The Role of Nuclear Power in Space Exploration and the Associated Environmental Issues: An Overview

AAPG Energy Minerals Div.
Uranium Committee
Special Report of 2009
for the
Astrogeology Committee,
AAPG EMD Annual Meeting,
Denver, Colorado
June 9, 2009

Chairman: Michael D. Campbell, P.G., P.H.

Committee Members:

Henry M. Wise, P.G.
Joseph Evensen, Ph.D.
Bruce Handley, P.G.
Stephen M. Testa, P.G.
James Conca, Ph.D., P.G., and
Hal Moore

The Role of Nuclear Power in Space Exploration and the Associated Environmental Issues: An Overview

A Report by the Uranium Committee
of the
Energy Minerals Division, AAPG

by

Michael D. Campbell, P.G., P.H. [1]

Jeffery D. King, P.G., [2]

Henry M. Wise, P.G., [3]

Bruce Handley, P.G.[4]

and

M. David Campbell, P.G. [5]

Version 2.3

June 2, 2009

Sponsored by

M. D. Campbell and Associates, L.P.
Houston and Seattle

Contents

The Role of Nuclear Power in Space Exploration and the Associated Environmental Issues: An Overview

Version 2.3

Abstract

Once humans landed on the Moon on July 20, 1969 the goal of space exploration envisioned by President John F. Kennedy in 1961 was already being realized. Achievement of this goal depended on the development of technologies to turn his vision into reality. One technology that was critical to the success was the harnessing of nuclear power to run these new systems. Nuclear power systems provide power for satellite systems and deep-space exploratory missions. In the future, they will provide propulsion for spacecraft and drive planet-based power systems. The maturing of these technologies 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 provide new sources for our dwindling resources and offset their increasing prices on Earth. Mining for increasingly valuable commodities such as thorium and samarium is envisaged on the Moon and selected asteroids 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" to deliver space-derived materials to Earth's surface and personnel and equipment into space, and a "space gravity tractor" to nudge errant asteroids and other bodies out of orbits that would collide with the Earth. Nuclear systems will enable humankind to expand beyond the boundaries of Earth, provide new frontiers for exploration, protect the Earth, and renew critical natural resources.

Introduction

In 2005, the International Atomic Energy Agency (IAEA) published a comprehensive review of the history and status of nuclear power used in space exploration. Based on this review and on our research, the objective of this report is to place some perspectives around the role nuclear power will likely play in the future, from developing and fueling the technology for use on Earth

(Campbell, *et al*., 2007) to developing the ability to explore for and to recover natural resources that likely await our discovery on the Moon or elsewhere in the Solar System. 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 could 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, powered by solar energy for low electrical demands and by nuclear energy for missions with heavy requirements.

Satellites

In late 1953, 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). 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 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 few per cent of the sunlight it would receive were it in Earth orbit. In that case, solar panels would have to be so large that employing them would be impractical (Rosen and Schnyer, especially page 157, 1989).

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. It would be tempting to believe that all power after launch could be supplied by solar energy. However, in many cases, missions will take place in areas too far from sufficient sunlight, areas where large solar panels will not be appropriate.

Limitations of solar power have logically lead 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 (RHUs). These units have been employed on both U.S. 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).

RTGs evolved out of a simple experiment in physics. In 1812, a German scientist (named T. J. Seebeck) discovered that when two dissimilar wires are connected at two junctions, 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 a number of 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 customized to fit the intended use of the electricity and for the planned mission duration.

The IAEA report (2005a) suggests that nuclear reactors can provide almost limitless power for almost any duration. However, they are not practicable for applications below 10 kW. 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 the powering of experiments are 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 a kilowatt 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 often needed rapid surges of large amounts of energy.

Lunar-Solar or Lunar-Nuclear Power

In the past, solar power was generally considered to be the most efficient for constant power levels of some 10–50 kW for as long as it was needed in some missions, given the availability of sufficient solar power. However, higher output could be obtained via a lunar-solar system suggested by Criswell (2001, 2004a and 2004b) where microwaves could be generated by large solar arrays on the Moon. In addition to supplying the Moon-base requirements, the excess power could be transferred by large aperture radar/microwave (i.e., power beaming) to the Earth for distribution conversion to power existing electrical grids.

The typical output ranges for the different power sources to supply missions are illustrated in Figure 1.

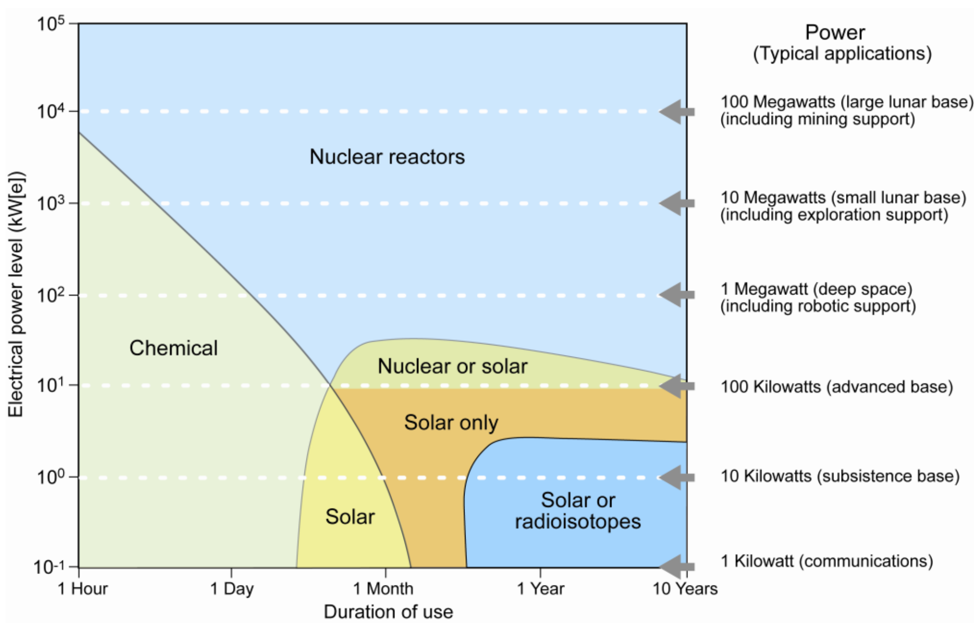


Figure 1 - Sources of Electricity for Application in Missions in Space
After IAEA (2005a)

Criswell (2001) 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, he 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 the Earth in a similar fashion, with similar apparent 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 provide 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 half a kilowatt, with more available by combining modules. The IAEA report (2005a) indicates that "small nuclear reactors have also been used in space, one by the U.S. in 1965 (called the SNAP-10A experimental reactor) which successfully achieved orbit, the only nuclear reactor ever orbited by the United States. The SNAP-10A reactor provided electrical power for an 8.5 mN ion test engine using cesium propellant. The test engine was shut off after one 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 kWt and more than 500 watts of electrical power for 43 days before the spacecraft's telemetry ultimately failed." It remains in a stable orbit and re-entry into the Earth's atmosphere is anticipated in about 4,000 years. The U.S. Atomic Energy Commission funded its account of the SNAP 10A program (see Atomics International, 1964).

The former Soviet Union routinely flew spacecraft-powered by nuclear reactors: 34 were launched between 1970 and 1989. The general consensus remains that the investigation of outer space (beyond Earth-space) is "unthinkable without the use of nuclear power sources for thermal and electrical energy". The U.S. researchers agreed (see IAEA, 2005a).

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/pound to lift a payload into orbit and about US$100,000 to deliver a pound of supplies to the Moon.

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 the red planet. By comparison, a nuclear-powered mission will be completed in 870 days for a stay of 550 days (see IAEA 2005a report). 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 Figure 2).

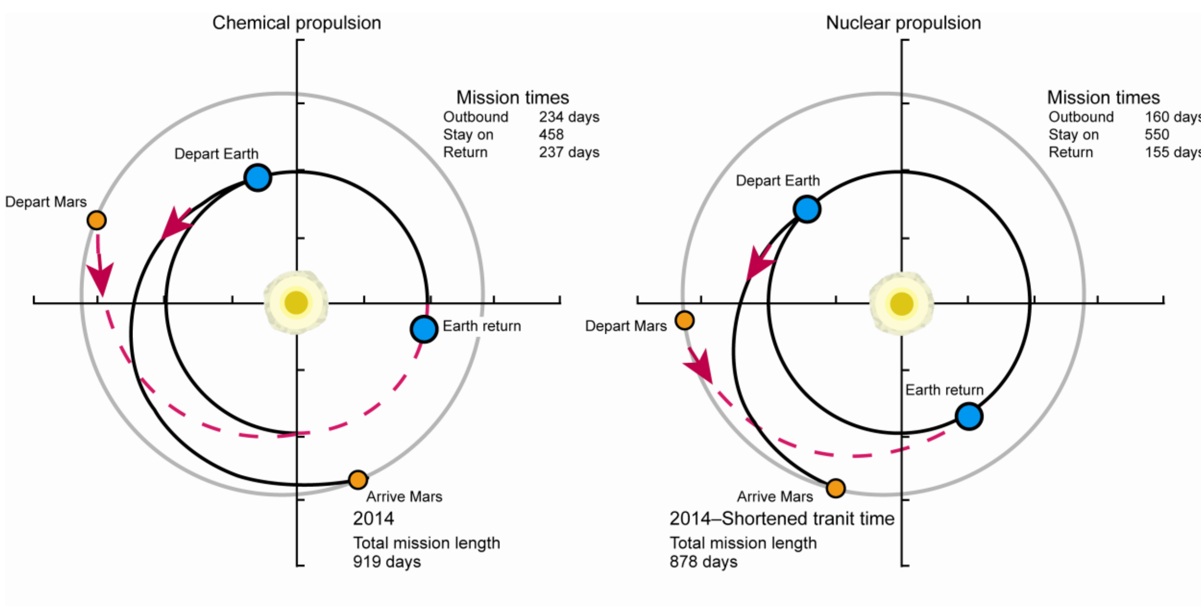


Figure 2 - Mission Duration - Chemical versus Nuclear Propulsion Systems (after IAEA 2005a)

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 (2005a) report indicates that the two parameters that provide a measure of the efficiency of a rocket propulsion energy source are the theoretical specific impulse(s) and the ratio of the take-off mass to the final mass in orbit.

Chemical reactions using hydrogen, oxygen or fluorine can achieve a specific impulse of 4,300 seconds 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 at the same time having a mass ratio of 3.2:1. With different cores, the specific impulse can be as much as seven times greater again 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*. While these missions use an electric arc to ionize xenon, the principal is the same. A nuclear engine would simply produce a higher thrust by causing xenon to become a plasma, rather than an ion, resulting in higher velocities.

Combining nuclear power with electrical thrusters will result in a high efficiency of the specific impulse for thrust; building power/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 50–100 kW of electrical power and more for onboard instrumentation over periods of 10 years or more.

There are new approaches to space travel now in effect that 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 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 these 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 Leonhand 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 3.

There will be additional Lagrange points available throughout the solar system to aid such travel, combined with orbital altering by fly-bys of planets and large moons, but propulsion will still be required even with optimized fuel consumption.

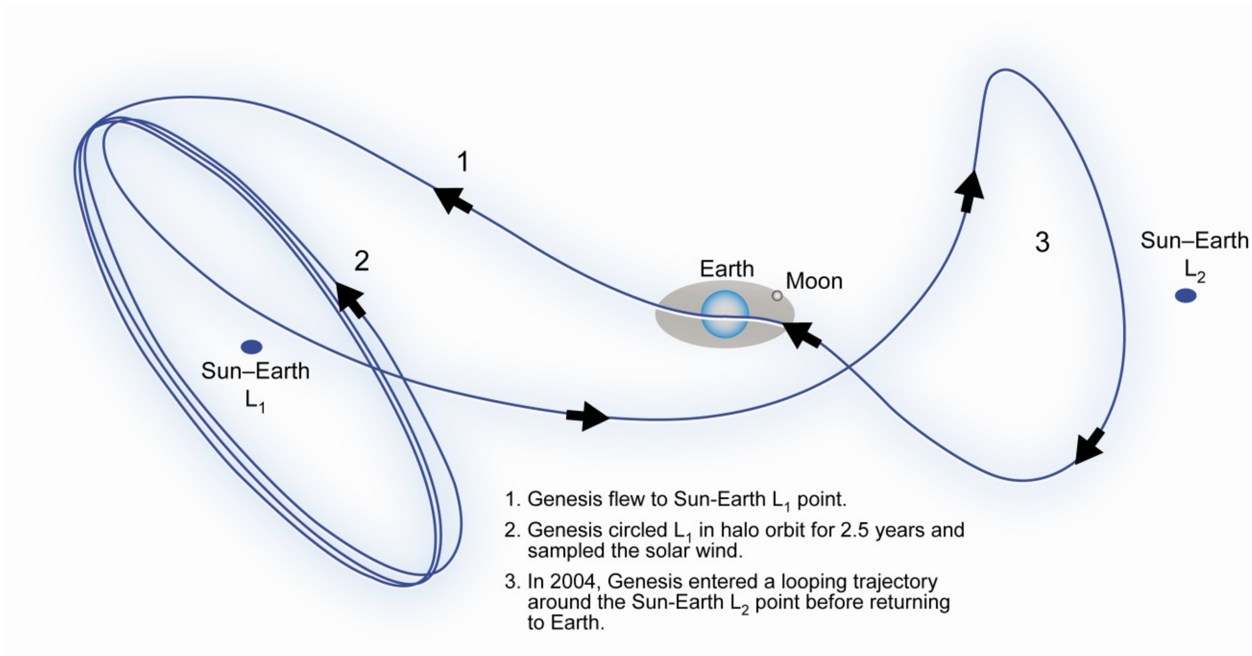


Figure 3 – Genesis Mission Pathways (Reddy, 2008)

Tracking orbits of bodies in space have expanded considerably over the past 20 years. The NASA/IPAC Extragalactic Database (NED) contains positions, basic data, and over 16,000,000 names for 10,400,000 extragalactic objects, as well as more than 5,000,000 bibliographic references to over 68,000 published papers, and 65,000 notes from catalogs and other publications (see NASA, 2008b). In addition, the Planetary Data System (PDS) is an archive of data from NASA planetary missions, which is sponsored by NASA's Science Mission Directorate and has become a basic resource for scientists around the world (see NASA (2008c).

