2

Schmitt, H. H., 2013, Lunar helium-3 energy resources, *in* W. A. Ambrose, J. F. Reilly II, and D. C. Peters, eds., Energy resources for human settlement in the solar system and Earth's future in space: AAPG Memoir 101, p. 33–51.

Lunar Helium-3 Energy Resources

Harrison H. Schmitt

University of Wisconsin-Madison, Department of Engineering Physics, 1415 Engineering Dr., Madison, Wisconsin, 53706, U.S.A. (e-mail: hhschmitt@earthlink.net)

ABSTRACT

The financial, environmental, and national security carrot for helium-3 fusion power requires access to low-cost lunar helium-3. Helium-3 fusion potentially would provide an environmentally benign means of helping to meet an anticipated ninefold or increase in energy demand by 2050. Not available in other than research quantities on Earth, this light isotope of ordinary helium-4 reaches the Moon as a component of the solar wind. Embedded continuously in the lunar dust for billions of years, concentrations have reached levels of potential economic interest. Near the United States Apollo 11 landing site in Mare Tranquillitatis, 2 km^2 (0.8 mi^2), to a depth of 3 m (9.8 ft), contains about 100 kg (220 lb) of helium-3, that is, more than enough to power a 1000 MWe (1 gigawatt [GW]) fusion power plant for a year.

In 2008, the energy equivalent value of helium-3 relative to \$2.50/million Btu (0.25 × 10^6 kcal) industrial coal equaled about US \$1.4 billion a metric tonne (1.1 tons). One metric tonne (1.1 tons) of helium-3, fused with deuterium, a heavy isotope of hydrogen, has enough energy to supply a city of 10 million with a year's worth of electricity or more than 10 GW of power for that year.

The financial envelope within which helium-3 fusion must fit to be of interest to potential investors, as related to other 21st century energy sources, includes total development cost approximately US \$15 billion, competitive coal costs US \$2.50 or higher/million Btu (0.25 × 10^6 kcal), and payload costs to the Moon approximately US \$3000/kg (\$1360/lb).

INTRODUCTION

Settlers of space face a remarkable and diverse spectrum of challenges, whether on the Moon, Mars, or some other distant outpost (Figure 1). Survival, economics, physiological space adaptation, life support, energy supply, and international competition make up just a few of the more obvious concerns directly related to available resources on the Moon. Accessing, producing, marketing, and using those lunar resources, and doing so efficiently, require imaginative planning and execution and a full understanding of the lessons of United States Apollo lunar exploration led by the National Aeronautics and Space Administration (NASA) (Figure 2). Such requirements become particularly relevant if a primary economic objective of future lunar

DOI:10.1306/13361568 6M1013541

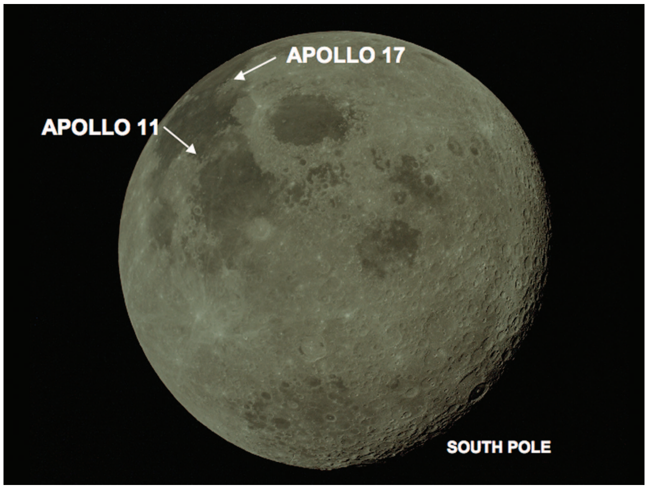


FIGURE 1. Apollo 17 view of parts of the near- and farsides of the Moon after leaving lunar orbit to return to Earth, December 16, 1972 (National Aeronautics and Space Administration Photograph AS17 152 2331).

settlers involves production and export of energy resources in the form of helium-3 fusion fuel (Wittenberg et al., 1986; Kulcinski and Schmitt, 1987).

Low-power-level steady state demonstrations of controlled fusion of helium-3 with deuterium (D) and with itself have moved forward in recent decades (Kulcinski et al., 2009). Commercial viability of either of these fusion processes as power cycles requires significantly more research and development as well as a competitively priced source of helium-3. It appears that an achievable means of access to and production and delivery of lunar helium-3 to Earth can compete in energy equivalent price with steam coal (Schmitt, 2006).

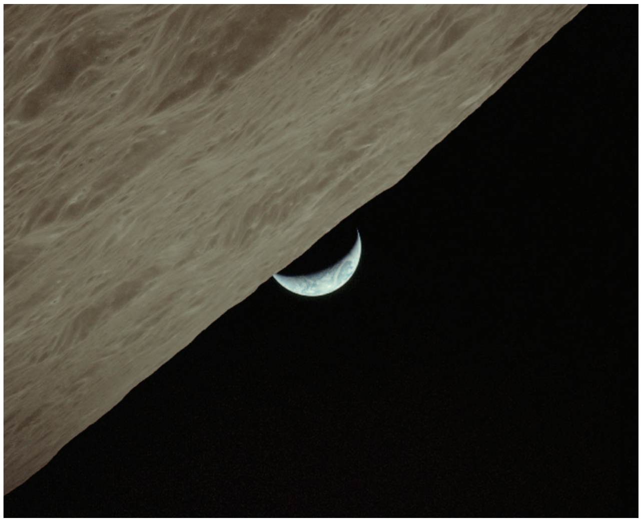


FIGURE 2. Earthrise from behind the Moon. One of the lasting symbols of Apollo (National Aeronautics and Space Administration Photograph AS17 152 23274).

FIGURE 3. Apollo 17 view of a nearly full Earth as photographed by the author from about 50,000 km (~30,000 mi) on the way to the Moon (National Aeronautics and Space Administration Photograph AS17 148 22727).

