Developing Industrial Minerals, Nuclear Minerals & Commodities of Interest via Off-World Exploration and Mining

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

by

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

Bruce Handley, P.G.[2]

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

Jeffery D. King, P.G., [4]

and

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

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Abstract

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

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

Mining on the Moon, Mars and Asteroids

With many commodity prices at record highs today, and which are expected to stay high for decades, off-world exploration and mining are beginning to look attractive for development within the next 20 to 30 years. At present, mining company executives are essentially locked into meeting current needs but NASA and NASA's national laboratories and associated industrial contractors such as Boeing, Lockheed, and others, are beginning to take note that China, India, and other nations are expanding their economies at a rate higher than anticipated and are beginning to consider off-world resources to meet their future demand. Goodyear (2006), a corporate mining industry executive, reported a few years ago that the consumption of natural resources by China and India will place even greater stress on commodity prices, especially for copper, aluminum, nickel, iron ore and other metals and mined commodities, and that these resources will need to be replaced in the foreseeable future.

Campbell, *et al*., (2008 and 2009) suggest that it is not unreasonable to assume that economic mineral deposits will be discovered elsewhere in the solar system, i.e., on other planets, moons, or asteroids. Although the geological processes that form the younger types of uranium mineralization (of Tertiary age on Earth) and other deposits formed by hydrothermal processes require the presence of water, bacteria and associated enzymes, and may not be present on many of these distant bodies, water may be more pervasive than originally assumed. Geologically older types of uranium mineralization associated with igneous and metamorphic rocks similar to deposits that occur in Proterozoic gneisses and amphibolites (Christopher, 2007) and younger rocks in the U.S. (Armbrustmacher, *et al*., 1995), as well as the well-known, developed uranium deposits in Canada and northern Australia and those under development in Africa, would be analogues for the types of deposits that would be expected to occur elsewhere in the solar system. Speculations about uranium, thorium, and their associated geochemistry began a number of years ago (i.e., Surkov, *et al*., (1980); Zolotov, *et al*., (1993)). With the number of unmanned probes planned in the next few years, additional information should be available to begin looking actively for resources in our solar system, hopefully within the next 20 years, supported by solar and nuclear power (Campbell, *et. al.*, 2009).

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 initially developed for missions in space. The many activities presently under way by industry in uranium and thorium exploration on Earth (see Campbell, *et al.,* 2008 and 2009) 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, 2008).

Target Commodities

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

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 the natural resources needed on Earth (i.e., nuclear and industrial minerals). The other is to protect the Earth (Campbell, *et al.,* 2009).

Table 1 – Commodities Imported to U.S. in 2008
(Red Dots Indicate Commodities of Special Interest in Space Exploration.)
(From *Mining Engineering*, July, (Anon, 2008)

	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, Germany
	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 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 that while we search for, mine and process the very nuclear fuels that provide the power needed on Earth and later in space (i.e., uranium, thorium, and later, helium-3), this also allows us to explore for other various mineral commodities in space (i.e., aluminum, rare earth oxides, nickel, etc.). Mineral deposits on Earth not now considered to be economic will continue to be developed until the economics, environmental pressures, or substitutions render such deposits non-viable. Substitutions have been at the core of industrial research since the beginning of the Industrial Revolution and, driven by a predicted future population growth of about 20% by 2025, will continue until the economics turn to new sources off-world.

Economic and Technological Impact on World Economy

The potential rewards in terms of developing new mineral resources with large-scale, off-world mining operations would contribute to the world economy on an unprecedented level making the immense industrial investment worthwhile (after Schmitt, 2006).

Identifying and mining nickel, cobalt, and a variety of other commodities that are in short supply on Earth, or those that could be mined, produced, and delivered more cheaply in space than on Earth could contribute to and drive the world's technology and associated economy to a scale never before contemplated. This is based, of course, on the assumption that the economics are favorable. Large 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. In the beginning, the economics would likely be underwritten by governmental support, perhaps by a group of governments cooperating in funding and technology but followed later by some governments funding programs to accommodate their own particular self-interests.

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

Also in the decades ahead, mining for such high-volume, low-grade commodities (e.g. aluminum-thorium-uranium) on Earth will be of only historical interest. Even some of the low volume-high grade operations (e.g. nickel-cobalt-platinum-rare earth elements) may disappear on Earth because they will be more economic to produce off world 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). The time has arrived to begin to consider mining certain commodities on the Moon in addition to helium-3, as well as on the outlying planets, their moons, and asteroids. This will require long-duration robotic missions and manned-space missions that will involve working in adverse conditions. A combination of nuclear-powered and solar-powered systems will provide the needed energy for such missions. The former will provide the high-amp power while solar will provide the primary and back-up power needed for lower-amp requirements where possible.