The experience accumulated in developing space NPSs, electrical thrusters and NTPSs has enabled a number of missions focused on the Earth, such as round-the-clock all-weather radar surveillance and global telecommunication systems for both military and business interests. This includes global systems for communication with moving objects (as in GPS tracking). Needless to say, technology is leading the way in all areas in the exploration of space.

Planet-Based Power Systems

Getting to Mars may be the attainment of a primary objective for some but for humans to survive on the surface of a non-hostile planet, moon, or asteroid, a reliable source of electrical energy is needed. Approximately 3–20 kW(e) would be required, which exceeds the capabilities of RTG’s because of the mass of plutonium required. 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 remaining viable option.

The reactor, designated HOMER, designed and built by NASA contractors in the 1980s fulfills the need for a small power source. It was designed specifically for producing electricity on the surface of a planet, moon, or asteroid. The low-power requirement means that the reactor operates within well-understood regimes of power density, burn up and fission-gas release. The number of impacts of radiogenic particles is so low that there is no significant irradiation damage to core materials and hence has a long life.

Earth-Based Power Systems

The space research and development carried out in both the former Soviet Union/Russian Federation and the U.S. 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 are 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 (for detailed report, see IAEA (2004). In particular, one resulting benefit is the use of heat pipes in the SAFE-400 and HOMER 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.

Environmental Safeguards in Orbit

The risks associated with employing nuclear power in space are similar to those encountered on Earth. A few accidents have occurred but aside from the Chernobyl disaster (see the recent 2004 IAEA report), the use of nuclear power brings with it a risk no higher than other industrial environmental risks on Earth. We attempted to place the risks into perspective, see Campbell, *et al.,* (2005).

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 miles. 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 back-up emergency approach involves the dispersion of fuel, fission products and other materials with induced activity into the upper layers of the Earth's atmosphere. During the descent, aerodynamic heating, thermal destruction, melting, evaporation, oxidation, etc., 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 backup safety system was introduced after the failure of the change in orbit of the of Cosmos-954 spacecraft (for details, see the IAEA 2005a report). The descent of the Soviet Union's spacecraft resulted in large radioactive fragments of wreckage being strewn across a thin strip of northern Canada in 1978.

Safety, both for astronauts and other humans on Earth, has been a long-time 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 re-enter 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.

The IAEA (2005a) suggests 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 re-entry. Further, the ceramic is highly insoluble and primarily fractures into large pieces rather than 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) There are multiple layers of protective containment, 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 re-entry 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 U.S. launch vehicle resulted in the burn up of the SNAP-9A RTG during re-entry. This resulted in the dispersion of plutonium in the upper atmosphere. As a result of this accident and the consequent redesign of the RTGs, the current level of safety has been improved substantially.

A second accident occurred on May 18, 1968 after a launch aborted in mid-flight above Vandenberg Air Force Base and crashed into the sea off California. The SNAP-19 reactor's heat sources were found off the U.S. coast at a depth of 300 feet. 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, re-entered the atmosphere and plunged into the ocean close to the Tonga Trench, sinking to a depth of between four and six miles. 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 indicated earlier in this report, there was a major accident on January 24, 1978 when Cosmos-954 could not be boosted to a higher orbit and re-entered the Earth's atmosphere over Canada. Debris was found along a 400-mile 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. There were also 47 beryllium rods and cylinders and miscellaneous pieces recovered, all with some contamination (see IAEA 2005a).

As a result of this accident, the Russian Federation redesigned its systems for backup safety. Further, a United Nations Working Group has developed aerospace nuclear safety design requirements where:

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 re-entry 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 a re-boost 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 the postulated launch vehicle explosions or range of safety destruct actions.

Thus, as in all advances in technology, experience corrects previous oversights. The causes of the reentry of Cosmos-954, for example, have been rectified. Fortunately, this incident resulted in no danger to humans because of the remoteness of where in Canada the remnants of the reactor came to rest. In the future, because of advanced anti-satellite technology, failing orbiting space craft will be intercepted and destroyed by ground- or ship-based guided missiles before reaching the surface. The IAEA 2005a report indicates that each member country has employed 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 over the past 50 years have created safety issues of a different variety (see insert above). 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 (see Rincon, 2009).

Other Environmental Considerations in Space

Human physiological and psychological adaptations to the conditions and duration of space travel and working represent significant challenges. 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 over long periods of time. 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 (see Prado (2008a).

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 (see Prado (2008b) and others).

International Development: The Nuclear Genie is Out of the Bottle

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

Many of these countries and groups are monitoring activities while others are participating in U.S. and Russian programs, sometimes as part of the ESA. Others are going it alone in conducting or participating in the burgeoning commercial business of launching a number of communication and surveillance satellites. For example, Europe has been launching cooperative international satellites from Vandenberg Air Force Base in California, Woomera in South Australia and Cape Canaveral in Florida, since at least 1968. On the other hand, 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. There is no need for nuclear power 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, *Dongfanghong-I*, 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 over 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 were 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. Zhuang Fenggan, vice-chairperson of the China Association of Sciences, declared in October 2000 that one day the Chinese would create a permanent lunar base with the intention of mining the lunar soil for helium-3 (to fuel nuclear fusion plants on Earth), (see IAEA 2005a).

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, neither for steady operation nor for peak demand. The compact design makes spacecraft operation easier and simplifies the orientation system for highly accurate guidance (see IAEA 2005a).

Research and Development

Earth-based NPSs were originally designed to be very large installations giving economies of scale for baseload applications. Earth-based nuclear power was originally based on the prospects for 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 over the past 30 years, the prospects for re-starting research into reprocessing spent fuel have improved over the past few years (see 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, on the other hand, is characterized by the need for small, light-weight systems that are independent of gravity and have heat-transfer systems that support both direct and indirect conversion. Additionally, 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 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 removal 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 U.S. 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 contribute significantly to the operational safety of both current and future nuclear reactors on Earth and in space due to its superior thermal conductivity and associated decrease in risks of overheating or meltdown (see IBC, 2008).

Along with their main purpose of space exploration, many of the advanced technologies have Earth-based applications since 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 U.S. and by the Kurchatov Institute in the Russian Federation. Also, the IAEA (2007b) supports the development of non-electric applications of nuclear power used in seawater desalination, hydrogen production and other industrial applications.

Small Earth-Based NPSs

The development of small automatic modular NPSs having power outputs in the 10–100 kW range could find new Earth-based applications. District heating, power for remote applications such as for installations underwater, remote habitation and geological exploration and mining are candidates for such power systems (see section: **Earth-Based Spin Off from Space Research**, later in this report).

Direct-Conversion Systems

RTGs were used 25 years ago for lighting at remote lighthouses, but more applications await these semi-permanent batteries. While not currently on the market, the use of RTGs in small industries and even in electric cars and the home have the potential for 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 over 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. Some of the most important initiatives to be taken in space with respect to nuclear power in the 21st century are:

1) Development of a new generation of international systems for communication, television broadcasting, navigation, remote sensing, exploration for resources, ecological monitoring and the forecasting of natural geological events on earth;

2) Production of special materials in space;

3) Establishment of a manned station on the moon, development of a lunar NPS, 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 the Earth of thermonuclear fuel — thorium, ^{3}He isotope, etc. 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 the Earth from potentially dangerous asteroids and other NEAs; and

9) Restoration of the Earth's ozone layer, adjustment of CO_2 levels, etc.

Off-World Mining

In the future, space NPSs and combined nuclear power/propulsion systems (NPPSs) with an electrical power level of several hundred kilowatts make possible and will 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. 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 economics scholars, e.g., see Simpson, *et al.,* 2005; Tilton, 2002; and Ragnarsdottir, 2008.

Interest in the industrialization of space began many years ago. One of the first professional geologists to state the necessity of going into space was Dr. Phil Shockey (see Shockey, 1959), former Chief Geologist for Teton Exploration in the late 1960s and a former co-worker of Campbell and Rackley. The need continues to draw supporters (see Lewis, 1997).

Aside from the orbital activities presently focused on the International Space Station, geological exploration began in the 1960s with the *Apollo* missions. Only one geologist (Schmitt) walked on the Moon to sample the rocks and the regolith and, along with other non-geologists, brought back thousands of pounds of samples for further study on Earth (see Figure 4). The recent *Mars Phoenix* investigations are sampling the regolith of Mars by remote-controlled geological 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 solar radiation, solar wind, and perhaps erosion by water during the early wet period of Mars' geologic history. These are the first steps in mineral evaluation, whether it is on Earth, the Moon, Titan, or now on Mars. They all involve reconnaissance 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, (see Karunatillake, *et al.,* 2008).

The former was conducted by one geologist and other non-geologists, the latter 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* also allowed additional steps to be taken and lessons learned. Europa, one of Jupiter's moons, will be visited one day, as will most of the others.

All such deep-space activities assume that sufficient power will be available. This is evident in a series of industrial planning papers (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.

Figure 4 – The Only Geologist on the Moon (William "Jack" Schmitt)
Apollo 17, 1972

The Debate on a Lunar or Mars Base

NASA's Albert Juhasz suggested in 2006 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 is : Al, 13 percent; Mg, 5.5 percent; Ca, 10 percent; and Fe, 6 percent. The iron content of the "Maria" soil has been shown to reach 15 percent (from Eckart, 2006)."*

Once target areas on the Moon and within the asteroid belt have been selected, geological exploration can begin in earnest. *Lunar Prospector* was launched in 1998 and was 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 H, U, Th, K, O, Si, Mg, Fe, Ti, Al, and Ca with special emphasis on the detection of polar water-ice deposits (see Hiesinger and Head, 2006). Recently, even evidence of significant water has been reported in some lunar volcanic glasses (see Saal, *et al*., 2007). High-quality photographic coverage and advanced planning for returning to the Moon are increasing almost daily; see NASA Lunar Program (here), *Google Moon* (here), and for a summary of all lunar missions by all countries, see (2009a).

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, i.e., 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 to determine ore grades and tonnage of the deposit will be conducted. 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 to 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 done in mining projects on Earth.

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 the Earth. Thorium and samarium (and maybe additional rare-earth elements since they often occur together) have been located in what appears to be anomalous concentrations in the regolith around the Mare Imbrium region (see Figures 5 and 6). There are other constituents of interest as well that may drive the economics to justify a permanent base on the Moon.

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 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 Ni, Co, Ir, Au, and other highly siderophile elements (see Korotev, 1987; Hiesinger and Head, 2006; and 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 industry (see Spudis, 2008).