Making helium-3 fusion power available to humankind, as well as to successful space settlement, will require use of the lessons of what has worked and has not worked during 50 years of human activities in space (Figure 3). The Apollo program constitutes a critically relevant case study. Particularly important lessons from Apollo relative to future complex space endeavors include (1) using well-educated engineers and technicians in their twenties and managers and systems engineers in their thirties; (2) establishing independent internal design engineering activities in parallel with those of contractors or in-house efforts; (3) streamlining and downward delegation of management responsibilities to proven individuals; (4) seeding experienced systems engineers throughout the implementing organizations; and (5) placing senior managerial and technical leadership in the hands of experienced, competent, and courageous men and women. This essential personnel and leadership environment must exist within well-conceived and proven structures of program management, risk management, and financial management. In aggregate, such fundamentals will ensure the sustained corporate competence and discipline necessary to operate successfully for the long term in the still very high risk and complex deep space environment.

A pervasive environment of liberty also constituted an indispensable component of the success of Apollo.

Liberty to innovate, change direction, and make suggestions for improvement, coupled with operational discipline, permeated the day-to-day activities at all implementation levels of Apollo. History ultimately may conclude that a culture of liberty is an essential ingredient for success in such extraordinary complex endeavors. With the Declaration of Independence 233 years ago, the United States, now with like-minded international partners, assumed a permanent responsibility for preserving that natural right of humanity. The first Apollo landing on the Moon in 1969 expanded that irrevocable commitment into space.

Increasingly, sustained success in the perpetuation of liberty in space assures its perpetuation on Earth. Consider only America's continued insistence that space communications, space remote sensing, and space navigation capabilities be freely accessible to the world, contrasted with the restrictions placed on their own people for these same services by nondemocratic regimes such as China, Iran, and the former Soviet Union. Space domination by the enemies of human liberty would begin the psychological erosion of hope of preserving and extending the natural right of human liberty on Earth. That unfortunate outcome also would vastly increase the political, economic, and technical strength of regimes opposed to liberty. The values of space dominance that accrued to the United States as a result of Apollo have not been lost on the nondemocratic regimes of the world.

As the leading space-faring people, Americans have two fundamental choices as to their approach to furthering liberty by moving forward with space exploration and eventual settlement. On the one hand, they could find a means to restructure, revitalize, and adequately fund the National Aeronautics and Space Administration (NASA) and other space agencies and to provide them with a guarantee of continued funding as well as knowledgeable oversight. That funding must include irrevocable budget reserves sufficient to do the job in the face of inevitable encounters with unknown and unknown-unknown development challenges. Apollo's budget reserve approximated 100%, and NASA needed every bit of it to succeed. We know a great deal more about the technical requirements of working and living in space, so a 30 to 50% budget reserve for future lunar projects probably should be adequate.

Returning to the Moon, NASA's Constellation program, has been a tough order in the current national political environment, but one United States President George W. Bush and the Congress directed NASA to undertake (National Aeronautics and Space Administration, 2004). That direction has been changed by the administration of President Barack Obama. The National Aeronautics and Space Administration has found managing Constellation nearly impossible under the fiscal and programmatic restraints imposed by United States administrations and congresses. Following the critical lessons of Apollo, particularly without the necessary budget reserves, forces the slipping of development schedules to keep the program alive. At the current time, Constellation faces a highly uncertain and high-risk future as does the entire human spaceflight program of the United States.

Obviously, the option of rebuilding NASA is highly unpredictable. Its sustainability through changes in Congress and the presidency probably depends on the appearance and recognition of a set of world circumstances comparable to those facing the United States Congress and presidents Dwight D. Eisenhower, John F. Kennedy, and Lyndon B. Johnson in the late 1950s and throughout the 1960s. Some, including the writer, would argue that circumstances comparable to the Cold War exist today, but no clear bipartisan consensus exists on this point as it had at the time of President Kennedy's challenge for Americans to go to the Moon. Polarization, fed by a voracious, selfish, and historically illiterate media and political class, characterizes the American political environment much more now than when the Soviet Union constituted a clear and present danger. Unlike during Apollo (Lambright, 1995), a sufficient, sustained federal funding for a major space initiative, including contingencies, cannot be assumed in this intellectual morass.

Alternatively, the country's entrepreneurial private sector might persuade investors to make sustaining commitments based on the long-term economic potential of lunar helium-3 and its by-products and of many nearer term spin-off business opportunities arising from such a space resource initiative. This alternative also presents a difficult path forward, but, at least, it has predictable outcomes in terms of the sustained use of risk capital. Put as a critical question, what conditions do investors require to be met by a lunar helium-3 fusion power initiative relative to other uses of their capital? A discussion of this and other relevant questions follows.

WHAT WILL BE THE GLOBAL ENERGY DEMAND IN THE FUTURE?

The economic, technical, and political potential of returning to the Moon for helium-3 to fuel fusion reactors on Earth must be evaluated in the context of

Table 1. **Projected global growth in electricity demand by 2050 (revised from Schmitt, 2006).**

Growth Category	*Per Capita*
Current demand per capita	12 BOE*
Total for 6.5 billion persons	78 billion BOE*
Added per capita demand for economic growth (= U.S. today)	50 BOE*
New technology demand	?
Climate change mitigation	?
2050 demand per capita	62 BOE*
Total for 12 billion persons	744 billion BOE*
Ratio of current demand to 2050 demand	>9.5

**BOE = barrels of oil equivalent.*

probable global demand for energy and reasonably competitive alternatives for meeting that demand. In this context, the immediate challenge to civilization's global energy future lies in meeting the needs and aspirations of the 10 to 12 billion Earthlings who will be on this planet by 2050 (Edwards, 2001; Bartlett, 2004; Weisz, 2004). Current per capita use of energy is equivalent to about 13 bbl of oil/yr for a global total equivalent of about 88 billion bbl of oil equivalent (BOE)/yr or about 500 quads (quad = 10^{15} Btu or 0.25×10^{15} kcal)/yr.