The availability and development of these off-world resources could easily overwhelm the markets on Earth for many years. The impact would drive the commodity prices down, hence making Earth-based operations unprofitable and eventually obsolete. As a natural progression 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 low-grade deposits, dumps and landfills until either the costs or the lack of political cooperation via NIMBY attitudes ("not in my back yard") will bring the activities to a close. Society will also encourage or require industry to expand the recycling of products until population demand exceeds such recoveries.

Exploration and Mining

Mining plans and the associated economics of operating in space would involve a new scale of operations never before attempted by humans. Mining, whether on the Moon or selected asteroids, would likely require new methods and technologies to create pit excavations and to handle materials and equipment in zero gravity. "Controlled" drilling and blasting would be required to break up selected parts of asteroids or hard-rock areas of the Moon into smaller fragments which would settle back into the pit created by the blast, followed by loading the ore material into crushers, and grinding the ore 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 plants on the asteroids or the Moon for further processing into concentrates. These concentrates then would be smelted to rid the ore of unwanted materials and formed into ingots useful to industry or be sent directly back to Earth's surface via space elevators or other future transfer methods for further processing.

Sonter (1998) identified the geologic and mining engineering requirements that must be satisfied to identify an orebody as a resource that can justify the expense of producing metal(s) or other commodities.

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

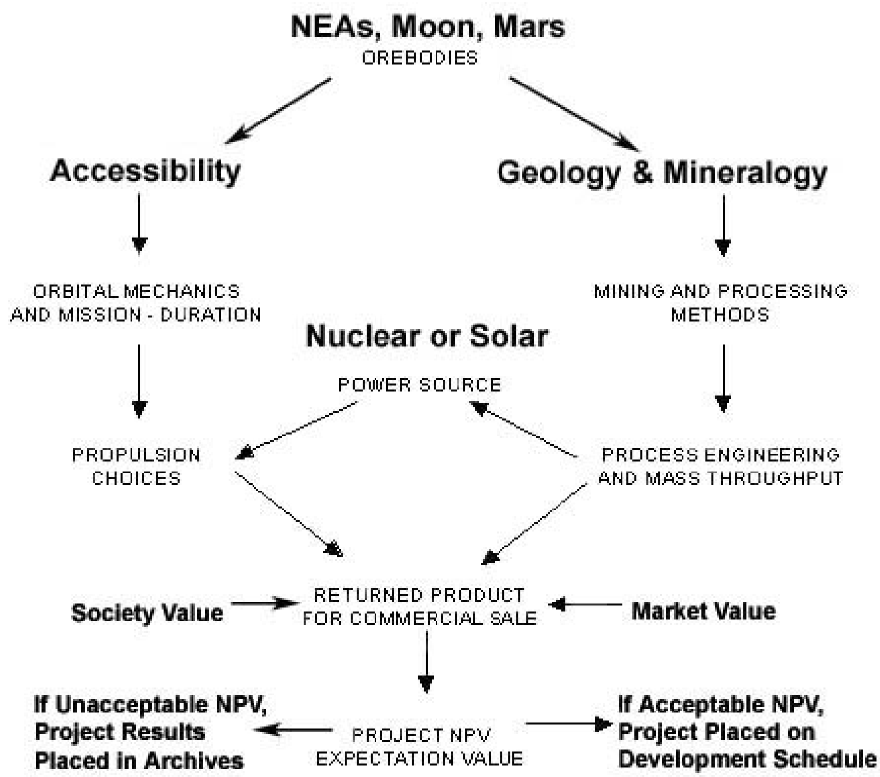


Figure 1 – Flowchart for Determining Technical and Economic Feasibility of Mining in Space
(After Sonter, 1998).

These economic and technical requirements are:

1. A *market* exists or will exist in the future for the products produced and delivered;

2. Adequate *spectral data* indicates presence of the desired materials to justify a manned mission to explore the anomalous sites by direct sampling, by geophysical surveys of the subsurface of the anomaly;

3. Known or established *orbital parameters* provide reasonable accessibility to the anomalous site and will allow the mission(s) to be of sufficient duration to permit the completion of the required exploration;

4. Feasible *concepts for mining and processing* have been developed and tested to allow successful drilling and sampling, mining factors, project life, and a meaningful assessment of the product price to be realized throughout a long mine life;

5. Feasible *retrieval concepts* have been developed and tested to produce (a smelter product) and returned materials of economic interest (a delivered product to/from the Moon/asteroid); and

6. A positive economic *Net Present Value* would be derived incorporating all of the above issues and using appropriate engineering concepts. All appropriate economic parameters would be applied in assessing the off-world mining venture, including government subsidy at the outset of the project.

Source of Materials

Of particular irony is the 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, Canada, 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.

These impact sites are tempting candidates for being of off-world origins, although the prevailing thought is that such deposits on Earth are either of progenetic (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, 2009). In any event, exploration continues on the Moon and in the more remote regions on Earth and will continue off-world in this century and beyond.

