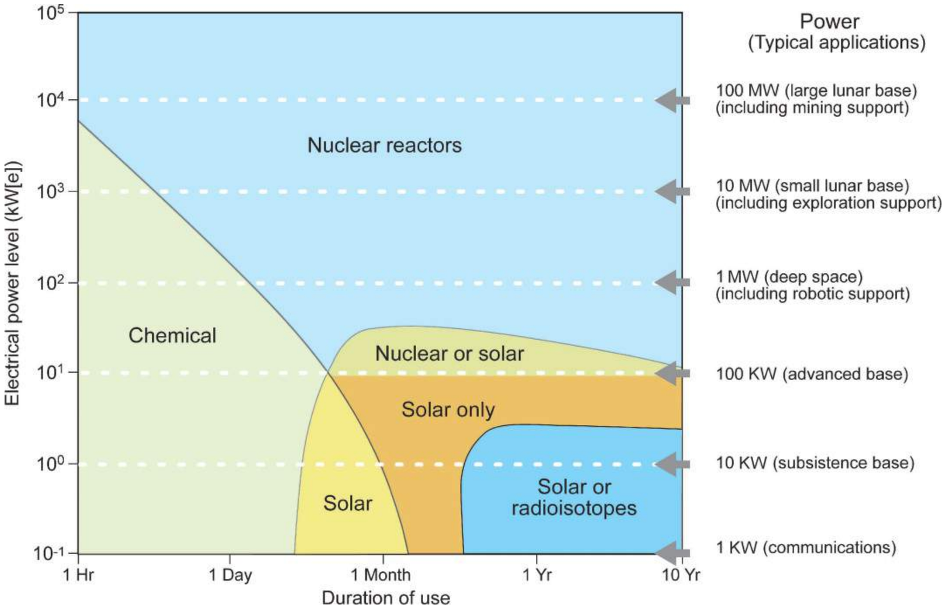

FIGURE 1. Sources of electricity for application in missions in space. Modified from International Atomic Energy Agency (2005b).

Excess power generated on the Moon by either nuclear or solar installations could provide a benefit to Earth.

Criswell (See Chapter 8, this text, and 2001) also suggests that a preferred power beam is formed of microwaves of about 12 cm wavelength or about 2.45 GHz. This frequency of microwaves apparently travels with negligible attenuation through the atmosphere and its water vapor, clouds, rain, dust, ash, and smoke. Also, Criswell indicates that this general frequency range can be converted into alternating electric currents at efficiencies in excess of 85%. These power beams could be directed into industrial areas where the general population could be safely excluded. Hazards to birds and insects can be minimized, and humans flying through the beam in aircraft would be shielded safely by the metal skin of the aircraft's fuselage. Presumably, power generated by nuclear reactors located on the Moon could also be beamed to Earth in a similar fashion with similar advantages and disadvantages.

As opposed to the solar-energy conversion to microwaves process, heat is emitted from all nuclear processes. This heat may either be converted into electricity or be used directly to power heating or cooling systems. The initial decay produces some decay products, and the use of the thermal energy will cause some additional excess thermal energy to be rejected. Nuclear processes can either be in nuclear reactors or from radioisotope fuel sources, such as plutonium oxide. In either case, the heat produced can be converted to electricity either statically through thermocouples or thermionic converters, or dynamically using turbine generators in one of several heat cycles (such as the well-known Rankine, Stirling, or Brayton designs; see Mason, 2006b).

The nuclear workhorses used in space missions through 2004 are RTGs and the TEGs powered by radioisotopes in the Russian Federation that provided electricity through static (and therefore reliable) conversion at power levels of up to 0.5 kW, with more power available by combining modules. The International Atomic Energy Agency (2005b, p. 4) report indicates that ''small nuclear reactors have also been used in space, one by the United States in 1965 (called the SNAP-10A reactor) which successfully achieved orbit, the only nuclear reactor ever orbited by the United States. The SNAP [Systems for Nuclear Auxiliary Power] -10A reactor provided electrical power for an 8.5-mN ion engine using cesium propellant. The engine was shut off after 1 hour of operation when high-voltage spikes created electromagnetic interference with the satellite's attitude-control system sensors. The reactor continued in operation, generating 39 kW and more than 500 W of electrical power for 43 days before the spacecraft's telemetry ultimately failed.''

The former Soviet Union routinely flew spacecrafts powered by nuclear reactors; 34 were international artificial satellites launched between 1970 and 1989. The general consensus is still that the investigation of outer space (beyond Earth space) is ''unthinkable without the use of nuclear power sources for thermal and electrical energy'' (International Atomic Energy Agency, 2005a). Up to this point, nuclear energy was discussed solely as a means to power onboard mission systems that were launched using chemical rocket thrusters.

Ongoing research suggests that nuclear power may also have an application in spacecraft propulsion.

SPACECRAFT PROPULSION

The use of space NPSs is not restricted to the provision of thermal and electrical power. Considerable research has been devoted to the application of nuclear thermal propulsion (NTP). Research is underway on propulsion units that will be capable of transferring significantly heavier payloads into Earth orbit than is currently possible using conventional chemical propellants, which today costs about US $10,000/lb to lift a payload into orbit and about US $100,000 to deliver a pound of supplies to the Moon. The Apollo program was supported by the four-stage launch vehicle shown on the pad in Figure 2.

For the propulsion of spacecraft, the use of nuclear power once in space is more complicated than simply selecting one over several power options. The choice of nuclear power can make deep space missions much more practical and efficient than chemically powered missions because they provide a higher thrust-to-weight ratio. This allows for the use of less fuel for each mission. For example, in a basic comparison between a typical chemical propulsion mission to Mars with one using nuclear propulsion, because of the different mass-ratio efficiencies and the larger specific impulse, the chemically powered mission requires a total of 919 days for a stay of 454 days on Mars. By comparison, a nuclear-powered mission took a planned total of 870 days for a stay of 550 days (see

FIGURE 2. Apollo launch vehicle. Photograph (1968) courtesy of the National Aeronautics and Space Administration.

International Atomic Energy Agency, 2005b). The outward-bound and return journeys would take 30% less time and allow for a longer stay on Mars. In considering orbital positions involving time, weight, and a variety of payloads, nuclear power wins out most of the time (see comparison in Figure 3).

For a nuclear-power rocket propulsion system, a nuclear reactor is used to heat a propellant into a plasma that is forced through rocket nozzles to provide motion in the opposite direction. The IAEA indicates that the two parameters that provide a measure of the efficiency of a rocket propulsion energy source are the theoretical specific impulse and the ratio of the take-off mass to the final mass in orbit (International Atomic Energy Agency, 2005b). Specific impulse is a property that is measured in such a way that the answer reveals how long in seconds a given mass of propellant will produce a given thrust (see Ambrose, Chapter 1, this text).

Chemical reactions using hydrogen, oxygen, or fluorine can achieve a specific impulse of 4,300 s with a mass ratio for Earth escape of 15:1, which is about 20 times the efficiency of conventional bipropellant station-keeping thrusters (Nelson, 1999). However, hydrogen heated by a fission reactor instead of a chemical reaction achieves twice the specific impulse with a solid core while having a mass ratio of 3.2:1. With different cores, the specific impulse can be as much as seven times greater with a mass ratio of only 1.2:1. This type of engine was used in the Deep Space 1 mission to asteroid Braille in 1999 and Comet Borrelly in 2001. This system also powers the current Dawn mission to asteroids Vesta and Ceres. Although these missions use an electric arc to ionize xenon, the principle is the same. A nuclear engine would simply produce a higher thrust by causing xenon to become a plasma, instead of an ion, resulting in higher velocities (see Chapter 4, Cutright, this text). Ambrose also discusses power and propulsion requirements necessary for recovering valuable commodities from space (see Chapter 1, this text).

Combining nuclear power with electrical thrusters will result in a high efficiency of the specific impulse for thrust; building power and/or propulsion systems on this basis will allow interplanetary missions with payload masses two to three times greater than those possible with conventional chemical propellants. This can also be achieved while supplying 50 to 100 kW of electrical power and more for onboard instrumentation for 10 years or more.

New approaches to space travel now in effect reduce the need for long-term engine burns, whether chemical or nuclear. Reddy (2008), in a summary article, indicates that the solar system is now known to

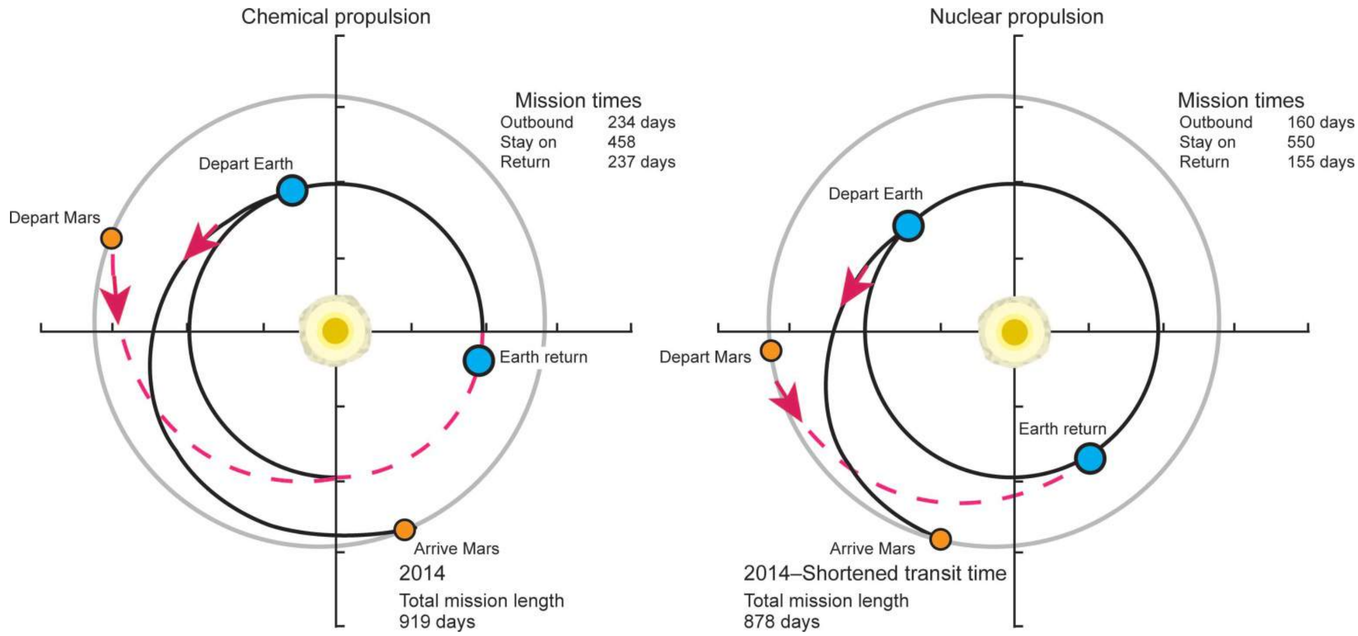

FIGURE 3. Mission duration: Chemical versus nuclear propulsion systems (Modified from the International Atomic Energy Agency, 2005b).

be a complex dynamic structure of swirling and interconnecting pathways in space shaped by the effects of mutual gravitation between the planets, moons, and other bodies. These pathways constitute a natural transportation network somewhat like major currents in the ocean that enables orbiting bodies to move throughout the solar system with ease, although the time required to reach a destination would be longer but with less fuel consumption. So-called balance points in space between orbiting bodies such as the Sun and Earth were discovered in the 18th Century by the Swiss mathematician Leonhard Euler. Additional balance points were found by Joseph-Louis Lagrange, which eventually became known as Lagrange points. Such points are principally used as stable parking points for satellites and for orbiting purposes. For example, the Genesis mission used Lagrange points to sample solar wind in 2001 with minimal fuel, as illustrated in Figure 4. There will be additional Lagrange points available throughout the solar system to aid such travel, combined with orbital altering by flybys of planets and large moons, but propulsion will still be required even with optimized fuel consumption.

Tracking orbits of bodies in space have expanded considerably during the past 20 years. The National Aeronautics and Space Administration (NASA)/Infrared Processing and Analysis Center Extragalactic Database contains positions, basic data, and more than 16,000,000 names for 10,400,000 extragalactic objects, as well as more than 5,000,000 bibliographic

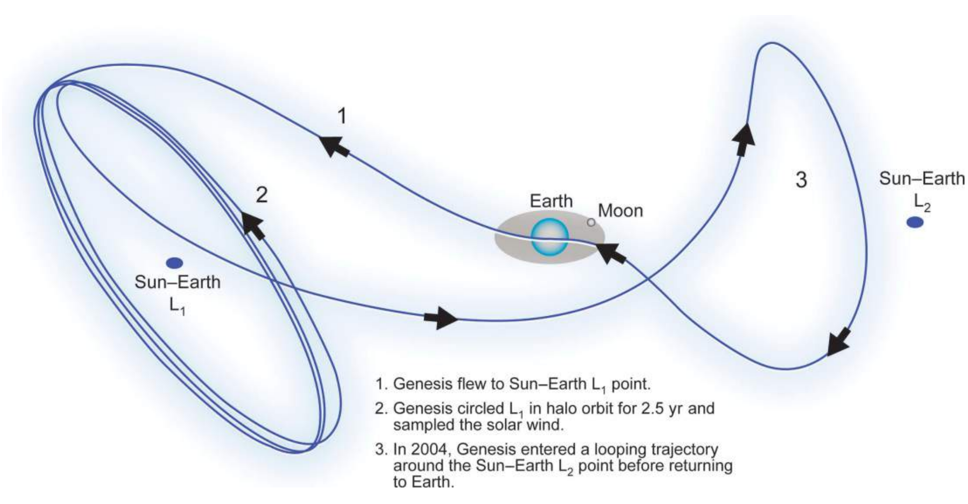

FIGURE 4. Genesis mission pathways. Modified from Reddy, 2008.

references to more than 68,000 published articles and 65,000 notes from catalogs and other publications (NASA, 2008b). In addition, the Planetary Data System is an archive of data from NASA planetary missions. It is sponsored by NASA's Science Mission Directorate and has become a basic resource for scientists around the world (National Aeronautics and Space Administration, 2008c).

The experience accumulated in developing space NPSs, electrical thrusters, and nuclear thermal propulsion systems (NTPS) has enabled several missions focused on Earth, such as round-the-clock all-weather radar surveillance and global telecommunication systems for both military and business interests. These include global systems for communication with moving objects (as in Global Positioning System tracking). Needless to say, technology is leading the way in all areas in the exploration of space. These technologies will enable us to explore the solar system and, with appropriate power systems, to establish colonies and to deal with hostile environments.

PLANET-BASED POWER SYSTEMS

A reliable source of electrical energy is needed for humans to survive on the surface of a nonhostile planet, moon, or asteroid. Approximately 3 to 20 kW(e) from electrical generators would be required, and that, because of the mass of plutonium required, exceeds the capabilities of some smaller types of RTGs. Solar power is impractical because of the distance of Mars from the Sun and because of seasonal and geographic sunlight issues. Thus, nuclear power is the only viable option currently remaining.

In the 1980s, NASA contractors designed and built a reactor, designated HOMER, specifically for producing electricity, on a small scale, on the surface of a planet, moon, or asteroid. The low-power requirement meant that the reactor operated within well-understood regimes of power density, core burn-up, and fission-gas release. In a reactor of this type, the number of impacts of radiogenic particles is so low that no significant irradiation damage to core materials occurs and hence it offered a long life.

EARTH-BASED POWER SYSTEMS

The space research and development conducted in both the former Soviet Union/Russian Federation and the United States have provided substantial benefits to comparable research and development on innovative reactor concepts and fuel cycles currently being conducted under international initiatives. This is particularly true after the Chernobyl disaster, where approximately 4,000 Soviet citizens were thought to have died as a direct result of exposure to the released radiation resulting from the meltdown of a poorly designed nuclear reactor installed during the Cold War (International Atomic Energy Agency, 2004; World Nuclear Association, 2009). In particular, one resulting benefit is the use of heat pipes in the SAFE (Safe Affordable Fission Engine)-400 and HOMER (Heatpipe-Operated Mars Exploration Reactor) reactors that have only recently been applied to small Earth-based reactors. Such heat pipes now greatly reduce the risk by distributing heat more safely. Furthermore, the research and development of extremely strong materials for NPSs designed to withstand harsh environments also could be beneficial for deep-ocean or polar use. The risks associated with reactors based on Earth have also been identified during the design of space-based systems, where environmental safeguards are also critical components.

ENVIRONMENTAL SAFEGUARDS IN ORBIT

The risks associated with using nuclear power in space are similar to those encountered on Earth. A few accidents have occurred, but aside from the Chernobyl disaster (International Atomic Energy Agency, 2004), the use of nuclear power brings with it a risk no higher than other industrial environmental risks on Earth. Campbell, et al. (2005) placed the risks into perspective.

Radiation safety is provided in two ways:

1) The basic approach to safety in orbit relies on moving the spacecraft into a stable long-term storage orbit, close to circular, at a height of more than 530 mi (>853 km). There, nuclear reactor fission products can decay safely to the level of natural radioactivity or they can be transported away from Earth sometime in the future.
2) The backup emergency approach involves the dispersion of fuel, fission products, and other materials with induced activity into the upper layers of Earth's atmosphere. During the descent, aerodynamic heating, thermal destruction, melting, evaporation, oxidation, and so on, are expected to disperse the fuel into particles that are sufficiently small as to pose no excess radiological hazard to Earth's populations or to the environment.

> The worst known example of these impacts happened during the descent of the Soviet Union's Cosmos-954 spacecraft in 1978. During its descent, the Cosmos-954 failed to be boosted to a higher orbit and reentered Earth's atmosphere, resulting in large radioactive fragments of wreckage being strewn across a thin strip of northern Canada. Since this failure, backup safety systems were introduced to minimize the potential of this occurrence happening again (for details, see International Atomic Energy Agency, 2005b).

Safety, both for astronauts and other humans on Earth, has been a longtime prime concern of the inherently dangerous space program in general. Fortunately, any hardware placed in orbit, including nuclear reactors, have been designed so that when they eventually reenter the atmosphere, they will break up into such small fragments that most of the spacecraft and reactor will atomize and burn up as they fall back to Earth.

The International Atomic Energy Agency (2005b) suggested that both RTGs and TEGs, the workhorse auxiliary power systems, also have several levels of inherent safety:

1) The fuel used is in the form of a heat-resistant ceramic plutonium oxide that reduces the chances of vaporization in the event of a fire or during reentry. Furthermore, the ceramic is highly insoluble and primarily fractures into large pieces instead of forming dust. These characteristics reduce any potential health effects if the fuel were released;
2) The fuel is divided into small independent modules each with its own heat shield and impact casing. This reduces the chance that all the fuel would be released in any accident; and
3) Multiple layers of protective containment are present, including capsules made of materials such as iridium, located inside high-strength heat-resistant graphite blocks. The iridium has a melting temperature of 4,449 K, which is well above reentry temperatures. It is also corrosion resistant and chemically compatible with the plutonium oxide that it contains.

However, a few accidents occurred during the 1960s and 1970s. One accident occurred on April 21, 1964, when the failure of a United States launch vehicle resulted in the burn up of the SNAP-9A RTG during reentry. This resulted in the dispersion of plutonium in the upper atmosphere. This accident, and the consequent redesign of the RTGs, has improved the current level of safety substantially.

A second accident occurred on May 18, 1968, after a launch aborted in midflight above Vandenberg Air Force Base and crashed into the Pacific Ocean off California. The SNAP-19 reactor's heat sources were found off the United States coast at a depth of 300 ft (91 m). They were recovered intact, with no release of plutonium. The fuel was removed and used in a later mission. A third accident occurred in April of 1970 when the Apollo 13 mission was aborted. The lunar excursion module that carried a SNAP-27 RTG reentered the atmosphere and plunged into the Pacific Ocean close to the Tonga Trench, sinking to a depth of between 4 and 6 mi (6.4 –9.7 km). Monitoring since then has shown no evidence of any release of radioactive fuel.

The former Soviet Union routinely flew spacecraft that included nuclear reactors in low Earth orbits. At the end of a mission, the spacecraft was boosted to a higher, very long-lived orbit so that nuclear materials could decay naturally. As previously indicated, a maj -or accident occurred on January 24, 1978, when Cosmos-954 could not be boosted to a higher orbit and reentered Earth's atmosphere over Canada. Debris was found along a 400 mi (644 km) tract north of Great Bear Lake. No large fuel particles were found, but about 4,000 small particles were collected. Four large steel fragments that appeared to have been part of the periphery of the reactor core were discovered with high radioactivity levels. Forty-seven beryllium rods and cylinders and miscellaneous pieces were also recovered, all with some contamination (International Atomic Energy Agency 2005b).

As a result of this accident, the Russian Federation redesigned its systems for backup safety. Furthermore, a United Nations working group has developed aerospace nuclear safety design requirements whereby:

1) the reactor shall be designed to remain subcritical if immersed in water or other fluids, such as liquid propellants;
2) the reactor shall have a significantly effective negative power coefficient of reactivity;
3) the reactor shall be designed so that no credible launch pad accident, ascent, abort, or reentry from space resulting in Earth impact could result in a critical or supercritical geometry;
4) the reactor shall not be operated (except for zero power testing that yields negligible radioactivity at the time of launch) until a stable orbit or flight path is achieved and it must have

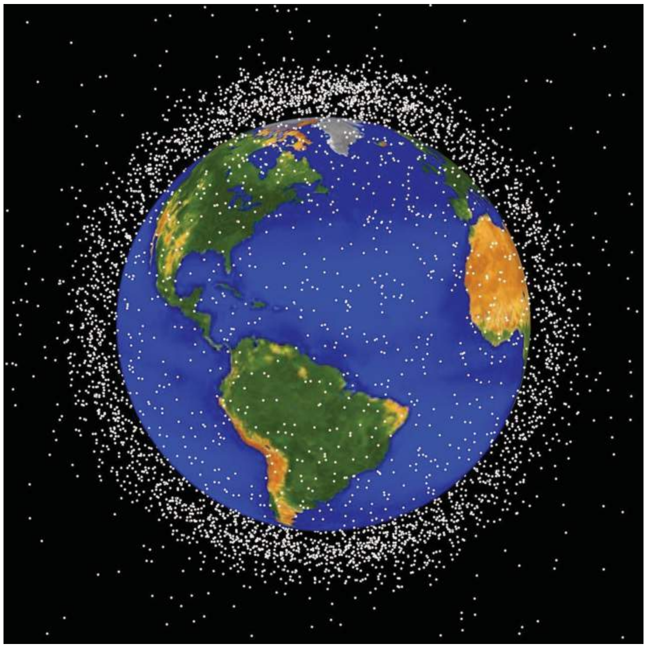

FIGURE 5. Cartoon of space debris in orbit. Photograph courtesy of the National Aeronautics and Space Administration.

a reboost capability from low Earth orbit if it is operated in that orbit;

5) two independent systems shall be provided to reduce reactivity to a subcritical state, and these shall not be subject to a common failure mode;
6) the reactor shall be designed to ensure that sufficiently independent shutdown heat removal paths are available to provide decay heat removal;
7) the unirradiated fuel shall pose no significant environmental hazard; and
8) the reactor shall remain subcritical under the environmental conditions of a postulated launch vehicle explosions or range of planned safety-destruct actions.

Thus, as in all advances in technology, experience corrects previous oversights. The causes of the re-entry of Cosmos-954, for example, have been rectified. Fortunately, this incident resulted in no danger to Canadians because of the remoteness and clean-up of the debris field. In the future, because of advanced antisatellite technology, failing orbiting spacecrafts will be intercepted and destroyed by ground- or ship-based guided missiles before reaching the surface. The International Atomic Energy Agency (2005b) indicates that each member country has used the new international rules, and some have expanded them to meet their own requirements. As an example, in 1998 the Russian Federation published a new policy governing safety and recovery.

However, the number of satellites and the associated space debris amounting to some 17,000 pieces of hardware that have accumulated in various orbits during the past 50 years have created safety issues of a different variety (Figure 5). A recent collision of old and new satellites over Siberia has illustrated the serious threat to other satellites, including the Hubble and even the International Space Station (Rincon, 2009). This threat will only increase with time.

OTHER ENVIRONMENTAL CONSIDERATIONS IN SPACE

Human physiological and psychological adaptations to the conditions and duration of space travel represent significant challenges (European Space Agency, 2009). Millions of man-hours of research for well over a century have been spent on the fundamental engineering problems of escaping Earth's gravity and on developing systems for space propulsion. In recent years, there has been a substantial increase in research into the issue of the impact on humans in space during long periods. This question requires extensive investigations of both the physical and biological aspects of human existence in space, which has now become the greatest challenge, other than funding, to human space exploration. The impact of artificial gravity and the effects of zero gravity on humans are at the core of the research today (Prado, 2008a). Therefore, a fundamental step in overcoming this challenge is in trying to understand the effects and the impact of long space travel on the human body. The expansion into space depends on this research and on the plans of contemporary futurists, ultimately affecting the plans of all space agencies on Earth (Prado, 2008b, and others).