It can be argued, conservatively, that more than a ninefold increase in annual energy production should be available by the middle of the 21st century (Table 1). That increase includes a twofold increase to account for world population growth from 6.5 to 12 billion and a fivefold increase to meet the major aspirations of four-fifths of the world's peoples whose standards of living are far below those of developed countries. Even a fivefold aspiration increase barely brings the rest of the world to the 2006 average per capita energy use in the United States of about 62 BOE/yr. These estimates do not include, however, the increased energy consumption demanded by new consumer technologies or by climate change mitigation.

The choice of an aspiration or economic growth increase of a factor of five is somewhat arbitrary. It represents, however, a level that not only creates a more favorable international ground for stable representative democracies but would also relieve much of world poverty and many international tensions. Higher standards of living also would provide a measure of indirect control of population growth and potentially stabilize world population at 10 to 12 billion. With respect to aspirations, China and India represent special cases in which a desire for economic and political dominance in the world, particularly on the part of China, also drives increasing electrical power and portable fuel consumption. Because of their huge populations and accelerated growth, these two countries will have inordinate influence on the future of total global demand for raw materials like fossil, nuclear, and fusion fuels. The contribution of the total standard of living aspirations to future global growth in per capita electricity demand can only be roughly estimated today. If it is as great, however, in the next 40 years as it has been for South Korea and other countries that have successfully entered the modern industrialized world, then growth of a factor of at least five will be viewed as a conservative estimate.

Large new sources of commercial energy can reduce and eventually eliminate dependence of the world's democracies on unstable sources of energy supply. Most of such a supply comes from nondemocratic sources over which exists little or no long-term market control of prices. In this context, however, financing of new capacity must come largely from the private sector. Historically, inefficient government financing and control of any major increase in energy production capacity through higher tax levies would be self-defeating in terms of economic growth and would drive down living standards.

Conservation, increased end-use efficiency, and altruistic purchase of non-cost-effective alternatives can contribute in small ways to increased energy availability; however, the laws of physics and self-interest severely limit the potential of such behavior-based alternatives. Fossil fuels and nuclear fission provide the only two energy sources that can be considered developed today and available for major unsubsidized increases in use during the next one-half century. Unfortunately, political, geologic, terrorism, and environmental factors combine to prevent a major increase in supply from these two sources by 2050, much less support a factor of nine or more increase.

Anyone who thinks that large-scale use of batteries, hydrogen, wind, solar electric, grain ethanol, and the like can provide the growth needed by 2050 has not done honest math. Such ideologically driven so-called alternatives all use more energy to function within the total energy and food economy than they can provide for end use. True cradle-to-grave analyses, including unintended consequences, will show that this is so. For example, batteries must be charged using electricity from inherently inefficient power plants. Hydrogen must be produced from natural gas or water, either of which have much greater value as natural resources than as energy sources. Until vastly more efficient and less costly large-scale energy storage systems can be found, clouds and nighttime limit the growth of solar electric systems and wind power to the excess capacity of the existing power grid or new base load plants must be built. In the absence of commercial storage systems, that excess power, of course, must be available when the sun does not shine and the wind does not blow.

Although not considered further here because of uncertainties about their scientific, technical, business, and political cases, space solar, ocean thermal, and geothermal power possibilities should be examined as possible future energy sources in objective trade-off studies.

WHAT IS HELIUM-3 FUSION?

Many nations have spent many billions of dollars since World War II on developing controlled thermonuclear fusion as a possible source of electrical power. Schmitt (2006) has summarized the various generations of fusion research. Research efforts have focused almost entirely on fusion of deuterium (D) and tritium (T). Both of these materials are heavy isotopes of hydrogen—D, being a trace component of terrestrial water, and T, which is primarily used to enhance the yield of nuclear weapons (hydrogen bombs), being a radioactive (~13-yr half-life) product of nuclear fission reactions. The fusion products consist of high-energy neutrons and alpha particles (^{4}He ions) with a total kinetic energy of 17.6 meV (millielectron volts). The D-T fusion might potentially produce electrical power by extracting the kinetic energy of the neutrons as heat after they have been captured in reactor walls and then using that heat to create steam or hot gas to drive turbine generators. This heat cycle limits any future D-T fusion plant's efficiency to no more than the best coal and nuclear power plants.

Without question, important scientific knowledge of the physics of high-temperature plasmas has come and continues to come from D-T fusion power research. Unfortunately, many practical roadblocks will prevent the commercialization of D-T fusion power for the foreseeable future. Research reactors, demonstration plants, and actual power plants require extremely complex and capital intensive engineering approaches in design, manufacturing, and construction. Confining and fueling very high temperature neutral plasmas with extremely large supercooled magnets and dealing with radioactive T fuel constitute just two of the major engineering challenges. Nor do materials exist, nor do they appear possible on the horizon, for the reactor walls that must extract heat from the kinetic energy of 14 meV neutrons and still withstand the destructive power of those neutrons. Removal of damaged reactor walls every few years requires that the plant be shut down and the irradiated wall material be disposed of as large volumes of high-level radioactive waste. The generation of high fluxes of neutrons also creates the potential for the production of weapons-grade plutonium from uranium.

Another first-generation cycle fuses D with itself, producing, along two reaction branches, equal numbers of neutrons plus helium-3 (^{3}He) ions (3.3 meV) and protons plus T ions (4.0 meV). The relatively low energy production and high neutron and T production make D-D fusion even less commercially attractive than D-T fusion.