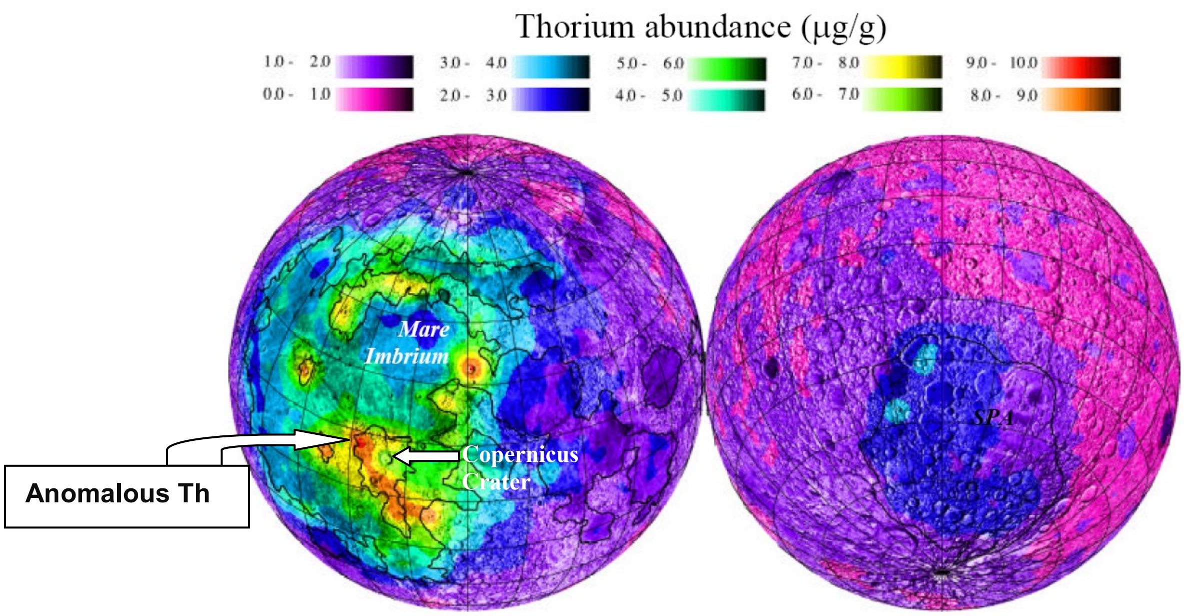


Figure 5 – Inferred Thorium Abundance on a Two-Hemisphere Map Projection. From Elphic, *et al.*, 2000.

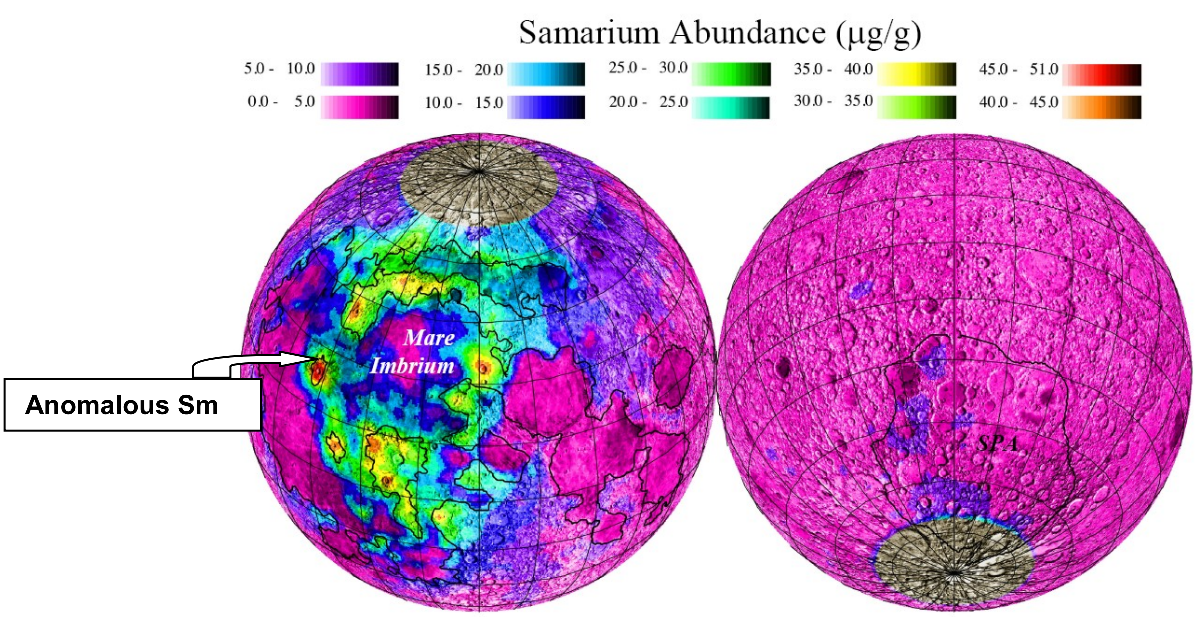


Figure 6 - Inferred Samarium Concentrations in the Imbrium/Procellarum Regions. From Elphic, *et al.*, 2000.

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 industry and from a number of 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/thorium-based nuclear reactors on Earth and in space, this discovery is of major importance (see IAEA, 2005b).

To conduct exploration on the Moon, Mars or other body, there must be sufficient mapping of the body to provide the basic geological relationships, 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 Gadis, (2008), discuss the progression of geologic mapping on the Moon. The quality and detail of such maps are illustrated in Figure 7. Vast areas will need to be explored on the Moon and Mars. Reliable transportation for sampling will be required (see Elphic, *et al.,* 2008) in exploring for strategic commodities, such as nickel, cobalt, rare-earth minerals, or for nuclear fuels, whether uranium or thorium.

Today, uranium is the only fuel used in nuclear reactors. However, thorium can also be utilized as a fuel for Canada's Deuterium Uranium (CANDU) reactors or in reactors specially designed for this purpose (WNA, 2008a). The CANDU reactor was designed by Atomic Energy of Canada, Limited (AECL). 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}. Then the thorium (Th^{232}) atom captures a neutron in the reactor 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 (see IAEA, 2005b). In October, 2008, Senators Orrin Hatch, R-Utah and Harry Reid, D-Nevada introduced legislation that would provide $250 million over five years to spur the development of thorium reactors. RTG research also has progressed on a number of recent missions (see Bennett, *et al*., 2006).

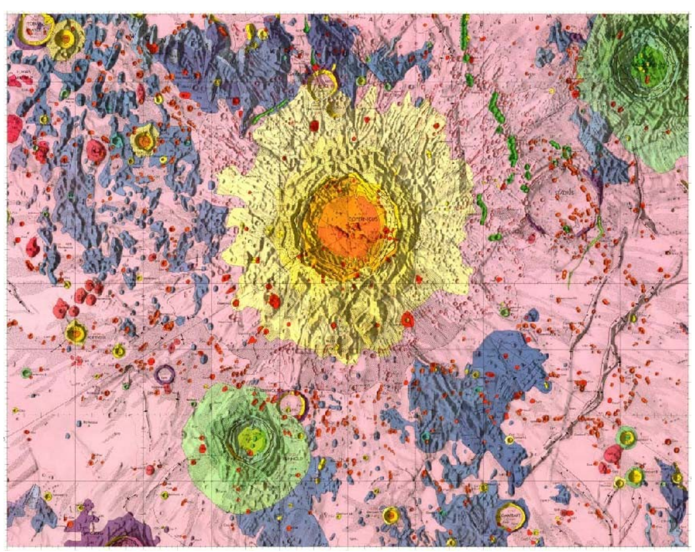


Figure 7 – Copernicus Quadrangle (Skinner and Gadis, 2008)
(For detail, click (here).

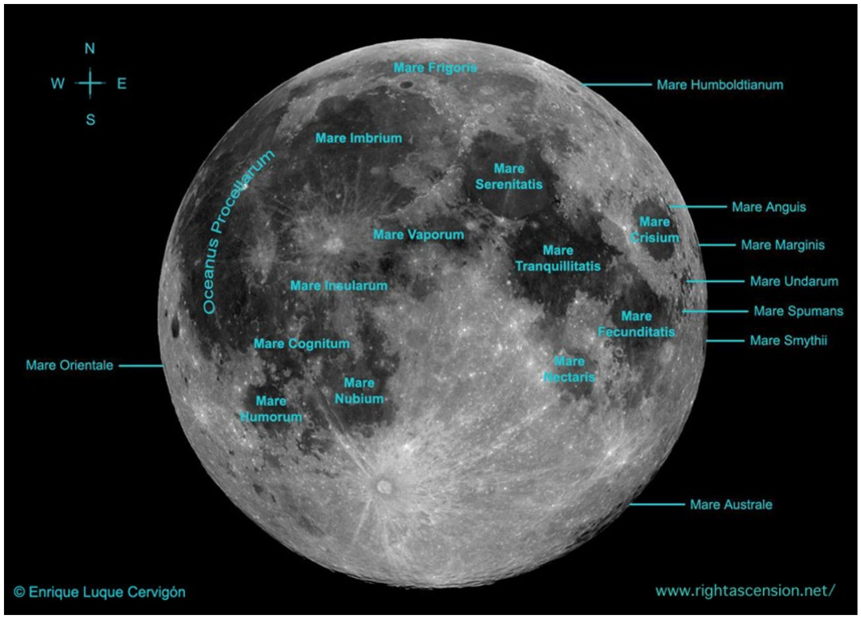
The thorium-fuel cycle has some attractive features, though it is not yet in commercial use (WNA, 2008b). Thorium is reported to be about three times as abundant in the Earth's crust as uranium. The IAEA-NEA "Red Book" gives a figure of 4.4 million tonnes of thorium reserves and additional resources available on Earth, but points out that this excludes data from much of the world (IAEA, 2007a). Recent estimates are much higher (Chong, 2009). 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 is likely present in concentrations with economic potential on the Moon, making certain assumptions regarding the costs to mine on the Moon (see: Metzger, *et al.,* 1977). Multi-recovery operations combining the recovery of high-demand samarium with other commodities of interest further enhances the economics of any operations on the Moon (see Figure 8).

Figure 8 - Conceptual View of Moon Base for Mining (after Schmitt, 2004)
(Courtesy of *Popular Mechanics*)

Based on the sampling to date on the Moon, 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 (see Taylor (2004), Lawrence, *et al.*, (1998 and 1999), and Meyer (ND) for an inventory of some of the constituents reported from lunar sampling to date).

These constituents can also 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 (see Zanda and Rotaru, 2001, and Norton 2002).

In conducting exploration on Mars, the Moon, or asteroids, safety considerations have a major role in the design and cost of extraterrestrial facilities built in such remote locations. Protection from bullet-like micrometeors and from coronal mass ejections (CMEs) from the Sun requires the construction of underground facilities.

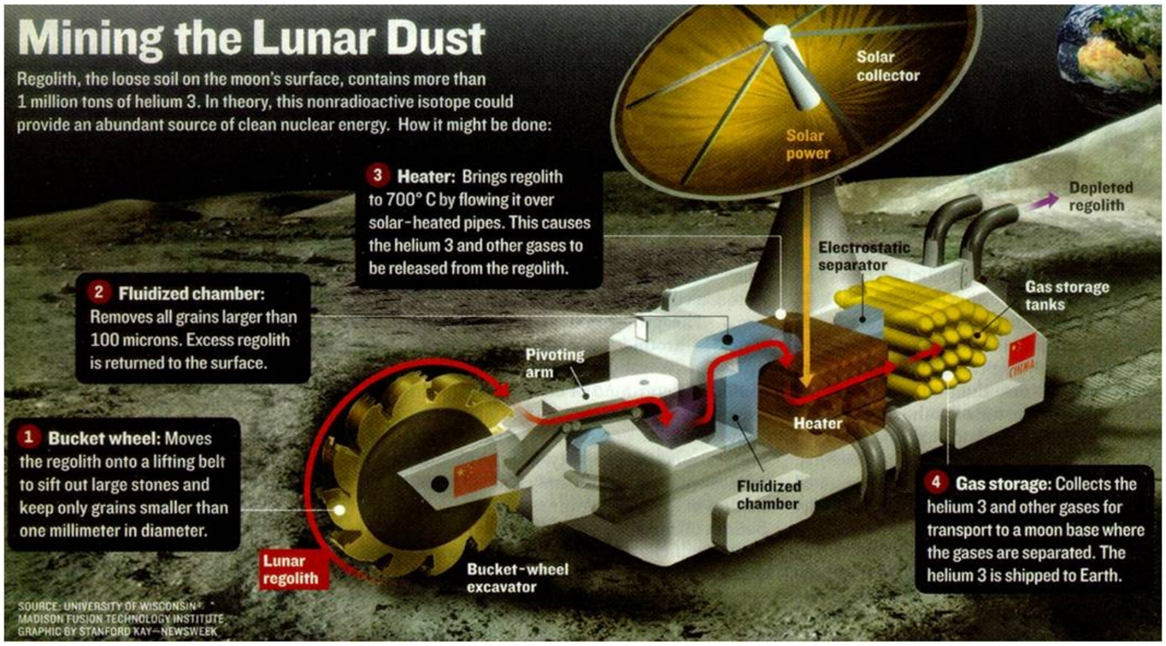


The Maria on the Moon Facing Earth.
See *Google Moon* for Apollo and Luna sites (2008).

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 (Clark and Killen, 2003; and Gasnault and Lawrence, 2002). 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.

Over the past 10 years, helium-3 (aka ^3He) has received considerable attention for its potential to produce significant fusion energy. ^3He, 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 ^3He is a gas imbedded as a trace, non-radioactive isotope in the lunar soils. Datta and Chakravarty, 2008, indicate that ^3He diffuses from lunar-silicate grains. However, the mineral ilmenite ($FeTiO_3$) that is abundant in certain areas of the Moon retains ^3He. This represents a potential energy source of such scale that it is expected by many energy planners to one day meet the Earth's rapidly escalating demand for clean energy, assuming the present difficulties in maintaining and controlling the fusion process can be overcome.