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

The metal-rich impact sites known on Earth also have off-world analogues (see Campbell, *et al.,* 2009). On the Moon, for example, early indications of anomalous sites containing high levels of thorium (Figure 2) and of samarium (Figure 3) are on NASA's list for follow-up investigations when the U.S. returns to the Moon with manned missions, assuming China, India, Russia or other countries do not claim the sites first.

In order to assess off-world deposits for their economic viability, an assessment is required of the resources available on the Earth in context with what could be expected off world. We focus here on thorium, samarium and nickel.

Thorium

Australia conducted a comprehensive assessment of their thorium resources (Geoscience Australia, 2008). They estimate that the average abundance of thorium in the Earth may never be precisely known but its abundance has been measured extensively at the Earth's surface and interpreted for the Earth's interior from indirect evidence. The three main sources of data are:

1. Chemical and radiometric analysis of meteorites interpreted to be representative of different Earth layers,
2. Chemical and radiometric analysis of surficial rocks, and
3. Estimation of values for the Earth's interior from heat-flow and rock-conductivity data.

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

1. The formation of a metal core very early in the history of the Earth. Core formation was complete at about 30 million years after the beginning of the solar system (Kleine, *et al.,* 2002).

2. The formation of the continental crust by partial melting of the silicate mantle. This process has continued with variable intensity throughout the history of the Earth.

The Earth's Mantle

The composition of Earth's primitive mantle has been estimated from chondritic meteorites (i.e. meteorites with chemical compositions essentially equivalent to the average solar system composition). Alternatively, the mantle composition has been reconstructed by mixing appropriate fractions of basalts (i.e. partial melts from the mantle) and peridotites (the presumed residues from the partial melts) or it has been calculated from trends in the chemistry of depleted mantle rocks. The concentration of thorium in the primitive mantle has been estimated to be 29.8 ppb (as derived from chondritic meteorites) or 83.4 ppb (as derived by Palme and O'Neill, 2004). On the Moon, the surface debris from a major impact surrounding the *Mare Imbrium* area contains anomalous concentrations of thorium (see Figure 2 and bright to dark red areas). These areas would be targets for follow-up exploration in locating higher grades of thorium.

A large majority of the Earth's mantle (~70%) is made of magnesium perovskite, which has great potential for fractionating elements. It is interesting to note that calcium perovskite [$CaSiO_3$], which is also expected to exist in the mantle, has enormous storage potential for lithophile elements. Its ability to host thorium and uranium make it an especially important phase to understand with respect to long term storage of these elements in the deep Earth (Righter, 2004). Asteroids or asteroid-debris fields on the Moon and on other bodies consist of fragments of primitive mantles and cores once making up other planetary bodies. These should be relatively easy to identify and evaluate compared to the buried deposits on Earth that require extensive drilling and excavation.

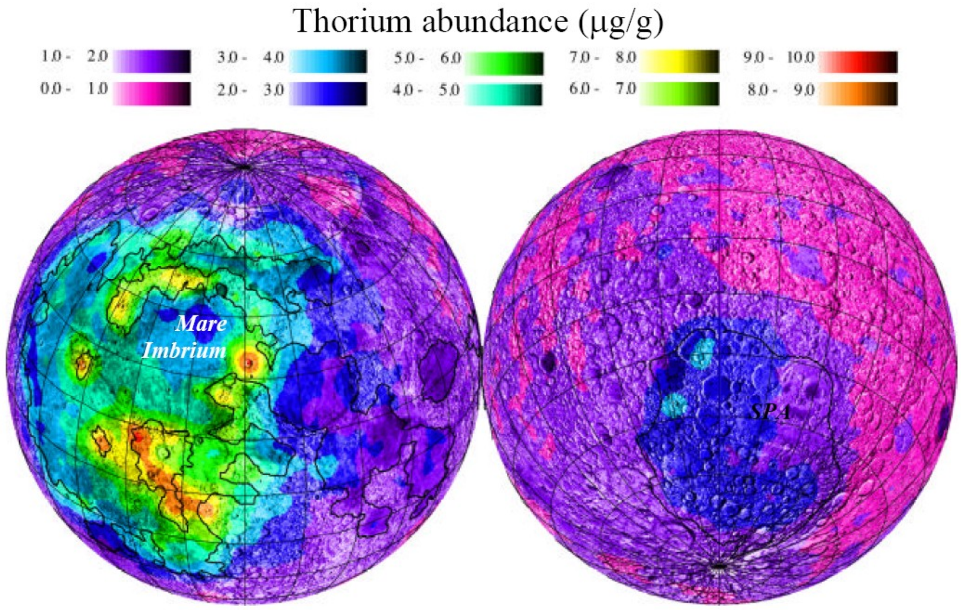


Figure 2 – Inferred Thorium Abundance on a Two-Hemisphere Map Projection. (From Elphic, *et al.,* 2000.)