The second-generation approach to controlled fusion power involves combining D and helium-3. Helium-3 is a light isotope of helium, most of which is helium-4 (^{4}He), the familiar birthday balloon gas and rocket pressurization gas. The fusion of D-^{3}He produces a high-energy proton (positively charged hydrogen ion) and an alpha particle (^{4}He ion) for a total kinetic energy of 18.4 meV. Dealing only with charged particles as fusion products inherently simplifies engineering design and construction. Electrostatic fields instead of large magnets can control D-^{3}He fusion fuel ions as well as the charged reaction products. At high power levels, stabilization of electron cathodes will require the use of configurations of relatively small magnets. Fusion protons, as positively charged particles, can be converted directly into electricity through the use of electrostatic deceleration as well as other possible techniques. Potential conversion efficiencies of 70% may be possible because conversion of proton energy to heat is not needed. Some side D-D fusion reactions result in minor low-energy neutron production (3.3 meV), minimized by optimizing the amount of excess helium-3 introduced into the reactor. These neutrons will result in a need to dispose of a small amount of low-level radioactive waste, equivalent to hospital radioactive waste, at the end of the power plant's life.

The third-generation approach to fusion power fuses helium-3 with itself, producing only protons and alpha particles with a total energy of 12.9 meV, eliminating any neutron-producing reactions and also eliminating all radioactive waste at the end of the plant's life. Nuclear power without nuclear waste, therefore, becomes the ultimate promise of pure helium-3 fusion. The theoretically predicted reaction rate for

D-^{3}He fusion has been demonstrated in the laboratory electrostatic confinement research reactors at continuously increasing power levels, and the demonstration of significant numbers of ^{3}He-^{3}He reactions in a controlled reaction environment recently has followed (Kulcinski et al., 2009).

The D-^{3}He fusion power promises much lower capital and operating costs than its 21st century competitors because of potentially less technical complexity, higher conversion efficiency, smaller size, no radioactive fuel, no air and water pollution, a major reduction in cooling water requirements, and only low-level radioactive waste disposal requirements. Recent estimates suggest that about US $5 billion in investment capital will be required to develop and construct the first commercial prototype of a helium-3 fusion power plant (Schmitt, 2006). The development program would pursue, in parallel, several fusion approaches optimized for helium-3 fuel, ultimately focusing on two approaches for a power plant demonstration fly-off before beginning prototype plant construction. Financial breakeven at wholesale electricity prices of US $0.05/kW hr could occur after five 1000 MWe (1 GW) plants were on line, replacing old conventional plants or meeting new demand. (A price of US $0.05/kW hr reflects the 20-day moving average minimum, with maximum at ~US $0.14 in the 2005–2009 period [Perry, 2008].)

DOES CLIMATE CHANGE MITIGATION REQUIRE HELIUM-3 FUSION?

An additional source for growth in electricity demand may come from the need to mitigate the adverse effects of natural climate change, particularly in the face of growing and more concentrated populations. One certain conclusion comes from analysis of historical, archeological, and geologic records: climate will change for centuries and sometimes change rapidly during a few decades. Independent of any possible human influence, climate change has existed as a gradual warming for almost four centuries within the 10 k.y. period of erratic but gradual global warming after the last major Ice Age. During this last four centuries, as well as the last 10 k.y., rapid cooling or warming for a decade or more or oscillations for a century or two have occurred (Broecker, 2001; Bradley et al., 2003; Hansen et al., 2004).

No capability exists as yet to reliably predict which way inevitable future change will occur as the complexity of climate precludes anything but speculative modeling. What can be reliably predicted? More electricity and more energy will be required to mitigate the adverse consequences of change whether from warming or cooling.

The largest current driver relative to consideration of alternatives to fossil fuel energy continues to be a politically motivated scare that humans caused climate change. First of all, should this scare be taken seriously, scientifically? Certainly not, but within the science of climate, critical differences exist between scientists who observe weather and climate and those who, in good faith, attempt to model nature's complexities. Those who observe the natural, historic, economic, and sociological aspects of climate change see nothing unusual in the climate variations of the last 100 years or so or since the economic impact of the industrial revolution began in earnest (Fagan, 2000; Idso and Singer, 2009; Goldberg, 2010). The modelers, however, believe that their intricate mathematics and broad assumptions about Earth's most complex system, outside of human activity, show that the continued use of fossil fuels will accelerate global warming to catastrophic levels.

Observations provide two important facts about atmospheric carbon dioxide (CO_2), the alleged perpetrator of global warming before about 2000. First, careful analyses by geophysicist Khilyuk and Chilingar (2006), Akasofu (2009) of the International Arctic Research Center, and Spencer (2009) of the University of Alabama-Huntsville show that a natural but irregular trend of global warming, by 0.5°C/100 yr (30.9°F), has existed since about 1660, the coldest part of the Little Ice Age. Obviously, this slow warming persisted for hundreds of years before industrialization began to add CO_2 to natural emissions from the biosphere and the oceans. Warming and cooling intervals during this multicentury warming trend have occurred as they have for thousands of years, and warming has not accelerated during industrialization. Second, detailed studies of ice cores show that increases in CO_2 follow global temperature increases by many centuries instead of leading those increases (Idso and Singer, 2009). Furthermore, actual observations of the recent 50 yr increase in carbon dioxide of one molecule per 10,000 molecules of air every 5 yr show no measurable long-term alteration of climate patterns during the last century's slow increase in atmospheric CO_2.

Where, then, is all the carbon dioxide from fossil fuels? Geoscientists have long known that atmospheric CO_2 cycles through the oceans every 5 to 10 year or at most every few decades (Segalstad, 1997). Furthermore, for every 51 fossil-fuel-produced CO_2 molecules added to the atmosphere, the ocean soaks up about 50 such molecules within a decade (Revelle and Suess, 1957; Skirrow, 1975; Segalstad, 1996). These observational facts mean that humans cannot cause any doomsday doubling of atmospheric CO_2.

Should there be panic over actual climate change and a lunge toward socialism to combat it? No, is the best scientific answer. It also is the best constitutional and economic answer. Actual observations show that climate varies in response to natural forces and that human burning of fossil fuels has had negligible if any effect during the last 100 years. In fact, global cooling once again has been in place since about 2000 (Easterbrook, 2008). Given what we actually know about climate, as well as the remaining uncertainties, Americans and others should think long and hard before giving up liberties and incomes to politicians who just want to do something to satisfy particular special interests. Prudent protection of local environments is one thing; a long-term ideological agenda to gather power at the expense of liberty is quite another.