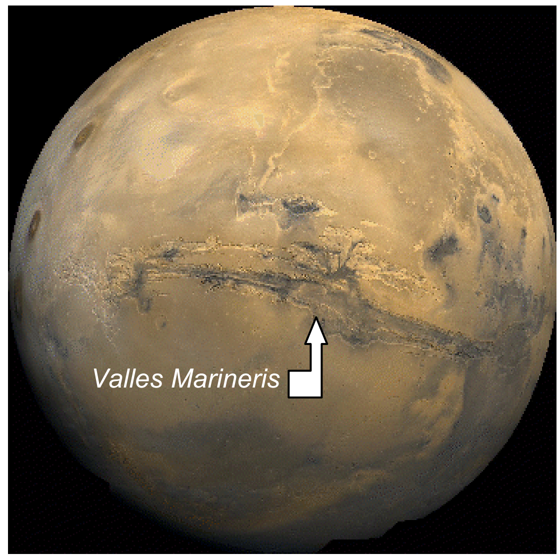
The resource base of ^3He present in just the upper nine feet of the mineable areas of titanium-rich regolith (containing ilmenite) of *Mare Tranquillitatis* on the Moon for example (the landing region for Neil Armstrong and Apollo 11 in 1969 shown in the insert above) has been estimated by Cameron (1992) to be about 22 million pounds (11,000 tons of regolith containing ^3He gas). The energy equivalent value of ^3He, relative to that of coal, would be about \$2 million per pound. On the basis that ^{3}He is concentrated within ilmenite minerals of particle sizes smaller than 100 mesh, its concentration by heating the concentrates to temperatures greater than 700° C for collection and shipment of the ^{3}He gas to Earth or for use on the Moon or elsewhere should not be difficult to achieve in a lunar processing plant (see Cameron, 1992) and illustrated in the insert below:



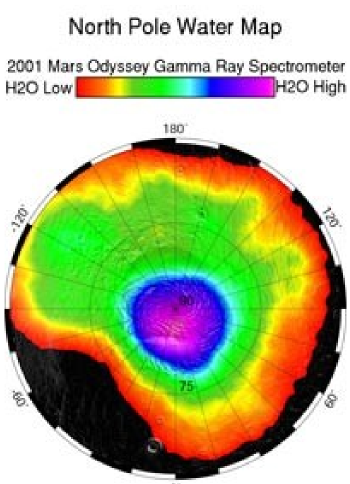
Proponents of turning to ^{3}He as an energy source indicate that the fusion process involves the fusing of deuterium (^{2}H) with ^{3}He producing a proton and helium-4 (^{4}He). The products weigh less than the initial components and the missing mass produces a huge energy output. Capturing this energy 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 ^{3}He, NASA labs, 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 ^{3}He resources. They also cite Chinese science leaders who claim that one of the main objectives of their space program will be to develop the ^{3}He resource on the Moon.

The IAEA report (2005a) indicates that personnel from both China and the Russian Federation have reported that the lunar regolith could be mined for ^{3}He for use in nuclear fusion power plants on Earth in a few decades. They claim that the use of ^{3}He 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 (2006) treats the subject in great detail, from mining on the Moon to energy production (see Livo, 2006 for review of text). 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 doesn't 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 was signed less than two years ago and they are already having problems with both the design and budget (see Anon, 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. Add 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** there were reserves of Deuterium in sea water 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 ^{3}He 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 ^{3}He?

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 Dr. Harrison "Jack" Schmitt, Apollo 17 Astronaut and former Senator from New Mexico.



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 (see Mason, 2006a).



Mars is also being considered for establishing a base. Although seeking water (and some form of life) is the present objective, Mars may also contain useful mineral resources as suggested in early reports on meteorites (McSween, 1994), and by Surkov, *et al*., 1980, and by Zolotov, *et al.,* 1993, but sampling has been limited to date (See Taylor, 2006 and 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.

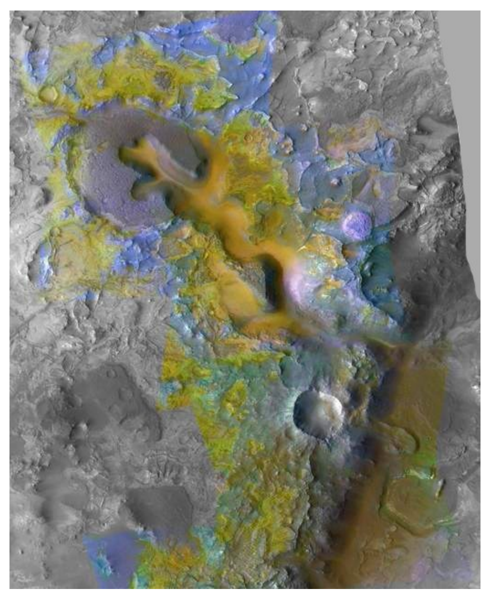
In addition, K/Th is distinctly higher in the central part of the *Valles Marineris* than the average in other regions. They speculate that possible explanations include: 1) water-magma interactions that may have led to the elevated K/Th signal in the surface sediments, or 2) the lava-flow materials are intrinsically high in K/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, with the exception of water ice at or around the poles, see insert. 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 ground water. Risner (1987) 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.

Outcrop in *Victoria Crater* with angular unconformity (?).

This would be expected to include deep intrusives interacting with the ground water to form various types of mineralization, some of potentially economic importance. Recently, NASA researchers have reported the presence of methane on Mars (NASA, 2008f). With this development, the Oklo uranium deposit dated at 1.6 billion years located in Gabon, Africa and other older deposits known on Earth become useful analogues 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 (see USDOE, ND). Other deposits present on Earth of Pre-Cambrian age should be investigated further as possible additional analogues for various types of mineralization. Volcanism and water seem to be more widespread in the Solar System than previously considered. To date, in addition to Earth, they have been indicated on Jupiter's moon, *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.

NASA's Mars Reconnaissance Orbiter (MRO) has produced some new information that supports the likelihood of mineralization of economic interest to industry. The color coding on the composite image below shows an area about 12 miles wide 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 non-acidic 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 below photo.



Canyons of *Nili Fossae* region.

Based on information released by NASA (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 that: "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 (2008e). High-quality photographic coverage of Mars is increasing almost daily; see NASA Mars Program (here), *Google Mars* (here), and for a summary of all lunar missions by all countries, see (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, e.g., hydrogen, methane for ascending from and descending to the moon's surface. Hydrogen, ^{3}He, and ices found deep in Uranus and Neptune are considered to be potentially crucial to exploration beyond the Solar System as well.

Mining Asteroids

With commodity prices at record highs, and which are expected to stay high for decades, lunar and asteroid exploration and mining are beginning to look attractive. Mining companies are beginning to take note that China, India, and other nations are expanding their economies at a rate higher than anticipated.

Goodyear (2006), a corporate mining industry executive, reports that 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 soon. Some asteroids (C-, S-, and M-types) are more prospective than others due to their detected and estimated compositions (see Ambrose and Schmidt, 2008).

The candidate list of potential minerals and compounds that may be in short supply or be uneconomic to produce on Earth but are available in the Solar System are shown in Table 1 (indicated by red dots). The potential rewards in terms of new mineral resources and in an expansion of human activities are large enough to make the investment worthwhile (Schmitt, 2006). Identifying and mining nickel, cobalt, and a variety of other commodities that are in short supply on Earth, or that could be mined, produced, and delivered more cheaply in space would contribute to and drive the world's technology to a scale never before contemplated. This is based, of course, on the assumption that the economics are favorable. Large multi-national, quasi-governmental industrial groups are likely to develop over the next few decades to handle projects of such magnitude, if they haven't 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 could become operations in space as secondary-recovery projects. In the early 1990s, work began in earnest to consider near-Earth asteroids (NEAs) as resources of the future (see Lewis, *et al.,* 1993) and continues today (see Ruzicka, *et al*., 2008).

Table 1 – Commodities Imported to U.S. in 2007

(Red Dots Indicate Commodities of Special Interest in Space Exploration.)

(From *Mining Engineering*, July, (Anon, 2008b, p.17)

Commodity	Percent	Major Import Sources (2003-06)[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 Kingdor
PLATINUM	94	South Africa, United Kingdom, German
STONE (dimension)	90	Italy, Turkey, China, Mexico
DIAMOND (natural industrial stone)	88	Botswana, Ireland, Namibia, South Afric
ANTIMONY	86	China, Mexico, Belgium
RHENIUM	86	Chile, Germany
BARITE	83	China, India
TITANIUM MINERAL CONCENTRATES	82	South Africa, Australia, Canada, Ukrain
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, Zimb
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, Republic of
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

[1]In descending order of import share

The time has arrived to begin to consider mining certain commodities on the Moon in addition to ^{3}He, as well as on the outlying planets, their moons, and asteroids. This will require long-duration manned-space missions that will involve adverse conditions. This creates an even greater need for nuclear-powered systems as well. Therefore, when planners begin to examine return space-travel goals beyond Earth orbit, after construction of the International Space Station (ISS) has been completed, they will be faced with deciding which propulsion systems are ready for the next push into space. Advances in demonstrated technology, some of which were abandoned almost 30 years ago, will include nuclear ion propulsion engines powered by main-stay on-board nuclear reactors. Nuclear-powered generators are now commonly used in many of the Mars and other missions.

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 shown in Figure 9 is about 1.3 miles in diameter, which is about the size of a typical metal mine on Earth. Its mass is calculated to be about 30 billion tons and assuming it contains 20 oz/ton of nickel, it could contain almost 20 million tons of nickel, that's 40 billion pounds of metal worth nearly a trillion dollars in today's market (i.e., ~$50,000/ton of metal concentrate).

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 which 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.

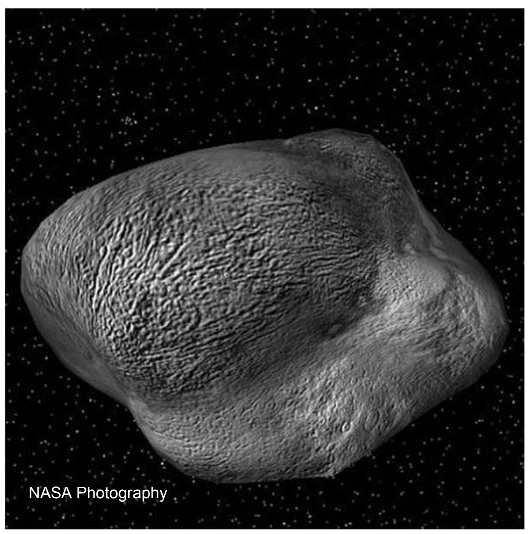


Figure 9 - A Class M Asteroid: Named 3554 Amun-NEA
(From Ambrose and Schmitt (2008)

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, followed by loading the blocks into crushers, grinding the blocks into smaller fragments suitable for loading into special transport vehicles. These transport vehicles would be built to interlock creating "space trains" which 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 transfer methods for processing. 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 source that can support an economic materials retrieval project (also see Campbell, *et al*., 2009).

These economic and technical requirements are:

1. A *market* for the products produced and delivered;
2. Adequate *spectral data* indicating presence of the desired materials;
3. *Orbital parameters* give reasonable accessibility and mission duration;
4. Feasible *concepts for mining and processing*;
5. Feasible *retrieval concepts; and*
6. Positive economic *Net Present Value*, using appropriate engineering concepts.

The following diagram is intended to show how the various requirements interact.

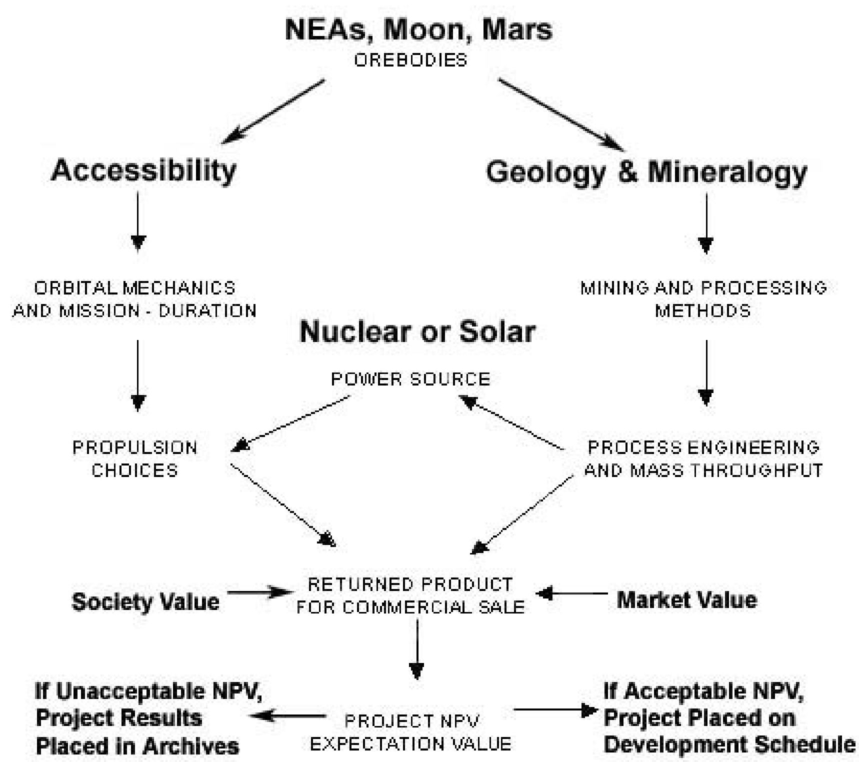


Figure 10 – Flowchart for Determining Technical and Economic Feasibility of Mining in Space
(After Sonter, 1998).