Expansion of activities beyond the surface of the Earth into space and onto other bodies such as the Moon, Mars, and the larger asteroids will entail a significantly different set of risks compared with historic activities on Earth (Ambrose and Schmitt, 2008). Fortunately, a large amount of information on human risk has accumulated since space programs began in the 1960s, particularly from the Skylab project of the 1970s and the International Space Station (ISS) that began operations on November 2, 2000, with the first resident crew, Expedition 1. Since then, the ISS has provided an uninterrupted human presence in space.

Special interest is given to the risk of increased radiation exposure from not having shielding by the

Earth's atmosphere and structures such as the van Allen belts. In particular, the inappropriateness of the linear no-threshold dose hypothesis (LNT) to space environments will be discussed, and an alternative hypothesis with a threshold of approximately 10 rem (0.1 Sv) is proposed.

Note that the acceptable levels of risk for space exploration beyond low Earth orbit have not been defined at this time by the National Council on Radiation Protection and Measurements (NCRP). This must be dealt with before sending manned missions to the moon or to Mars. The NCRP (2008) has released Report 153, which is an excellent first step in this process.

Radiation Doses on Earth and in Space

Humans are constantly bombarded with various types of ionizing and nonionizing radiation. Although a global background average at sea level of approximately 250 millirem (mrem) or 2.5 millisieverts (mSv) exists, the background strongly depends on geographic location. Radiation in terrestrial environments comes from a combination of natural sources (83% of total) and anthropogenic sources (17% of total), although the ratio varies geographically and culturally. The major sources for humans in developed countries comes from cosmic rays (30 mrem/yr [0.3 mSv/yr]) from intake of food and air, primarily radon from decay of natural uranium and potassium-40 (^{40}K) in food (160 mrem/yr [1.6 mSv/yr]) and from naturally occurring radioactive materials such as soil and rock that include uranium, thorium, radium, and potassium (50 mrem/yr [0.5 mSv/yr]). Indoor exposure rates are approximately 20% higher than outdoor because of trapping of radon and other decay products in in-door air and the use of uranium- and thorium-containing building materials. Radiological and nuclear-medical procedures have become more common in the last decade, and recent discussions have suggested they could add another 50 mrem/yr (0.5 mSv/yr) to the United States average (National Council on Radiation Protection and Measurements, 2009).

Variations in background doses across the globe range from less than 100 mrem/yr (1 mSv/yr) in areas at sea level on carbonate and nonsilicate bedrock, for example, Bermuda, to more than 10 rem/yr (0.1 Sv/yr) in Ramsar, Iran. Although more than 90% of the Earth's surface has an annual dose of less than 400 mrem/yr (<4 mSv/yr), some notable areas that exceed 1 rem/yr (0.01 Sv/yr) include Kerala, India (3.8 rem/yr), Yangjiang, China (3.5 rem/yr), and Guarapari, Brazil (5.5 rem/yr). Note that no adverse health effects or increased cancer rates in these high-radiation background areas are found (Hiserodt, 2005).

In space, the situation is different. The primary sources of radiation are high-energy particles and/or rays from galactic cosmic radiation (GCR) and from solar particle events (SPEs). As discussed by the National Research Council, Committee on the Evaluation of Radiation Shielding for Space Exploration (2008), satellite data have characterized GCR and SPEs near Earth to a great degree, and these results apply well to the incident radiation on the surface of the Moon. Knowledge of the secondary radiation produced by GCR and SPEs interacting with lunar surface materials is based on Apollo, Lunar Prospector, and Clementine data and calculations. The extrapolation of GCR from Earth to Mars is also fairly well understood based on measurements from satellites traveling outward through the solar system. However, few measurements of SPEs are present in the vicinity of Mars, and extrapolation of near-Earth measurements of SPEs to Mars is inadequate (National Research Council, Committee on the Evaluation of Radiation Shielding for Space Exploration, 2008). Calculations and measurements taken by spacecraft in Mars orbit can be used to estimate the secondary radiation environment on the Martian surface. Knowledge of other sources of radiation come from short trips through Earth's trapped radiation belts.

Distinguishing radiation from radioactive materials, such as uranium and thorium (and their daughter products such as radium and radon), is important. The latter are particularly important because they can attach to dust particles that continuously emit radiation after being inhaled or ingested. Such radiation can damage tissues in the lungs and other organs. Terrestrial sources of radiation are weighted toward radioactive materials, whereas radiation in space is not. The high energies of space radiation can generate highly penetrating secondary particles, such as neutrons and light ions, by interacting with materials in the spacecraft or space habitat. Because less is known about the relative biological effects of highly energetic particles, dose and medical monitoring of travelers and colonists should be a priority. The sources of radiation doses to humans within the van Allen belts, an ozone layer, and other intervening atmospheric structures (according to the National Research Council, Committee on the Evaluation of Radiation Shielding for Space Exploration, 2008) are dominated by:

- solar particle events—high-energy protons (tens to a few hundred million electron volts

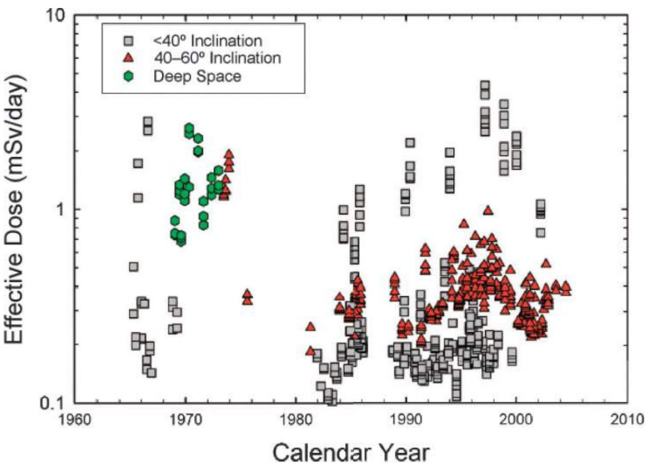

FIGURE 6. Astronaut radiation exposure history (United States) from 1962 to 2005 (Cucinotta, 2007; National Research Council, Committee on the Evaluation of Radiation Shielding for Space Exploration, 2008). Scatter results from differences in altitude, orbital inclination, vehicle orientation and shielding, position within the vehicle, and position within the solar cycle and variations in solar activity.

per nucleon); temporal variations in flux not well known but highest at solar maximum; reduction provided by shielding of at least 10 g/cm^2 aluminum-equivalent, provided by most spacecraft hull designs, and

- galactic cosmic radiation — high-energy protons, alpha, electrons, neutrons, muons and larger nuclei (million electron volts to billion electron volts per nucleon); steady flux varying during the 11-year solar cycle roughly by a factor of 2; shielding ineffective because of high energies, but materials development must consider the induced secondary radiation, that is, more use of low atomic number materials such as graphite.

Like environments on Earth, ^{40}K internal to the body and radioactive constituents in food contributes about 70 mrem/yr (0.7 mSv/yr) of background radiation. The NASA dose records for astronauts have been very detailed and are presented in Figure 6.

Astronaut doses in all missions have never exceeded 10 rem/yr (0.1 Sv/yr) (Cucinotta et al., 2005; and National Research Council, Committee on the Evaluation of Radiation Shielding for Space Exploration, 2008). According to studies by the Canadian Space Agency (2010), average doses to astronauts are approximately 5.4 rem/yr (0.054 Sv/yr), about 20 times higher than Earth average, similar to Earth radiation worker dose limits, but missions are never long enough to approach this limit.

Health Risks of Chronic Radiation Doses in Space:

The Linear No-threshold Dose Hypothesis

The need to revise our operational radiation dose limits for working and living in space stems from human health considerations, resource and weight limitations in space, and costs. Invalid limitations on low doses will unnecessarily prevent most moderate to long duration activities in space or necessitate costly and unreasonable shielding requirements and materials.

As previously described, unshielded radiation exposures in extraterrestrial environments will be chronic doses on the order of 5 rem/yr (0.05 Sv/yr). The existing regulatory framework for radiation safety is based on current ionizing radiation protection standards established by the United States Environmental Protection Agency (EPA). The EPA set these standards decades ago using a linear extrapolation of World War II atomic bomb survivor data that is referred to as the linear no-threshold dose hypothesis (LNT). According to the LNT (National Research Council, 2006), any and all radiation doses, even background and below, are harmful; that is, they increase the risk of cancer and other radiation-induced health effects. The LNT was formulated by extrapolation of exposures of acute high doses at high-dose rates to regions of low doses from chronic exposure at low-dose rates (Figure 7) using mostly Japanese atomic bomb survivors and accidents such as Chernobyl (Castronovo, 1999; International Atomic Energy Agency, 2004; World Nuclear Association, 2009). However, little scientific data currently exist to verify this extrapolation below 5 to 10 rem/yr (0.05 – 0.1 Sv/yr), and a large amount of data exists that refute it (Hiserodt 2005; World Nuclear Association 2009).

The LNT does not distinguish between high dose (>10 rem) and low dose (<10 rem) or between acute (high-dose rates, >10 rem/yr) and chronic (low or continuous dose rates, <10 rem/yr), and it is this difference between acute and chronic that is the primary disconnect between LNT and existing data from chronic low doses and that has large ramifications for space exploration. Another potential problem with the LNT is the incorrect assumption that cytogenic and mutagenic effects at the individual cellular level linearly extrapolate to the organismal level, that is, that no extracellular immunological mechanisms address cell damage and death (Jaworowski, 1999; National Council on Radiation Protection and Measurements, 2001; Mitchel, 2002; National Research Council, 2006).

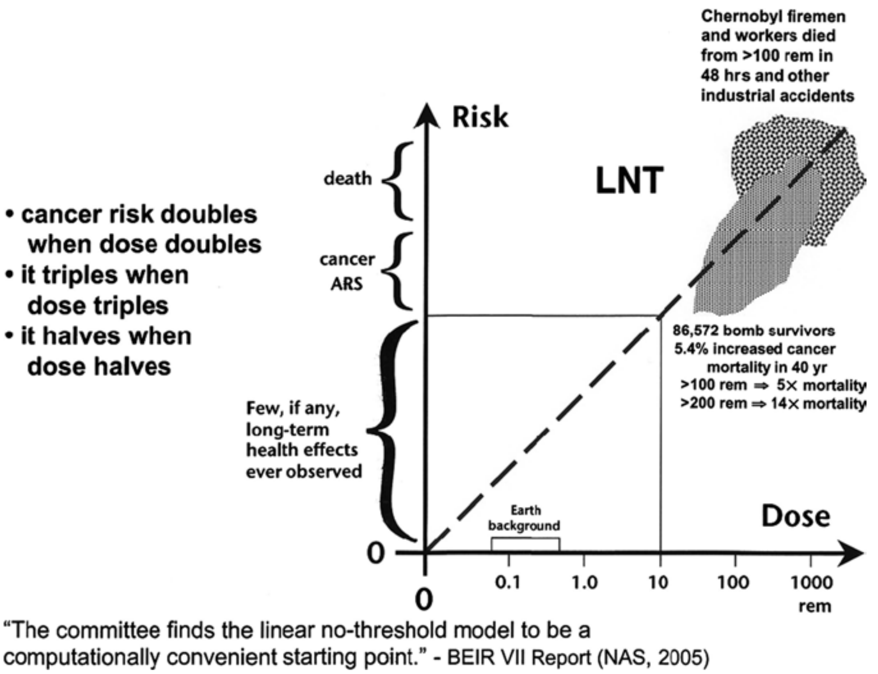

FIGURE 7. Linear no-threshold dose hypothesis (LNT). In this scenario, even the smallest amounts of radiation are harmful. NAS = National Academy of Sciences; ARS = advanced radiation sickness.

Acute Versus Chronic Dose

Acute high doses derive from incidents such as an atomic bomb detonation, high activity accidents or unintentional exposures, and high-dose medical treatments. Chronic low doses derive from continuous environmental or nearby sources such as background, industrial sources, radioactive waste, radiologically contaminated soil and water, or unusual environments such as outer space, and in the many high-radiation level hot springs and "healing" waters that occur in France, Austria, Japan, and Germany and are commonly used as health spas.

The difficulty in addressing this issue by obtaining scientific data below chronic doses of 10 rem/yr (0.1 Sv/yr) is that these levels are within the range of naturally occurring background. Studies conducted using small doses of ionizing radiation do not indicate that rates of cancer incidence increase (Jaworowski, 1999; Mitchel, 2002; Hiserodt, 2005). Lack of an observable increase, however, does not preclude the possibility of an unobservable effect. For example, solid tumors and leukemia have a high spontaneous incidence that varies according to lifestyle and heredity. Because the possible increase in cancer incidence following radiation exposure is very low, large study populations are required to demonstrate statistically significant results. Unfortunately, in any population, confounding factors caused by genetic and random variations mask possible effects of low levels of ionizing radiation. Consequently, epidemiological studies may not detect a small effect of low levels of ionizing radiation because of lack of statistical power, even if it exists.

Assessing Chronic Dose Effects

The ultimate chronic radiation source for all humans is background radiation. Therefore, to address the effects of chronic background levels in space, it is essential to review the relationship of variations in chronic background radiation with cancer and mortality in sufficiently large population cohorts across the Earth, under unusual conditions, from accidental or intentional exposures, and during long periods where such conditions exist.

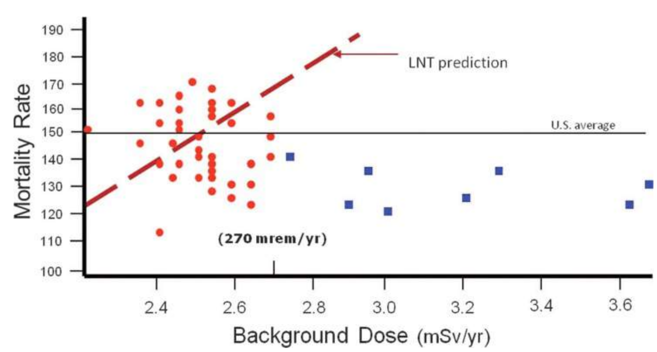

FIGURE 8. Background radiation differences on annual cancer mortality rates/100,000 for each state in the United States (U.S.) during a 17-yr period. Adapted from Frigerio and Stowe (1976), with correction for dose using more recent background data from radon. LNT = linear no-threshold dose hypothesis; mrem = millirem.

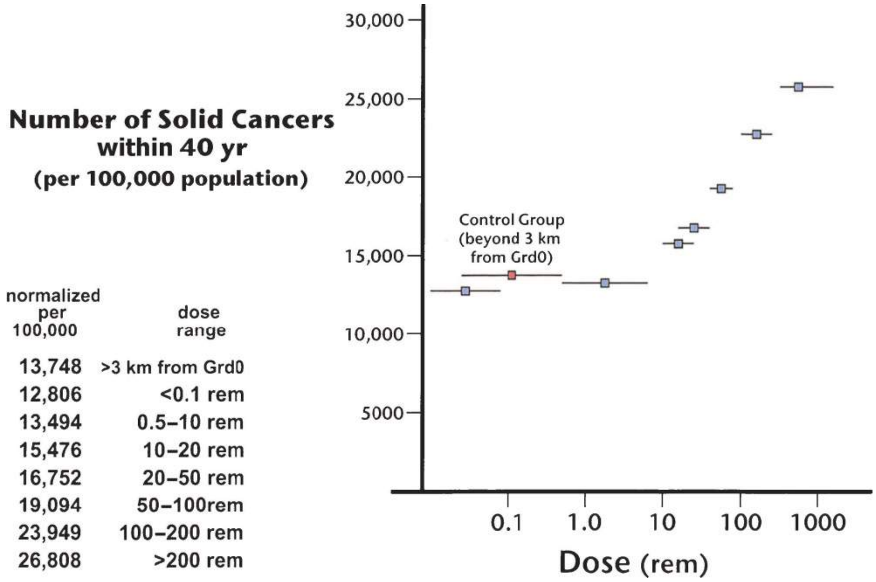

FIGURE 9. Solid cancers per 100,000 population in the atomic bomb survivor cohort of 79,901 subjects. Data from International Commission on Radiological Protection (1994). Grd0 = Grid 0,0,0.

Figure 8 illustrates the variation of cancer mortality rates as a function of background radiation for each state in the United States, showing not an increase in rates with dose as predicted by LNT, but a substantial decrease. Blue squares are those states with background doses more than 270 mrem/yr (2.7 mSv/yr) and whose cancer rates should be significantly higher. This relationship is observed in studies throughout the world: nowhere is increased background radiation associated with increased cancer rates, mortality, or other health issues. In fact, increased background radiation is almost always coupled with decreased cancer rates and mortality (Hiserodt, 2005). This suggests that other factors are more important to human health than chronic radiation doses below 10 rem/yr (<0.1 Sv/yr).

Even looking at more acute dose effects, there appears to be a threshold at about 10 rem. Figure 9 shows the number of solid cancers per 100,000 population in the atomic bomb survivor cohort of 79,901 subjects (data from International Commission on Radiological Protection, 1994, normalized to 100,000 population).

A fairly strong relationship exists between dose and cancer occurrence at high doses, but the relationship disappears below 10 rem. These observations, taken together with the fact that there has not been a single death in more than 20 years in the civilian nuclear industry in the United States, suggest that the risk associated with chronic low doses of radiation less than 10 rem/yr (0.1 Sv/yr) appear to be small with respect to any other risk associated with normal living and working activeities, certainly in an extraterrestrial environment.

Therefore, we propose here that risk from chronic low doses of radiation anticipated during operations in space and under extraterrestrial conditions be based on a threshold dose of between 5 and 10 rem/yr (0.05-0.1 Sv/yr) (Figure 10). It is anticipated that keeping radiation exposures to astronauts, space workers, and colonists below 10 rem/yr will not add significant additional risk to human health and should be achievable without prohibitive costs, material requirements, or procedures.

However, adopting a no-threshold model or choosing a threshold, whether it is about 10 rem/yr (0.1 Sv/yr) or some other value, still appears to be based at present on anecdotal evidence, the reports from NCRP and others notwithstanding. It is imperative that this issue be studied in greater depth with respect to actual human health effects as soon as possible because it will continue to affect Earth-based radiological issues, such as nuclear medicine, nuclear power and disposal and/or cleanup of radioactive waste, as well as space-based activities. However, we can use the information we have to make some recommendations.

Shielding Against Radiation in Space

In space, the lack of indigenous materials makes shielding more problematic, and shielding alone cannot guarantee protection in all situations because of the very high energies of the incident ions and the production of highly penetrating secondary particles, such as neutrons and light ions, coupled with mass constraints on the spacecraft. For operations within Earth's geomagnetic field, little or no supplemental shielding is needed to ensure astronaut safety in a spacecraft or habitat.

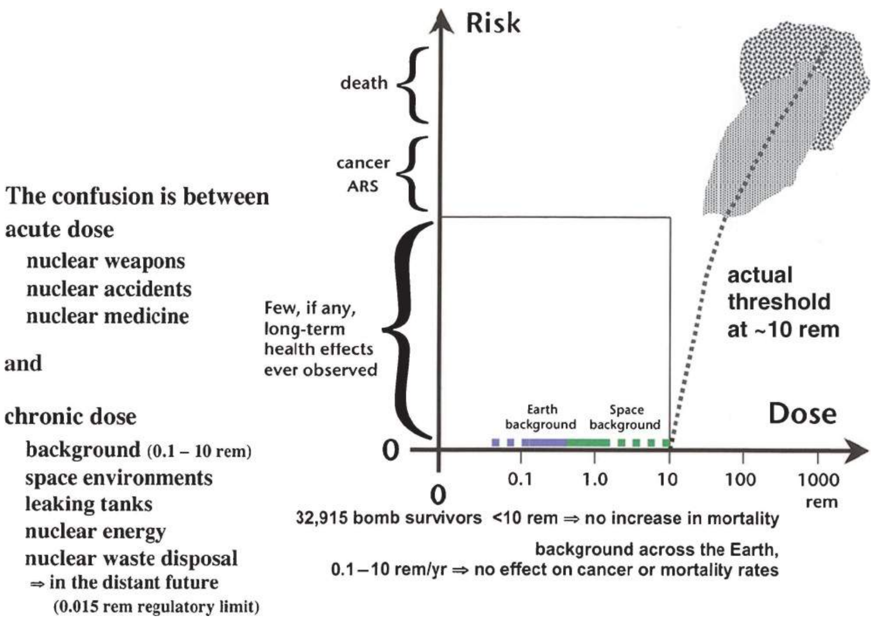

FIGURE 10. Proposed threshold dose of about 10 rem/yr. In this scenario, small amounts of radiation are not harmful. ARS = advanced radiation sickness.

However, on leaving this protective geomagnetic shield, the astronauts are subjected fully to the natural galactic cosmic radiation environment and susceptible to serious radiation fluxes from solar particle events.

Shielding requirements differ among the different environments and missions that will be faced in future space activities. For short missions to solid bodies, the spaceflight can be met with existing spacecraft designs because most of the time spent by personnel will be on the surface of a body such as the Moon or Mars, where existing geologic materials can be used to construct shielding, such as basaltic rocks of the lunar maria, especially those rich in ilmenite. Even regolith can be used as inexpensive abundant shielding material. The key element to indigenous materials is their abundance; they can be made as thick as necessary.

In space, however, a complete dependence on materials within the payload exists. Traditional space-vehicle materials have been developed primarily as a result of engineering and performance requirements, for example, density, strength, longevity, weight, machining and construction properties, and so on. The short durations of previous missions have not necessitated the development of new materials designed expressly for radiation shielding. However, new materials are being developed for other applications that may be ideal for this purpose. The most promising materials are hydrocarbon based, such as high-density polyethylene, or graphite nanofiber, a material designed for lightweight construction and clothing materials (National Geographic News, 2010). Carbon and hydrocarbon-based materials are best at radiation shielding because of their average low atomic number.

An excellent recent discussion of shielding (and space radiation effects in general) comes from the National Academy of Sciences (NAS) (National Research Council, Committee on the Evaluation of Radiation Shielding for Space Exploration, 2008). The recommendations of the NAS report are essentially to continue implementing the permissible exposure limits specified in current NASA radiation protection standards and not compromise them simply to meet engineering, funding, or resource targets. These standards vary with mission length, age, and sex, but as an example, a 30-year-old male spending 142 days in deep space during his career may not exceed 0.62 Sv total (National Research Council, Committee on the Evaluation of Radiation Shielding for Space Exploration, 2008). An independent radiation safety assessment should continue to be an integral part of mission design and operations, and a limit for radiation risk should be established in go/no-go decisions for every mission (National Research Council, Committee on the Evaluation of Radiation Shielding for Space Exploration, 2008).

The NASA considers that the use of surface habitat and spacecraft structure and components, provisions for emergency radiation shelters, implementation of active and passive dosimetry, careful scheduling of extravehicular operation to avoid excessive radiation exposure, and proper consideration of the ALARA (As Low As Reasonably Achievable) principle are good strategies for the human exploration of the Moon.

However, the LNT concept still dominates the thinking of all radiation safety discussions, although it is refreshing to see it discussed in a more scientific and critical manner with respect to space exploration than in the literature, with respect to historical radiation events on Earth (Health Physics Society, 2001, 2004; National Research Council, Committee on the Evaluation of Radiation Shielding for Space Exploration, 2008). A thorough evaluation of all radiation biological effects, from both observations and experiments, needs to be performed before any long-term space missions are implemented. From previous work presented here, it is expected that the existing ALARA principles followed by NASA, careful scheduling of off-planet missions and extra-vehicular activities, and the use of indigenous materials on other space bodies such as the Moon and Mars for additional shielding, will be adequate to ensure a safe environment for workers and colonists in space.

INTERNATIONAL DEVELOPMENT: THE NUCLEAR GENIE IS OUT OF THE BOTTLE

Although the former Soviet Union/Russian Federation and the United States have conducted extensive space initiatives based on earlier rocket programs beginning as early as the 1920s and 1930s, (in Germany, et al.), other nations have established successful space programs in the past three decades: Australia, Austria, Brazil, Canada, China, Denmark, France, Germany, India, Italy, Japan, Netherlands, Norway, South Korea, Spain, Sweden, Taiwan, Turkey, and Ukraine. The United Kingdom and most of Europe participate in the European Space Agency (ESA).

Many of these countries and groups are monitoring activities, whereas others are participating in United States and Russian programs, sometimes as part of the ESA. Others are doing it alone in conducting or participating in the burgeoning commercial business of launching several communication and surveillance satellites. For example, Europe has been launching cooperative international satellites from Vandenberg Air Force Base in California, from Woomera in South Australia, and Cape Canaveral in Florida, since at least 1968. However, Canada has launched its own satellites from Vandenberg since 1969. Most, if not all, of the cooperative programs launch telecommunication and meteorological satellites into Earth orbit and use solar arrays to power the communications once the satellites are in stable orbits. Nuclear power is not needed in these low-power systems, and the use of RTGs has been minimal.