Doing something will not work against natural climate forces we can only incompletely understand. When we realize what personal liberties have been lost, we will deeply regret not just preparing for climate change but also trying to stop it. Instead, our focus should be on producing more energy, not less, to raise worldwide living standards. We certainly should not limit energy use and improvements in the human condition. In this regard, a good chance exists that lunar helium-3 can contribute to the Earth's inventory of energy sources as well as legitimate environmental demands for the future.

HOW IMPORTANT COULD HELIUM-3 BE TO FUTURE ENERGY SUPPLY?

Lunar helium-3 fusion power represents a relatively new entrant into the 21st century energy sweepstakes (Wittenberg et al., 1986; Kulcinski and Schmitt, 1987, 1992; Schmitt, 1997, 2006). Access to lunar helium-3 at competitive costs offers an environmentally benign means of helping to meet an anticipated ninefold or higher increase in energy demand by 2050. Not available in other than research quantities on Earth, this light isotope of ordinary helium reaches the Moon as a component of the solar wind, along with hydrogen, helium-4, carbon, and nitrogen.

FIGURE 4. View of mostly undisturbed regolith in the Valley of Taurus-Littrow from the right window of the Apollo 17 lunar module Challenger. The largest boulder in the near field is about 0.5 m (~1.6 ft) in diameter and the base of the valley wall to the northwest is about 5 km (~3 mi) away (National Aeronautics and Space Administration Photograph AS17 147 22472).

Embedded continuously in particles of the lunar dust for almost 4 billion years, and despite losses caused by thermal cycling and micrometeor impact, helium-3 concentrations have reached levels that can legitimately be considered of economic interest (Schmitt, 2006). Helium-3 comes to the airless Moon as part of the solar wind. Stirred continuously by meteor impacts, the nearly 4 billion-year-old rocky debris layer, referred to as regolith (Figures 4, 5), slowly accumulates helium-3 along with ordinary helium, hydrogen, carbon, and nitrogen. Although quantities sufficient for research exist, no commercial supplies of helium-3 are present on Earth—if there were, we probably would be using it to produce electricity today, considering its many technical, economic, and environmental advantages.

Apollo samples collected in 1969 by Neil Armstrong on the first lunar landing, and others collected on later missions, have shown that helium-3 concentrations in many lunar soils are at least 13 ppb by weight. Detailed analyses of lunar soil samples and other evidence indicate that helium-3 concentrations are probably between 20 and 30 ppb in undisturbed titanium-rich soils (Schmitt, 2006). Schmitt concludes that helium-3 averages about 20 ppb in the titanium-rich impact commutated basalt debris, the regolith, of Mare Tranquillitatis sampled by Apollo 11. Extrapolation of data from neutron spectrographic measurements of hydrogen concentrations in lunar polar regions (Feldman et al., 1998; Maurice et al., 2004) indicate that helium-3

FIGURE 5. View of the surface of mostly undisturbed regolith from about 75 m (~246 ft) from the Apollo 17 lunar module Challenger. The Challenger is 7 m (22.4 ft) high (National Aeronautics and Space Administration Photograph AS17 134 20509).

may triple in average abundance at latitudes greater than 70°.

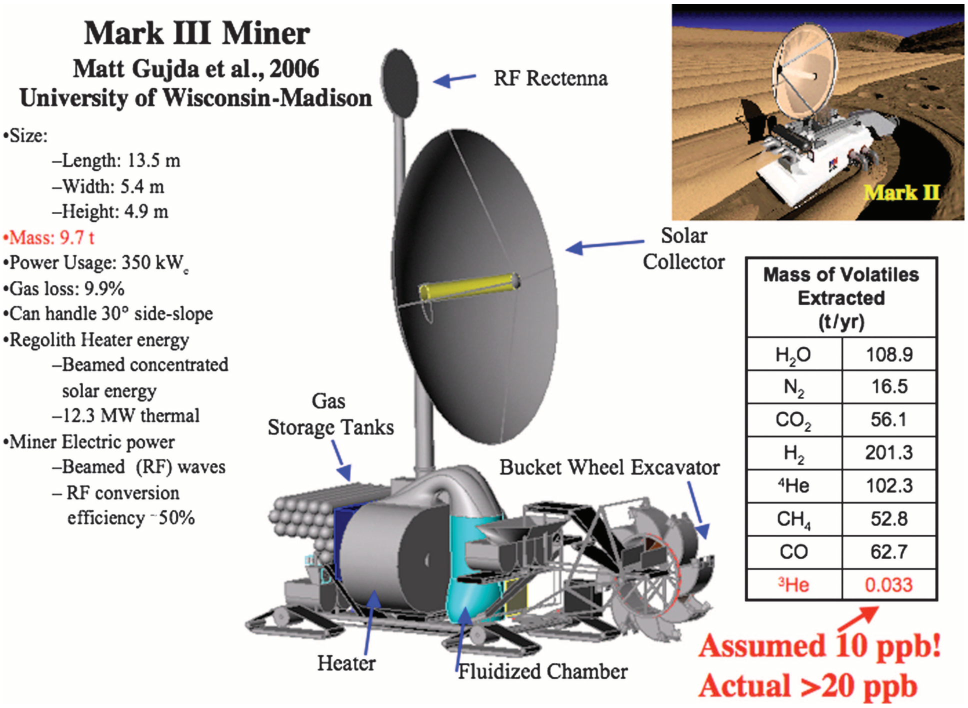
Twenty parts per billion may not seem like much; however, the value of helium-3 relative to the probable energy equivalent value of coal in 2010 to 2020, estimated conservatively at US $2.50/million Btu ($0.25 \times 10^6$ kcal), will be almost US $1400/g (US $40,000/oz)! This compares with about US $28/g (US $800/oz) for gold at the beginning of 2009. At US $1400/g, 100 kg (220 lb) of helium-3 would be worth about US $140 million. One hundred kilograms constitutes more than enough fuel to potentially power a 1000 MWe electric plant for a year when fused with D, the terrestrially abundant heavy isotope of hydrogen. A plant that size will fill the needs of a city about the size of Dallas, Texas, in the United States or Adelaide, Australia, for about one year.