Because these bodies have now been fragmented as a result of collisions in the solar system or by gravity stresses exerted by Jupiter or Saturn, they now exist in the asteroid belt beyond Mars or in rogue orbits after being knocked out of the belt or after their orbits were altered by larger bodies.

Thorium Development Issues

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

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

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

The use of thorium in several different types of reactors was demonstrated in the 1950s and 60s, when it was thought that uranium was a limited resource. Later, when additional discoveries of uranium were made and its availability increased, the use of thorium was largely ignored. In modern times, the scrutiny received by all energy sources by a public concerned with the future health of the planet has resulted in a reevaluation of thorium-based reactors because of a number of benefits. Thorium-fueled reactors provide for increased resistance to proliferation, longer fuel cycles, higher burn up, improved waste characteristics, reduction of plutonium inventories, and a capacity for the in-situ use of bred-in fissile material (see IAEA, 2005). Although significant challenges still remain, it is thought that these difficulties can be overcome as industrial experience with thorium fuel cycles increase.

Of particular interest is the recent research into energy systems like THORIMS-NES, the Thorium Molten Salt Nuclear Energy Synergetic system (see Hoatson, *et al.,* 2006). These systems consist of a Molten Salt Reactor (MSR), like the Fuji mini-MSR, currently being developed by a consortium which includes the U.S., Japan, and Russia, a chemical process plant, and an Accelerator Molten Salt Breeder reactor (AMSB). Nuclear engineers find these developments useful, as they offer increased safety of operation, flexibility in plant size, nuclear proliferation resistance, fuel economy, and flexibility in the fuel cycle. There are those who foresee a "Thorium Era" where the need for a global low-carbon footprint becomes imperative as coastlines are exposed to possible inundation from rising sea levels. The presence of economic grades of thorium on the Moon, with inferred concentrations much higher than the 10 micrograms per gram reported in preliminary assessments, makes this resource an important piece of the world's future energy picture (see Furukawa, *et al.,* 2007).

Samarium

Samarium is another resource which has been identified on the Moon, where significant areas show concentrations in the range from 35 to 51 micrograms per gram (see Figure 3), (see Furukawa, *et al.,* 2007). Samarium is a member of the lanthanide series appearing in row 6 of the periodic table. Referred to as one of the 15 rare earth elements, it is not considered rare because of its scarcity on Earth but rather because they were once very difficult to separate from each other. Samarium has relatively few uses by itself but its properties make it very desirable where it is incorporated. It is added to glass to produce special optical properties, to make special application lasers, as a nuclear absorber in nuclear fuel rods, and as a component of very powerful samarium-cobalt (SmCo) magnets. It is in the last of these uses that samarium will provide its greatest contribution to the future.

As with thorium, impact sites on the Moon also indicate samarium geochemical anomalies, notably around the *Mare Imbrium* region (see areas of bright red in Figure 3 below).

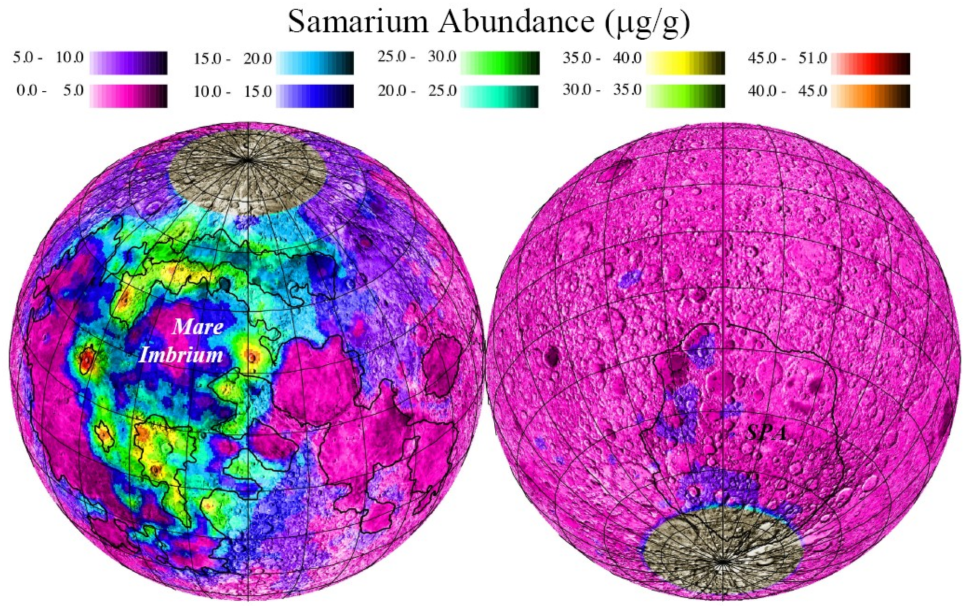


Figure 3 - Inferred Samarium Concentrations in the Imbrium/Procellarum Regions.
(From Elphic, *et al.,* 2000.)