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 make them primary targets for exploration and possible development (see NASA, 2009).

Astronomical work over the last fifteen 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 dramatically in the last few decades, drawing on spectroscopic and dynamical studies of asteroids and comets, and meteorite studies. Reasonable correlations can now be made between spectral/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 there is a continuum from asteroidal to dormant cometary bodies, within the population of NEAs. Exploring asteroids, moons, and planets beyond Mars will require a power source different from those now deployed in American spacecraft. As indicated earlier, radioisotope thermal generators and solar energy cannot meet the challenges posed by proposed missions to the cold, dark regions of our Solar System. NASA's scientists from Oak Ridge National Laboratory are convinced that nuclear fission power will accomplish the goals (see NASA Oak Ridge National Laboratory (2004).

It should be re-emphasized that for spacecraft 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 spacecraft 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, unwieldy arrays of photovoltaic cells. As preliminary exploration programs move beyond Mars, an alternative source of electrical power is required. Radioisotope thermal generators are a very good option for providing low levels of electrical power for such missions as Voyager, Galileo, and Cassini, which only required about 1 kilowatt (1 kW) 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 employ nuclear reactors in space. NASA will explore different planets (and their moons) with more robust spacecraft 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 by using spacecraft 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.

The Space Elevator

The space elevator in concept is a vertical conveyance system with one end anchored on the Earth and the other 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 the 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 (see Anon, 2008a).

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, see Figure 11 and 12 for general concepts).

Once again, the power to operate the electrical motors needed to conduct the high-speed lifts are likely to be generated by small nuclear power units capable of producing significant amps for lifting outbound materials, such as personnel and equipment, etc. 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 the Earth or for storage on the Moon as a future resource.

In another application, 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 often generated by a dedicated mine-mouth coal plant. This plant is also usually located on or near a lake or river as a source of cooling water and for other uses.

Modern aluminum smelters operate at 200-600 MW of alternating current electric power, which is converted in a rectifier yard to direct current for use in the aluminum reduction pots (Anon, ND). 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.

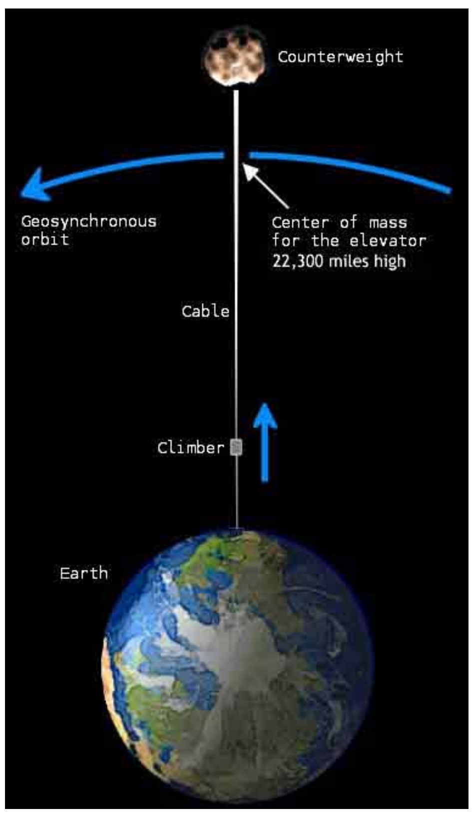


Figure 11 – Basic Space Elevator Concept (Hoagland, 2005).

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 the 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 the Earth that are also available on the Moon or elsewhere in the Solar System may move their operations off world. 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. Disposal of spent pot liners, for example, on the Moon would also be less of a problem than on Earth. The "not in my backyard" (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 (see White, 1997). Once such international treaties are signed, disagreements, disputes, litigation, and NIMBY issues usually follow. Regulations will then evolve to address grievances even in space, especially over mineral resources.

The space elevator 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 $10,000 per pound. In doing so, NASA would transfer its focus to matters related to activities in space. In the process, industry would likely play an increasing role in the development of various off-world projects. Safety issues and potential hazards associated with building and operating such facilities would require responsible consideration.

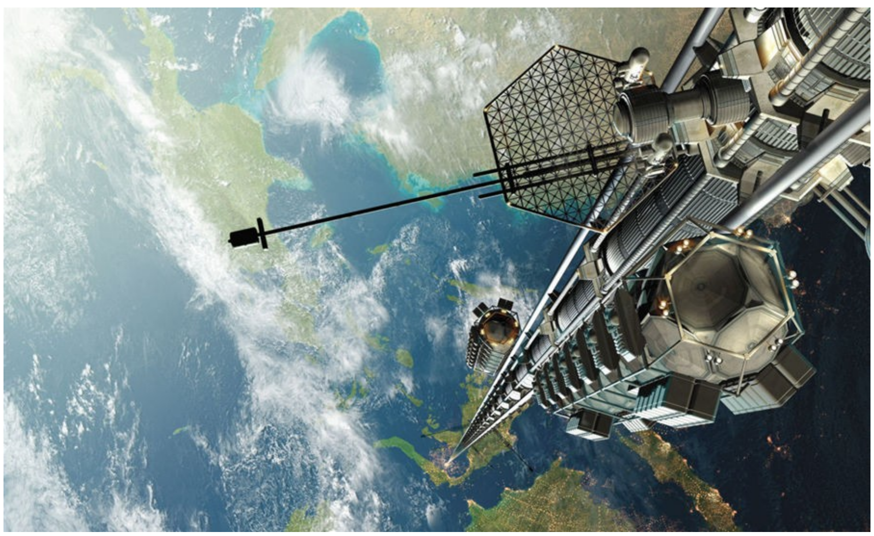


Figure 12 – Conceptual View of the Space Elevator (Hoagland, 2005).

Aluminum, iron and steel, metal mining, and other 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 the Earth from life-extinguishing events (LEEs) coming from deep space in the form of impacts by near-Earth asteroids (NEAs) and comets (summarized by Chapman, 2004). Monitoring NEAs has increased substantially over the past 10 years but determining what to do when an NEA is found to be heading for a collision with the 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 and will happen again in the future (see Figure 13) and represent possible species-extinguishing events, including humans.

NASA operates a robust program of monitoring research on astrophysics through the NASA Astrophysics Data System (NASA, 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.

Figure 13 - Artist's Conception of a Large-Mass Impact on the Earth **(Courtesy of Don Davis)**

However, Russell Schweickart, Apollo 9 Astronaut and presently 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 (pers. comm., 2008) suggests that infra red (IR) telescopes (dual band) 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 employing such approaches as a gravity tractor (see Figure 14 below) and other methods (see B612 Foundation News).

Safety issues and potential hazards associated with operating such equipment would require responsible consideration to insure that control of NEAs are maintained and represent a minimal threat to the 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.

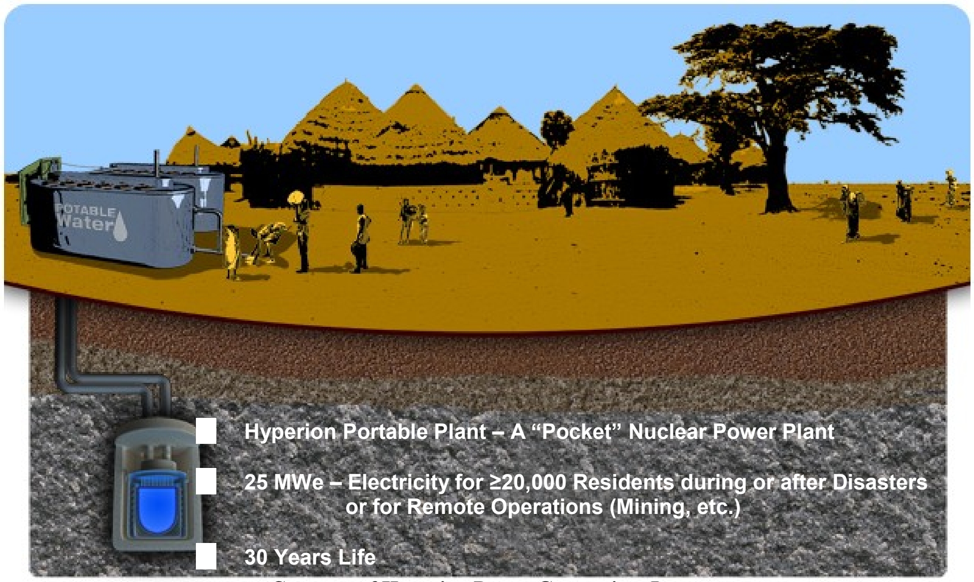
Figure 14 - A So-Called Robotic "Gravity Tractor" Moving an Asteroid into a New Orbit (Courtesy of R. L. Schweickart (ND))

The IAEA (2005a) 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. There are currently no alternatives 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 provides a focus on the science and technology of deep space travel (see website for publications (here)).

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 (see Hyperion insert below for example), medicine, laser equipment and electronic devices, optics, time-keeping processes, refrigeration equipment and materials technology.

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 spacecraft 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.



Courtesy of Hyperion Power Generation, Inc.

High-end technologies will need to be developed in space. For a variety of reasons, certain technology processes cannot take place on Earth. For example, superpure materials, single crystals and inorganic materials 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 the 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 non-electric applications of nuclear power are being used in seawater desalination, hydrogen production and other industrial applications. All this requires significant energy and, thus, necessitates the use of nuclear power systems in space and on Earth.

Conclusions

We have concluded that nuclear power is an important source of energy on Earth and that it is also needed 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 re-examination 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.

However, all this research does not indicate much more than speculation about the material benefits of space exploration. Benefits naturally will arise during the preparation for such 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 the 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 industry and associated research personnel within each country. Governments facilitate, industry personnel execute. Space development will likely result in the creation of large multi-national, quasi-governmental industrial groups to handle the complex scale and investment required for such projects, not unlike NASA or the ESA.

The Russian Federation is already making plans to go to the Moon, providing the funds can be found (see: Anon, 2005). China, India and Japan have recently sent spacecraft 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 (see Sengupta, 2008 and Data and Chakravarty, 2008).

The findings of the U.S. 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, geological, 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 largely 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 U.S. core value of using private sector resources to meet mission goals.

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 (NASA, 2008a). It should be noted here that although neither NASA nor the President's Commission emphasize it, one of the two primary justifications for going into space is to locate and develop natural resources needed on Earth (i.e., nuclear and industrial minerals). The other is to protect the Earth. The work performed by astronauts upon reaching the Moon, asteroids, and Mars first will be geological in nature, followed by engineering activities to develop the next steps in the industrialization of the Solar System. Of particular importance is 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 various mineral commodities in space.

Because long-term planning is a prerequisite to exploration and development in orbit, in space, or on the Moon, Mars or other bodies, these programs will proceed step by step over the decades ahead as they make sense politically to the American population for government-funded projects, but 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.

The road ahead will be fraught with potential hazards and accidents will occur, as accidents have occurred in new ventures throughout human history. But with the perceived need to develop new sources of energy to power Earth and the ventures into and around the Solar System and even beyond, the intended consequences will encourage the exploration and development of mineral resources as secondary objectives. This will reduce the cost of these resources as the last of the cheap commodities are recovered on Earth. As a natural progression over 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 bring 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 non-viable. 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 turn to new sources off-world.

Finally, the Earth still holds the promise of new discoveries of mineral resources, especially in the remote reaches of Canada, Alaska, Antarctica, China, Russia, and elsewhere (see Laznicka, 1999). The power supplies required for developing such remote resources will soon be provided by the "pocket" nuclear power plants discussed earlier. The many activities presently under way by industry in uranium and thorium exploration on Earth (see Campbell, *et al.,* 2008) confirm that the 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 multi-national programs over the centuries ahead.

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

Of particular irony is the role that meteor and comet impacts may have played in bringing not only water but also metals of economic value to Earth, such as nickel, uranium, thorium, etc. 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, in the Bushveld-Vredefort structures in South Africa and others in association with ring structures in Baltic Shield rocks of Sweden and Finland and elsewhere. They are tempting candidates for being of off-world origins, although the prevailing thought is that such deposits on Earth are either of progenetic (pre-impact), syngenetic (contemporaneous), or epigenetic (post-impact) origin. 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, there are about 170 terrestrial impact structures presently known on Earth, with a discovery rate of about 5 new structures per year (see PASSC,2009c). In any event, exploration continues on the Moon and in the more remote regions on Earth and will continue off-world, this century and beyond (see Campbell, *et al.,* 2009).