The production of 100 kg (220 lb) of helium-3 per year would require annual mining and processing of about 2 km^2 (1.6 mi^2) of the lunar surface to a depth of 3 m (9.8 ft) (Schmitt, 2006). In turn, that annual rate requires hourly mining of an area about 28 m^2 (~92 ft) and 3 m (9.8 ft) deep along with the hourly processing of the finest 50% of the mined soil (~2000 t/hr or 4400 tons/hr) to extract its gases. This is not a high mining and processing rate by terrestrial standards, although a high degree of automation will be required on the Moon relative to mining and processing of raw materials on Earth. The annual rate only mandates two 10 hr mining shifts per day, 20 days out of each lunar month (~27 Earth days long). If experience shows that preventive and actual maintenance takes less than seven days per lunar month, then mining and processing rates can be higher. Personnel needed per miner are estimated at an average of eight, including operations, maintenance, and support crew (Schmitt, 2006). As miner-processors are added, some personnel will assume broader supervisory functions.

Once the hydrogen, helium, carbon, and nitrogen in the soil are extracted by a combination of agitation and heat, cooling to near absolute zero will provide sequential distillation. At very low temperatures, helium-3 can be separated from ordinary helium (superleak process). Current estimates indicate that development of this lunar mining, processing, and refining capability and supporting facilities, once design and development began, would consume about US $2.5 billion of investment capital for about five years. This cost estimate relates to several factors: (1) private entrepreneurial efficiencies relative to traditional government-funded spacecraft development; (2) conceptual design work done to date (see below); (3) available detailed geotechnical data on the lunar regolith; (4) relevant terrestrial mining and robotic design experience; and (5) publicly available technical lessons from the government's experience with design, construction, and operation of the International Space Station.

Financial breakeven for the lunar mining and processing operation, at a sales price of US $140 million/100 kg (220 lb), including the costs of launching equipment to the Moon discussed below, would occur when about five miner-processors are in operation, expected to occur about five year from the start of initial production with the activation of the 15th miner-processor (Schmitt, 2006). This breakeven point, of course, would change depending on competitive energy prices, particularly that for steam coal.

Extrapolation of the Apollo 11 sample data by remote sensing indicates that the 84,000 km^2 (~53,000 mi^2) of the highest grade regolith on Mare Tranquillitatis contains at least 5000 t (10,100 tons) of recoverable helium-3 (Cameron, 1990; Schmitt, 2006). That amount would provide a 50 yr supply (assumed plant life) for 100 helium-3 fusion power plants on Earth, each with a capacity to produce 1000 MW of electricity. Near the lunar poles, 84,000 km^2 (~53,000 mi^2) may supply three times the above number of power plants. The discovery that at least three times more hydrogen exists at high latitudes (Feldman et al., 1998; Eke et al., 2009) because of cold trapping of migrating gas and possible cometary water-ice deposits also indicates that helium concentrations will be higher in those regions as well (Schmitt et al., 2000). Future direct remote sensing and/or sample



Mass of Volatiles Extracted (t/yr)	
H_2O	108.9
N_2	16.5
CO_2	56.1
H_2	201.3
^4He	102.3
CH_4	52.8
CO	62.7
^3He	0.033

FIGURE 6. Wisconsin Mark III miner-processor. Modified from Gujda (2006).

data from high-latitude regions of the Moon may positively influence the calculation of inferred helium-3 reserves as well as the production costs per 100 kg (220 lb).

The process of regolith gardening, mixing, and thermal cycling causes some solar wind gases to be released as they also are being captured. Upon release, these initially neutral species are exposed again to the solar wind. They are then reionized and either lost to space or reimplanted elsewhere on the Moon. The gradual migration of some of these pickup ions to colder average surface temperatures and permanently shadowed cold traps probably is the reason hydrogen concentration in the regolith gradually increases by several factors toward the lunar poles and away from higher average temperatures in lower latitudes. Recent remote sensing by lunar orbiting and impacting spacecraft indicates the presence of OH and H_2O in polar regions (Clark, 2009; Dino, 2009), further supporting the probability of volatile cold trapping in general. No measurements of polar region concentrations of helium-3 have yet been possible, although in theory, the 20.6 meV gamma rays released by natural neutron capture by helium-3 (Zurmühle et al., 1963; Harris-Kuhlman, 1998) could provide such measurements from lunar orbit.

By-products of lunar helium-3 production will add significantly to future economic returns, as customers for these products develop in space. No such by-products have values that would warrant their return to Earth; however, locations in Earth's orbit, Mars, and elsewhere in deep space constitute potential markets for their sale as life- and mission-sustaining consumables. The immediately available by-products from helium-3 production include hydrogen, water, and compounds of nitrogen and carbon. Oxygen can be produced by electrolysis of water, formed by the reaction of solar wind hydrogen with oxygen-bearing lunar minerals and glass (Duke et al., 2006). Finally, space construction materials and metallic elements useful for lunar self-sufficiency, such as iron, titanium, aluminum, and silicon, can be extracted from mineral and glass components in the lunar regolith (soil).

Production of helium-3 and other resources on the Moon will require a permanent base of operations on the lunar surface even with a high degree of cost-cutting automation of various mining, processing, and refining activities (Schmitt, 2006). Since the mid-1960s, many individuals and groups and the United States government have studied the establishment and operation of lunar bases (Mendell, 1985, 1992; Schmitt, 1992; Eckart, 1999; Schrunk et al., 1999; Beattie, 2001; Koelle and Mertens, 2004). In addition, there exists the applicable foundation of technical and operational experience in space from Apollo, Skylab, Mir, Spacelab, the Space Shuttle program, and the International Space Station. Relevant experience on Earth includes resource production in geographically isolated locations and supply of remote settlements and Antarctic research stations.