Samarium Development Issues

What situations might develop that would promote the development of samarium resources on the Moon? One situation that demands consideration is geopolitical in nature. The 2008 world mine production of rare earths was approximately 124,000 tons with 96.7% of this total coming from China (see Hedrick, 2009b). The total world reserve base is estimated at 150,000,000 tons, with China holding 89,000,000 tons, or 59.3% of the world total. By comparison, the domestic reserve base is 9.3% of the world total. The only rare-earth separation plant in the U.S. is located at Mountain Pass, California and has only recently resumed operations after dealing with environmental problems associated with its wastewater discharge. Only mine stockpiles are being processed and only lanthanum concentrate and didymium (75% neodymium and 25% praseodymium) are being produced. Current rare earth oxide (REO) uses and prices are shown in Table 2. As these prices continue to rise, off-world resources assume greater importance in meeting the demands of the future.

Table 2

Rare Earth Oxide Industry Uses and Market Prices

Conversion:
2.2 Kg to #

Metal Oxide	Principal Uses	Price US$ / kg	US$ / Pound Range	
Lanthanum Oxide 99% min	Re-chargeable batteries	8.50 - 9.00	3.86	4.09
Cerium Oxide 99% min	Catalysts, glass, polishing	4.70 - 4.90	2.14	2.23
Praseodymium Oxide 99% min	Magnets, glass colourant	31.80 - 32.70	14.45	14.86
Neodymium Oxide 99% min	Magnets, lasers, glass	32.50 - 33.00	14.77	15.00
Samarium Oxide 99% min	Magnets, lighting, lasers	4.25 - 4.75	1.93	2.16
Europium Oxide 99% min	TV colour phosphors: red	470.00 - 490.00	213.64	222.73
Terbium Oxide 99% min	Phosphors: green, magnets	720.00 - 740.00	327.27	336.36
Dysprosium Oxide 99% min	Magnets, lasers	115.00 - 120.00	52.27	54.55
Gadolinium Oxide 99% min	Magnets, superconductors	10.00 - 10.50	4.55	4.77
Yttrium Oxide 99.999% min	Phosphors, ceramics, lasers	15.90 - 16.40	7.23	7.45
Lutetium Oxide 99.99% min	Ceramics, glass, phosphors and lasers	Up to 2,000 / kg	454.55	909.09
Thulium Oxide 99.99% min	Superconductors, ceramic magnets, lasers, X-ray devices	Up to 3,000 / kg	681.82	1,363.64

Source: Metals-Pages, October 2008

China has recently become a controlling entity in the global rare-earth market. While world demand for REOs is growing, China is cutting back on exports to maintain high-profit margins. The state-owned China Nonferrous Metal Mining Group (CNMC) has a goal of investing heavily to improve the industry's competiveness. In keeping with this policy, China recently acquired a controlling interest in Australia's Lynas Corporation, Ltd., for $185.7 million dollars U.S. This purchase gives China access to the world-class rare-earth deposit at Mt. Weld in Western Australia. The Lynas Corporation has stated that the "Mt. Weld Rare Earths Oxide (REO) deposit known as the 'Central Lanthanide Deposit' (CLD) is without a doubt the world's richest Rare Earths ore body, easily capable of supplying up to 20% of the global market for 30 years," (see Lynas, 2006). From the actions of the CNMC, it is apparent that prices for REOs will continue to escalate, in spite of rising world demand. With its low-cost labor force and less stringent environmental regulations, it is doubtful that other nations with rare-earth resources will be able to afford to compete with the Chinese.

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

Another potential demand for SmCo magnets derives from developing innovations in the production and installation of very high speed rail systems. The French corporation Alstom has developed rail systems designed for transport between major urban centers (see Alstom, 2009). With speeds ranging from 300 to 360 km/hr, these trains employ motors operating with SmCo permanent magnets. The company's new AGC line of very high speed trains boasts 15% energy savings due to the use of new composite materials and the efficient traction system. In fuel-equivalent terms, the AGV consumes only 0.4 liters of oil/100Km/passenger, about 1/15th that of an airplane. In addition to cars and trains, the development of highly efficient Internal Permanent Magnet (IPM) motors may give HEV mass transit systems the boost they need to become widely accepted (see Alstom, 2009).

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

Nickel

In August 2006, a ton of nickel on the world market was worth a record $US 35,000, a 7.7-fold increase from 2001. This increase was driven mainly by the urbanization and industrialization of China. At that price, global stockpiles of nickel have virtually disappeared, while exploration expenditure and activity are at all-time highs, especially in Australia. Australia's nickel industry has experienced a 'boom phase' of unparalleled opportunities. Nickel is one of the most common metals used in modern industrial applications, with important characteristics such as resistance to oxidation, resistance to corrosion by alkalis, strength at high temperatures, and the ability to form alloys used in general fabrication and in specialized applications (see Jaireth, *et al.,* 2008).