In other activities, China's space program began in 1959, and its first satellite, Dong Fang Hong-1, was successfully developed and launched on April 24, 1970, making China the fifth country in the world with such capability. By October 2000, China had developed and launched 47 satellites of various types, with a flight success rate of more than 90%. Altogether, four satellite series have been developed by China: recoverable remote sensing satellites; Dongfanghong telecommunications satellites; Fengyun meteorological satellites; and Shijian scientific research and technological experiment satellites. A fifth series includes the Ziyuan Earth resource satellites launched in the past few years. China is the third country in the world to master the technology of satellite recovery, with a success rate reaching an advanced international level, and it is the fifth country capable of independently developing and launching geostationary telecommunications satellites. In October, 2000 Zhuang Fenggan, Vice Chairperson of the China Association of Sciences, declared that one day the Chinese would create a permanent lunar base, with the intention of mining lunar soil for helium-3 (to fuel nuclear fusion plants on Earth) (International Atomic Energy Agency, 2005b).

The forecast for the 21st Century's space activities is that power and propulsion units for advanced space vehicles will be driven by nuclear power. The advantage of nuclear power units is that they are independent of solar power. Thus, near-Earth space vehicles using NPSs do not need batteries either for steady operation or for peak demand. The compact design makes spacecraft operation easier and simplifies the orientation system for highly accurate guidance (International Atomic Energy Agency, 2005b).

RESEARCH AND DEVELOPMENT

Earth-based NPSs were originally designed to be very large installations, giving economies of scale baseload applications. Earth-based nuclear power was originally based on the prospects of reprocessing partially spent fuel and using plutonium-based fuels in Generation IV fast breeder reactors both to minimize waste and to conserve nuclear resources. Although this has not materialized during the past 30 years, the prospects for restarting research into reprocessing spent fuel have improved during the past few years (Campbell et al., 2007). Breeder reactors are once again being evaluated because they have the capability to burn actinides present in partially used fuel, thus generating less waste with lower activity levels, as well as producing more fuel than they use, hence the name breeder reactor.

Space nuclear power, however, is characterized by the need for small lightweight systems that are independent of gravity and have heat transfer systems that support both direct and indirect conversion. In addition, they must operate in hostile environments, achieve a very high degree of robustness and reliability, and, in some applications, operate with high efficiencies. This research and development can also be the basis for innovative nuclear reactor and fuel cycle developments for different terrestrial missions on planets, moons, and asteroids.

An example of the relevance of such research and development for innovative Earth-based concepts can be found in the development of materials resistant to high flux of radiation and temperature. Improved, more reliable and innovative heat transport and reoval systems are other areas where common research and development objectives exist. In particular, advances in space nuclear systems can apply to small and/or remote Earth-based applications, provide for more reliable heat-transfer systems, and open the door to the use of plasma or ionic conversion systems. Another research and development area having considerable synergy potential is energy production. Advanced cycles for energy production and alternative energy products (such as hydrogen) are good examples. Commonalities are also found in the need to enhance reliability for concepts with long lifetimes and/or for use in hostile environments (e.g., deep water and subarctic/arctic and other remote locations).

Recent industry-sponsored research in the United States by Purdue University nuclear engineers has demonstrated that an advanced uranium oxide-beryllium oxide (UO_2-BeO) nuclear fuel could potentially save billions of dollars annually by lasting longer and burning more efficiently than conventional nuclear fuels. However, if confirmed, this will increase the demand for beryllium (Be) and beryllium oxide (BeO). An advanced UO_2-BeO nuclear fuel could also significantly contribute to the operational safety of both current and future nuclear reactors on Earth and in space because of its superior thermal conductivity and associated decrease in risks of overheating or meltdown (see IBC Advanced Alloys, 2010).

Along with their main purpose of space exploration, many of the advanced technologies have Earth-based applications because they are or can be used for the fabrication of products, equipment, and substances for different markets. The following examples are areas of Earth-based technology that have benefited, or could easily benefit, from work done by NASA in the United States and by the Kurchatov Institute in the Russian Federation. Also, the International Atomic Energy Agency (2007b) supports the development of nonelectric applications of nuclear power used in seawater desalination, hydrogen production, and other industrial applications.

Small Earth-based Nuclear Power Systems

The development of small automatic modular NPSs having power outputs in the 10 to 100 kW range could find new Earth-based applications. District heating, power for remote applications such as for installations under water, remote habitation, and geologic exploration and mining are candidates for such power systems (see the Earth-based Spin-off from Space Research section, later in this chapter).

Direct Conversion Systems

The RTGs were used 25 years ago for lighting at remote lighthouses, but more applications await these semipermanent batteries. Although not currently on the market, the use of RTGs in small industries and even in electric cars and the home has the potential of reducing reliance on natural gas and oil. A reliable, long-lived, maintenance-free 10 kW source of electricity for the home is foreseeable within the next 20 years or so. An initial high price could be amortized within a few years to be comparable to electricity prices available on the national grid.

PROBLEMS TO BE SOLVED

NASA, the Russian Aviation and Space Agency (called MINATOM), ESA, and others have defined a list of long-term space problems, the solutions to which will require higher power levels than those currently available. Listed below are some of the most important initiatives to be taken in space with respect to nuclear power in the 21st Century:

1) Development of a new generation of international systems for communication, television broadcasting, navigation, remote sensing, exploration for resources, ecological monitoring and forecasting of natural geologic events on Earth;
2) Production of special materials in space;
3) Establishment of a manned station on the Moon and development of a lunar NPS for industry-scale mining of lunar resources;

4) Launch of manned missions to the Moon, Mars, and to the other planets and their satellites;
5) Transportation to Earth of thermonuclear fuel - thorium, helium-3 isotope, and so on, if merited;
6) Removal of radioactive waste that is not in deep underground storage for storage in space;
7) Clearing of refuse (space satellites and their fragments) from space to reduce potential orbital hazards;
8) Protection of Earth from potentially dangerous asteroids and other near-Earth asteroids (NEAs); and
9) Restoration of Earth's ozone layer, adjustment of carbon dioxide levels, and so on.

OFF-WORLD MINING

In the future, space NPSs and combined nuclear power and/or propulsion systems (NPPSs) with an electrical power level of several hundred kilowatts will make possible and enable long-term space missions for global environmental monitoring, mining-production facilities in space, supply of power for lunar and Martian missions, and even Earth (see Ambrose, Chapter 1, this text). Future missions will include systematically evaluating planetary bodies and the asteroid belt for minerals of interest, such as uranium and thorium, nickel, cobalt, rare-earth compounds, and a list of other minerals now in short supply on Earth (see Haxel et al., 2002 on the need for rare-earth commodities). The need for developing natural resources from off-world locations has become a common topic of discussion by selected economics scholars; for example, see Tilton (2002), Simpson et al. (2005), Ragnarsdottir (2008).

Interest in the industrialization of space began many years ago. One of the first professional geologists in the U.S. to state the necessity of going into space was Phil Shockey (1959), former chief geologist for Teton Exploration in the late 1960s and a former coworker of the senior author and Ruffin I. Rackley; the latter of which is a special consultant and founding member of Energy Minerals Division's Uranium (Nuclear Minerals) Committee. The need continues to draw supporters (Lewis, 1997).

Aside from the orbital activities presently focused on the International Space Station, geologic exploration began in the 1960s with the Apollo missions. Only one geologist (Harrison (Jack) Schmitt, see Chapter 2, this text) has walked on the Moon to date to evaluate first-hand and sample the rocks and the regolith and, along with other nongeologists,, albeit engineers and other scientists, brought back thousands of pounds of samples for further study by geoscientists on Earth (Figure 11).

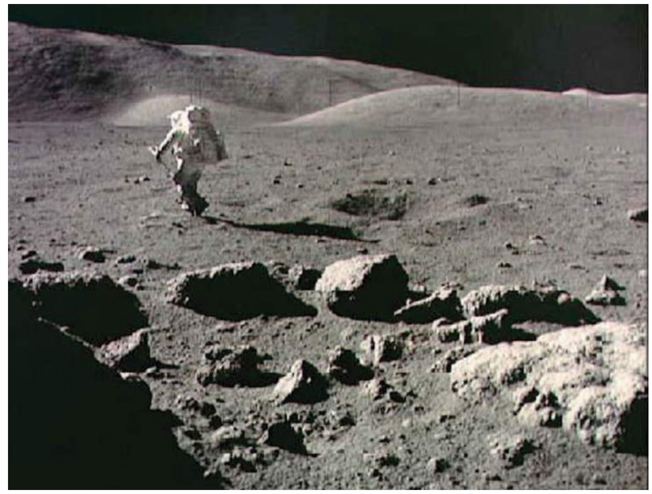

FIGURE 11. The only geologist on the Moon to date, Harrison Schmitt, Apollo 17 (1972). Photograph courtesy of the National Aeronautics and Space Administration.

The recent Mars Phoenix investigations are sampling the regolith of Mars by remote-controlled geologic probes. Earlier ground studies by the rovers Spirit and Opportunity also involved rock sampling and evaluations designed to determine the minerals present below the desert varnish covering the rock outcrops after millions, if not billions, of years of exposure to erosional impact by local wind, solar radiation, solar wind, and perhaps erosion by water during the early wet period of Mars's geologic history. These are the first steps in mineral evaluation, whether it is on Earth, the Moon, Saturn's largest moon, Titan, or now on Mars. They all involve reconaissance and preliminary sampling accompanied by detailed photographs of the rocks being sampled. Such investigations that were conducted during the bold days on the Moon in the late 1960s and early 1970s have now begun on Mars (Karunatillake et al., 2008).

Although Moon exploration activities were conducted by only one geologist and other nongeologists, exploration of Mars and the other planets are being performed by probes guided by geologists and engineers on Earth but designed to do the same as if geologists were present on Mars or in other hostile locations. The visit to Saturn and its largest moon, Titan, by Cassini and its probe Huygens suggested that Titan is relatively level (<50 m [<164 ft] in elevation), that it may have extensive hydrocarbon lakes, and that ice is present (see Curchin and Clark, Chapter 6, this text, for remote sensing of hydrocarbons on Titan). Probes such as these are clearly useful for laying the groundwork for future exploration. Europa, one of Jupiter's moons, will be visited one day, as will most of the others if justified.

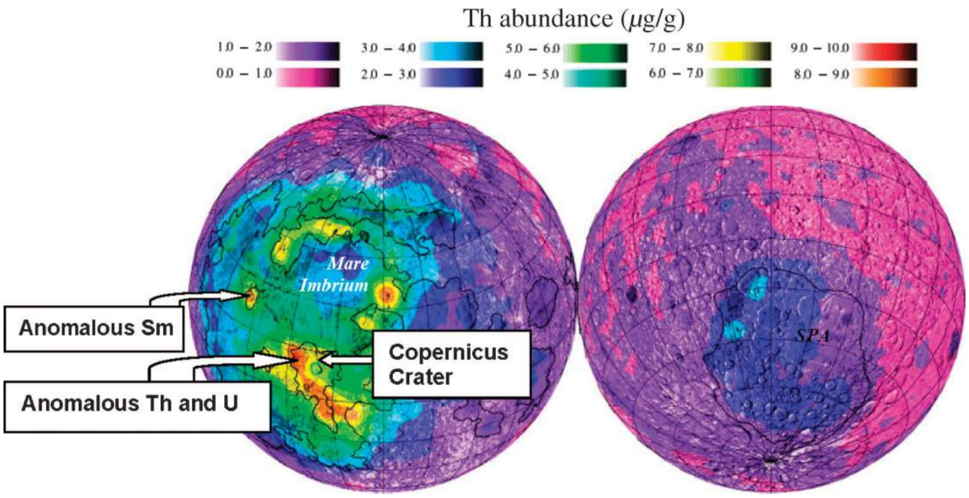

FIGURE 12. Inferred thorium (Th) abundance on a two-hemisphere map projection. Data for Th and samarium (Sm) are from Elphic et al. (2000), and data for uranium (U) and Th are from Yamashita et al. (2009).

All such deep space activities assume that sufficient power will be available. This is evident in a series of industrial planning articles (in the form of extended abstracts) wherein no mention is made of the power requirements for heavy-industry mining on asteroids (Westfall et al., ND). Fortunately, given sufficient fuel, nuclear power systems appear to be ready to provide the power required.

The Debate on a Lunar or Mars Base

The first exploration and mining targets will probably be the Moon or Mars because of their proximity to Earth. Albert Juhasz (2006, p. 1) of NASA suggested that

> ''. . .lunar bases and colonies would be strategic assets for development and testing of space technologies required for further exploration and colonization of favorable places in the solar system, such as Mars and elsewhere. Specifically, the establishment of lunar mining, smelting, and manufacturing operations for the production of oxygen, helium-3, and metals from the high-grade ores (breccias) of asteroid impact sites in the highland regions would result in extraordinary economic benefits for a cis-lunar economy that may very likely exceed expectations. For example, projections based on lunar soil analyses show that average metal content mass percentage values for the highland regions are Al, 13%; Mg, 5.5%; Ca, 10%; and Fe, 6%. The iron content of the Maria soil has been shown to reach 15% (Eckart, 1999).''

Once target areas on the Moon and on selected asteroids have been identified, geologic exploration can begin in earnest. The Lunar Prospector was launched in 1998, the first NASA-supported lunar mission in 25 years. The main goal of the Lunar Prospector mission was to map the surface abundances of a series of key elements such as hydrogen, uranium, thorium, potassium, oxygen, silicon, magnesium, iron, titanium, aluminum, and calcium, with special emphasis on the detection of polar water-ice deposits (Hiesinger and Head, 2006). Recently, even evidence of significant water has been reported in some lunar volcanic glasses (Saal et al., 2007). Recent exploration on the Moon has confirmed the presence of water ice in the craters at the lunar poles, which will likely one day provide hydrogen and oxygen for fuel and for operating on the Moon (see Ambrose, Chapter 1, this text). High-quality photographic coverage and advanced planning for returning to the Moon are increasing almost daily; see National Aeronautics and Space Administration (2009b) and Google Moon (2008). For a summary of all lunar missions by all countries, see National Aeronautics and Space Administration (2009b).

Target selection will depend on the preliminary assessment of the economics of mining on the Moon and asteroids. This will include assessments of exploration costs, the methods used, that is, remote sensing in proximity to selected targets, aerial topographic surveys, and then later, visits by geologists or probes to obtain rock samples. If favorable results suggest a deposit of possible economic interest, drilling would be conducted to determine ore grades and minimum tonnage of the deposit. Once the average ore grade and tonnage (of the thorium, nickel, cobalt, or other deposits) have been established, a mineability study will be undertaken, and the results compared with the competing resources available on Earth. The volume of the orebody, the ore grade of the deposit, and the cost to make concentrates on site, plus overhead and supporting costs, will determine whether off-world mining of the deposit is justified. This economic assessment would be completed before funding is committed to the project, just as practiced in projects on Earth.

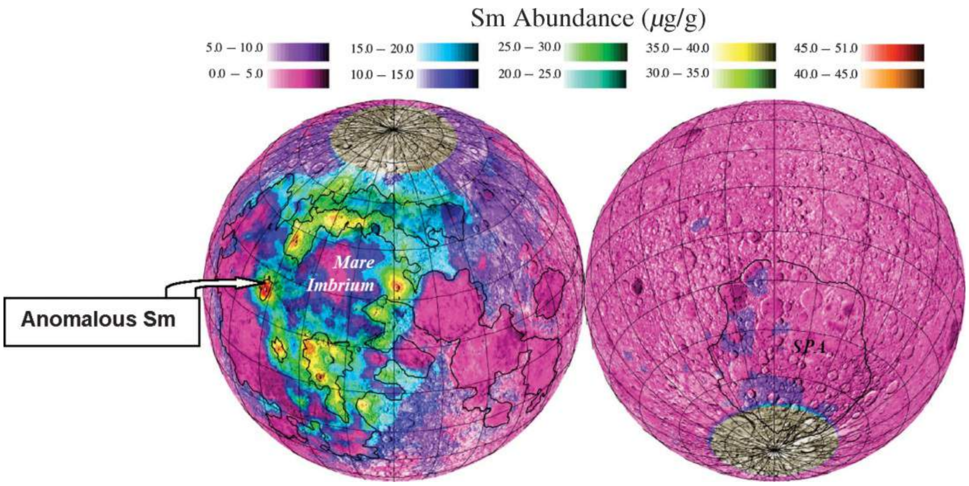

FIGURE 13. Inferred Samarium (Sm) concentrations in the Imbrium/Procellarum regions. Modified from Elphic et al. (2000).

Any preliminary study on the economics of mining on the Moon for a particular suite of commodities available in the regolith has to conclude that the unit costs would be substantially below the costs of competitive operations on Earth. Thorium and samarium (and maybe additional rare-earth elements because they commonly occur together) have been located in what appears to be anomalous concentrations in the regolith around the Mare Imbrium region (Figures 12, 13).

Other constituents of interest as well may drive the economics to justify a permanent base on the Moon. Based on the lunar sampling to date, the following elements have been reported in significant concentrations: aluminum, copper, cobalt, chromium, gallium, germanium, thorium, tin, tungsten, rhenium, iridium, gold, silver, polonium, osmium, praseodymium, cadmium, and others — some of the building blocks of human civilization (Lawrence et al., 1998, 1999; Taylor, 2004; Meyer, ND, for an inventory of some of the constituents reported from lunar sampling to date).

These constituents can be anticipated on other moons and asteroids as well, as indicated from lunar sampling during the 1960s and their presence in meteorites analyzed on Earth. The work conducted on the lunar samples and on meteorites collected over the years has formed a sound foundation on what may be expected in space (Zanda and Rotaru, 2001; Norton, 2002).

Elphic et al. (2000) report that the high thorium and samarium concentrations are associated with several impact craters surrounding the Mare Imbrium region and with some features of the Apennine Bench and the Fra Mauro region. Remnants of meteorites impacting the Moon are evident by the detection of high concentrations in the regolith of nickel, cobalt, iridium, gold, and other highly siderophile elements (Korotev, 1987; Hiesinger and Head, 2006; Huber and Warren, 2008). As anomalous sites, these areas would be followed up with detailed sampling.

These sites would be candidates for follow-up for the next mission to the Moon to confirm the occurrences. The anomalies should be considered as indications that higher concentrations may be present in the area, likely associated with impact craters (Surkov and Fedoseyev, 1978). The availability of the thorium (and samarium) in the rock or regolith, combined with the concentration of these constituents, is a primary indicator in any assessment of the constituents for possible development by the mining industry (Spudis, 2008).

The associated costs for infrastructure, mining, processing, personnel, and transportation will determine if and when such a project of this magnitude would receive funding from the mining industry and from several governments. The anomalies appear to occur over large areas, and if available from within the lunar regolith, mining of fine-grained material removes the need to crush the raw ore to produce concentrates on the Moon. This would improve the economics of such a venture. Because thorium will be in great demand to fuel uranium- and/or thorium-based nuclear reactors on Earth and in space, this discovery is of major importance (International Atomic Energy Agency, 2005c).

To conduct exploration on the Moon, Mars, or other body, there must be sufficient mapping of the body to provide the basic geologic relationships and structural relationships and features that can be accessed from aerial photography and other aerial geophysical and remote sensing techniques. This provides a way to establish priorities for subsequent surface investigations and sampling. Skinner and Gaddis (2008) discuss the progression of geologic mapping on the Moon. The quality and detail of such maps are illustrated in Figure 14 (USGS, 1962 –1982).

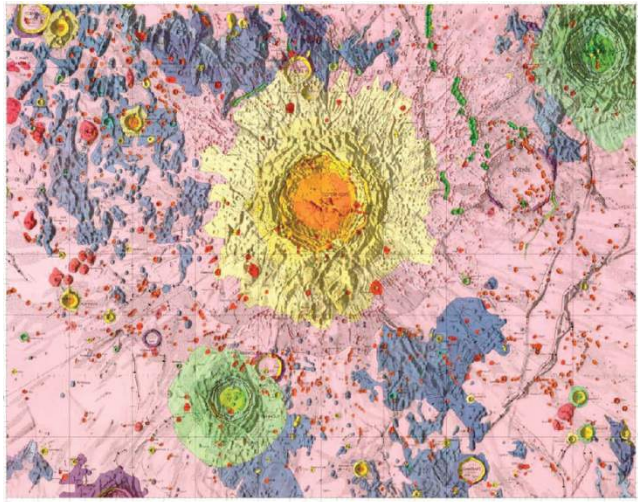

FIGURE 14. Copernicus Quadrangle. From USGS (1962 – 1982).

Vast areas will need to be explored on the Moon and Mars, and reliable transportation for field investigation and sampling will be required (Elphic et al., 2008) in exploring for strategic commodities, such as nickel, cobalt, rare-earth minerals, or for nuclear fuels, whether uranium or thorium. Recent results from the exploration underway using the Selene gamma-ray system on the Moon indicate that anomalous uranium, thorium, and iron (which infers the above strategic commodities as well) appear to be concentrated in Procellarum KREEP Terrain and South Pole Aitken Basin, although they appear to be depleted in the Lunar Highlands (Gasnault et al., 2009; Yamashita et al., 2009; Gasnault, O., 2009; and Ambrose, Chapter 1, this text; and Ambrose, W.A., et al., 2012; and Cutright, Chapter 4, this text, for further information on asteroids).

Any discovery of off-world uranium and thorium in potentially economic concentrations could have a major impact on nuclear power development on Earth and accelerate lunar exploration. This may well result in a new space race among international interests to develop mineral resources on the Moon (Campbell and Ambrose, 2010). Uranium deposits found on Earth that may have analogs on the Moon are likely those found in Canada and northern Australia (Jefferson et al., 2007). The orebody tonnage and associated ore grade will need to be higher than those found on Earth before economic advantages are likely to justify off-world development (Figure 15).

Today, uranium is the only fuel used in nuclear reactors. However, thorium can also be used as a fuel for Canada's deuterium uranium (CANDUR) reactors or in reactors specially designed for this purpose (World Nuclear Association, 2008a). The CANDU reactor was designed by Atomic Energy of Canada, Limited. All CANDU models are pressurized heavy-water cooled reactors. Neutron efficient reactors, such as CANDU, are capable of operating on a high-temperature thorium fuel cycle once they are started using a fissile material such as U^{235} or Pu^{239}. Once started, the thorium (Th^{232}) atom captures a neutron to become fissile uranium (U^{233}), which continues the reaction. Some advanced reactor designs are likely to be able to make use of thorium on a substantial scale (International Atomic Energy Agency, 2005c). In October 2008, Senator Orrin Hatch, Republican from the state of Utah, and Harry Reid, Democrat from the state of Nevada, introduced legislation that would provide US $250 million within five years to spur the development of thorium reactors. The RTG research also has progressed (Bennett et al., 2006) and is expected to continue.

The thorium fuel cycle has some attractive features, although it is not yet in commercial use (World Nuclear Association, 2008b). Thorium is reported to be about three times as abundant in Earth's crust as uranium. The IAEA-NEA Red Book gives a figure of 4.4 million tons of thorium reserves and additional resources available on Earth but points out that this excludes data from much of the world (International Atomic Energy Agency, 2007a). These also exclude potential thorium resources on the Moon, which can only be evaluated, of course, by lunar sampling. Early reports are encouraging that thorium may be present on the Moon; this assumes certain assumptions regarding the costs to mine on the Moon (Metzger et al., 1977). Multi-recovery operations combining high-demand samarium with other commodities of interest further enhance the economics of any future operations on the Moon (Figure 16).

In conducting exploration on the Moon, Mars, or asteroids, safety considerations have a major function in the design and cost of extraterrestrial facilities built in such remote locations. Protection from bullet-like micrometeors and from coronal mass ejections from the Sun requires the construction of protected facilities, either underground or on the surface. In the case of the Moon, the regolith and underlying volcanics in most locations would be easier to excavate than the hard rocks of the metallic asteroids would allow (Gasnault and Lawrence, 2001; Clark and Killen, 2003). Some asteroids are composed of an agglomeration of space rubble, primal ice, and other materials that would likely be low on the list of targets for containing useful commodities, aside from water, although even this may be more widespread than previously thought.

During the past ten years, helium-3 has received considerable attention for its potential to produce significant fusion energy.