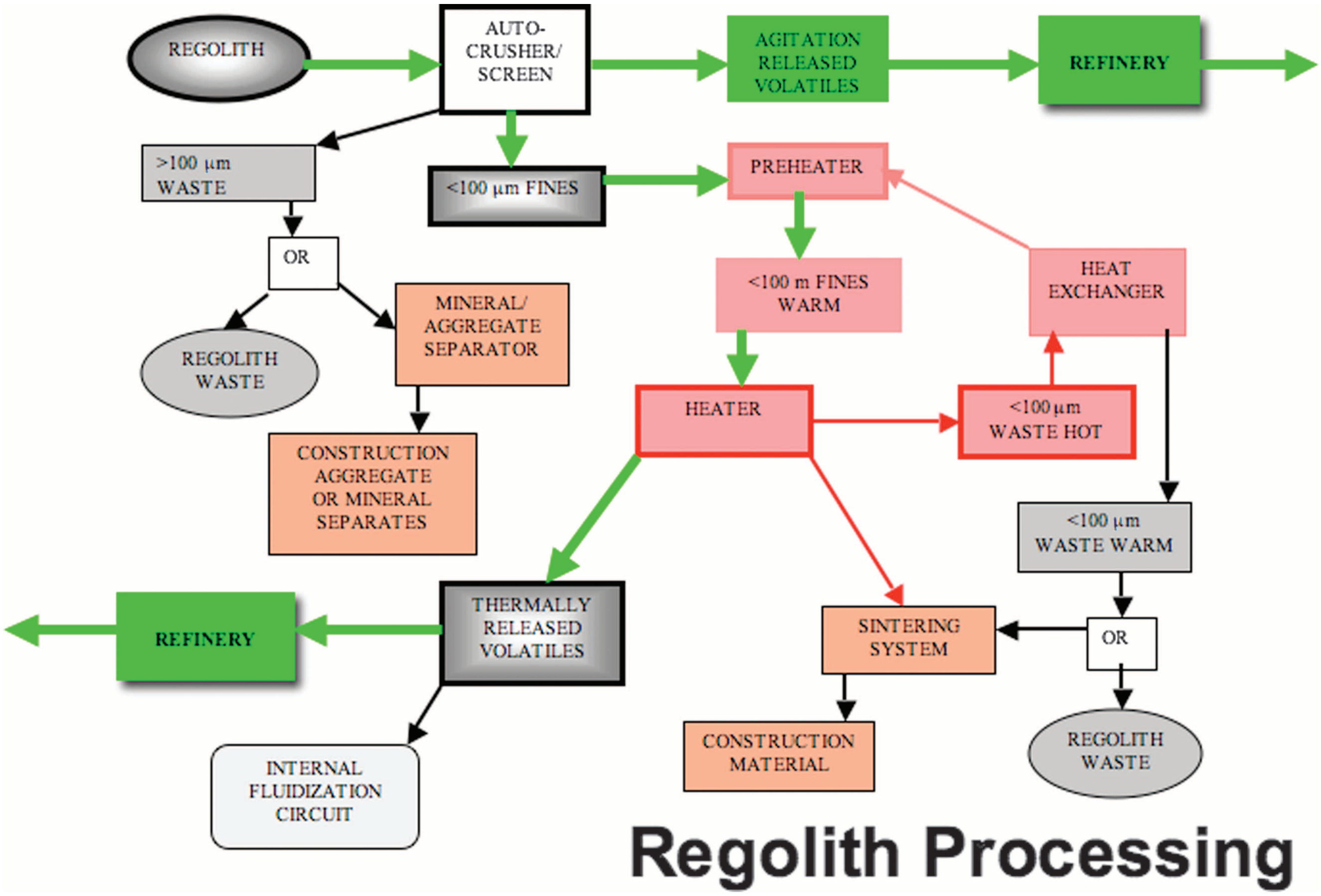


FIGURE 7. Conceptual flow diagram for regolith mining and processing lunar regolith for lunar helium-3 and other volatiles. Modified from Schmitt (2006, 2008).

A mostly privately financed initiative to use lunar helium-3 for terrestrial fusion power, with a primary focus on business instead of policy issues, will require deviation from past experience in space. For example, such an initiative must focus on minimizing both capital costs and recurring operational costs and maximizing reliability for the very long term. This will affect decisions on reactor design, choice of launch vehicles, degree of mining and processing automation, settlement of workers versus their periodic return to Earth, storage of by-products, approach to helium-3 shipment, and many other necessary components of a complex enterprise.

A few detailed efforts have been undertaken to design a lunar regolith miner-processor (Sviatoslavsky, 1993; Boucher and Richard, 2004). Sviatoslavsky of the University of Wisconsin's Fusion Technology Institute made the first cut at the essential concepts that will be required of any large-scale regolith miner-processor with his Mark II miner. More recently, Gujda (2006) has refined this design. Gujda's Mark III miner-processor (Figure 6) has a launch mass of about 10 t (~22 tons) and can produce about 66 kg (~145 lb) of helium-3 per year, two thirds of that required for a 1000 MWe fusion power plant. Refinement of this design to provide higher production rates will come as part of preparation for lunar operations after demonstration of the viability of commercially viable helium-3 fusion power. The general requirements for helium-3 mining and processing, however, are known, as shown in the flow diagrams of Figures 7 and 8, respectively.

Significant electrical and thermal energy will be required for mining, processing, and refining the lunar regolith as well as for the needs of the facilities and habitats constituting a lunar settlement. The flow diagram in Figure 9 illustrates the general requirements of a lunar power system whether it depends on energy from solar, solar-fuel cell, fission, or fusion systems.