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

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

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

The Australian analysis of the world's major komatiite provinces reveals that the most prospective komatiite sequences are generally of late Archaean (~2700 Ma) or Palaeoproterozoic (~1900 Ma) age, have dominantly Al-undepleted chemical affinities (Al_2O_3/TiO_2 = 15 to 25), and form compound sheet flows with internal pathways and dunitic compound sheet flow facies (see Jaireth, *et al*., 2008). The preferred pathways assist in focusing large volumes of primitive magma flow (i.e., high-magma flux environments) and facilitate interaction of the magma with potential sulphur-bearing substrates (see Figure 4). This figure summarizes mineralizing systems from the Beasley, Mt. Keith and Kambalda mines in Western Australia (Modified after Dowling and Hill, 1998).

Komatiites are ultramafic mantle-derived volcanic rocks (Wikipedia, 2009). They have low SiO_2, low K_2O, low Al_2O_3, and high to extremely high MgO. True komatiites are very rare and essentially restricted to rocks of Archaean age, with few Proterozoic occurrences known (although similar high-magnesian lamprophyres are known from the Mesozoic). Jaireth, *et al*., (2008) suggest that this restriction in age is due to secular cooling of the mantle, which may have been up to 500°C hotter during the early to middle Archaean (4.5 to 2.6 Ga). The early Earth had much higher heat production, due to the residual heat from planetary accretion, as well as the greater abundance of radioactive elements. The identification of magmatic facies in komatiitic systems is therefore important for assessing the economic attractiveness of nickel-rich deposits.

There is considerable potential for the further discovery of komatiite-hosted deposits in Archaean granite–greenstone host rocks, including large and smaller high-grade deposits (5–9% Ni), that may be enriched (2–5 g/t) in platinum-group elements.