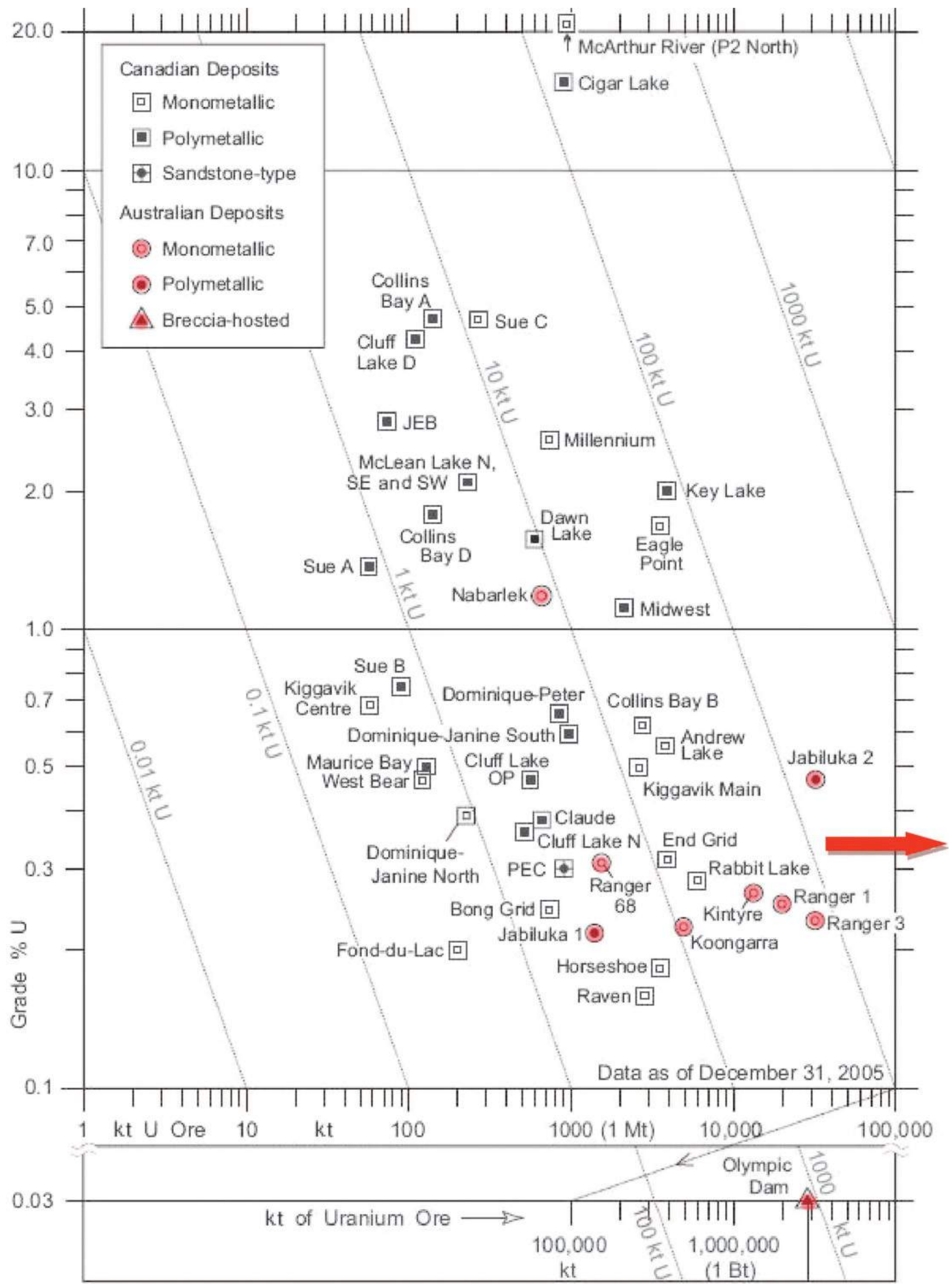

FIGURE 15. Major Canadian and Australian uranium deposits, tonnage, and ore grade. Modified from Jefferson et al. (2007). Kt = kilotonnes; Bt = billion tonnes; Mt = million tonnes; JEB = JEB mine; OP = OP mine; PEC = PEC prospect; A = Allan Fault; C = Carswell; D = Douglas; N = Narakay volcanic complex (or D = Dufferin Fault); P2 = P2 Fault at McArthur River.

Helium-3, a gas, is apparently present in substantial concentrations trapped within certain minerals present in the lunar regolith having accumulated after billions of years of bombardment by the solar wind. Helium has two stable isotopes: helium-4, commonly used to fill blimps and balloons, and the even lighter gas helium-3. Lunar helium-3 is a gas embedded as a trace nonradioactive isotope in the lunar soils. Datta and Chakravarty (2008) indicate that helium-3 diffuses from lunar-silicate grains. However, the mineral ilmenite ($FeTiO_3$) that is abundant in certain areas of the Moon retains helium-3. This represents a potential energy source of such scale that it is expected by many energy planners to one day meet Earth's rapidly escalating demand for clean energy, assuming that the present difficulties in maintaining and controlling the fusion process can be overcome.

The resource base of helium-3 present in just the upper 2.7 m (9 ft) of the minable areas of titanium-rich regolith (containing ilmenite) of Mare Tranquillitatis on the Moon (the landing region for Neil Armstrong and Apollo 11 in 1969), for example, has been estimated by Cameron (1992) to be about 22 million pounds (11,000 tons of regolith containing helium-3 gas). The energy equivalent value of helium-3, relative to that of coal, would be about US $2 million/lb. Helium-3 is concentrated within ilmenite minerals of particle sizes smaller than 100 mesh.

FIGURE 16. Conceptual view of Moon base for mining. From Schmitt (2004). Permission to reprint courtesy of Popular Mechanics.

Heating the ore containing ilmenite to temperatures greater than 7008C (12908F) to release the helium-3 gas should not be difficult to achieve in a lunar processing plant. It could then be shipped to Earth or elsewhere or used on the Moon (Cameron, 1992) as conceptualized in Figure 17.

Proponents of turning to helium-3 as an energy source indicate that the fusion process involves the fusion of deuterium (^{2}H) with helium-3, producing a proton and helium-4 (He-4). The products weigh less than the initial components, and the missing mass produces a huge energy output. Capturing this energy at a useful scale is being investigated by many countries on Earth, including China, India, Russia, and others. Although NASA management apparently has been silent on its plans regarding lunar helium-3, NASA laboratories, consultants, and contractors have not. Bonde and Tortorello (2008) summarize work performed by the Fusion Technology Institute at the University of Wisconsin-Madison regarding the value of the lunar helium-3 resources. The advantages of using helium-3 are these:

- Helium-3 produces charged ions instead of high-energy neutrons, so less damage occurs to the containment vessel.
- These charged ions, in addition to producing heat, can be manipulated by electric and magnetic fields for direct energy conversion, which is more efficient than thermal conversion.
- Efficiency is estimated to be 60 to 70%.
- Current price estimated at US $40,000/oz.
- 1,100,000 tons or more of helium-3 product is estimated to exist in the Moon's regolith.

Bonde and Tortorello (2008) also cite Chinese science leaders who claim that one of the main objectives of

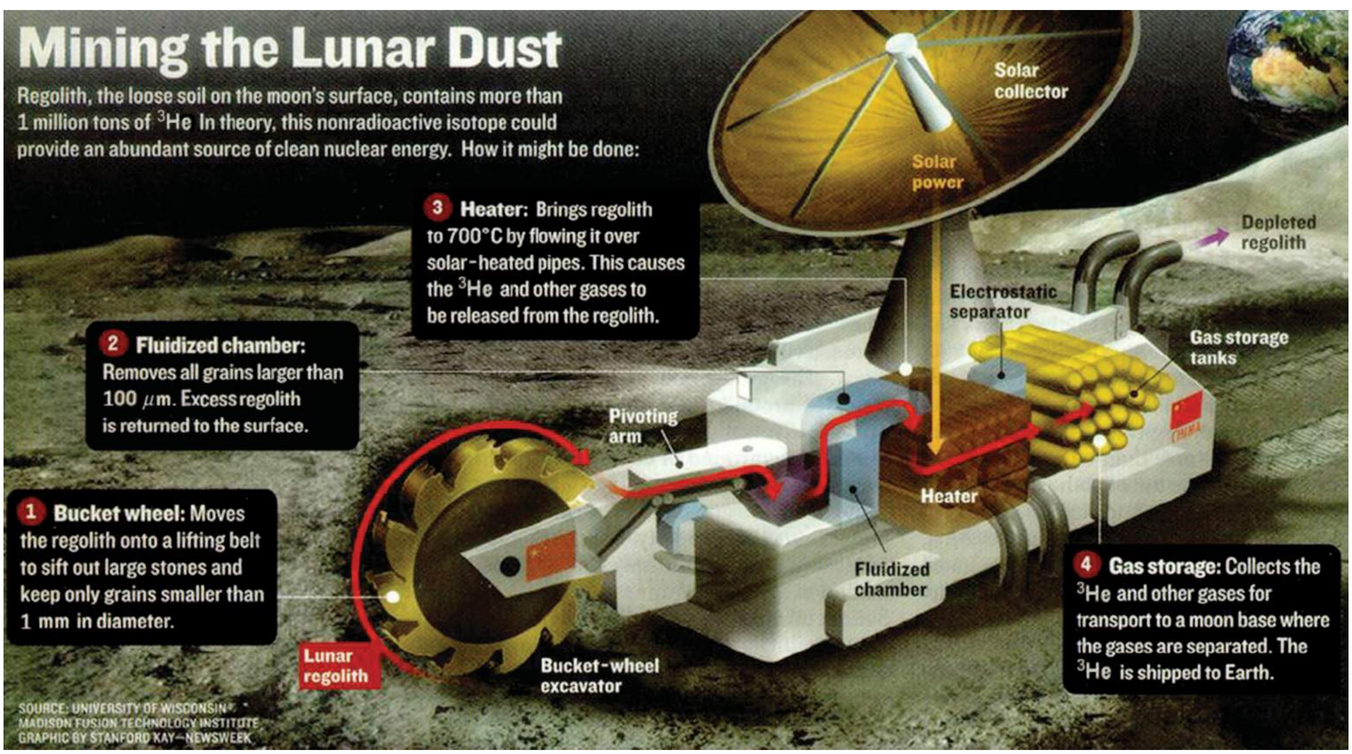

FIGURE 17. Conceptual mobile lunar processing plant for helium-3 (He-3) recovery. From the University of Wisconsin Fusion Technology Institute, Madison, Wisconsin, redrawn by Newsweek New York (2007), printed with permission of Dr. Gerald Kulcinski.

their space program will be to develop the helium-3 resource on the Moon. It is estimated that three space shuttles per year could bring back enough helium-3 to supply all of the world's needs for a year.

The International Atomic Energy Agency (2005b) indicates that personnel from both China and the Russian Federation have reported that the lunar regolith could be mined for helium-3 for use in nuclear fusion power plants on Earth in a few decades. They claim that the use of helium-3 would perhaps make nuclear fusion conditions much easier to attain, removing one of the major obstacles to obtaining fusion conditions in plasma containment reactors for power production on Earth. Schmitt (Chapter 2, this text, and 2006) treats the subject in great detail, from mining on the Moon to energy production (see Livo, 2006). However, Wiley (2008), a 37-year veteran of fusion research and a former senior physicist (retired) at the Fusion Research Center of the University of Texas at Austin, indicates that the higher the temperatures produced in the containment vessel, the more radiation losses occur. Also, confinement problems have yet to be solved, and he does not expect the problems to be resolved for many decades. This is based on the fact that the simplest reaction, deuterium-tritium (D-T), is going to require many more years to harness.

Wiley indicated that the agreement on ITER (International Thermonuclear Experimental Reactor) was signed less than two years before (2008), and problems already exist with both the design and budget (Anonymous, 2008c). It will be at least ten years, and probably much longer, before encouraging results emerge from work at the ITER facility in France. He suggested that the ITER plans do not include a demonstration reactor, which means adding another 20 years to build a demonstration reactor and then another 20 years to build a single power plant. Wiley also indicated that the standard fusion argument is that even if reserves of sea water deuterium were sufficient to fuel an operation for 1,000 years, the tritium has to be retrieved from a breeder reactor, which has not yet been constructed. So, even if helium-3 is readily available, what real value is the resource until the physics problems have been solved and the plants are built to use D-T or helium-3?

In any event, if and when the technology is ready, the resource will be assessed for use and will be available. In the meantime, the Fusion Technology Institute at the University of Wisconsin-Madison continues the research with optimistic schedules; see UWFTI (2008). The group has also been offering a comprehensive academic curriculum on exploration and mining in space under the guidance of Harrison Schmitt, Apollo 17 astronaut and former senator from New Mexico. See Chapter 2, this text.

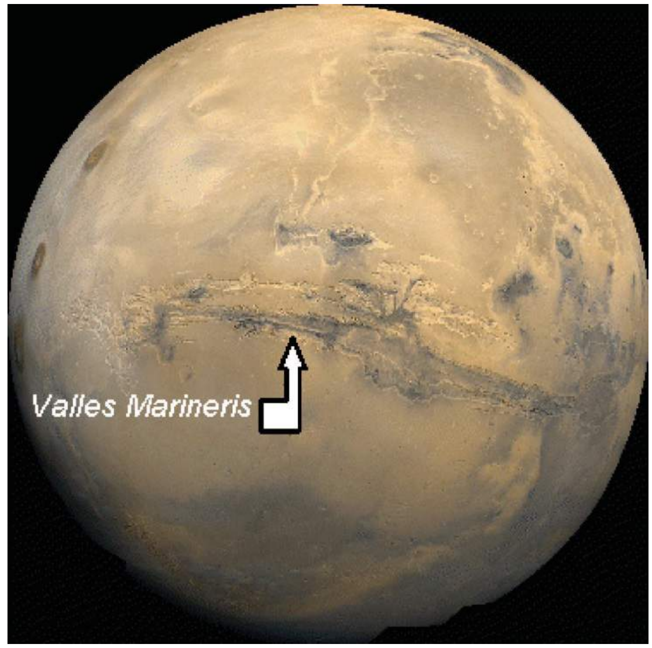

FIGURE 18. One site of geologic interest on Mars. Courtesy of the National Aeronautics and Space Administration.

Other pressing target commodities of opportunity may exist on the Moon and in our solar system, especially within the asteroid belt just beyond Mars. Given other considerations, the Moon is ideal as a training base for operating in low and zero gravity, working out equipment issues and as a staging base for long-term mining and exploration missions. A fixed long-term base on either the Moon or Mars (or any other suitable body) would be powered by NPSs to provide the heavy electrical needs of the base (Mason, 2006a).

Mars is also being considered for establishing a base. Although seeking water (and some form of life) is the present objective (Irwin and Schulze-Makuch, 2001), Mars may also contain useful mineral resources as suggested in early reports on meteorites (McSween, 1994) and by Surkov et al. (1980) and Zolotov et al. (1993), but sampling has been limited to date (Taylor et al., 2006; Karunatillake et al., 2008). Nevertheless, Dohm et al. (2008) report that rifting, magma withdrawal, and tension fracturing have been proposed as possible processes involved in the initiation and development of the Valles Marineris, which is a site of potential economic mineralization (Figure 18).

In addition, amounts of K and/or Th are distinctly higher in the central part of the Valles Marineris than the average amounts in other regions. Dohm et al. (2008) speculate that possible explanations include

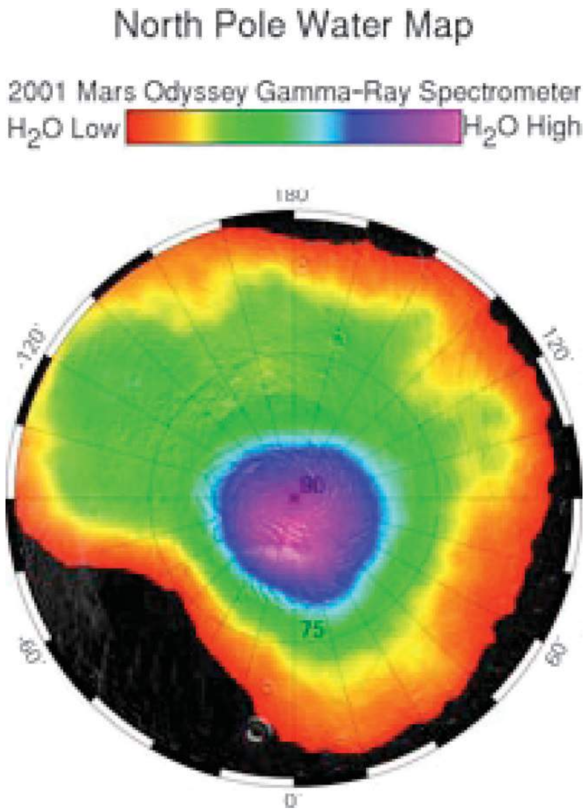

FIGURE 19. Water abundance map in north Polar Regions on Mars. Data are from the Mars Odyssey gamma-ray spectrometer. Courtesy of the National Aeronautics and Space Administration.

(1) water-magma interactions that may have led to the elevated K and/or Th signal in the surface sediments or (2) the lava-flow materials are intrinsically high in K and/or Th and thus emphasize the compositional heterogeneity of the Martian mantle, suggesting that mineral segregations of economic interest may be possible, including radiogenic and metallic minerals.

With the hostile-looking surface environment on Mars, water was not anticipated until recently, with the exception of water ice at or around the poles, (Figure 19). The volume of water available at the Mars North Pole has been estimated at about 100 times that present in the Great Lakes of North America. Water ice has recently also been identified in large volumes at mid-latitudes covered by regolith and debris (Holt et al., 2008). With evidence of water ice also showing up in some crater and valley walls, water will likely be found in the subsurface in the form of groundwater. Risner (1989) addressed the subject in terms of available photographs of the time and in terms of what hydrogeological processes observed on Earth should also apply in general on Mars.

This would be expected to include deep intrusives interacting with the groundwater to form various types of mineralization, some of potentially economic importance. Recently, NASA researchers have reported the presence of methane on Mars (see Max, Johnson, and Clifford, Chapter 5, this text, and National Aeronautics and Space Administration, 2008f). With this development, the Oklo uranium deposit dated at 1.6 b.y. and located in Gabon, Africa, and other older deposits known on Earth also become useful analogs to apply to Mars and other bodies where volcanics, water, and bacteria have produced methane and other gases that also may be present (or may have been present in the past) on Mars and elsewhere. Other deposits present on Earth of Precambrian age should be investigated further as possible additional analogs for various types of mineralization. Volcanism and water seem to be more wide- spread in the solar system than previously considered. To date, in addition to Earth, they have been indicated on Jupiter's moons Io and Europa, Saturn's moon Enceladus, and Neptune's moon Triton. This suggests that mineralization of economic interest also may be common, and nuclear power will be needed to explore in the far reaches of our solar system to develop these resources.

The NASA's Mars Reconnaissance Orbiter has produced some new information that supports the likelihood of mineralization of economic interest to industry. The color coding on the composite image in Figure 20 shows an area about 12 mi (~19 km) wide

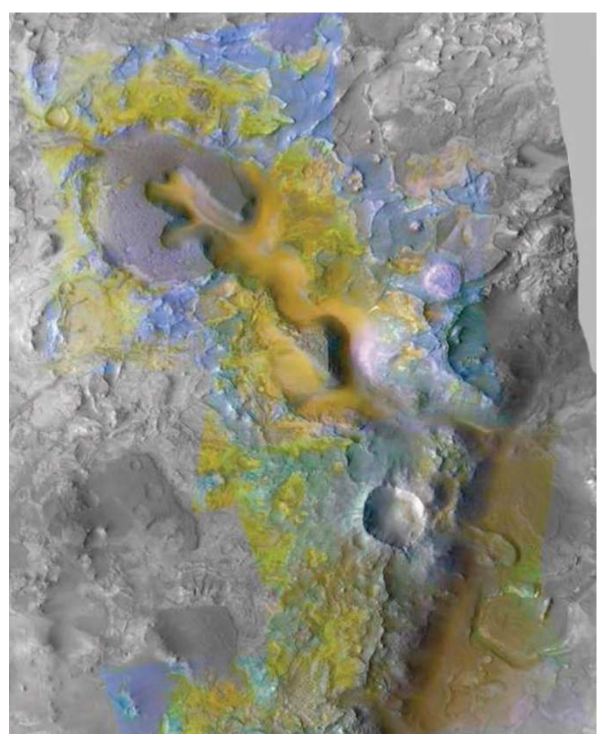

FIGURE 20. Nili Fossae region of Mars. Courtesy of the National Aeronautics and Space Administration.

on Mars and is based on infrared spectral information interpreted by NASA as evidence of various minerals present. Carbonate, which is indicative of a wet and nonacidic geologic history, occurs in very small patches of exposed rock and appears green in this color representation, such as near the lower right corner of the photograph below.

Based on information released by National Aeronautics and Space Administration (2008e), the scene consists of heavily eroded terrain to the west of a small canyon in the Nili Fossae region of Mars. It was one of the first areas where researchers on NASA's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) science team detected carbonate in Mars rocks. The team has reported, ''The uppermost capping rock unit (purple) is underlain successively by banded olivine-bearing rocks (yellow) and rocks bearing iron-magnesium smectite clay (blue). Where the olivine is a greenish hue, it has been partially altered by interaction with water. The carbonate and olivine occupy the same level in the stratigraphy, and it is thought that the carbonate formed by aqueous alteration of olivine. The channel running from upper left to lower right through the image and eroding into the layers of bedrock testifies to the past presence of water in this region. That some of the channels are closely associated with carbonate (lower right) indicates that waters interacting with the carbonate were neutral to alkaline because acidic waters would have dissolved the carbonate.'' The spectral information used in the above figure comes from infrared imaging by CRISM and is available in NASA's report (National Aeronautics and Space Administration, 2008e). High-quality photographic coverage of Mars is increasing almost daily; see National Aeronautics and Space Administration (2009c), Google Mars (2008). For a summary of all Martian missions by all countries, see Planetary and Space Science Centre (2009b).

As human exploration reaches into the outer solar system, travel time and natural hazards will require in-situ resources along the way. Palaszewski (2006) suggests that shielding from radiation can be found among the rocks of the moons or in using shields of hydrogen and other liquefied gases from the various planetary atmospheres. High-speed travel could be augmented by nuclear fission and advanced future fusion propulsion, both fueled by atmospheric gases. The gases found in those atmospheres are considered to be excellent for fuels in chemical and nuclear propulsion systems with hydrogen and methane available for ascending to the moon's surface. Hydrogen, helium-3, and ice found deep in Uranus and Neptune are considered to be potentially crucial to exploration beyond the solar system as well.

As the availability of important mineral deposits on Earth declines, including nuclear minerals, or as they are consumed at increasing cost, price-competitive resources from off-world will be required sooner or later as technology and large-scale project management systems are developed to handle such projects. Both exploration and mining programs will be powered by electricity generated by solar and nuclear energy in a variety of plant sizes located in deep space and on the Moon, Mars, or other bodies. Realistic economic studies comparing the price of resources available on Earth with off-world resources will be required to justify the large funds required to mine off-world resources by multinational corporations. With the primary objective of exploration in the solar system being the development of mineral and nuclear resources, sampling in remote regions in new environments will be challenging to Earth-bound planners both in terms of economic justification and technical feasibility.

Exploration programs will need to be innovative and guided by sound geologic and geophysical principles and procedures, whether they be on the Moon, on Mars, or on asteroids located near Earth or within the asteroid belt beyond Mars or on the moons of Jupiter or Saturn. They will be guided first by remote sensing probes to assess the target quality, followed up by remote sampling robotics. After these programs become well tested, manned missions will follow that will oversee detailed exploration and ultimately mining programs. Exploration targets will be nuclear materials (uranium, thorium, and helium-3), metals (nickel, cobalt, platinum), rare-earth oxides (REOs) (such as lanthanum, samarium, etc.), and other commodities (aluminum, titanium, etc.). Models of mineralization known on Earth will provide guidance and analogs for the type of mineralization anticipated off-world, emphasizing those associated with igneous and metamorphic rocks. There will also likely be new types of mineralization of industrial interest encountered off-world that are currently not known on Earth.