But until some form of fusion technology is available, the 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 the 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*

Acknowledgements

A number of individuals were instrumental in initiating and pursuing the research on the subjects treated throughout our investigations for this project, including:

- Dr. William A. Ambrose, serving as Co-Chair for the Astrogeology Committee of the AAPG, for suggesting that our group [the Uranium Committee (and Associates) of the Energy Minerals Division, AAPG)] look into the role that nuclear energy is playing in off-world missions to the Moon and elsewhere in the Solar System and it's likely role in the foreseeable future,

- Dr. H. H. "Jack" Schmitt, for his input on future lunar exploration and development, and on developing helium-3 as the next possible source of energy used on Earth,

- Dr. James C. Wiley, for his views on the future of fusion technology and on the likely timing of commercialization of such energy,

- Dr. R. L. "Rusty" Schweickart, who not only provided input for this report on the various methods of Earth defense from rogue asteroids or comets, and on methods that could be used to monitor and alter the orbits of such bodies, he also wrote the Forward to the Senior Author's first book published by *McGraw-Hill* on developing natural resources in 1973 (pages 8-11).

- Dr. David R. Criswell, for his input on energy and the World economy, and on the role that solar energy harnessed on the Moon and beamed to Earth could serve in the immediate future,

- Mr. Ruffin I. Rackley, M.S., for his perspectives and current views toward mining off-world,

- Dr. Thomas C. Sutton, P.G., for his reviews and comments during the various drafts of this document, and

- Dr. William H. Tonking, for his reviews and comments with special emphasis on safety issues regarding the use of reactors in space and the development and operations of the Space Elevator and Space Tractor.

The views expressed here are solely those of the authors and may not represent the views of: 1) those listed above who provided input to the authors during this investigation, 2) those members of the Uranium Committee who were not involved in this project, or 3) those cited in the references below.

Finally, the research for this project was conducted by selected members of EMD's Uranium Committee and associates. The funds involved in support of the research for this project were provided by M. D. Campbell and Associates, L.P., Houston, Texas, and Seattle, Washington. (http://www.mdcampbell.com). We have included the citations below with links, when available, to copies of the respective papers/reports for additional educational purposes only.

References

Aftergood, S., 1989, "Background on Space Nuclear Power," in *Science & Global Security*, Vol. 1, pp. 93-107, Accessed Internet June 12, 2008 via: http://www.mdcampbell.com/Aftergood1989.pdf

Ambrose, W. A., and H. H., Schmitt, 2008, "Energy Minerals in the Solar System: Resources for the 21st Century", AAPG Annual Convention, April 21, (PDF), Accessed Internet July 30, 2008 via: http://www.aapg.org/committees/astrogeology/ EnergyMineralsSolarSys.pdf

Anon, ND, "Plasma Torch Processing of Spent Aluminum Smelter Pot Liner," Patent Registration, (WO/1993/021479) PatentScope: World Intellectual Property Organization (WIPO), Accessed Internet July 30, 2008via: http://www.wipo.int/pctdb/en/wo.jsp?IA=WO1993021479 &wo=1993021479&DISPLAY=DESC

Anon, 2005, "Private Space Companies Start Competing for Cheaper Tickets to the Moon," Pravda OnLine, December 27, Accessed Internet August 4, 2008 via: http://english.pravda.ru/print/science/tech/ 9450-moon-0

Anon, 2008a, "The Space Elevator Reference," Accessed Internet July 30, 2008 via: http://www.spaceelevator.com/

Anon, 2008b, "Commodity Imports," *Mining Engineering Journal*, Vol. 60, No. 7, July, p. 17 (Corrected Table).

Anon, 2008c, The ITER Project - Status Report, Accessed Internet August 16, 2008 via: http://www.mdcampbell.com/BeyondITER.pdf

Atomics International, 1964, *Nuclear Reactor in Space*, for the U.S. Atomic Energy Commission, November, Accessed Internet via: http://link.brightcove.com/services/player/bcpid46203255001?bclid= 0&bctid=47102563001

Bennett, G. L., 2006, "Space Nuclear Power: Opening the Final Frontier," *in Proc. 4th International Energy Conversion Engineering Conference*, June 26-29, San Diego, CA, Paper # AIAA 2006-4191,17 p., Accessed Internet August 29, 2008 via: http://www.mdcampbell.com/Bennett0606.pdf

Bennett, G. L., *et al*., 2006, "Mission of Daring: The General-Purpose Heat Source Radioisotope Thermoelectric Generator," *in Proc. 4th International Energy Conversion Engineering Conference*, June 26-29, San Diego, CA, Paper # AIAA 2006-4096, 23 p., Accessed Internet August 30, 2008 via: http://www.mdcampbell.com/bennett0706.pdf

Bone, J., and A. Tortorello, 2008, "Helium-3 – The Energy Source of Tomorrow?," Accessed Internet December 30, 2008 via: http://web.mit.edu/22.012/www/ (see: http://mdcampbell.com/Helium-3version2.pdf).

Cameron, E. N., 1992, "Helium resources of Mare Tranquillitatis,", Wisconsin Center for Space Automation and Robotics, University of Wisconsin – Madison, Technical Report WC8AR-TR-Ar3-8207-1July, 67 p., Accessed Internet December 27, 2008 via: http://mdcampbell.com/Helium3Moon.pdf

Campbell, M. D., *et al*., 2009, "Developing Industrial Minerals, Nuclear Minerals and Commodities of Interest via Off-World Exploration and Mining," *Paper/Poster at Conference of the American Association of Petroleum Geologists (AAPG), Energy Minerals Division,* June 9, Denver, CO., 27 p. Accessed Internet June 5 , 2009 via: http://www.mdcampbell.com/SpaceMiningEconomics060909.pdf

Campbell, M. D., *et al*., 2008, "The Nature and Extent of Uranium Reserves and Resources and their Environmental Development in the U.S. and Overseas," *Proc. Conference of the American Association of Petroleum Geologists (AAPG), Energy Minerals Division,* April 23, San Antonio, Texas, 14 p. Accessed Internet July 26, 2008 via: http://www.mdcampbell.com/AAPGEMDSanAntonio2008Final.pdf

Campbell, M. D., *et al.,* 2007, "Nuclear Power: Winds of Change," *Report of the Uranium Committee, Energy Minerals Division, AAPG*, March 31, Accessed Internet July 26, 2008 via: http://www.mdcampbell.com/EMDUraniumCommitteeReport033107FINAL.pdf

Campbell, M. D., *et al*., 2005, "Recent Uranium Industry Developments, Exploration, Mining and Environmental Programs in the U.S. and Overseas," *AAPG, Energy Minerals Div., Uranium Committee Report for 2005,* March 25, 22p. Accessed Internet July 23, 2008 via: http://www.mdcampbell.com/EMDUraniumCommittee2005Report.pdf

Chapman, C. R., 2004, "The Hazard of Near-Earth Asteroid Impacts on Earth," *Earth and Planetary Science Letters*, Vol. 222, pp. 1-15, Accessed Internet July 30, 2008 via: http://www.mdcampbell.com/Chapman_hazard_EPSL.pdf

Chong, N. A., 2009,"Sharp Increase of Thorium Ore Reserves, a Greener Alternative to Uranium for Use in Nuclear Power Generation, Reflected in Latest U.S.G.S. Report, Says Thorium Energy, Inc." March 17 Press Release Accessed Internet March 27, 2009 via: http://www.mdcampbell.com/Thorium Ore Reserves.pdf

Clark, P. E., and R. Killen, 2003, "Understanding the Nature of Metal Segregation in Asteroid Regolith," *in Proc. Lunar and Planetary Science XXXIV*, Paper 1868, 2 p. Accessed Internet October 30, 2008 via: http://www.mdcampbell.com/ClarkKillen2003.pdf

Criswell, D. R., 2004a, "Lunar-Solar Power System*, in Encyclopedia of Energy*, Vol. 3, pp.677-689, Accessed Internet December 17, 2008 via: http://www.mdcampbell.com/Criswell2004LSPS.pdf

Criswell, D. R., 2004b, "Lunar Solar Power," *IEEE Potentials*, December-January, pp. 20-25, Accessed Internet December 8, 2008 via: http://www.mdcampbell.com/Criswell2004.pdf

Criswell, D. R., 2001, "Lunar Solar Power System: Industrial Research, Development and Demonstration*," in Proc. 18th Congress World Energy Council*, Buenos Aires, Argentina, October, 17 p. Accessed Internet December 8, 2008 via: http://www.mdcampbell.com/Criswell2001.pdf

Datta, J., and S. C. Chakravarty, 2008, *Chandrayaan-1* – India's First Mission to the Moon, Indian Space Science Office, ISRO Headquarters, Bangalore, October, 75 p. Accessed Internet December 8, 2008 via: http://www.isro.org/Chandrayaan/resources/Chandrayaan-1-booklet.pdf

Dohm, J.M., *et. al., 2008,* "New Evidence for a Magmatic Influence on the Origin of Valles Marinaris," *Lunar and Planetary Science XXXIX, 194,* Accessed Internet October 30, 2008 via: http://www.mdcampbell.com/MarsKTh.pdf

Eckart, P., (editor), 1999, *The Lunar Base Handbook*, McGraw Hill Companies Inc., 435 p. Accessed Book Promotion Webpage: http://www.amazon.com/gp/product/0073294446

Edwards, B. C., 2003, "The Space Elevator - NIAC Phase II Final Report," March 1, Accessed Internet July 31, 2008 via: http://www.niac.usra.edu/files/studies/final_report/521Edwards.pdf

Elphic, R. C., *et al.,* 2000, "Lunar Rare Earth Element Distribution and Ramifications for FeO and TiO2: Lunar Prospector Neutron Spectrometer Observations," Published by the Lunar Research Institute, Houston, Tx., Accessed Internet July 26, 2008 via: http://www.lunar-research-institute.org/images/science/ 2000/LP_JGR_ REE_plus_figs.pdf

Elphic, R. C., *et al.,* 2008, "Preliminary Results of Hydrogen Prospecting with a Planetary Rover, "*in Proc. 39th Lunar and Planetary Science Conference*, Paper 2400.pdf, 2 p. Accessed Internet October 30, 2008 via: http://www.mdcampbell.com/Elphic2008.pdf

Engler, R. E., 1987, "Atomic Power in Space," U.S. DOE, by Planning and Human Systems, Inc., Washington, D.C., DOE/NE/32117-H1, DE87 010618, March, 125 p., Accessed Internet July 31, 2008 via: http://www.mdcampbell.com/Englier1987DOE.pdf

Gasnault, O., and D. J. Lawrence, 2001, "Th and Fe Contents in Geological Units of the Apollo 12 and 14 Region," *in Proc. 32nd Lunar and Planetary Science Conference, 1p.,* Accessed Internet July 31, 2008 via: http://www.mdcampbell.com/gasnault2001.pdf

Goodyear, C., 2006, Presentation at the Society of Economic Geologists Conference: "Wealth Creation in the Minerals Industry," CEO of BHP Billiton Mining, May 14-16, Keystone, CO

Google Mars, Accessed December 12, 2008 via: http://www.google.com/mars/

Google Moon, Accessed December 22, 2008 via: http://www.google.com/moon/

Grieve, R.A.F*., 2005*, "Economic Natural Resource Deposits at Terrestrial Impact Structures," *Geological Society, London, Special Publications*; Vol. 248, p. 1-29, Accessed Internet July 26, 2008 via: http://www.mdcampbell.com/DepositsImpacts2005.pdf

Haxel, G. B., *et al*., "Rare Earth Elements – Critical Resources for High Technology," U.S. Geological Survey, Fact Sheet 087-02, Accessed Internet July 26, 2008 via: http://www.mdcampbell.com/RareEarthUSGS.pdf

Hiesinger, H., and J. W. Head, III, 2006, "New Views of Lunar Geoscience: An Introduction and Overview," Reviews in Mineralogy & Geochemistry, Vol. 60, Accessed Internet July 26, 2008 via: http://www.mdcampbell.com/HiesingerHeadLunar.pdf

Hoagland, R. C., 2005, "Moon with a View: Or, What Did Arthur Know …and *When* Did He Know it?" Part 5, Accessed Internet July 23, 2008 via: http://www.enterprisemission.com/moon5.htm

Holt, J. W., *et al.,* 2008, **"**Radar Sounding Evidence for Buried Glaciers in the Southern Mid-Latitudes of Mars," *Science* November 21 ,Vol. 322. no. 5905, pp. 1235–1238, Accessed Internet February 9, 2009 via: http://www.sciencemag.org/cgi/content/abstract/322/5905/1235