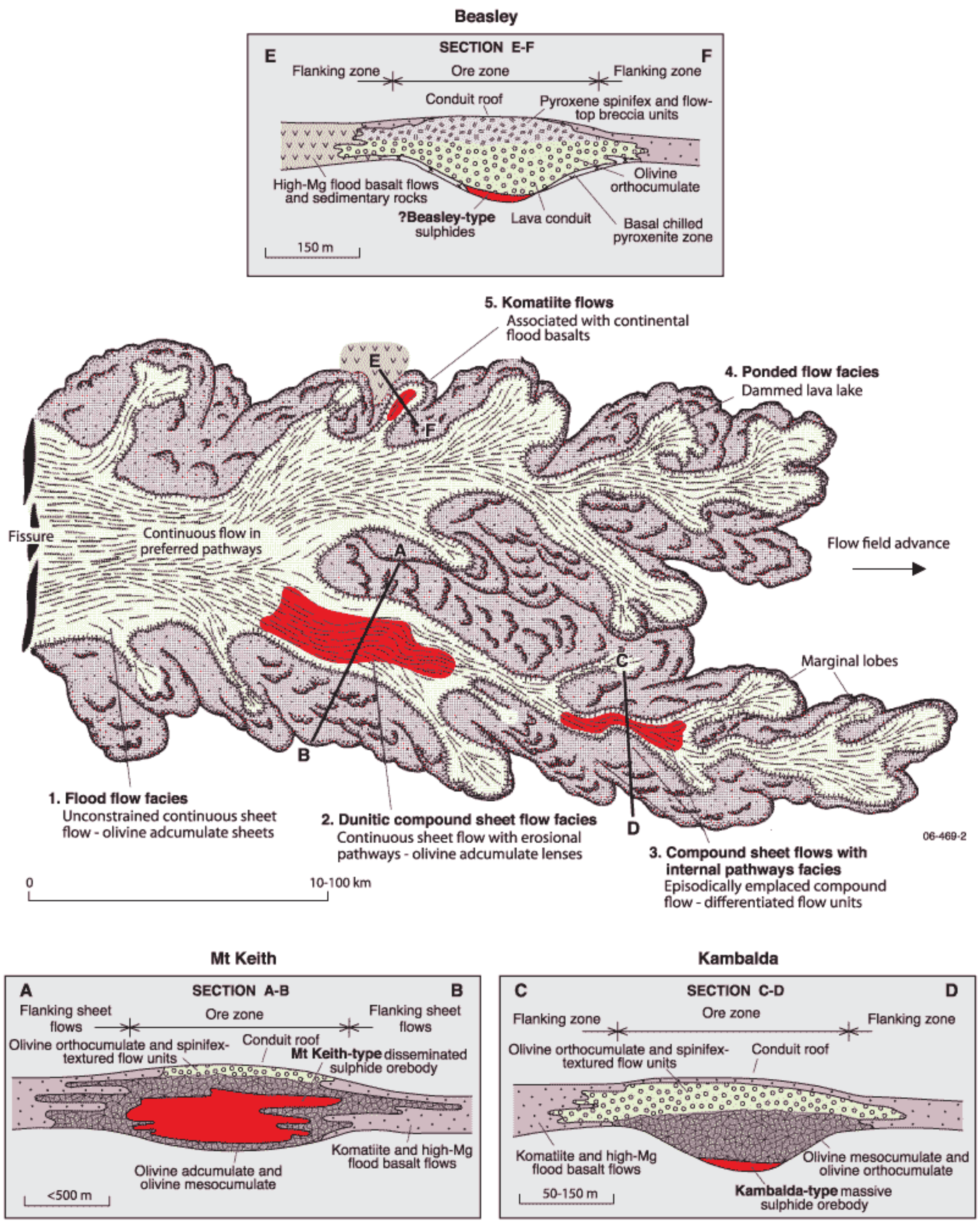
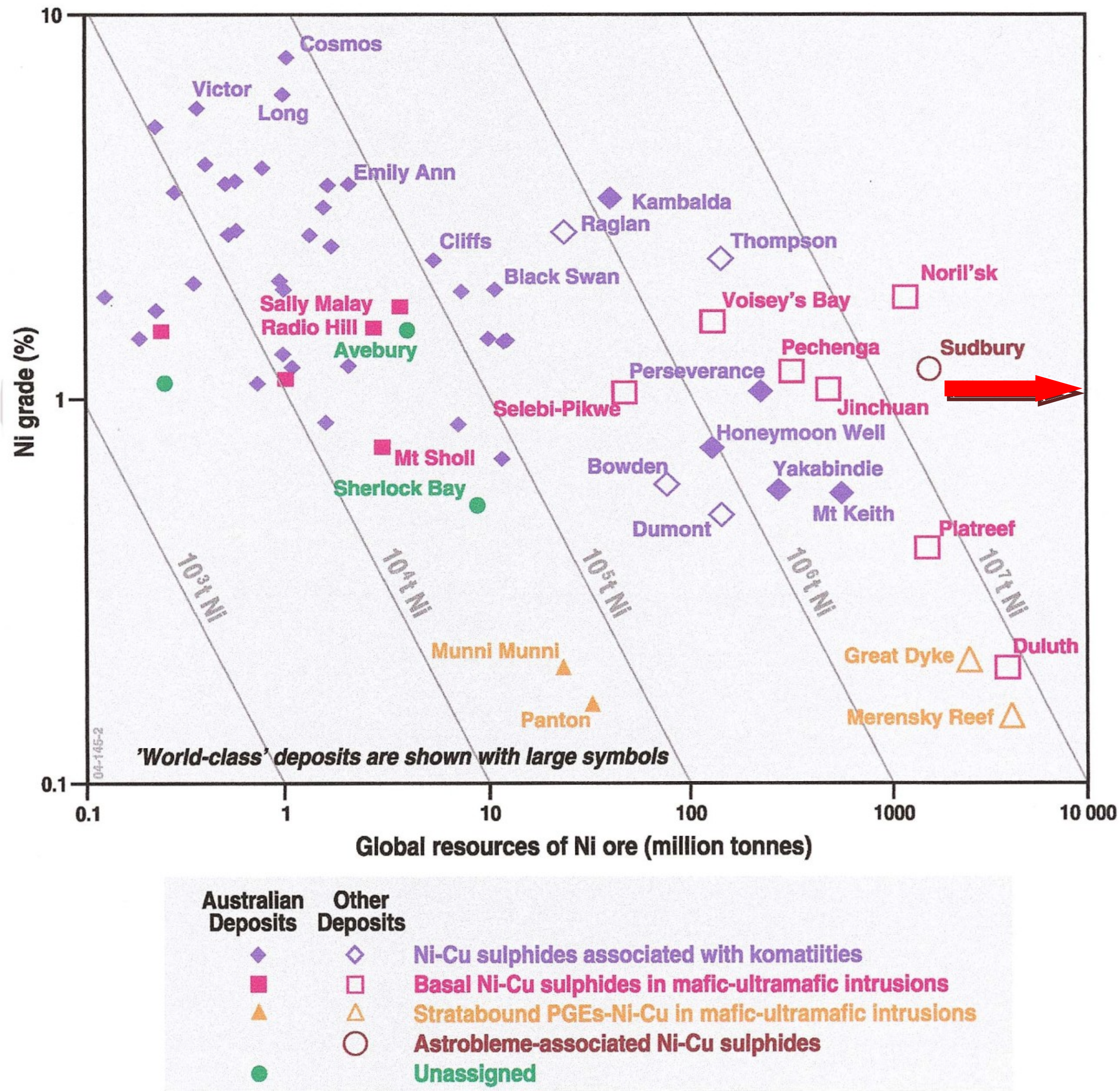


Figure 4 Komatiitic mineralizing systems. Schematic section through an inflationary komatiite flow field that developed through sustained eruption of komatiite. (Dowling and Hill, 1998)

These are clearly analogues for guiding exploration off world, especially in the assessment of asteroids of the Class M variety. The size and grade of world-class nickel deposits are plotted in Figure 5.