MINING ON THE MOON, MARS, AND ASTEROIDS

With many commodity prices at record highs today and expected to stay high for decades to come, off-world exploration and mining are beginning to look attractive for development within the next 20 to 30

Table 1. Rare-earth oxide industry uses and market prices.*

Metal Oxide	Principal Uses	Price US$/kg	Conversion: 2.2 kg to U.S. $/lb Range	
Lanthanum oxide 99% min	Rechargeable batteries	8.50 –9.00	3.86	4.09
Cerium oxide 99% min	Catalysts, glass, polishing	4.70 –4.90	2.14	2.23
Praseodymium oxide 99% min	Magnets, glasses colorant	31.80–32.70	14.45	14.86
Neodymium oxide 99% min	Magnets, lasers, glass	32.50–33.00	14.77	15.00
Samarium oxide 99% min	Magnets, lighting, lasers	4.25 –4.75	1.93	2.16
Europium oxide 99% min	TV color phosphors: red	470.00–490.00	213.64	222.73
Terbium oxide 99% min	Phosphors: green magnets	720.00–740.00	327.27	336.36
Dysprosium oxide 99% min	Magnets: lasers	115.00–120.00	52.27	54.55
Gadolinium oxide 99% min	Magnets, superconductors	10.00–10.50	4.55	4.77
Yttrium oxide 99.99% min	Phosphors, ceramics, lasers	15.90–16.40	7.23	7.45
Lutetium oxide 99.99% min	Ceramics, glass, phosphors and lasers	Up to 2.000/kg	454.55	909.09
Thulium oxide 99.99% min	Superconductors, ceramic magnets, lasers, x-ray devices	Up to 3.000/kg	681.82	1363.64

*Source: Substantially modified from MetalPrices.com, October 2008.

years. At present, mining company executives are essentially locked into meeting current needs, but NASA and NASA's national laboratories and associated industrial contractors such as Boeing, Lockheed, and others are beginning to take note that China, India, and other nations are expanding their economies at a rate higher than anticipated and are beginning to consider off-world resources to meet their future demand. Goodyear (2006), a corporate mining industry executive, reported a few years ago that the consumption of natural resources by China and India will place even greater stress on commodity prices, especially for copper, aluminum, nickel, iron ore, and other metals and mined commodities, and that these resources will need to be replaced in the foreseeable future. Campbell et al. (2008, 2009a) suggest that it is not unreasonable to assume that economic mineral deposits will be discovered elsewhere in the solar system, that is, on other planets, moons, or asteroids. Chapter 4 discusses the relative economic value of some types of near-Earth asteroids (Cutright, 2013). Although the geologic processes that form the younger types of uranium mineralization (of Tertiary age on Earth) and other deposits formed by hydrothermal processes require the presence of water, bacteria, and associated enzymes and may not be present on many of these distant bodies, but water may be more pervasive than originally assumed. Geologically older types of uranium mineralization associated with igneous and metamorphic rocks similar to deposits that occur in Proterozoic gneisses and amphibolites (Christopher, 2007) and younger rocks in the United States (Armbrustmacher et al., 1995), the well-known developed uranium deposits in Canada and northern Australia, and the deposits under development in Africa would be analogs for the types of deposits that would be expected to occur elsewhere in the solar system. Speculations about uranium, thorium, and their associated geochemistry began several years ago (i.e., Surkov et al., 1980; Zolotov et al., 1993). With the number of unmanned probes planned in the next few years, additional information should be available to begin looking actively for resources in our solar system, hopefully within the next 20 years, supported by solar and nuclear power (Campbell et al., 2009a,b).

We conclude that Earth still holds the promise of new discoveries of mineral resources, especially in the remote reaches of Canada, Alaska, Antarctica, China, Russia, and elsewhere (Laznicka, 1999). The power supplies required for developing such remote resources will soon be provided by the small nuclear power plants initially developed for missions in space. The many activities presently under way by the industry in uranium and thorium exploration on Earth (Campbell et al., 2008, 2009a) confirm that Earth still has such resources to contribute. However, as opposition to development and political disagreements between countries increase, commodity prices rise, and as the distribution of resources is withheld from the world economy, secure sources of materials will likely be sought off-world in either national or multinational programs during the centuries ahead.

What situations might develop that would promote the development of off-world resources?

One situation that demands consideration is geopolitical in nature. The 2008 world mine production of rare earths was approximately 124,000 tons with 96.7% of this total coming from China (Hedrick, 2009b). The total world reserve base is estimated at 150,000,000 tons, with China holding 89,000,000 tons or 59.3% of the world total. By comparison, the domestic reserve base is 9.3% of the world total. The only rare-earth separation plant in the United States is located at Mountain Pass, California, and has only recently resumed operations after dealing with environmental problems associated with its wastewater discharge. Only mine stockpiles are being processed, and only lanthanum concentrate and didymium (75% neodymium and 25% praseodymium) are being produced. Current REO uses and prices are shown in Table 1. As these prices continue to rise, off-world resources assume greater importance in meeting the demands of the future.

China has recently become a controlling entity in the global rare-earth market. Although world demand for REOs is growing, China is cutting back on exports to maintain high-profit margins. The state-owned China Nonferrous Metal Mining Group (CNMC) has a goal of investing heavily to improve the industry's competiveness. In keeping with this policy, China recently acquired a controlling interest in Australia's Lynas Corporation, Ltd., for US $185.7 million. This purchase gives China access to the world-class rare- earth deposit at Mt. Weld in Western Australia. Lynas Corporation, Ltd., has stated that the Mt. Weld rare-earth oxide deposit known as the central lanthanide deposit is without a doubt the world's richest rare-earth orebody, easily capable of supplying up to 20% of the global market for 30 years (Lynas Corporation, 2011). From the actions of the CNMC, it is apparent that prices for REOs will continue to escalate despite rising world demand. With its low-cost labor force and less stringent environmental regulations, it is doubtful that other nations with rare-earth resources will be able to afford to compete with the Chinese.

As the United States, China, India, and others continue to conduct robotic exploration programs, we learn more about the geology of other bodies. Applying well-studied analogs on Earth to geologic environments on bodies in the solar system or finding new geologic associations off-world that offer commodities needed by humans, these new resources will provide the means to maintain Earth and to establish bases off-world as we learn to survive and prosper in space and in other environments (NASA, 2008g).

TARGET COMMODITIES

The candidate list of potentially available commodities that are in short supply on Earth (shown in Table 2 and indicated by red dots) (Anonymous, 2008a) may be uneconomic to produce from low-grade ore or from recycled materials in the foreseeable future but may be available off-world. The Moon shows evidence of offering some of these commodities and some asteroids (types C, S, and M) are more prospective than others based on the known compositions indicated by meteorites and impact sites on Earth (see Ambrose, Chapter 1, this text; and Ambrose and Schmitt, 2008; and Cutright, Chapter 4, this text; and other chapters of this text).

Since 2004, NASA has been developing new capabilities to go into space, to the Moon, and then on to Mars and elsewhere in the solar system (National Aeronautics and Space Administration, 2008a). It should be noted here that although neither NASA nor the President's Commission on Implementation of United States Space Exploration Policy (2004) emphasize it, one of the two primary justifications for going into space is to locate and develop the natural resources needed on Earth in the future (i.e., nuclear and industrial minerals). The other is to protect Earth from collisions with asteroids or comets (Campbell et al., 2009a, and b).

The work performed by astronauts on reaching the Moon, asteroids, and Mars first will be geologic in nature, followed by engineering activities to develop the next steps in the industrialization of the solar system. Of particular importance is that while we search for, mine, and process the very nuclear fuels that provide the power needed on Earth and later in space (i.e., uranium, thorium, and later, helium-3), this also allows us to explore for other various mineral commodities in space (i.e., aluminum, REOs, nickel, etc.). Mineral deposits on Earth not now considered to be economic will continue to be developed until the economics, environmental pressures, or substitutions render such deposits nonviable. Substitutions have been at the core of industrial research since the beginning of the Industrial Revolution and, driven by a predicted future population growth of about 20% by 2025, will continue until the economics demand new resources from off-world.

ECONOMIC AND TECHNOLOGICAL IMPACT ON WORLD ECONOMY

The potential rewards in terms of developing new mineral resources with large-scale, off-world mining

Table 2. Commodities imported to the United States in 2007*.

Commodity	Percent	Major Import Sources (2003–2006)[1]
ARSENIC (trioxide)	100	China, Morocco, Hong Kong, Chile
ASBESTOS	100	Canada
BAUXITE and ALUMINA	100	Guinea, Jamaica, Australia, Brazil
CESIUM	100	Canada
FLUORSPAR	100	China, Mexico, South Africa, Mongolia
GRAPHITE (natural)	100	China, Mexico, Canada, Brazil
INDIUM	100	China, Japan, Canada, Belgium
MANGANESE	100	South Africa, Gabon, Australia, China
MICA, sheet (natural)	100	India, Belgium, China, Brazil
● NIOBIUM (columbium)	100	Brazil, Canada, Estonia, Germany
QUARTZ CRYSTAL (industrial)	100	Brazil, Germany, Madagascar, Canada
● RARE EARTHS	100	China, France, Japan, Russia
RUBIDIUM	100	Canada
STRONTIUM	100	Mexico, Germany
● TANTALUM	100	Australia, Brazil, China, Germany
THALLIUM	100	Russia, Netherlands, Belgium
● THORIUM	100	United Kingdom, France
● VANADIUM	100	Czech Republic, Swaziland, Canada,
● YTTRIUM	100	China, Japan, France, Austria
● GALLIUM	99	China, Ukraine, Japan, Hungary
GEMSTONES	99	Israel, India, Belgium, South Africa
● BISMUTH	95	Belgium, Mexico, China, United Kingdom
● PLATINUM	94	South Africa, United Kingdom, Germany
STONE (dimension)	90	Italy, Turkey, China, Mexico
● DIAMOND (natural industrial stone)	88	Botswana, Ireland, Namibia, South Africa
ANTIMONY	86	China, Mexico, Belgium
● RHENIUM	86	Chile, Germany
BARITE	83	China, India
● TITANIUM MINERAL CONCENTRATES	82	South Africa, Australia, Canada, Ukraine
POTASH	81	Canada, Belarus, Russia, Germany
● TIN	79	Peru, Bolivia, China, Indonesia
● COBALT	78	Norway, Russia, Finland, China
● PALLADIUM	73	Russia, South Africa, United Kingdom,
● TUNGSTEN	70	China, Canada, Germany, Portugal
● TITANIUM (sponge)	64	Kazakhstan, Japan, Russia, Ukraine
● CHROMIUM	62	South Africa, Kazakhstan, Russia, Zimbabwe
PEAT	60	Canada
● ZINC	58	Canada, Peru, Mexico, Australia
MAGNESIUM COMPOUNDS	57	China, Canada, Austria, Australia
GARNET (industrial)	56	Australia, India, China, Canada
SILICON (ferrosilicon)	56	China, Venezuela, Russia, Norway
● SILVER	55	Mexico, Canada, Peru, Chile
● MAGNESIUM METAL	54	Canada, Russia, Israel, China
● DIAMOND (dust, grit, and powder)	52	China, Ireland, Russia, Ukraine
NITROGEN (fixed), AMMONIA	44	Trinidad and Tobago, Canada, Russia,
VERMICULITE	40	South Africa, China
● COPPER	37	Chile, Canada, Peru, Mexico
MICA, scrap and flake (natural)	32	Canada, China, India, Finland
PERLITE	30	Greece
ALUMINUM	26	Canada, Russia, Brazil, Venezuela
GYPSUM	26	Canada, Mexico, Spain, Dominican Republic
SULFUR	24	Canada, Mexico, Venezuela
PUMICE	20	Greece, Italy, Turkey
SALT	18	Canada, Chile, The Bahamas, Mexico
CEMENT	17	Canada, China, Thailand
● NICKEL	17	Canada, Russia, Norway, Australia
PHOSPHATE ROCK	14	Morocco
BROMINE	13	Israel, United Kingdom
IRON and STEEL	12	Canada, European Union, Mexico, Brazil
IRON and STEEL SLAG	7	Canada, Italy, France, Japan
LIME	1	Canada, Mexico

*Red dots indicate commodities of special interest in space exploration. Substantially modified from Mining Engineering (Anonymous, 2008a).

operations would contribute to the world economy on an unprecedented level, making the immense industrial investment worthwhile (see Schmitt, Chapter 2, this text; 2004; and 2006). Identifying and mining nickel, cobalt, and a variety of other commodities that are in short supply on Earth, or those that could be mined, produced, and delivered more cheaply in space than on Earth in the future, could contribute to and drive the world's technology and associated economy to a scale never before contemplated. This is based, of course, on the assumption that the economics are favorable. Large multinational quasi-governmental industrial groups are likely to develop during the next few decades to handle projects of such magnitude, if they have not already begun to assemble. In the beginning, the economics would likely be underwritten by governmental support, perhaps by a group of governments cooperating in funding and technology but followed later by some governments funding programs to accommodate their own particular self-interests.

Because long-term planning is a prerequisite to exploration and development in space, these programs will proceed step by step within the decades ahead as they make sense politically and economically within industry. Although funding by the federal government has provided the basic research required to send probes to study the solar system as well as the early applied research in the Apollo Lunar program involving astronauts, in the decades ahead, the mining industry will likely assume the lead in ventures into space that are based solely on the perceived economic value to the corporations and their stockholders.

Also in the decades ahead, mining for such high-volume, low-grade commodities (e.g., aluminum-thorium-uranium) on Earth will be of only historical interest. Even some of the low-volume, high-grade operations (e.g., nickel, cobalt, platinum, rare-earth elements) may disappear on Earth because they will be more economical to produce off-world as secondary recovery projects.

In the early 1990s, work began in earnest to consider NEAs as resources of the future (Lewis et al., 1993), and the work continues today (Ruzicka et al., 2008). The time has arrived to begin to consider mining certain commodities on the Moon, as well as on the outlying planets, their moons, and asteroids. This will require long-duration robotic missions followed by manned space missions that will involve working in adverse conditions. A combination of nuclear-powered and solar-powered systems will provide the needed energy for such missions. The former will provide the high-amp power whereas solar will provide the primary and backup power needed for lower amp requirements where possible.

The availability and development of these off-world resources could easily overwhelm the markets on Earth for many years. The impact would drive the commodity prices down, hence making Earth-based operations unprofitable and eventually obsolete. As a natural progression during the next 40 to 50 years and beyond, natural resource corporations will certainly wring out the last of the metals and other commodities on Earth from low-grade deposits, dumps, and landfills until either the costs or the lack of political cooperation via NIMBY (not in my back yard) attitudes will bring the activities to a close (Campbell et al., 2005, 2007). Society will also encourage or require the industry to expand the recycling of products until population demand exceeds such recoveries.

EXPLORATION AND MINING

Mining plans and the associated economics of operating in space would involve a new scale of operations never before attempted by humans. Mining, whether on the Moon or selected asteroids, would likely require new methods and technologies to create pit excavations and to handle materials and equipment in very low and zero gravity. Controlled drilling and blasting would be required to break up selected parts of asteroids or hard-rock areas of the Moon into smaller fragments that would settle back into the pit created by the blast. In the very low gravity fields found on small asteroids, drilling apparatuses will need to be anchored to the asteroid's surface to produce enough downward compression on the drill bit to provide efficient drilling. Blasting of the rock will also need to be carefully controlled to prevent the ore from being blasted into orbit.

After breaking the ore material into smaller fragments, it will be loaded into crushers and ground into fragments suitable for loading into special transport vehicles. These transport vehicles would be built to interlock creating space trains that would bring the raw ores back to plants on the asteroids or the Moon for further processing into concentrates. These concentrates would then be smelted to rid the ore of unwanted materials and formed into ingots useful to the industry or be sent directly back to Earth's surface via space elevators or other future transfer methods for further processing.

Sonter (1998) identified the geologic and mining engineering requirements that would be satisfied to identify an orebody as a resource that can justify the expense of producing metal(s) or other commodities. The following diagram (Figure 21) is intended to show how the various requirements interact.

The following are the economic and technical assumptions needed to be met to justify the expense of production:

1) A market exists or will exist in the future for the products produced and delivered;
2) Adequate spectral data indicate the presence of the desired materials to justify a manned mission to explore the anomalous sites by direct sampling, by geological and geophysical surveys of the subsurface of the anomaly;
3) Known or established orbital parameters provide reasonable accessibility to the anomalous site and will allow the mission(s) to be of sufficient duration to permit the completion of the required exploration;
4) Feasible concepts for mining and processing have been developed and based on successful drilling and sampling, mining factors, project life, and a meaningful assessment of the product price to be realized throughout a long mine life;

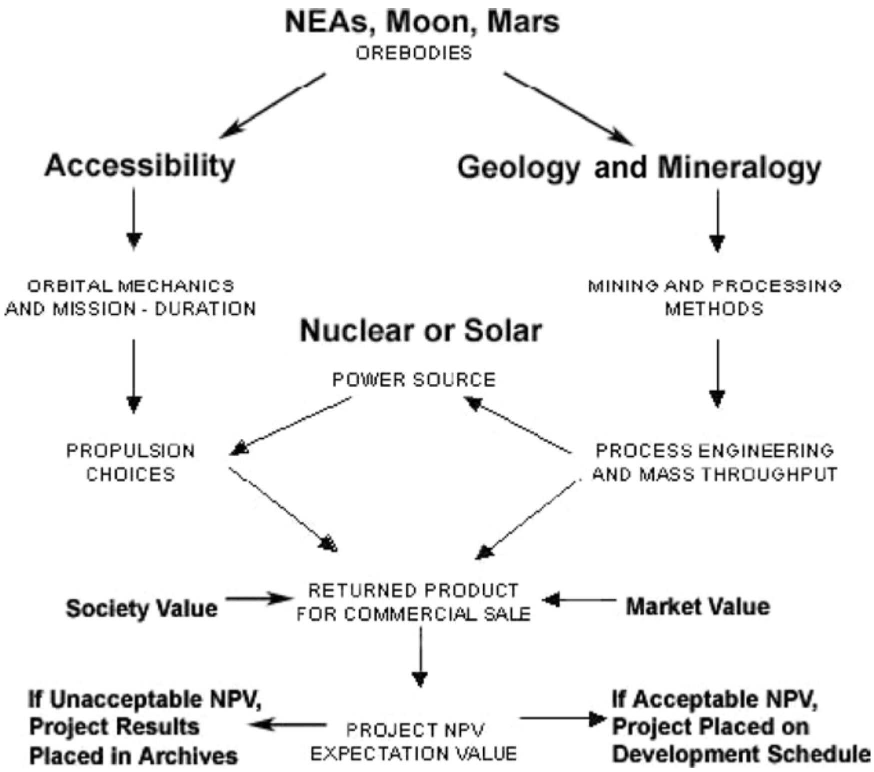

FIGURE 21. Flowchart for determining technical and economic feasibility of mining in space. NPV = net present value. Modified from Sonter (1998).

5) Feasible retrieval concepts have been developed and tested to produce (a smelter product) and return materials of economic interest (a delivered product to/from the Moon/asteroid); and
6) A positive economic net present value would be derived incorporating all of the above issues and using appropriate engineering concepts. All appropriate economic parameters would be applied in assessing the off-world mining venture, including government subsidy at the outset of the project.

SOURCE OF MATERIALS

Of particular irony is the function that meteor and comet impacts may have in bringing not only water but also metals of economic value to Earth, such as nickel, uranium, thorium, and so on. As previously discussed, thorium and samarium have been detected in and around certain impact craters in anomalous concentrations on the Moon. On Earth, known economic concentrations of nickel and other constituents occur near Sudbury in Ontario, Canada, in the Bushveld-Vredefort structures in South Africa, and in association with ring structures in Baltic Shield rocks of Sweden and Finland and elsewhere.

These impact sites are tempting candidates for being of off-world origins, although the prevailing thought is that such deposits on Earth are either of progenetic (preimpact), syngenetic (contemporaneous), or epigenetic (postimpact) origin, with the exception of the recent work by Willbold et al. (2011), who suggest that off-world origin of metals may have some merit. For the range in thought, see Grieve (2005), Reimold et al. (2005), Laznicka (1999), Witschard (1984), and, of historical note, Skerl (1957) and Quirke (1919). Currently, about 170 terrestrial impact structures are presently known on Earth, with a discovery rate of about five new structures per year (Planetary and Space Science Centre, 2009c). In any event, exploration continues on the Moon and in the more remote regions on Earth and will continue off-world in this century and beyond.

The discovery by Becker et al. (1996) of extraterrestrial carbon containing extraterrestrial helium (also known as helium-3) in the Onaping Formation at Sudbury has proven to be an important one. At least some material from the asteroid creating the Sudbury impact may have survived intact, although Ames et al. (2002) illustrate the complexity involved in the Sudbury structure. The presence of buckyballs (cage-like carbon molecules containing helium-3 atoms trapped within them) apparently are similar to the carbon found in Murchison and Allende carbonaceous chondrite meteorites. These occurrences also have off-world analogs on the Moon, although helium-3 apparently is trapped within selected silicate minerals of the regolith on the Moon (see Schmitt, Chapter 2; Beike, Chapter 3 of this text; and Campbell et al., 2009a).

The metal-rich impact sites known on Earth also have off-world analogs (Campbell et al., 2009a). On the Moon, for example, early indications of sites containing anomalous levels of thorium (Figure 12), samarium (Figure 13), and recently uranium (Yamashita et al., 2009) will be on NASA's list for follow-up investigations when the United States returns to the Moon with manned missions, assuming China, India, Russia, or other countries do not claim the sites first.

Recent discoveries of anomalous uranium, rare earths, titanium, and other resources on the Moon may change the political dynamics in space, especially with China, India, and other countries recently demonstrating an interest in space (Yamashita et al., 2009) (Figure 12).

ECONOMIC ASSESSMENT OF RESOURCES

To assess off-world deposits for their economic viability, evaluations will be required of the resources available on Earth in context with what could be expected off-world. We focus here on thorium, samarium, and nickel as examples.

Source of Metals: Earth's Mantle

The composition of Earth's primitive mantle has been estimated from chondritic meteorites (i.e., meteorites with chemical compositions essentially equivalent to the average solar system composition). Alternatively, the mantle composition has been reconstructed by mixing appropriate fractions of basalts (i.e., partial melts from the mantle) and peridotites (the presumed residues from the partial melts), and it has been calculated from trends in the chemistry of depleted mantle rocks. The concentration of thorium in the primitive mantle has been estimated to be 29.8 ppb (as derived from chondritic meteorites) or 83.4 ppb (as derived by Palme and O'Neill, 2004). On the Moon, the surface debris from a major impact surrounding the Mare Imbrium area contains anomalous concentrations of thorium (see Figure 12 and bright- to dark-red areas). These areas would be targets for follow-up exploration in locating higher grades of thorium and based on the recent work of Gasnault et al. (2009) for uranium as well.

Most of Earth's mantle (~70%) is made of magnesium perovskite, which has great potential for fractionating elements. Note that calcium perovskite, which is also expected to exist in the mantle, has enormous storage potential for lithophile elements. Its ability to host thorium and uranium makes it an especially important phase to understand with respect to long-term storage of these elements in the early Earth (Righter, 2004).

Asteroids or asteroid debris fields on the Moon and on other bodies consist of fragments of primitive mantles and cores once making up other planetary bodies. These should be relatively easy to identify and evaluate compared with the buried deposits on Earth that require extensive drilling and excavation. Because these bodies have now been fragmented as a result of collisions in the solar system or by gravity stresses exerted by Jupiter or Saturn, they now exist in the asteroid belt beyond Mars or in rogue orbits after being knocked out of the belt or after their orbits were altered by large bodies.

Thorium

Australian government geoscientists conducted a comprehensive assessment of their thorium resources (Geoscience Australia, 2008). They estimate that the Earth's average abundance of thorium in the mantle is not precisely known, but its abundance has been measured extensively at Earth's surface and interpreted for the interior from indirect evidence. The following are the three main sources of data:

1) chemical and radiometric analyses of meteorites interpreted to be representative of different Earth layers,
2) chemical and radiometric analyses of surficial rocks, and
3) estimation of values for Earth's interior from heat-flow and rock conductivity data.

The principal division of Earth into core, mantle, and crust is the result of two fundamental processes:

1) The formation of a metal core very early in the history of Earth. Core formation was complete at about 30 m.y. after the beginning of the solar system (Kleine et al., 2002).
2) The formation of the continental crust by partial melting of the silicate mantle. This process has continued with variable intensity throughout Earth history.

Thorium Off-World Development Issues

Technologies for the extraction and transportation of these commodities to Earth pose geologic and engineering challenges that, although substantial, are not insurmountable. Visionary solutions to these challenges are already on the drawing board, awaiting the conditions that would turn these visions into reality.

What conditions might arise that would result in serious considerations to develop exploration and mining on the Moon and elsewhere? Speculation using various economic and political scenarios can certainly shed some light on this question, but one need only look at developing situations now in progress to begin to understand how off-world resource development might become an attractive alternative to Earth-based operations. The three resources of current interest all have a function in an Earth economy already poised to undergo major transformations.

In a world that is increasingly disturbed by discussions of global climate change, the burgeoning need for nonpolluting energy sources, and the desire to eliminate nuclear proliferation, thorium has been held up as a way to confront all of these problems. Thorium is a fairly common element—about three to four times as abundant as uranium near Earth's surface (International Atomic Energy Agency, 2005a). Although it has a widespread occurrence, it is recovered from a restricted suite of geologic deposits with sufficiently high grades to be of commercial interest. These deposits comprise monazite in heavy-metal sand placer and vein deposits, thorite ores in vein deposits, and thorium recovered as a by-product of uranium mining (Hedrick, 2008). Accounts of world refinery production and world thorium demand are not available, but recent demand has been depressed, resulting from concerns over its natural radioactivity, industrial concerns over its potential liabilities, the cost of compliance with regulations, and the cost of disposal at approved burial sites (Hedrick, 2008). According to Hedrick, these problems are expected to continue to depress worldwide demand in nonenergy applications. However, the energy-related applications of thorium are what have sparked resurgence in the development of thorium fuel cycle reactors and discussion of thorium as an eventual replacement for uranium-based reactor designs. Thorium fuel cycle reactors, both power and experimental systems, are currently operating in Canada and India, which lead the world in the utilization of thorium, because in large part of their ownership of approximately one-fifth of the known world reserve base of 1.4 million tons (Campbell et al., 2009b; Hedrick, 2009a).