Huber, H., and P. H. Warren, 2008, "Enigmatic, Largely Granitic 73217: A Lunar Mixed Melt-Breccia, But is it Impact Melt?, *in Proc 39th Lunar and Planetary Science Conference, 2405.pdf. 2 p.,* Accessed Internet November 12, 2008 via: http://www.mdcampbell.com/HuberWarren2008.pdf

IAEA, 2007a, "Uranium 2007 - *Resources, Production and Demand*, Published by: OECD Publishing, 17 Jun, 422 p. Accessed Internet August 16, 2008 via: http://www.oecdbookshop.org/oecd/display.asp ?CID=&LANG=EN&SF1=DI&ST1=5KZLLSXQS6ZV

IAEA, 2007b, International Conference on Non-Electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications 16-19 April 2007Oarai, Japan, *Organized by the International Atomic Energy Agency In cooperation with the OECD Nuclear Energy Agency International Desalination Association*. *Hosted by the* Government of Japan through the Japan Atomic Energy Agency, Accessed Internet August 16, 2008 via: http://www-pub.iaea.org/MTCD/Meetings/Announcements.asp?ConfID=152

IAEA, 2005a, "*The Role of Nuclear Power and Nuclear Propulsion in Peaceful Exploration of Space, Vienna*," September, STI/PUB/1197. Accessed Internet July 23, 2008 via: http://www.pub.iaea.org/MTCD/publications/PDF/Pub1197_web.pdf

IAEA, 2005b, "*Thorium Fuel Cycle – Potential Benefits and Challenges*," May, IAEA-TECDOC-1450, 113 p., Accessed Internet July 23, 2008 via: http://www.pub.iaea.org/MTCD/publications/ PDF/TE_1450_web.pdf

IAEA, 2004, *Chernobyl - The True Scale of the Accident*, 2004, IAEA Video Report, Accessed Internet July 23, 2008 via: http://www.iaea.org/ NewsCenter/Multimedia/Videos/CNNChernobylReport/index.html

International Beryllium Corporation, 2008, International Beryllium Signs Collaborative Research Agreement with Purdue University to Develop Safer and More Efficient Uranium Oxide Beryllium Oxide Nuclear Fuel, 2008 Accessed Internet August 6, 2008 via: http://www.internationalberyllium.com/s/ NewsReleases.asp

Juhasz, A. J., 2006, "Multi-Megawatt Gas Turbine Power Systems for Lunar Colonies, Glenn Research Center, Cleveland, Ohio, NASA/TM-2006-214658, AIAA-2006-4117, December, 10 p., Accessed Internet November 15, 2008 via: http://www.mdcampbell.com/lunar_power.pdf

Karunatillake, S., *et al.,* 2008, "The Mars Odyssey Gamma Spectrometer Reveal Chemically Striking Regions on Mars," Seventh International Conference on Mars, 3190.pdf, Accessed Internet on July 26, 2008 via: http://www.lpi.usra.edu/meetings/ 7thmars2007/pdf/3190.pdf

Korotev, R. L., 1987, "The Nature of the Meteoritic Components of Apollo 16 Soil as Inferred from Correlations of Iron, Cobalt, Iridium, and Gold with Nickel," *Proc. Lunar Planetary Science Conf.,* Vol. 17, pp. 447-461, Accessed Abstract Internet August 3, 2008 via: http://www.agu.org/pubs/crossref/1987/JB092iB04p0E447.shtml

Lawrence, D. J., *et al.,* 1998, "Global Elemental Maps of the Moon: The Lunar Prospector Gamma-Ray Spectrometer," September 4, Vol. 281 Science, www.sciencemag.org, pp.1484-1489, Accessed Internet July 23, 2008 via: http://www.lunar-research-institute.org/images/science/1998/1484.pdf

Lawrence, D. J., *et al.,* 1999, "High Resolution Measurements of Absolute Thorium Abundances on the Lunar Surface," *Geophysical Research Letters*, Vol. 26, No. 17, pp. 2681-2684, September 1, Accessed Internet August 2, 2008 via: http://www.lunar-research-institute.org/images/science/ 1999/thorium_grl_1999.pdf

Laznicka, P., 1999, "Quantitative Relationships among Giant Deposits of Metals," *Economic Geology*, Vol. 94, June-July, No.4, pp.455-473, Accessed Internet February 10, 2009 via: http://www.mdcampbell.com/Laznicka1999.pdf

Lewis, J. S., 1997, *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets*, Published by Perseus Books Group, 274 p. Accessed Internet August 5, 2008 via: http://books.google.com/books?id=ruIJAJ3VWA0C&printsec=frontcover&dq=subject:%22Space+mining%22&sig=ACfU3U0PkINqMM8AMlMOhHx_RgIik6lJgw

Lewis, J. S., *et al.,* 1993, *Resources of Near-Earth Space*, The University of Arizona Press, Tucson, 977 p., Accessed Internet October 30, 2008 via: http://www.uapress.arizona.edu/onlinebks/ResourcesNearEarthSpace/contents.php

Livo, K. E., 2006, Review of the text*: Return to the Moon: Exploration, Enterprise, and Energy in the Human Settlement of Space*, Copernicus Books, New York, ISBM 0-387-24285-6, 352 p., Accessed Internet January 30, 2009 via: http://www.mdcampbell.com/SchmittReview2006.pdf

Mason, L. S., 2006a, "A Practical Approach to Starting Fission Surface Power Development," NASA/TM-2006-214366, Paper 6297, July, 12 p. Accessed Internet July 5, 2008 via: http://www.mdcampbell.com/Mason2006.pdf

Mason, L. S., 2006b, "A Comparison of Fission Power System Options for Lunar and Mars Surface Applications," NASA/TM-2006-214120, February, 14 p. Report E-15455, Accessed Internet November 15, 2008 via: http://www.mdcampbell.com/Mason2006SmallNPS.pdf

McSween, H. Y., 1994, What We Have Learned about Mars from SNC Meteorites," *Meteorites*, Vol. 29, pp. 757-779, Invited Review, Accessed Internet November 15, 2008 via: http://www.mdcampbell.com/McSween1994.pdf

Metzger, A. E., *et al.,* 1977, "Thorium Concentrations in the Lunar Surface, I: Regional Values and Crustal Content," *in Proc. 8th Lunar Science Conference*, pp. 949-999, Accessed Internet August 30, 2008 via: http://www.mdcampbell.com/ThoriumMoon.pdf

Meyer, C, ND, "Astromaterials Curation - Rocks and Soils from the Moon," Johnson Space Center, Houston, NASA http://www.curator.jsc.nasa.gov/lunar/compendium.cfm

Nelson, R. A., 1999, "Rocket Thrust Equation and Launch Vehicles: The Fundamental Principles of Propulsion and Launch Vehicle Physics," Accessed Internet July 26, 2008 via: http://www.aticourses.com/rocket_tutorial.htm

National Aeronautics and Space Administration (NASA): Oak Ridge National Laboratory, 2004, *Back to the Future: Nuclear Energy Research*, Vol 37, No. 1, pp. 10-11, Accessed Internet November 26, 2008 via http://www.mdcampbell.com/OakRidgeNLReactorPowerinSpace.pdf

National Aeronautics and Space Administration (NASA), 2008a, Moon and Mars Missions, Accessed Internet August 16, 2008 via: http://www.nasa.gov/topics/ moonmars/index.html

National Aeronautics and Space Administration (NASA), 2008b, "*NASA/IPAC Extragalactic Database (*NED)," Accessed Internet August 12, 2008 via: http://nedwww.ipac.caltech.edu/index.html

National Aeronautics and Space Administration (NASA), 2008c, "NASA Planetary Data System," Accessed Internet August 12, 2008 via: http://pds.jpl.nasa.gov/

National Aeronautics and Space Administration (NASA), 2008d, SAO/NASA Astrophysics Data System (ADS) Accessed Internet August 28, 2008 via: http://www.adsabs.harvard.edu/

National Aeronautics and Space Administration (NASA), 2008e, “Carbonate Rocks in Heavily Eroded Martian Terrain Identified by Mars Reconnaissance Orbiter (MRO),” Released December 12, Accessed Internet August 28, 2008 via: http://www.nasa.gov/mission_pages/MRO/multimedia /CTX_CRISM_rgb_blend_900dpi_cropped_combo.html

National Aeronautics and Space Administration (NASA), 2008f, Discovery of Methane Reveals Mars Is Not a Dead Planet,” Release: 09-006, Accessed Internet October 12, 2008 via: http://www.nasa.gov/ mission_pages/mars/news/marsmethane.html

National Aeronautics and Space Administration (NASA), 2008g, “NASA Exploration 101 - Public,” Accessed Internet December 30, 2008 via: http://www.mdcampbell.com/NASAExploration1012008.pdf

National Aeronautics and Space Administration (NASA), 2009, “Near Earth Object Program,” Accessed Internet March 10, via: http://www.mdcampbell.com/NEAMarch2009.pdf

Norton, O. R., 2002, *The Cambridge Encyclopedia of Meteorites*, Cambridge University Press, NY, 354 p., Accessed Contents via Internet on July 31, 2008: http://www.cambridge.org/uk/ catalogue/catalogue.asp?isbn=0521621437

Palaszewski, B., 2006. “Atmospheric Mining in the Outer Solar System,” NASA Len Research Center, Cleveland, Ohio, October, NASA/TM-2006-214122, AIAA-2005-4319, 24 p., Accessed Internet December 12, 2008 via: http://mdcampbell.com/TM-2006-214122AtmosphericMining.pdf

Planetary and Space Science Center (PASSC), 2009a, “*Lunar Missions*,” Accessed Internet February 8, 2009 via: http://www.unb.ca/passc/missions/moonmissions.html

Planetary and Space Science Center (PASSC), 2009b, “*Mars Missions*,” Accessed Internet February 8, 2009 via: http://www.unb.ca/passc/missions/marsmissions.html

Planetary and Space Science Center (PASSC), 2009c, “*Impact Database*,” Accessed Internet February 8, 2009 via: http://www.unb.ca/passc/ImpactDatabase/index.html

Prado, M., 2008a, “Artificial Gravity and the Effects of Zero Gravity on Humans,” Section 6.13; Accessed Internet on October 22, 2008 via: http://www.mdcampbell.com/ArtificialGravity.pdf

Prado, M., 2008b, “Purpose of PERMANENT Approach” Accessed Internet on October 22, 2008 via: http://www.mdcampbell.com/PERMANENTSiteMap.pdf

Quirke, T. T., 1919, “Metallic Copper in a Meteorite Vein,” *Economic Geology*, Vol. 14, pp. 619-624, Accessed Internet on August 20, 2008 via: http://www.mdcampbell.com/Quirke1919.pdf

Ragnarsdottir, K. V., 2008, “Rare Metals Getting Rarer,” *Nature Geoscience*, Vol. 1, November, pp. 720-721, Internet: http://www.mdcampbell.com/NatureGraremetal.pdf

Reddy, F., 2008, “How Scientists Discovered a Solar System “Superhighway,”’ *Astronomy*, November, pp 38-43, Accessed Internet on October 2, 2008 via: http://www.mdcampbell.com/Superhighway.pdf

Reimold, W. U., *et al*., 2005, “Economic Mineral Deposits in Impact Structures: A Review,” in *Impact Studies*, Springer Berlin Heidelberg, pp. 479-552, Accessed Internet on February 10, 2009 via: http://www.springerlink.com/content/x1446w4328575664/#ContactOfAuthor1

Rincon, P., 2009, “Satellite Collision Highlights Growing Threat,” *BBC Science News*, February 12, Accessed Internet on February 14, 2009 via: http://news.bbc.co.uk/2/hi/science/nature/7885750.stm?lss

Risner, J. K., 1989, “The Geohydrology of Mars,” *Ground Water*, Vol. 27, No.2, March-April, pp. 184-192, Accessed Internet on October 30, 2008 via: http://www.mdcampbell.com/MarsGeoHy89.pdf

Rosen, R., and A. D. Schnyer, 1989, "Civilian Uses of Nuclear Reactors in Space," *in Science and Global Security*, Vol. 1, pp. 147-164, especially p. 157. Accessed Internet on October 30, 2008 via: http://www.mdcampbell.com/RosenSchnyer1989.pdf

Ruzicka, A., *et al.,* 2008, Amoeboid Olivine Aggregates (A) As) in the Efremovka (CVR) Chondrite: First Trace-Element Results," *in Proc. 39th Lunar Planetary Science Conference*, paper 1764.pdf., Accessed on the Internet on October 3, 2008 via: http://www.mdcampbell.com/Ruzicka2008.pdf

Saal, A. E. *et al*., 2007, "The Volatile Contents (C02, H2O, F, S, Cl) of the Lunar Picritic Glasses," *in Proc. 38th Lunar Planetary Science Conference: Workshop on Water in Planetary Basalts*, Paper 2009.pdf, (Also available is revised form: *Nature*, Vol. 454, pp. 192-195 - July 10, 2008). Accessed on the Internet on October 29, 2008 via: http://www.mdcampbell.com/SaalMoonWater2007.pdf

Schmitt, H. H., 2006, *Return to the Moon: Exploration, Enterprise, and Energy in the Human Settlement of Space*, published by Copernicus Books in association with Praxis Publishing, Ltd., 335 p. Introductory Information, Accessed Internet on July 26, 2008 via: http://books.google.com/books?id=IerrQGC6S2YC

Schmitt, H. H., 2004, "Mining the Moon," in *Popular Mechanics*, October, with illustrations by Paul Dimare, Accessed Internet on July 26, 2008 via: http://mdcampbell.com/ SchmittPMArticle1004.pdf

Schweickart, R. L., 2008, Personal Communication re B612 Foundation Activities and Objectives, Accessed Internet July 30, 2008 via: http://www.b612foundation.org/about/welcome.html

Sengupta, S., 2008, "India Launches Unmanned Orbiter to Moon," New York Times. October 21, Accessed on the Internet on October 20, 2008 via: http://www.nytimes.com/2008/10/22/world/asia/22indiamoon.html?_r=2&ei=5070&emc=eta1&oref=slogin&oref=slogin (PDF).