Figure 5 World Nickel Orebody Grade vs. Deposit Tonnage
(Jaireth, *et al*., 2008)



The above figure is a logarithmic plot of nickel grade (wt%) versus global resources of nickel ore (production plus reserves and resources in millions of tonnes) for the major nickel sulphide deposits of the Earth. Australian deposits are shown with filled symbols and other deposits are shown as open symbols. The grey diagonal lines show contained Ni metal in tonnes. The size of nickel ore bodies developed off world will likely exceed those discovered on Earth to date, larger than the Sudbury and Noril'sk deposits. Some of the known deposits may have analogues on asteroids, Mars and the Moon.

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

Nickel-metal hydride batteries will be in demand for HEVs and electric mass transport. As worldwide fresh water shortages appear, nickel will provide the corrosion-resistant alloys used in desalination plants. Impact-resistant ductile iron will find increasing use in the exploitation of wind energy. Lastly, corrosion-resistant alloys have a pivotal role to play in the "Thorium Era" scenario presented above. The THORIMS-NES system could provide nuclear energy on a variety of scales, allowing local power providers the flexibility to design the nuclear power grid to meet the needs of a locality or region. The containment for the molten salt reactor will be made of a superalloy called "Hastelloy". Combined with up to 10 other elements, Hastelloy alloys incorporate approximately 70% nickel (Wikipedia, 2009).

Nickel Development Issues

Given these new developments, the global demand for nickel may experience a very significant increase between now and the day when land-based nickel resources are exhausted. But where would the replacement for this critical resource come from? The mining of extraterrestrial resources has been proposed by several authors. Campbell, *et al.,* (2009) speculated on the size of the resource available in one Class M asteroid named 3554 Amun-NEA.

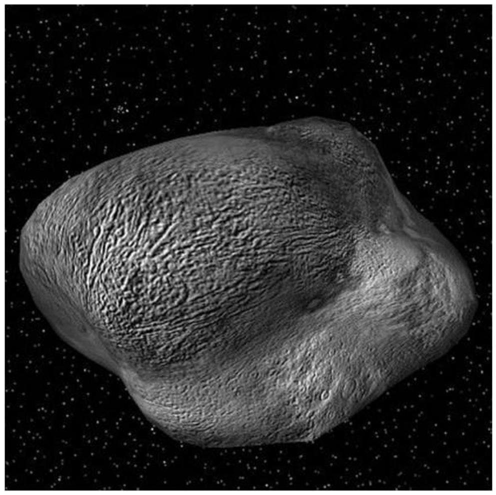


Figure 6 - A Class M Asteroid: Named 3554 Amun-NEA
(From Ambrose and Schmitt (2008)

Class M meteorites typically are composed of iron, nickel, cobalt, and platinum-group metals, the last three of which are in great demand on Earth. The asteroid 3554 Amun-NEA is about 1.3 miles in diameter, which is about the size of typical metallic ore zones on Earth. Its ore zone mass is calculated to be about 30 billion tons and assuming it contains 20 oz/ton of nickel, it could contain almost 17 million tons of nickel, or about 34 billion pounds of metal worth almost $600 billion dollars in today's market (i.e., about $35,000/ton of metal concentrate), (see British Geological Survey, 2008). Mining at sites among the asteroid belt between Mars and Jupiter, which includes about 10% of Class M asteroids, would provide a substantial supply of nickel, cobalt, and platinum-group metals.

Clearly, there are challenges to be met to develop off-world resources for use on Earth. The immense power requirements needed to develop such resources will likely come from nuclear energy, of either fission or later fusion sources. Although meeting these challenges will be difficult and will require foresight by government and industry, within 100 years there will be a different world economy, one that will likely be struggling with limited resources, environmental degradation, and population issues unless the difficult choices are made and forward-looking plans are initiated soon.

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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 developed a strong interest in the industrialization of space early in life. This interest was then reinforced years later after serving in a business partnership with the late Dr. Ted H. Foss, NASA's Chief of the Geology & Geochemistry Branch of the Science Directorate during the 1960s. He trained many of the original 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 1960s and 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/or 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 & http://aeg-tx.org. For CV information, see http://mdcampbell.com/mdcCV.asp.

[2] **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: http://www.mdcampbell.com/handleyCV.asp

[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 Pawlik 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] **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 Personnel at: http://mdcampbell.com/jdking.asp.

[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 Partner, and Senior Project Manager for M. D. Campbell and Associates, L.P. based in Houston, Texas. Previously, he has served in progressive professional positions with groups such as: Environmental Resources Management (ERM), Delta Environmental Consultants, and Carter & Burgess, Inc., 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 (http://www.mdcampbell.com/dcCV.asp).

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