The use of thorium in several different types of reactors was demonstrated in the 1950s and 1960s, when it was thought that uranium was a limited resource. Later, when additional discoveries of uranium were made and its availability was increased, the use of thorium was mostly ignored. In modern times, the scrutiny received by all energy sources by a public concerned with the future health of the planet has resulted in a reevaluation of thorium-based reactors because of several benefits. Thorium-fueled reactors provide for increased resistance to proliferation, longer fuel cycles, higher fuel burn-up, improved waste characteristics, reduction of plutonium inventories, and a capacity for the in-situ use of bred-in fissile material (International Atomic Energy Agency, 2005a). Although significant challenges still remain, it is thought that these difficulties can be overcome as industrial experience with thorium fuel cycles increases.

Of particular interest is the recent research into energy systems like the thorium molten salt nuclear energy synergetic system (THORIMS-NES) (Hoatson et al., 2006). These systems consist of a molten salt reactor (MSR), like the Fuji mini-MSR, currently being developed by a consortium that includes the United States, Japan, and Russia; these include a chemical process plant, and an accelerator molten salt breeder reactor. Nuclear engineers find these developments useful, as they offer increased safety of operation, flexibility in plant size, nuclear proliferation resistance, fuel economy, and flexibility in the fuel cycle. According to the World Nuclear Association (2009), molten salt reactors operate with lower pressures, which results in higher safety margins and higher temperatures that will allow the thermochemical production of hydrogen.

Some foresee a thorium era, where by the need for a global low-carbon footprint becomes imperative as coastlines are exposed to possible inundation from rising sea levels because of global warming (Chong, 2009). Nuclear energy is currently the most efficient method for carbon-free electricity production. Couple that with a capability to efficiently produce hydrogen as a renewable energy source for use in cars, homes, and industry, and the number of nuclear reactors could eventually outstrip the production capabilities on Earth. The presence of economic grades of thorium (and uranium) on the Moon, with inferred concentrations much higher than the 10 mg/g reported for thorium in preliminary assessments, makes these resources an important part of the world's future energy picture (Furukawa et al., 2007).

Samarium

Samarium is another resource that has been identified on the Moon, where significant areas show concentrations in the range from 35 to 51 mg/g (Figure 13) (Furukawa et al., 2007). Samarium is a member of the lanthanide series appearing in row 6 of the periodic table. Referred to as one of the 15 rare-earth elements, it is not considered rare because of its scarcity on Earth but instead because these elements were once very difficult to separate from each other. Samarium has relatively few uses by itself, but its properties make it very desirable where it is incorporated. It is added to glass to produce special optical properties, to make special-application lasers, as a nuclear absorber in nuclear fuel rods, and as a component of very powerful samarium-cobalt (SmCo) magnets. It is in the last of these uses that samarium will provide its greatest contribution to the future. Samarium-cobalt magnets have high demagnetization resistance, excellent anticorrosion properties, and outstanding thermal stability that make them particularly useful in motors, positional detectors, generators, radar communications, medical equipment, and electrical engineering applications (DailyMag International (Ningbo) Limited, 2009).

As with thorium and uranium, impact sites on the Moon also indicate samarium geochemical anomalies, notably around the Mare Imbrium region (see areas of bright red shown in Figure 13).

Samarium Off-World Development Issues

As previously discussed, China has become a controlling entity in the global rare-earth market. The price of REOs will continue to escalate because world demand is growing and China is cutting back on exports to maintain high profit margins. It is doubtful that other nations with rare-earth resources will be able to compete with the Chinese because of their low-cost labor force and lower environmental regulations.

Rising world demand for REOs and for samarium is expected for the future as the pressing needs to reduce energy consumption and preserve environmental integrity become central issues of the world economy. Indications of this rising demand stem from the need for low- carbon transportation options. In the future, samarium will play a pivotal function in reducing emissions resulting from fossil-fuel-based transportation mainly because of its importance in the fabrication of high-performance permanent magnets using SmCo. Fabrication of custom SmCo magnets is currently expensive because of the brittle nature of the alloy, but new research promises to overcome this problem, allowing SmCo magnets to become primary elements in the next generation of hybrid electric vehicles (HEVs). The newly developed SmCo magnets will provide advanced electric motors with high magnetic performance, high resistivity, thermal stability, and low cost. Demand for HEVs is expected to increase greatly during the next decade because of rising energy costs and more stringent environmental regulations.

Another potential demand for SmCo magnets derives from developing innovations in the production and installation of very high speed rail systems. The French Alstom Corporation (2009) has developed rail systems designed for transport between major urban centers. With speeds ranging from 300 to 360 km (186 – 224 miles/hr, these trains use motors operating with SmCo-permanent magnets. The company’s new antigravity line of very high speed trains boasts 15% energy savings because of the use of new composite materials and the efficient traction system. In fuel-equivalent terms, the AGV consumes only 0.4 L of oil/ 100 km (62 miles) per passenger, about one-fifteenth that of an airplane. In addition to cars and trains, the development of highly efficient internal permanent magnet motors may give HEV mass transit systems the boost they need to become widely accepted (see Alstom, 2009).

Samarium promises to be a material in high demand in the coming decades, as evidenced by the growing reliance on low-carbon technologies for transportation. The fact remains that policies now under way in China will serve to reduce the availability of REOs, although China’s own research into the uses of these materials proceeds at a slower pace. This has the double impact of making China a world leader in the development of technologies using REOs as well as the owner of most of the global resource. As far as samarium goes, we have only to look toward the Moon or elsewhere in space. Earth does not appear to be unique in offering such resources. As time passes, we will likely realize that mining in space is easier and more profitable than mining on Earth for many reasons — difficult in the beginning as we learn, but without gravity, materials handling becomes easier than on Earth.

Nickel

In August 2006, a ton of nickel on the world market was worth a record US $35,000, a 7.7-fold increase from 2001. This increase was driven mainly by the urbanization and industrialization of China. At that price, global stockpiles of nickel had virtually disappeared, whereas exploration expenditure and activity were at all-time highs, especially in Australia. Australia’s nickel industry experienced a boom phase of unparalleled opportunities. Nickel is one of the most common metals used in modern industrial applications, with important characteristics such as resistance to oxidation, resistance to corrosion by alkalis, strength at high temperatures, and the ability to form alloys used in general fabrication and in specialized applications (Jaireth et al., 2008). With the world economic recession, the price dropped to US $9,000. by December 2008 and then rebounded to US $17,000 in October 2009 (MetalPrices.com, 2009). The price drop was the result of a drop in world demand because of the global recession. As the recession recovered, the price of nickel increased. These periods of boom and bust will speed up and slow exploration efforts. However, long-term demand always increases, so the price for nickel, although not currently high enough to support extraterrestrial exploration and mining, eventually will remain strong.

The 2007 estimate of world mining production was 1,660,000 tons from a reserve base of 150,000,000 tons (Kuck, 2008). Canada and Russia dominate world production with the United States lacking any domestic refining capacity. According to the International Nickel Study Group (INSG), the land resource base is thought to be greater than 100 years at the present mining rate (Jaireth et al., 2008). Nickel resources do not include the metal present in deep-sea nodules, which may represent a resource several times as large as that on land. The sea-floor occurrence of manganese-nickel-copper as nodules is not considered an economic target at this time because of the technological challenges inherent in deep-sea mining, the environmental impacts to be overcome, and the uncertain ownership issues of minerals occurring on the sea floor.

The INSG states that about two-thirds of nickel consumption goes to the manufacture of stainless steel, a market that is growing at the rate of 5 to 6% per year, with nickel demand expected to increase at a rate of 2 to 3% per year. If this rate of growth is sustained and the resource is predicted to last only another 100 years, there will be an eventual shortfall in nickel production, resulting in strong price pressure. Countries with sufficient resources will be loath to export nickel because of its critical importance in several industries. Another factor that may hinder the future availability lies in its mode of occurrence. Nickel occurs in two main types of deposits: laterites and magmatic sulfides, which includes komatiite ultramafics.

Laterites comprise a preponderance of the land-based resource but account for only 40% of world production mainly because of the difficulties involved in mineral processing and the fact that strip mining of large areas presents some environmental challenges in land use and associated water supplies. The experience of nickel-mining giant Vale Inco in the development of their Goro Plateau lateritic deposit in New Caledonia is a case in point. Similar resistance to the mining of undeveloped laterite deposits is to be expected elsewhere as well.

Magmatic sulfide deposits, also known as nickel-copper sulfide deposits, are associated with hot mantle material rising into the crust and becoming contaminated with sulfur. When sulfur saturation occurs, sulfide liquid separates from the magma and, because sulfides are denser than the magma, settles into the lower part of the magma chamber. As the sulfide settles, metals such as nickel, copper, platinum, and palladium become concentrated in the sulfide. Basaltic lavas undergo sulfide segregation, forming magmatic sulfide deposits.

A specific type of magmatic sulfide deposit is the komatiite deposit. This type of deposit occurs in ultramafic volcanic rock and is rich in pentlandite, a nickel sulfide mineral that is a major ore source for nickel. The Australian analysis of the world's major komatiite provinces reveals that the most prospective komatiite sequences are generally of late Archean (~2,700 Ma) or Paleoproterozoic (~1,900 Ma) age, have dominantly Al-undepleted chemical affinities (Al_2O_3 /TiO_2), and form compound sheet flows with internal pathways and dunitic compound sheet flow facies (Jaireth et al., 2008). The preferred pathways assist in focusing large volumes of primitive magma flow (i.e., high-magma flux environments) and facilitate interaction of the magma with potential sulfur-bearing substrates (Figure 22). This figure summarizes mineralizing systems from the Beasley, Mt. Keith, and Kambalda mines in Western Australia.

Komatiites are ultramafic mantle-derived volcanic rocks. They have low SiO_2, low K_2O, low Al_2O_3, and high to extremely high MgO (Liu, 2008). True komatiites are very rare and essentially restricted to rocks of Archean age, with few Proterozoic occurrences known (although similar high-magnesium lamprophyres are known from the Mesozoic). Jaireth et al. (2008) suggest that this restriction in age is caused by secular cooling of the mantle, which may have been up to 500 C (932 F) hotter during the early to middle Archean (4.5 – 2.6 Ga). The early Earth had much higher heat production because of the residual heat from planetary accretion (and impacts), as well as the greater abundance of radioactive elements. The identification of magmatic facies in komatiitic systems is therefore important for assessing the economic attractiveness of nickel-rich deposits on Earth and off-world.

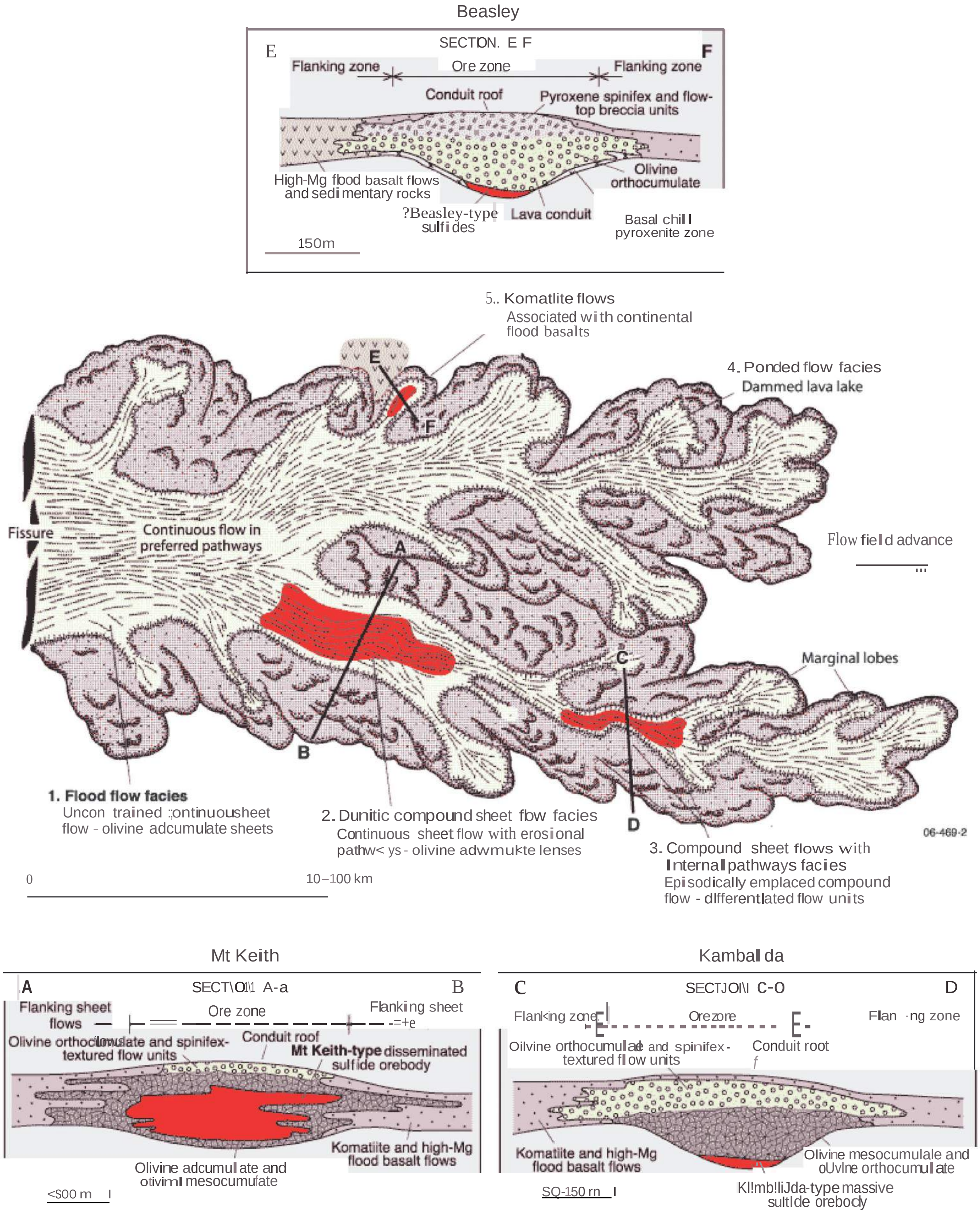

FIGURE 22. Typical analog geologic relationships for off-world exploration of volcanics. Modified from Dowling and Hill (1998) and Hill (2001).

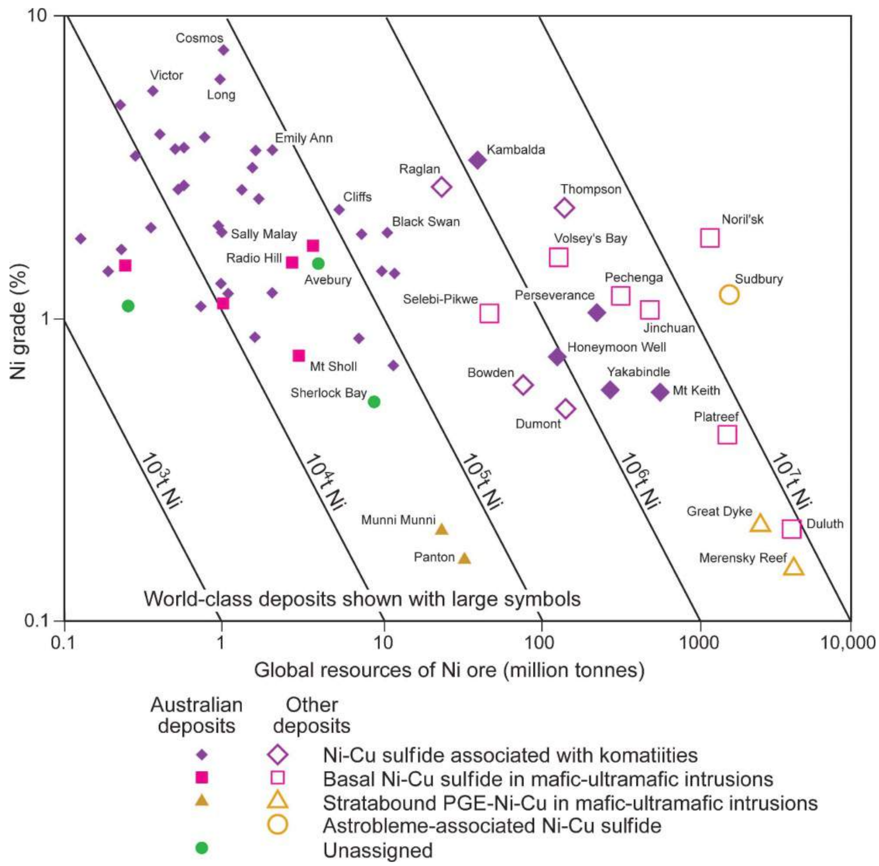

FIGURE 23. World nickel orebody grade versus deposit tonnage as a guide to off-world exploration targets. Reprinted with permission from Jaireth et al. (2008). PGE = platinum group elements.

Considerable potential exists for the further discovery of komatiite-hosted deposits in Archean granite-greenstone host rocks, including large and smaller high-grade deposits (5–9% nickel) that may be enriched (2–5 g/t) in platinum group deposits. These are clearly analogs for guiding exploration off-world, especially in the assessment of asteroids of the class M variety. The size and grade of world-class nickel deposits are plotted in Figure 23. Notice Sudbury site.

The figure is a logarithmic plot of nickel grade (in weight percent) versus global resources of nickel ore (production plus reserves and resources in millions of tons) for the major nickel sulfide deposits. Australian deposits are shown with filled symbols, and other deposits are shown as open symbols. The gray diagonal lines show contained nickel metal in tons. The size of nickel orebodies developed off-world will likely exceed those discovered on Earth to date, larger than the Sudbury and Noril'sk deposits. A recent discovery of nickel (and copper) has been made in Greenland (see page 206, this chapter). Some of the known deposits may have analogs on asteroids, Mars, and the Moon. Pentlandite has been found on the Moon and in meteorites that originated on Mars.

With demand for nickel rising at a rate of 5 to 6% a year, the effect of increased demand resulting from innovations in emerging technologies would further escalate nickel prices. The new world economy, with its increased emphasis on solving the energy crisis and in managing the impact of global climate change, can be expected to use nickel to a greater extent than ever before. Because of its special properties incorporated into alloys, nickel will have an ever-increasing function in solving these problems. For example, corrosion-resistant alloys will find use in wave energy fields and high-temperature alloys will serve in biogas microturbines.

Nickel-metal hydride batteries will be in demand for HEVs and electric mass transport. As worldwide freshwater shortages appear, nickel will provide the corrosion-resistant alloys used in desalination plants. Impact-resistant ductile iron, which uses nickel, will find increasing use in the exploitation of wind energy. Last, corrosion-resistant alloys, which also require nickel, have a pivotal function in the thorium era scenario presented above. The THORIMS-NES system could provide nuclear energy on a variety of scales, allowing local power providers the flexibility to design the nuclear power grid to meet the needs of a locality or region. The containment for the molten salt reactor will be made of a superalloy called HastelloyR made by Haynes International, Inc.

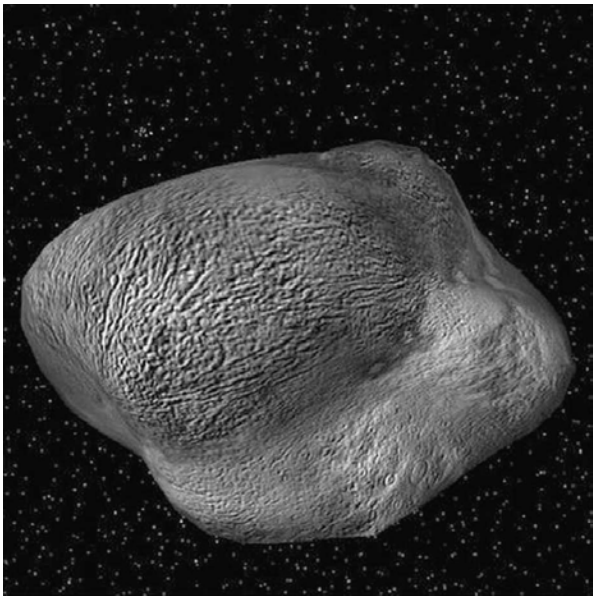

FIGURE 24. A class M asteroid named 3554 Amun-NEA. From Ambrose and Schmitt (2008) and Chapters 1 and 4.

Combined with up to ten other elements, Hastelloy alloys incorporate approximately 70% nickel (Haynes International, Inc., 2012).

NICKEL OFF-WORLD DEVELOPMENT ISSUES

Given these new developments, the global demand for nickel may experience a very significant increase between now and the day when land-based nickel resources are exhausted. But where would the replacement for this critical resource come from? Aside from sea-floor deposits of nickel, in the early 1990s, work began in earnest to consider NEAs as resources of the future (Lewis et al., 1993), and the work continues today (Ruzicka et al., 2008). Recently, Ambrose, Chapter 1; Cutright, Chapter 4, of this text; and Campbell et al. (2009a) speculated on the size of the nickel resource available in one class M asteroid named 3554 Amun-NEA (Figure 24).

Class M meteorites typically are composed of iron, nickel, cobalt, and platinum group metals, the last three of which are in great demand on Earth. The asteroid 3554 Amun-NEA is about 1.3 mi (~2 km) in diameter, which is about the size of typical metallic mineralized zones on Earth. Its ore zone mass is calculated to be about 30 billion tons and assuming it contains 20 oz/ton of nickel, it could contain almost 17 million tons of nickel, or about 34 billion pounds of metal worth almost US $600 billion in today's market (i.e., about US $35,000/ton of metal concentrate) (British Geological Survey, 2008). Mining at sites among the asteroid belt between Mars and Jupiter, which includes about 10% of class M asteroids, would provide a substantial supply of nickel, cobalt, and platinum group metals. Clearly, challenges to develop off-world resources for use on Earth will be met. The immense power requirements needed to develop such resources will likely come from nuclear energy of either fission or later fusion sources. Although meeting these challenges will be difficult and will require foresight by government and industry, within 100 years, there will be a different world economy, one that will likely be struggling with limited resources, environmental degradation, and population issues, unless the difficult choices are made and forward-looking plans are initiated soon.

The identification and mining of nickel, cobalt, and a variety of other commodities that are or will be in short supply on Earth, or that could be mined, produced, and delivered at a lower cost in space would contribute to and drive the world's technology to a scale never before contemplated. This assumes that the economics become favorable. During the next few decades, large multinational quasi-governmental industrial groups are likely to develop to handle such projects, if they have not already begun to assemble. One day in the decades ahead, mining for such high-volume, low-grade commodities (e.g., aluminum, thorium, uranium) on Earth will only be of historical interest. Even some of the low-volume, high-grade operations (e.g., nickel, cobalt, platinum, rare-earth elements) may disappear on Earth because they would become operations in space as secondary recovery projects.

The availability of this resource could easily overwhelm the market for this metal on Earth for many years, as could that produced for other commodities mined in space as well. These operations would have large power demands that would be supplied by robust nuclear power systems to run heavy machinery specially designed to operate in space. The mining plan and associated economics of operating in space would involve a new scale of operations never before attempted by humans.

Mining would likely consist of pit excavation by controlled blasting to break up a selected part of the asteroid into smaller blocks and allowing them to settle back into the pit. The blocks would then be loaded into crushers to reduce the blocks into smaller fragments suitable for loading into transport vehicles. These transport vehicles would then be coupled together to form a space train that would bring the raw ores back to the Moon for further processing into concentrates. This could then be smelted on the Moon to a form useful to industry or sent directly back to Earth orbit for transfer of high-value concentrates, or metal product, to the surface via the so-called space elevator or new orbital transfer methods for processing. As indicated, Sonter (1998) identified the requirements that must be satisfied to make an orebody in the geologic and mining engineering sense, that is, to identify it as a resource that can support an economic materials retrieval project (also see Campbell et al., 2009b). Like mining projects on Earth, each project, whether it is located on the Moon, Mars, or an NEA, will have its own idiosyncrasies. The proximity of some NEAs makes them primary targets for exploration and possible development (see Ambrose, Chapter 1; Cutright, Chapter 4, this text, and NASA, 2009a).

Astronomical work during the last 15 years has increased the number of known NEAs from about 30 to about 430. In 1998, the discovery rate was in excess of 50 per year. Asteroid geology has also advanced greatly in the last few decades, drawing on spectroscopic and dynamical studies of asteroids and comets and on meteorite studies. Reasonable correlations can now be made between spectral and/or photometric asteroid types and inferred surface mineralogy. It is now believed that as many as 50% of NEAs may be volatiles bearing, containing clays, hydrated salts, and hydrocarbons. Sonter (1998) suggests that a continuum from asteroidal to dormant cometary bodies exists within the population of NEAs. Exploring asteroids, moons, and planets beyond Mars will require a power source different from power sources now deployed in American spacecrafts. As previously indicated, radioisotope thermal generators and solar energy cannot meet the challenges posed by proposed missions to the cold dark regions of our solar system. The NASA scientists from Oak Ridge National Laboratory are convinced that nuclear fission power will accomplish the goals (NASA Oak Ridge National Laboratory, 2004).