Shockey, P. N., 1959, "The Ultimate Necessity of Space Travel," *Space Journal*, March-May, pp. 5-8, (PDF), A Dedication Accessed on the Internet on October 20, 2008 via: http://www.paleofuture.com/2007/12/ultimate-necessity-of-space-travel-1959.html

Simpson, R. D., M. A. Toman, and R.U. Ayres, 2005, "Scarcity and Growth Revisited: Natural Resources and the Environment," published by RFF Press, Washington, D.C., 400 p. ISBN 1-93311-510-6

Skinner, J. A., and L. Gaddis, 2008, "Systematic Lunar Geologic Mapping: Results from the Copernicus Quadrangle," Geological Society of America Conference, Houston, Session: Lunar Stratigraphy, 15 p. Accessed on the Internet on October 20, 2008 via: http://www.mdcampbell.com/Skinner-Gaddis_Copernicus_GSA2008.pdf

Skerl, A. C., 1957, Scientific Communications: "The Cosmic Origin of Metallogenetic Provinces," *Economic Geology*, Vol. 52, pp. 307-310, Accessed Internet on February 6, 2009 via: http://www.mdcampbell.com/Skerl1957.pdf

Sonter, M. J., 1998, "The Technical and Economic Feasibility of Mining the Near-Earth Asteroids," Presented at the 49th International Astronautical Federation Congress, September 28 – October 2, Melbourne, Australia, Published by the National Space Society and Accessed on the Internet on December 22, 2008 via: http://www.nss.org/settlement/asteroids/sonter.html

Spudis, P. D., 2008, "Lunar Polar Exploration: Questions, Issues and Missions," *in Proc. 39th Lunar Planetary Science Conference*, Paper 1359.pdf., Accessed on the Internet on October 30, 2008 via: http://www.mdcampbell.com/Spudis2008.pdf

Surkov, Y. A., and G. A. Fedoseyev, 1978, "Natural Radioactivity if Regolith in Mare Crisium," *in Proc. 19th Lunar Planetary Science Conference*, pp. 2099-2109, Accessed on the Internet on October 20, 2008 via: http://www.mdcampbell.com/SurkovFedoseyev1978.pdf

Surkov, Y. A., *et al*., 1980, "Geochemical Interpretations of the Results of Measuring Gamma-Radiation of Mars," *in Proc. 11th Lunar Planetary Science Conference*, pp. 669-676, Accessed on the Internet on October 20, 2008 via: http://www.mdcampbell.com/Surkov1980.pdf

Taylor, G. J., *et al.,* 2006, "Mapping Mars Geochemically," Lunar and Planetary Science XXXVII, 1981 pdf, Accessed Internet on July 26, 2008 via: http://www.mdcampbell.com/Taylor2006Mars.pdf

Taylor, G. J., 2004, "New Lunar Meteorite Provides its Lunar Address and Some Clues about Early Bombardment of the Moon," Hawaii Institute of Geophysics and Planetology, November 22, Accessed Internet on July 26, 2008 via: http://www.mdcampbell.com/Taylor2004.pdf

Tilton, J. E., 2002, *On Borrowed Time? Assessing the Threat of Mineral Depletion,* Published by Resources for the Future, Washington, D.C., and 366 p.

University of Wisconsin – Madison Fusion Technology Institute, 2008, Accessed Internet on December 10, 2008 via: http://fti.neep.wisc.edu/fti , especially: http://fti.neep.wisc.edu/neep533/SPRING2004/neep533.html

U. S. Commission on Implementation of U.S. Space Exploration Policy, 2004, "A Journey to Inspire, Innovate, and Discover, "June, 64 p., Accessed Internet on December 22, 2008 http://www.mdcampbell.com/PresCommSpace2004.pdf

U. S. Department of Energy, Civilian Radiation Waste Management, Yucca Mountain Project (USDOE), ND, *Oklo: Natural Nuclear Reactors* (Fact Sheet), Accessed Internet on July 2, 2008 http://www.ocrwm.doe.gov/factsheets/doeymp0010.shtml

U. S. Geological Survey (USGS), 1962 – 1982, Lunar Geological Mapping, Accessed Internet on August 25, 2008 via: http://www.lpi.usra.edu/resources/mapcatalog/usgs/

Westfall, R. M., *et.al,* ND, "Beneficiation of Asteroidal Materials in Space," Galactic Mining Industries, Inc., Denver, CO, Series of Extended Abstracts of Papers. Accessed Internet on July 26, 2008 via: http://www.space-mining-com_beneficiation-html_ 5qe2w10v.pdf

White, W. N., 1997, "Real Property Rights in Outer Space," The paper was published by the American Institute of Aeronautics and Astronautics, Inc. with permission. Released to AIAA in all forms. Copyright 1997 by Wayne N White, Jr., Accessed Internet on July 26, 2008 via: http://www.space-settlement-institute.org/Articles/ research_library/WayneWhite98-2.pdf

Witschard, F., 1984, "Large-Magnitude Ring Structures on the Baltic Shield – Metallogenic Significance," *Economic Geology*, Vol. 79, pp. 1400-1405, with Discussions, Accessed Internet on August 20, 2008 via: http://www.mdcampbell.com/Witschard1984.pdf

Wikipedia, 2008,"Human Adaptation to Space," Accessed Internet on October 22, 2008 via: http://www.mdcampbell.com/HumanAdaptationtoSpace.pdf

Wiley, J. C., 2008, Personal Communication, Background Accessed Internet on July 27, 2008 via: http://www-pub.iaea.org/mtcd/NF/ws2001/usa/frc.html

World Nuclear Association (WNA), 2008a, "Supply of Uranium," Accessed Internet on August 20, 2008 via: http://www.world-nuclear.org/info/inf75.html

World Nuclear Association (WNA), 2008b, "Thorium," Accessed Internet on August 20, 2008 via: http://www.world-nuclear.org/info/inf62.html

Zanda, B., and M. Rotaru, (eds), 2001, *Meteorites – Their Impact on Science and History*, Cambridge University Press, NY, 128 p., Accessed Contents via Internet on July 31, 2008: http://www.cambridge.org/catalogue/catalogue.asp?isbn=9780521799409

Zolotov, M. Y., *et al.,* 1993, "K, U, and Th Behavior in Martian Environmental Conditions," *in Proc. 24th Lunar Planetary Science Conference*, pp.1585-1586," Accessed Internet on August 20, 2008 via: http://www.mdcampbell.com/Zolotov1993.pdf

About the Authors

[1] **Michael D. Campbell, P.G., P.H.,** serves as Managing Partner for the consulting firm, M. D. Campbell and Associates, L.P. based in Houston, Texas. He is a graduate of The Ohio State University in Geology and Hydrogeology in 1966, and from Rice University in Geology and Geophysics in 1976, and was elected a Fellow in the Geological Society of America. He was a Founding Member in 1977 of the Energy Minerals Division of AAPG and presently serves as Chairman of the Uranium Committee and on other professional committees, including the AAPG's newest, the Astrogeology Committee. Mr. Campbell was recently elected President-Elect (2010-2011) of EMD. Mr. Campbell developed a strong interest in the industrialization of space early in life and was then reinforced after serving in a business partnership for a number of years with the late Dr. Ted H. Foss, NASA's Chief of the Geology & Geochemistry Branch of the Science Directorate during the 1960s, who trained many of the early astronauts for exploring the moon. Mr. Campbell has a strong professional history in corporate and technical management of projects within major international engineering and mining companies such as CONOCO Mining, Teton Exploration, Div. United Nuclear Corporation, Texas Eastern Nuclear, Inc., and Omega Energy Corporation in uranium projects during the 1970s and such as Law Engineering, The DuPont Company, and others in environmental projects from the 1980s to the present. Mr. Campbell has over 40 years of mining, minerals and environmental project experience. He has published three technical books on uranium and other natural resources, and numerous associated reports, technical papers, and presentations in the U.S. and overseas. He is well-known nationally and internationally for his work as a technical leader, senior program manager, consultant and lecturer in hydrogeology, mining and associated environmental and geotechnical fields, and is a Licensed Professional Geologist and Hydrogeologist in the States of Washington, Alaska, Wyoming, Texas and Mississippi, and is nationally certified as a Professional Geologist and Professional Hydrogeologist. He is also a long-time member of the AIPG and AEG and has served as the Chairman of the Internet Committees, Texas Section of AIPG and AEG and Co-Editor for both of the professional societies' websites: http://www.aipg-tx.org and http://aeg-tx.org. For additional information, see his CV on his corporate website.

[2] **Jeffery D. King, P.G.,** serves as a Senior Program Manager for C&A and received his Bachelor's Degree in Geology from Western Washington University and has over 25 years of technical and managerial experience in the natural-resource field. Mr. King has extensive management experience, has managed the operations of a mining company, and large-scale re-development projects, has developed successful regulatory- and landowner-negotiation and public-relations programs; has conducted or directly managed all aspects of site permitting, and has been involved in the financial and technical evaluation of mining properties for a major mining company. He has also started, developed, and operated two successful companies. He is licensed as a Professional Geologist in the State of Washington. Between 1990 and 1998, Mr. King worked for the DuPont Company directing environmental projects in Washington, Oregon, Alaska and British Columbia, Canada. In 1998, Mr. King formed Pacific Environmental and Redevelopment Corporation to focus on large-scale projects involving the redevelopment of formerly contaminated properties. In completing these projects, Mr. King has developed or managed a team of professionals and associates with experience ranging from environmental sciences to master-planned community and golf-course construction. For additional information on Mr. King covering his training and professional experience, see his CV.

[3] **Henry M. Wise, P.G.,** has more than 30 years of professional experience in geological, uranium exploration and development and environmental remediation. His experience includes the exploration and in-situ leach mining of roll-front uranium deposits in South Texas where he was responsible for the delineation and production at the Pawilk Mine for U.S. Steel. He also has substantial experience in ground-water remediation projects in Texas. Mr. Wise is a graduate of Boston University, with a Bachelor's Degree in Geology, and obtained a Master's Degree from the University of Texas at El Paso in Geology. He is a Licensed Professional Geologist in Texas. He was a Founding Member in 1977 of the Energy Minerals Division of AAPG and is a member of the Uranium Committee, and a CPG of AIPG.

[4] **Bruce Handley, P.G.** serves as Senior Geological Consultant (C&A)**,** received a Bachelor's and Master's Degrees in Geology from University of Wisconsin. Mr. Handley has 20 years of professional experience, including oil and gas exploration and environmental consulting. Specialties relative to environmental and mining consulting include site characterization, health-based risk assessment, regulatory compliance issues, and litigation support. Project work accomplished includes compliance support for oil and gas exploration, refining, and pipeline operations. He has participated in a variety of field operations, including subsurface geologic and hydrogeologic investigations, safety audits, and emergency response actions. He is a member of the Uranium Committee of the Energy Minerals Division of AAPG. For additional information on Mr. Handley's experience, see Curriculum Vitae.

[5] **M. David Campbell, P.G.** is a Licensed Professional Geologist in Texas and holds a Bachelor's Degree in Geology from Texas A&M University. Mr. Campbell is the oldest son of the Senior Author and is a professional environmental hydrogeologist and mining geologist. With more than 15 years serving major environmental and engineering companies, he has considerable experience in managing field drilling and sampling operations employing a range of rig types and exploration functions. At present, he serves as a Senior Project Environmental Geologist for Environmental Resources Management (ERM), based in Houston, Texas. Previously, he has served in progressive professional positions with groups such as Delta Environmental Consultants, Carter & Burgess, Inc., and M. D. Campbell and Associates, L.P. He travels extensively overseas and has lived in Sri Lanka and Australia in his early years. For additional information on his background and professional experience, see his Curriculum Vitae.

xxx