NUCLEAR POWER REQUIREMENTS

It should be reemphasized that for spacecrafts carrying scientific instruments beyond Mars, solar energy is not an option, and command and control of crafts are more complicated. The traditional approach of mounting solar cells on unmanned space crafts works well for voyages to Venus, Mercury, and Mars. However, beyond Mars, this approach is not practical because the sunlight's intensity is so low that the space probe cannot capture enough solar energy without huge arrays of photovoltaic cells. As preliminary exploration programs move beyond Mars, an alternative source of electrical power is required.

Radioisotope thermal generators are a good option for providing low levels of electrical power for such missions as Voyager, Galileo, and Cassini, which only required about 1 kW (1,000 W) of power. Most have had only a few hundred watts of power.

The bulk of the solar system simply cannot be explored in any meaningful way unless we use nuclear reactors in space. The use of RTGs in the recent Cassini mission, for example, was not without public debate. To provide the level of power required for this mission, plutonium was used as the principal source of power. NASA will explore different planets (and their moons) with more robust spacecrafts that can maneuver around moons, collect more data, and communicate the information to Earth more quickly than can be done with current technologies. More electricity will be needed to operate the basic systems that will be required. Science packages, mission support systems, and electric propulsion all require significant power resources. These needs can be met only using spacecrafts powered by nuclear reactors. The future of science in space depends on the successful deployment of space-based reactor power systems, especially as heavy electrical demands are required in mining, processing, and delivering minerals and other commodities back to Earth.

Aluminum is one commodity that has large electrical requirements for processing. Aluminum is apparently available in the regolith on the Moon in significant concentrations. On Earth, the aluminum industry's smelting plants use large amounts of direct current electric power commonly generated by a dedicated mine-mouth coal plant. This plant is also commonly located on or near a lake or river as a source of cooling water and for other uses.

Modern aluminum smelters operate at 200 to 600 MW of alternating current electric power, which is converted in a rectifier yard to direct current for use in the aluminum reduction pots. In producing about 175,000 tons of aluminum ingots, each plant produces about 8,000 tons of spent pot liner (SPL) per year. Total world industry production is about 700,000 tons of SPL, which has been classified as a hazardous waste (Columbia Ventures Corporation, 1993).

If lunar aluminum resources, for example, could be mined, concentrated, and smelted using a nuclear power system to provide the large electricity needs, the cost of aluminum ingots delivered to Earth via the space elevator eventually could replace aluminum mining and smelting on Earth. Once facilities such as the space elevator are in place, it is conceivable that most heavy industries presently using resources on Earth could also find and mine them on the Moon or elsewhere in the solar system.

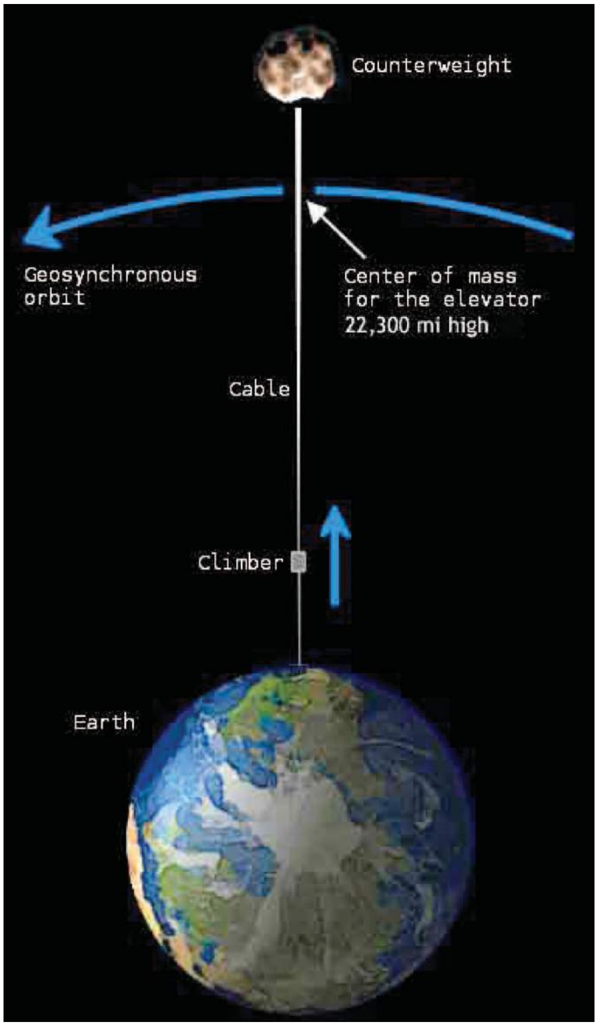

FIGURE 25. Basic space elevator concept. From Hoagland (2005); reprinted with permission.

This would result in decreased electrical usage and decreased stress that heavy industries inherently exert on the environment such as burning coal and using water resources on Earth. Disposal of SPLs, for example, on the Moon would also be less of a problem than on Earth. The NIMBY issue would seem at first not to be present on the Moon. However, international real property rights have been treated to some extent in the United Nations-sponsored 1967 Outer Space Treaty and in the 1979 Moon Treaty (White, 1997). Once such international treaties are signed, disagreements, disputes, litigation, and NIMBY issues commonly follow. Regulations will then evolve to address grievances even in space, especially over mineral resources (see Reilly, Chapter 7, this text).

Commodity Transportation to Earth

Once a commodity has been mined or refined, it will need to be transported back to Earth. Space trains could be used to transport the material back to Earth orbit. These trains would not be designed to reenter Earth's atmosphere, so other methods would need to be used to transport the material back to Earth once in orbit. Two such concepts are the space elevator and the space plane.

The space elevator in concept is a vertical conveyance system with one end anchored on Earth and the other attached to a satellite in geosynchronous orbit that will be used to ferry people and materials quickly and safely into Earth orbit and from orbit back to Earth. Edwards (2003) described the history of the space elevator concept, which is presently under development via government and industry funding. Recent conferences are discussing its feasibility and next steps in development (Anonymous, 2008b).

As technology has advanced, developments in nanotechnology have led to strong materials that apparently meet the primary need of the space elevator (i.e., a strong, flexible, seamless belt made of carbon nanotubes that can be made as long as needed; see Figures 25 and 26 for general concepts).

Once again, the power to operate the electrical motors needed to conduct the high-speed lifts in a space elevator is likely to be generated by small nuclear power units capable of producing significant amps for lifting outbound materials, such as personnel and equipment, and so on. The elevator would need to brake on the way down for incoming freight, such as mineral concentrates, personnel, and other materials. Even removal of high-level radioactive and hazardous wastes conceivably could be transferred by the space elevator into an orbiting craft for storage in a parking orbit around Earth or for storage on the Moon as a future resource.

Other concepts are also being considered, such as the space plane, a vehicle that has the potential to achieve orbit and return from orbit at costs far below those

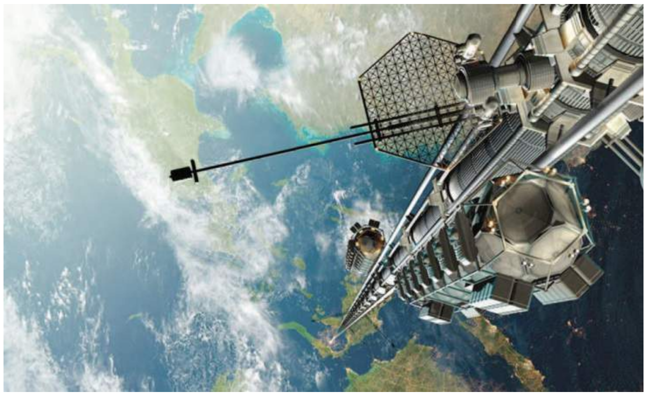

FIGURE 26. Conceptual view of the space elevator. From Hoagland (2005); reprinted with permission.

FIGURE 27. Artist's conception of a large-mass impact on Earth. Courtesy of Don Davis.

involved in present launch vehicles (NASA, 2009d). This approach has been under development for many years, and recent tests indicate that the space plane is scalable to a size capable of carrying heavy equipment into space.

The space elevator or space plane could open numerous space-related opportunities and would eliminate most of the need for payload lifting as now practiced by NASA at a cost of about US $10,000 per pound. In doing so, NASA would transfer its focus to matters related to activities in space. In the process, the industry would likely have an increasing function in the development of various off-world projects. Safety issues and potential hazards associated with building and operating such facilities would require responsible consideration.

Aluminum, iron, steel, metal mining, and other mining companies with special interests in operating in space or on the Moon could combine efforts to raise the necessary funds and to spread the risk of such projects. These new mega-mining companies could also raise funds via public stock offerings.

Near-Earth Asteroids and Comets

The principal need to be in space is clearly based on protecting Earth from life-extinguishing events coming from deep space in the form of impacts by NEAs and comets (summarized by Chapman, 2004). Monitoring NEAs has increased substantially during the past ten years using NASA's Spaceguard Survey (NASA). The Spaceguard Survey uses Earth-based telescopes to locate NEAs and comets that could threaten Earth. The Spaceguard Survey effectively located NEAs and comets with diameters greater than 1 km, which would have impact energy greater than 100,000 Mt (mega-tons TNT-equivalent). The NEAs and comets with diameters from approximately 100 m (328 ft) to 1 km (0.6 mi) (impact energies 20 – 100,000 Mt) do not pose a significant danger to civilization, and the Spaceguard Survey cannot detect all earth-crossing objects less than 100 m (328 ft) in diameter.

Determining what to do when an NEA is found to be heading for a collision with Earth is still under debate primarily because the subject has become heavily politicized and funding depends on Washington in supporting NASA. Collisions by large bodies have happened in the past on Earth and will happen again in the future (Figure 27) and represent possible species-extinguishing events, including humans. There have been five major mass extinctions that have resulted in exterminating one-half of the species present on Earth at those times. Of those events, two are thought to have been possibly the result of an asteroid(s) impacting Earth. One was at the end of the Permian period, 250 Ma, and it killed 90% of all species. The second was at the end of the Cretaceous period, 65.5 Ma, and it ended the reign of the dinosaurs and other species.

NASA operates a robust program of monitoring research on astrophysics through the NASA Astrophysics Data System (National Aeronautics and Space Administration, 2008d). If the Moon becomes a base for future exploration for resources, such operations could also incorporate NEA-monitoring facilities and response operations as required. However, Russell Schweickart, Apollo 9 astronaut and past chairman of the B612 Foundation, is leading the efforts to implement an alternate approach to the NEA issue. Instead of taking on the cost and long-term commitment of a Moon-based stand-alone monitoring facility, Schweickart (2008) suggests that infrared telescopes (dual band)

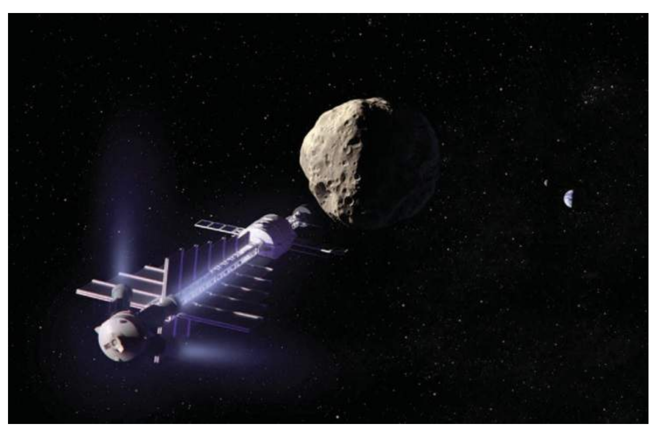

FIGURE 28. A so-called robotic gravity tractor moving an asteroid into a new orbit. Image courtesy of Dan Durda and the B612 Foundation.

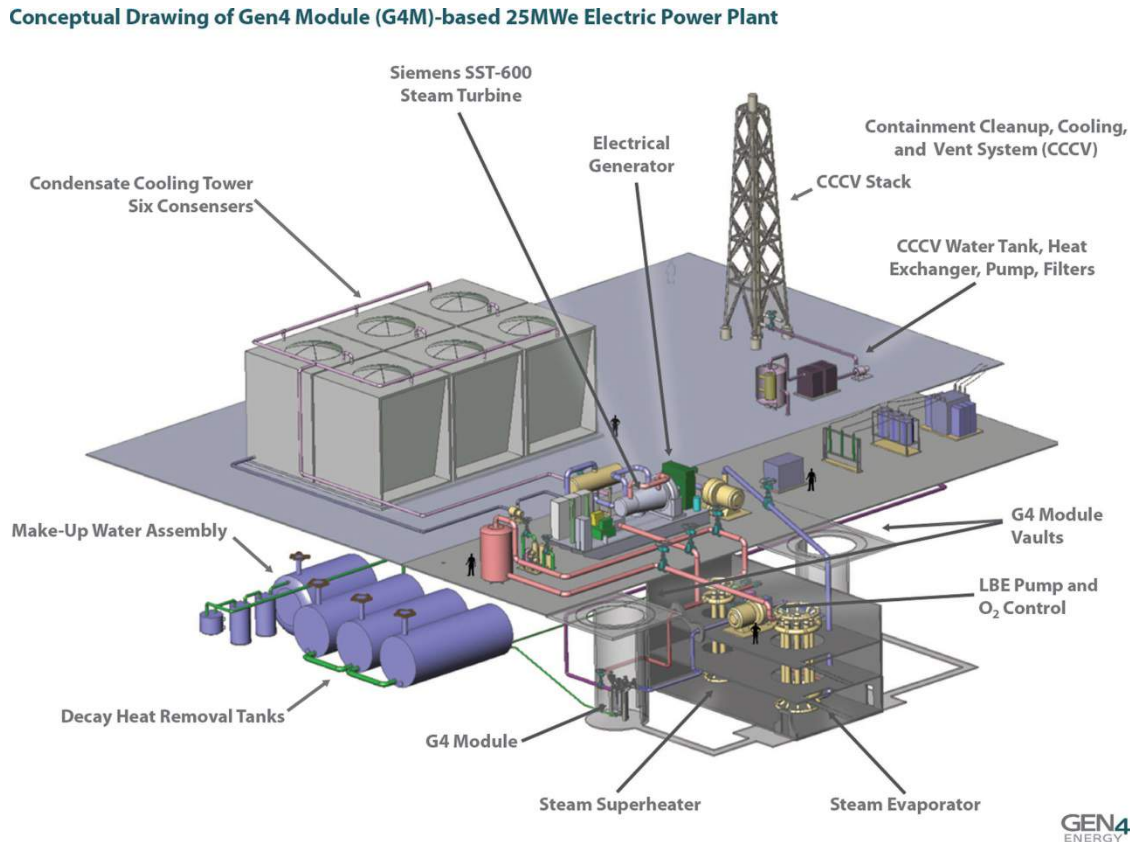

FIGURE 29. GEN4: A small modular nuclear power plant. Reprinted with permission.

in a Venus-trailing orbit would accelerate the NEA discovery process and provide better mass estimates to determine the risk and nature of the response to any threat. He also suggests that NEA deflection can be effectively handled by robotic Earth-launched missions using such approaches as a gravity tractor (Figure 28) and other methods (see Schweickart, 2008).

Safety issues and potential hazards associated with operating such equipment would require responsible consideration to ensure that control of NEAs are maintained and represent a minimal threat to Earth. Potential unintended consequences of operating such systems would require scrutiny by oversight management. This approach and all future approaches will be powered by a combination of solar and nuclear systems; the former for small electrical loads and the latter for heavy electrical loads.

The International Atomic Energy Agency (2005b) concludes that the increased growth and scale of pending space activities, the complication of tasks to be fulfilled, and the increasing requirements for power and propulsion logically lead to the use of nuclear power in space. Nuclear power will dominate in providing propulsion and power-generating units for future near-Earth and interplanetary missions. Currently, no alternatives exist for missions to outer space or for landing on planetary surfaces. International cooperative efforts to send more nuclear-powered probes for missions to the outer planets of the solar system and a manned mission to Mars are in various stages of planning. Once we are ready to leave the solar system, the space-time travel issues will need to be confronted and solved successfully. The Tau Zero Foundation (2009) provides a focus on the science and technology of deep-space travel (see the Tau Zero Foundation Web site for publications).

EARTH-BASED SPIN-OFF FROM SPACE RESEARCH

Just as it did in the 1960s, research in developing space objectives always brings many advances in a variety of scientific and engineering fields. Research on nuclear power can be expected to pay great dividends to technological development on Earth. These areas include domestic nuclear power systems of a variety of sizes and output power (Figure 29) and medicine, laser equipment and electronic devices, optics, timekeeping processes, refrigeration equipment, and materials technology.

The Hyperion Power Generation, Inc. (HPG), in cooperation with the United States Los Alamos National Laboratory is developing and commercializing a small factory-sealed, mass-produced, transportable nuclear power module that is inherently safe and proliferation resistant. Hyperion recently reorganized as Gen4 Energy. The technology uses and builds on similar features of more than 60 training reactors that have been safely operated for years in universities and laboratories around the globe. Currently identified applications include industrial use (oil shale and sand retorting), power for military installations, homeland security, emergency disaster response, and for use with remote communities and associated infrastructure for mining operations, including those located off-world.

The GEN4 uranium hydride, a molten core nuclear reactor, is designed to produce approximately 70 MW of thermal energy, or 27 MW of electricity when connected to a steam turbine. The reactor is termed inherently safe and proliferation resistant and uses the energy of low-enriched uranium fuel. For comparison, 4,000 GEN4 units would generate more nuclear power than the 104 nuclear reactors currently operating in the United States. Furthermore, that is equivalent of 108 GW for 4,000 GEN4 uranium hydride reactors versus 98 GW from all the reactors in the United States at present. The cost of the small reactors will be about US $1,400/kW. After five years, each reactor would have a softball-size amount of waste. The uranium hydride reactor can burn up to 50% of the uranium or about ten times more than current full-scale reactors (GEN4 Energy, 2012). Bill Gates (ex-Microsoft) has also endorsed using small-scale nuclear power plants (25,000 MW units or less), often called “nuclear batteries,” for cities after disasters such as hurricanes and in remote areas (see Schwartz (2010).

In the future, nuclear power will be needed for space missions with high-power demands. For example, the flow of data will grow enormously, and spacecrafts with sufficiently powerful nuclear systems placed in geostationary orbits will be needed to manage this flow of data. The currently used low-power RTGs simply will not handle the job.

High-end technologies will need to be developed in space. For a variety of reasons, certain technology processes cannot occur on Earth because they require microgravity and/or the hard vacuum that can only be found in space. For example, microspheres, and special-purpose ultrapure semiconductors, microencapsulation, and protein crystals that are needed on Earth can only be produced in space. In the long term, as discussed previously, it may be possible to transmit power to Earth from space by microwave or laser energy to provide the main power grid or inaccessible areas with electrical power. Technologies developing out of the nonelectric applications of nuclear power are being used in seawater desalination, hydrogen production, and other industrial applications. All of these require significant energy and, thus, necessitate the use of nuclear power systems in space and on Earth with new, perhaps smaller, reactors being developed today based on decades of research and development on space-related activities.

CONCLUSIONS

We have concluded that nuclear power is an important source of energy on Earth and that it will have an essential function in space to provide the electricity to power both propulsion systems of various types and all of the other mission electronic functions. We have found that ideas initially developed for space applications have also stimulated a new vision for Earth-based power systems, both large and small. These systems include new ion plasma propulsion systems and new high-efficiency gas-cooled reactors. This new vision also includes a reexamination of high-efficiency generation cycles perhaps involveing fluids other than steam and the use of heat pipes for compact reactors for very specialized and localized usage in nuclear reactors. However, all this research does not indicate much more than speculation about the material benefits of space exploration. In the past, benefits have been realized during the preparation for past missions through the innovations that are required in information transmission, the use of materials in extreme conditions, in precision and miniaturization technologies, and in human existence in space. The short- and long-term benefits to the humans of Earth can be divided into the following broad categories:

1) Further development of materials capable of withstanding very severe environments;
2) Advanced development of small nuclear power generators in remote locations (and perhaps in harsh environments) under remote control;
3) Advanced development of direct-energy conversion systems;
4) Increased knowledge of the medical effects of zero gravity and long-term confinement on humans and how to counteract this impact;
5) Precision technology (optics, lasers, time keeping, electronic devices, etc.); and
6) Commodities on Earth, such as nickel, cobalt, rare earths, and even nuclear resources, uranium

and thorium, and other commodities are likely to exist either on the Moon or elsewhere in the solar system in concentrations of potential economic interest to industry.

Although increased international cooperation will help create and maintain harmony among humans, the principal drivers of the industrialization of space will be built around commerce and the self-interest of each country, and although cooperation is preferred, future development of nuclear power in space depends to a large extent on the advances made by the industry and associated research personnel within each country. Governments facilitate, industry personnel execute. Space development will likely result in the creation of large, multinational, quasi-governmental industrial groups to handle the complex scale and investment required for such projects, not unlike those presently handled by NASA or the ESA.

The Russian Federation is already making plans to go to the Moon, providing the funds can be found (Anonymous, 2005). China, India, and Japan have recently sent spacecrafts to the Moon. South Korea is building its own space program following China's lead. India launched its first unmanned spacecraft to orbit the Moon in October of 2008. The Indian mission is scheduled to last two years, prepare a three-dimensional atlas of the Moon, and prospect the lunar surface for natural resources, including uranium (Datta and Chakravarty, 2008; Sengupta, 2008).

The findings of the President's Commission on Implementation of United States Space Exploration Policy (2004) present the general views outside of NASA and are summarized below:

1) Space exploration offers an extraordinary opportunity to stimulate engineering, geologic, and associated sciences for America's students and teachers and to engage the public in journeys that will shape the course of human destiny.
2) Sustaining the long-term exploration of the solar system requires a robust space industry that will contribute to national economic growth, produce new products through the creation of new knowledge, and lead the world in invention and innovation.
3) Implementing the space exploration vision will be enabled by scientific knowledge and will enable compelling scientific opportunities to study Earth and its environs, the solar system, other planetary systems, and the universe.
4) The space exploration vision must be managed as a significant national priority, a shared commitment of the President, Congress, and the American people.
5) NASA's relationship to the private sector, its organizational structure, business culture, and management processes - all mostly inherited from the Apollo era - must be decisively transformed to implement the new multi-decadal space exploration vision.
6) The successful development of identified enabling technologies will be critical to attainment of exploration objectives within reasonable schedules and affordable costs.
7) International talents and technologies will be of significant value in successfully implementing the space exploration vision and tapping into the global marketplace, which is consistent with the United States core value of using private sector resources to meet mission goals.

Because long-term planning is a prerequisite to exploration and development in orbit, in space, or on the Moon, Mars, or other bodies, we have concluded that these programs will proceed step by step within the decades ahead as they make sense politically to the American population for government-funded projects and also economically within industry for privately funded projects. Although funding by the federal government has provided the basic research required in sending probes to study the various bodies in our solar system as well as the early applied research in the Apollo lunar program involving astronauts, in the decades ahead, industry will likely assume the lead in ventures into space that are based solely on the perceived economic value to the corporations and their stockholders. Early signs of the transition are evident by Bill Gates' support of small nuclear reactors as discussed earlier and by Planetary Resources, Inc, whose current objective is to mine near-earth asteroids, see Wall, (2012). This will likely evolve into a base on the Moon. In the meantime, Planetary Resources, Inc. and a number of other groups and companies press forward into space, (see Planetary Resources Press Release, 2012 and Coppinger, 2013).

The expected increase in human activity in space and on other bodies in this solar system carries additional risks compared with similar activities on Earth. Along with the vacuum of space, low gravity, and the hostile atmospheres of other planets, the potential increase in adsorbed doses of radiation needs to be evaluated in light of recent data on the health effects of chronic radiation. The ease with which cumulative dose can be measured for individuals and for living and working environments makes dose monitoring extremely easy, allows accurate dose reconstruction, and makes tracking effects, implementing safety procedures, and mitigating adverse health effects highly applicable and predictive. In addition, recent data have shown that the LNT may not be correct and may not be applicable to the radiation doses expected in space. The actual threshold of between 5 and 10 rem/yr (0.05 – 0.1 Sv/yr) may be applicable to space environments and should be considered to regulate off-world operations and for design requirements with respect to shielding in construction and for long- term operations.

The road ahead also will be fraught with potential hazards, and accidents will occur because accidents and other setbacks have always occurred in new ventures throughout human history. Industrial accidents still occur on Earth today. But with the perceived need to develop new sources of energy to power Earth and the ventures around the solar system and even beyond, the intended consequences will encourage the exploration and development of mineral resources as primary objectives to the space program.

After initial research and technology development and as the last of the cheap commodities are exhausted on Earth, the cost of off-world resources will become economically attractive for development by the industry. As a natural progression during the next 40 to 50 years and beyond, natural resource corporations will certainly wring out the last of the metals and other commodities on Earth from dumps and landfills until either the costs or the lack of political cooperation via NIMBY brings the activities to a close. Society will also encourage or require industry to expand recycling of products until population requirements outstrip such recoveries. Mineral deposits on Earth not now considered to be economic will be developed until the economics, environmental pressures, or substitutions make such deposits uneconomic to produce. Substitutions have been at the core of industrial research since the beginning of the Industrial Revolution and, driven by population growth of about 20% by 2025, will continue until the economics force the industry to turn to new resources off-world.

Last, Earth still holds the promise of new discoveries of mineral resources, especially in the remote reaches of Canada, Australia, Alaska, Antarctica, China, Russia, and elsewhere (Laznicka, 1999). The power supplies required for developing such remote resources will soon be provided by the small-scale nuclear power plants previously discussed. The many activities presently under way by industry in uranium and thorium exploration on Earth (Campbell et al., 2008) confirm that Earth still has such resources to contribute. However, as opposition to development and political disagreements between countries increase, commodity prices rise, and as the distribution of resources are withheld from the world economy, secure sources of materials will likely be sought off-world in either national or multinational programs within the centuries ahead.

As the United States, China, India, and others continue to conduct robotic exploration programs, we will learn more about the geology of other moons, asteroids, and other bodies. Applying well-studied analogs on Earth to geologic environments on such bodies in the solar system or finding new geologic associations off-world that offer commodities needed by humans, these new resources will provide the means to maintain Earth and to establish bases off-world as humans learn to survive and prosper in space (NASA, 2008g).

The function that meteor and comet impacts may have in bringing not only water but also metals of economic value to Earth may have more merit than is currently assumed. As previously discussed, areas in and around certain lunar impact craters contain anomalous metals. On Earth, beyond those already known, recent discoveries in Greenland by North American Nickel Inc., for example, may change some views on this matter. The Geological Survey of Denmark announced that the Maniitsoq structure represents "…the remains of a gigantic, three-billion-year-old meteorite impact …", see news release in Mining.com, 2012, and Garde, et al., 2012. Large nickel-copper sulphide mineralization has been recognized to date over a very large area of the structure, which, if the metal grades are sufficient, it may be the largest deposit of nickel and copper known on Earth. In addition, the Ilimaussaq Complex in Southwestern Greenland, not far from the Maniitsoq structure, is young by comparison, with an age of only 1.2 million years and occurs in a relatively small area spanning two fjords. This complex of syenites and granites represent at least three pulses of magmas. The silica content of the associated minerals is much higher than elsewhere in the world. Numerous pegmatites and hydrothermal veins are found all over the intrusions. Many minerals in these areas are found nowhere else in the world to date.

Greenland Minerals and Energy, Ltd. (2011) has confirmed a substantial, new rare earth and uranium discovery along the northern area of the Ilimaussaq Complex, which offers the potential to produce both a light and heavy rare-earth product, uranium and zinc concentrates, fluoride compounds and a zirconium product. Whether the metals were brought with the meteor that created the Maniitsoq structure or came from below as a result of the impact creating deep cracks surrounding the structure creating avenues for metals to rise in complex magmas from either the lower crust or upper mantle remain to be studied.

Placed in context with the early history on Earth where impacts were common, it is logical that concentrations of metals formed from stars going supernova accreted into metallic bodies that later formed meteors that pummeled the Earth during Archean and Proterozoic times to form segregations of mineralized zones of various metals. These bodies were likely subsequently altered by Earth processes involving pressure and temperature at depth and then over geological time by erosion and/or uplift that exposed the metals to hydrothermal activity and oxidation along shear zones leading to the Earth's surface. These metals were then to be discovered billions of years later by geologists in outcrops or by drilling. Many such zones will go unrecognized because of their excessive depth, and geologists will have to turn to off-world exploration where mineral resources may be present on or near the surface of the Moon, nearby asteroids, and even on Mars.

The justification for continuing the move into space is well made by Yeomans (1998). As previously discussed, recent exploration discoveries on the Moon may accelerate our activities (Yamashita et al., 2009), setting off a new race into space to explore for and develop natural resources, including water (from dark craters to make hydrogen for fuel and oxygen, etc.), nuclear minerals (uranium, thorium, and helium-3), rare-earth minerals, and other industrial commodities needed for use in space and on Earth at a competitive cost to replace those nonviable.

With the President now clearly supporting the privatization of space exploration, NASA and the U.S. Air Force and others can remain focused on important orbital and other mission activities (Axe, 2011). But until some form of practical fusion technology is available, the required nuclear resources (uranium and thorium) needed today and in the foreseeable future to drive the nuclear power-generating systems on Earth and in space for the rest of this century depend on the technological development of current and future missions to the Moon and beyond. The general consensus is that some form of nuclear power (which includes solar) will take humans around our solar system in the 21st century and beyond just as the wind first took humans around Earth in the 16th and 17th centuries. We will share an understanding with the explorers of the past and the astronauts of the future by exhibiting a common human characteristic in exploring the final frontier.

''We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.''

– T. S. Eliot (Little Gidding, 1942)

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Press Release

AAPG Memoir No. 101 Has Been Released as Text

Energy Resources for Human Settlement in the Solar System and Earth's Future in Space

The U.S. Constellation project, although cancelled in 2010 by President Obama, was designed to return US astronauts to the Moon by 2020 and support long-term human settlement as well as *in situ* development of mineral and energy resources for infrastructure on the Moon, fuel and life support materials while in space and for use of such energy and mineral resources on Earth. We have not lost this dream, however, but the initiative has passed to a number of entrepreneurs and private entities working, sometimes with NASA and sometimes independently to fully realize these goals.

This AAPG Special Publication 101 is a comprehensive and integrated review of energy resources in the Solar System, including materials that could both sustain future manned expeditions as well as meet Earth's energy challenges in the 21st century and beyond. Any long-range program of human exploration and settlement of the solar system must consider in situ resource utilization; the vital role that extraterrestrial energy minerals and related resources must also support human habitation of near Earth Space as well as the nearby worlds of the Moon, Mars and the Near Earth Asteroids.

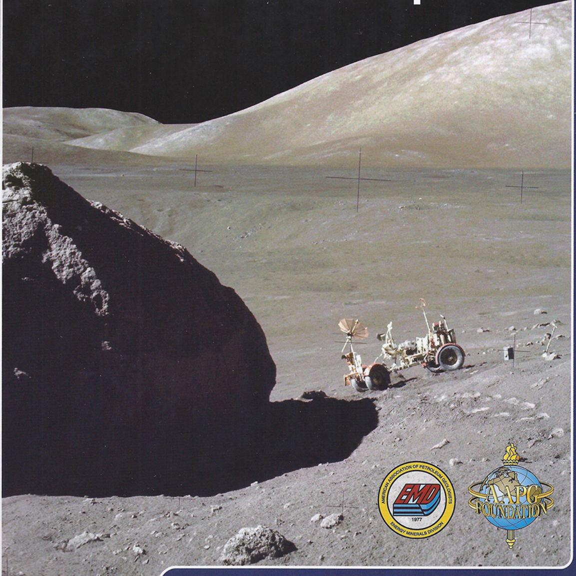
This volume is ambitious in scope, and encompasses three main themes related to energy and mineral resources in the Solar System as well as the economics and life-support considerations required for success in space:

(1) Sustaining and supporting human habitation and colonization of the solar system;
(2) Cost-effective manufacture of propellants for life support, human exploration of the solar system and transportation systems in space;
(3) Exploring for and developing sources of energy and materials for Earth importation to meet the growing demands for Rare Earth Elements, Platinum Group Metals, Nuclear Materials for both fission and fusion reactions and protection of sensitive environments on Earth.

This Memoir, produced in collaboration with AAPG's Energy Minerals Division and the Astrogeology Committee, is a clear reflection of AAPG's vision of advancing the science and technology of energy, minerals and hydrocarbon resources into the future and supporting exploration and development of the ultimate frontier, beyond Earth's atmosphere. For the Memoir 101 Table of Contents and Preface, see following pages. To place your order for the original publication (M101) in book format, see: http://store.aapg.org/detail.aspx?id=1179

AAPG Memoir 101

Energy Resources for Human Settlement in the Solar System and Earth's Future in Space



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Preface

Energy Resources for Human Settlement in the Solar System and Earth's Future in Space

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The solar system is the new and ultimate frontier for Earth. Future success in exploration and human habitation in the new frontier, beginning with the Moon, will depend on space missions and settlements becoming more self-sustaining through exploitation of extraterrestrial (i.e., local) energy and material resources. Missions to the new frontier can contribute meaningfully to the energy requirements of Earth because conventional energy resources such as oil, natural gas, and coal go beyond the period of peak capacity to production decline. Energy resources that can be harvested in space for the benefit of Earth include helium-3 that occurs in abundance on both the Moon and asteroids, as well as solar energy that can be collected and transmitted in concentrated form to Earth from orbit. Moreover, metals, platinum-group elements (PGEs), rare-earth elements (REEs), and volatiles (e.g., H, H_2O, and carbon compounds) are abundant on asteroids, many of which are relatively accessible from Earth. Hydrocarbons, hydrogen, and volatiles in the solar system are important for human exploration and habitation because they will provide essential high-energy, high-density fuels and feedstock for manufactured goods and materials for construction.

Since the United States National Aeronautics and Space Administration (NASA) conducted the Apollo 17 mission to the Moon in December 1972, human spaceflight has been confined to low Earth orbit (LEO), with the space shuttle and International Space Station. However, several nations including the United States, Japan, China, and India have recently expressed an interest in renewed manned expeditions to the Moon. The NASA Constellation program, although canceled in 2010 by United States President Barack Obama, was designed to return astronauts to the Moon by 2020. Unlike the NASA Apollo program, the Constellation program was envisioned to involve long-term human settlement as well as in-situ development of mineral and energy resources for infrastructure on the Moon. This would include supporting human resource needs

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and manufacturing rocket propellants from hydrogen from the lunar regolith and water ice, principally, in polar areas. The Constellation program would have contributed to mission costs as well as in decreasing reliance on expensive fuel-lifting costs from the gravity well of Earth. Moreover, the lower gravity well of the Moon could be used as a launching site for missions to Mars and other worlds in the solar system, given the possibility of water-ice and other lunar resources for such missions.

Improved rocket technology that goes beyond conventional liquid-propellant-fueled rockets will be needed to more efficiently access more distant targets such as Mars and the asteroid belt. Propulsion systems that use nuclear and ion technologies will provide greater specific impulse, defined as how many pounds or kilograms of thrust are attained from consuming 1 lb (or kilogram) of propellant per second. These advanced propulsion systems will reduce fuel costs, reduce transit time, and make human exploration of the solar system beyond the Moon more economically viable. However, although rocket technology can probably bring Mars and more distant planets into our grasp, the optimal target date for a United States manned mission to Mars is a distant 2035, 15 years beyond the projected return to the Moon in the Constellation program. Given the importance of learning how to establish and sustain a human presence in the solar system, a return to the Moon represents an advantage because knowledge gained from infrastructure development as well as mining and processing techniques can be later applied to Mars. Moreover, experience with the Apollo missions has proven that gravity on the Moon, one-sixth of Earth's gravity, is no impediment to the safe and efficient movement of both people and equipment. In contrast to the Moon, issues regarding maneuverability of both humans and mining equipment on near-Earth asteroids (NEAs) pose new technical challenges, resulting from microgravity conditions and enormous variations in rotational dynamics and consequent short-term variations in insolation (temperature) that are unique to each asteroid. In addition, although very little delta-v, defined as an incremental change in spacecraft velocity to achieve a new orbital configuration, may be needed to reach certain NEAs, a relatively large delta-v may be required for shipments of materials and the return trip for those whose orbits take them to remote positions relative to the Earth for extended periods. An even higher delta-v would be required to bring entire small asteroids or comets closer to the Earth orbit for resource extraction, as has been proposed by some in the past.

This special volume begins with three chapters dedicated to lunar resources (water ice, hydrogen, helium-3, and metals) and their impact on the economics and viability of human settlements on the Moon, as well as their potential as energy sources for importation to Earth. Survival, economics, physiological space adaptation, life support, energy supply, and international competition make up just a few of the more obvious concerns directly related to available resources on the Moon. Accessing, producing, marketing, and using those lunar resources, and doing so efficiently, require imaginative planning and execution and a full understanding of the lessons of the Apollo lunar exploration and other space missions that have provided human physiological information.

Chapter 1 by William A. Ambrose reviews lunar resources that could be used for in-situ production of propellants and other materials that could support human missions and settlements. These materials include hydrogen and oxygen occurring other than in water ice; helium-3; uranium and thorium; regolith-related metals such as titanium, iron, and aluminum; elements of pyroclastic origin, which include iron, zinc, cadmium, mercury, lead, copper, and fluorine; rare metals and PGEs such as nickel, platinum, palladium, iridium, and gold, which may occur within segregated impact melt sheets and layered mafic extrusives; and volatiles such as nitrogen, carbon, and lithium, which occur either with breccias or in exhalative deposits. This chapter summarizes the presently known occurrence and distribution of hydrogen and water-ice resources on the Moon. Water ice and other volatiles are particularly abundant at the lunar poles, where they have accumulated in cold traps for at least three billion years (3 Ga) in permanently shadowed or poorly illuminated deep crater floors. These cold traps are currently being investigated and evaluated by the Lunar Reconnaissance Orbiter (LRO) satellite, launched in June 2009. This chapter also includes results from a variety of recent missions such as Clementine and Lunar Prospector, as well as preliminary and recent results from Kaguya, Chang'e 1, Chandrayaan-1, and a host of instrument packages onboard LRO. This study also characterizes the potential for human settlement in five different regions on the Moon— polar, nearside equatorial, Oceanus Procellarum, nearside limb, and farside— in terms of access to in-situ resources and strategic location for efficiently transferring material from mining sites to launch and industrial facilities involving minimal propellant consumption and lower delta-v costs.

In the second lunar chapter, Harrison H. Schmitt explores financial, environmental, and energy-supply implications of helium-3 fusion power from lunar sources. Embedded continuously in lunar regolith (upper dust layers) more than billions of years of time, concentrations of helium-3 have reached levels of probable economic interest. For example, the lunar regolith near the Apollo 11 landing site in Mare Tranquillitatis, 0.8 mi^2 (2 km^2), to a depth of 10 ft (3 m), contains approximately 220 lb (~100 kg) of helium-3, for instance, more than enough to power a 1 gigawatt (GW) fusion power plant for a year. Low-power-level, steady-state demonstrations of controlled fusion of helium-3 with deuterium and with itself have moved forward in the recent decades. Commercial viability of either of these fusion processes as power cycles requires significantly more research and development as well as a competitively priced source of helium-3. Making helium-3 fusion power available to humankind, as well as to successful space settlement, will require the use of the lessons of what has worked and has not worked during 50 years of human activities in space. Lessons from Apollo relative to future complex space endeavors include (1) using well-educated engineers and technicians in their twenties and managers and systems engineers in their thirties, (2) establishing independent internal design engineering activities in parallel with those of contractors or in-house efforts, (3) streamlining and downward delegation of management responsibilities to proven individuals, (4) seeding experienced systems engineers throughout the implementing organizations, and (5) placing senior managerial and technical leadership in the hands of experienced, competent, and courageous men and women.

Chapter 3 by Dieter Beike provides additional details on the economics of lunar helium-3 and describes the technological and commercial aspects for a lunar helium-3 mining operation that could fuel power plants both on the Moon and for importation to Earth. Several probable technical and economic barriers must first be overcome for helium-3 power generation to be viable. Commercially, a helium-3 operation would have to compete with other energy supply sources that might become available in the future. Furthermore, space technology research, development, and demonstration (RD&D) and fusion research should be pursued separately and should only form a symbiosis once a common fit caused by separately achieved scientific and/or technical progress justifies a joint commitment of financial resources. The RD&D costs for these programs could be several hundred billion dollars, which will mostly be provided by public investments. The private sector, however, is emerging in space technology and could be a significant factor in such a helium-3 value chain.

Bruce L. Cutright gives an overview of NEAs and related comets, collectively described as near-Earth objects (NEOs), in chapter 4. They are interesting as scientific destinations that can provide an understanding of the origin of the planets and the solar system. As exploration expands into space beyond the Earth-Moon system, NEOs probably can provide rocket fuel, oxygen, and life-support materials for space explorers, as well as materials and metals for construction in space and for trade with Earth. With the cancellation of the Constellation program in 2010, human missions to NEOs have now assumed a higher priority. Those NEOs that closely approach Earth, and which can be accessed via LEO, are the most accessible objects in the solar system in terms of propulsion requirements, requiring less delta-v to reach than the Moon. More than 7870 NEOs were identified as of January 2011, and by June 2012 about 1270 were identified as greater than 0.6 mi (>1 km) in diameter. The NEOs contain all the elements and materials to make space exploration and resource development rational, economically achievable, and profitable. These include water and other volatiles that can be used for manufacturing propellants, a variety of organic materials for chemical manufacture, and a host of metals such as iron, cobalt, PGEs, and REEs. Platinum-group elements and REEs are essential for advanced technology industries but are sufficiently rare on Earth as to represent a viable market opportunity over an extended period of time to support planning, development, mining, and trade between Earth and settlements in space. Icy asteroids and comets can provide the water ice as fuel for refueling in orbit, thereby radically reducing the fuel requirements at launch for any subsequent missions and supporting extended exploration and exploitation efforts.

In chapter 4, Michael D. Max et al. discuss gas hydrates on Mars. Unaccountably high levels of methane (>10 ppb) have recently been detected in the Martian atmosphere. Although this is a low concentration, it is nevertheless anomalously high, given that methane is unstable in the Martian atmosphere, resulting from photodissociation in ultraviolet light. Whatever the immediate source of this methane, whether by biogenic or abiogenic process, may have occurred in association with liquid water in the deep (>3+ mi [>5+ km]) subsurface, where geothermal heating is thought to be sufficient to raise crustal temperatures above the freezing point of water. Evidence exists that Mars once possessed appreciable quantities of subpermafrost groundwater that may currently persist. Moreover, methane generation may have occurred throughout much of the geologic history of Mars. Hydrate formation requires either liquid water or ice. The amount of water on Mars is unknown; however, the present best geologic estimates suggest that the equivalent of a global layer of water 0.3 to 0.6 mi (0.5–1.0 km) deep may be stored as ground ice and groundwater. The authors' hydrocarbon system analysis indicates that the base of the gas hydrate stability zone (BGHSZ) for methane gas and hydrate deposits ranges from approximately 3 to 6 mi (~5–10 km) at the equator to approximately 7 to 14.4 mi (~12–24 km) at the poles, although the BGHSZ can occur at much shallower depths (tens of meters). Shallow methane deposits may constitute a critical probable resource that could make Mars an enabling stepping stone for the sustainable exploration of the solar system. They provide the basis, or feedstock, for constructing facilities and machines from local Martian resources and for making higher energy-density chemical rocket fuels for both return journeys to Earth and for more distant exploration.

Moving onward to the outer solar system, John N. Curchin and Roger M. Clark summarize in chapter 6 the current knowledge of hydrocarbons in the atmosphere of Titan with remote sensing. Hydrocarbon reservoirs at Titan occur in a variety of forms— as gases and condensates in the atmosphere; as liquids in lakes and bays; slushy soils and solid sediments within sand dunes; and in the subsurface, possibly bound in clathrate hydrates or even within a global hydrocarbon aquifer. The challenge for the petroleum geologist at Titan is to identify the specific type and amount of each compound present, the function each takes in a global cycling of various hydrocarbon components, and how the size and distribution of many reservoirs change through time. Because the atmosphere of Titan contains multiple haze layers, it is difficult to obtain compositional information on surface features and, therefore, instruments that operate at wavelengths less affected by haze are used. Unfortunately, many of the data are low in resolution and divergent interpretations abound. However, with the Cassini spacecraft currently orbiting Saturn, the surface composition of Titan is slowly coming into focus. Curchin and Clark's review synthesizes the current state of knowledge of hydrocarbon presence and distribution at Titan, emphasizing those observations that have a direct compositional relevance to compounds in the atmosphere and on the surface.

The final three chapters in this special volume deal with policy and energy resource issues and technology in space. James F. Reilly II discusses in chapter 7 the issues that may arise from a space treaty similar to that in place for Antarctica. Discovery and exploration phases in frontier exploration eventually undergo a transition into an exploitation phase, inevitably requiring a regulatory framework to coordinate and govern research and economic activities. For example, the Earth orbital regime has entered the exploitation phase with the advent of a permanent research facility in the form of the International Space Station and an increasing activity in the private sector. The lunar regime and perhaps NEAs will be probably entering the exploitation phase within the next two decades. A structure in the form of an international agreement using elements similar to those from the Antarctic Treaty and the Intergovernmental Agreement (IGA) for the International Space Station could be used as an example of a probable regulatory structure for space exploration and exploitation. Economic development will eventually follow an initial research phase if not specifically prohibited in any future treaties or agreements. To manage these activities, an organization similar to the World Trade Organization (WTO) could form the basis of a management body for economic activities. The WTO model would also provide a means to resolve disputes with mandatory actions and recommendations binding to all parties. Finally, a regulatory agency similar to WTO could enforce the fiscal rules outlined in the International Space Station IGA regarding participation rights and allocations of resources so that the political risk of redistribution economics that plague the Law of the Sea Convention will not impede future extraterrestrial mining operations.

Chapter 8 by David R. Criswell on solar energy in space places this almost limitless power source in context with Earth energy sources and offers a case for developing space-based solar energy from a lunar array. Although the Earth continually intercepts approximately 175,000 terewatts (TW) of solar power, only a fraction of this sunlight is captured every year by the biosphere in the form of atmospheric carbon (CO_2) and the oxygen (O_2) separated from water. Moreover, it is impractical and too costly to gather high-yield solar power on Earth because of adsorption from the atmosphere and reflection from clouds back to space. Currently, a stand-alone solar array on Earth provides an average energy output of 3 W equivalent per square meter (We/m^2) of ground area. Earthbound power storage, conversion systems, and long-distance transmission lines greatly decrease the effective output of solar cells or concentrators and increase expense. For example, 20 TW of Earth-based electric power require approximately 2.7 million mi^2

(~7 million km^2) of collector area, representing approximately 5% of the landmass of Earth. In contrast, the Moon, containing no appreciable atmosphere, is a reliable platform for the collection of solar energy. A lunar solar-power (LSP) system can economically gather diffuse solar power and convert it into streams of electromagnetic waves that are designed to dependably and safely deliver power efficiency to inexpensive receivers (rectennas) on Earth when power is needed. Moreover, materials for the collection of solar energy can be manufactured in situ on the Moon. Space-based solar energy has the potential for significantly augmenting earthbound energy systems and boosting the international economy. For example, the economic growth of the wealthy nations would accelerate as they finance both the LSP system and the growing consumer economies of the other nations. Poor nations could then afford to expend approximately 10% of their per capita gross domestic product to purchase approximately 2000 We/person (~2 kW hr equivalent per person) in power to build sustainable economies. For the first time in its existence, the human race could gather affordable net new worth from beyond the biosphere and build sustainable net new wealth of enormous scale.

Michael D. Campbell et al. review in chapter 9 the strategic significance of space-based nuclear resources, principally on the Moon. Nuclear systems already provide power for satellite and deep space exploratory missions. In the future, they can also serve as the source of propulsion for spacecraft and drive planet-based power systems. Mining is anticipated on the Moon for increasingly valuable radionuclide commodities, such as thorium and samarium, as well as REEs. Nuclear power is an important source of energy on Earth. Ideas initially developed for space applications have also stimulated a new vision for Earth-based power systems at a variety of scales. These systems include new ion-plasma propulsion systems and new high-efficiency, gas-cooled reactors. This new vision also includes a reexamination of high-efficiency generation cycles perhaps involving fluids other than steam and the use of heat pipes for compact reactors for very specialized and localized usage in nuclear reactors. Space-based nuclear power will provide the means necessary to realize this vision whereas advances in other areas will provide enhanced environmental safeguards in using nuclear power in innovative ways, such as a space elevator or a ramjet to deliver materials to and from the surface of Earth and personnel and equipment into space and a space gravity tractor to nudge errant asteroids and other bodies out of collision orbits. Nuclear systems will enable humankind to expand beyond the boundaries of Earth, provide new frontiers for exploration, ensure our protection, and renew critical natural resources while advancing spin-off technology on Earth. Until some form of fusion technology is available, required nuclear resources (uranium and thorium) needed today to drive the nuclear power-generating systems on Earth and in space for the rest of this century await further exploration and technological development on missions to the Moon and elsewhere. The general consensus is that some form of nuclear power will take humans around our solar system in the 21st century and beyond just as the wind first took humans around Earth in the 16th and 17th centuries. We will share an understanding with the explorers of the past and the astronauts of the future by exhibiting a common human characteristic in exploring the solar system and beyond.

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