Exporting lunar helium-3 to Earth and its by-products to elsewhere in space constitutes a relatively small challenge compared with the development of commercial fusion power plants, heavy lift boosters, and a lunar mining and processing capability. The mass of each shipment of helium-3 probably would be less than a hundred kilograms (worth ~US $140

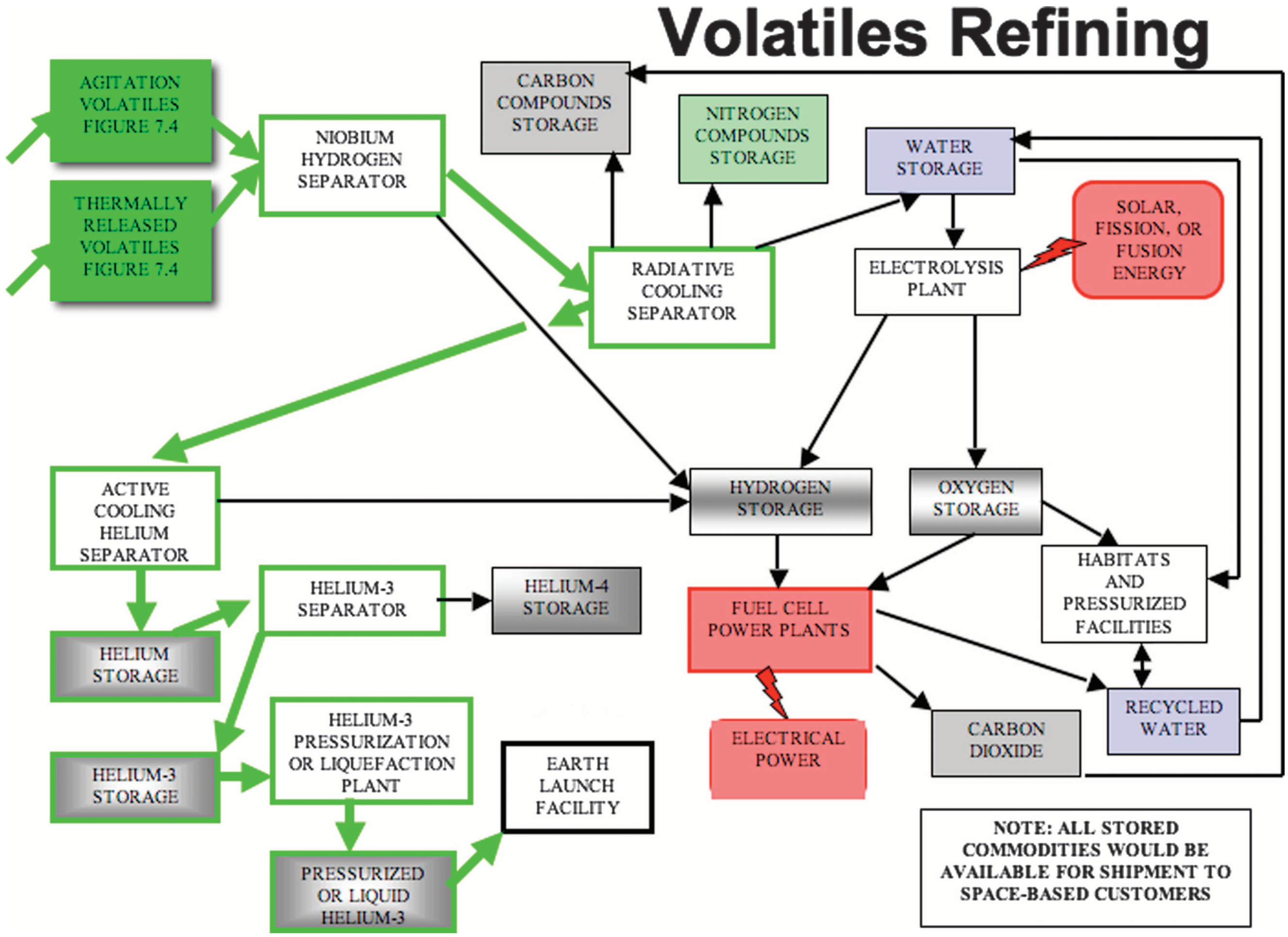


FIGURE 8. **Conceptual flow diagram for refining lunar helium-3 and other volatiles. Modified from Schmitt (2006, 2008).**

million at current coal prices) so as to manage the risk of losing a high-value shipment. The optimum shipment mass will be determined by consideration of shipment value, insurance costs, risk assessment, shipment costs versus shipment mass, and customer inventory requirements.

WHAT MUST INVESTORS CONSIDER ABOUT LUNAR HELIUM-3 FUSION?

Long-term trends in both the price of coal and the cost of money help define the overall financial and technical envelope into which a commercial lunar helium-3 fusion power option must fit if it is to be a source of pre-2050 energy supply (Schmitt, 2006). Like other undeveloped power concepts, potential investors will require a prototype demonstration of a helium-3-fueled power plant along with a financial and risk comparison relative to its future competitors. In addition, investors will need to see the definition of a clear path to lunar launch and lunar production costs that permit helium-3 power to be competitive as well as produce an adequate return on investment. Of particular importance to serious investors will be initially uncommitted financial reserves sufficient to avoid delays when unexpected technical issues arise as they always do in complex engineering endeavors.

Economic viability of helium-3 fusion power in the terrestrial marketplace must be demonstrated to investors before significant capital expenditures can be made in accessing and producing lunar helium-3. Commercial feasibility of helium-3 fusion power constitutes the first long pole in the tent that would make a private return to the Moon financially feasible. Required investment capital cannot be attracted to the development or purchase of a new Saturn-class heavy-lift rocket booster for lunar access until investors are convinced that a path to commercial fusion power exists and that energy markets will support commercial demand for lunar helium-3. Likewise, until those conditions exist, financial support will not be available for the development of space and terrestrial

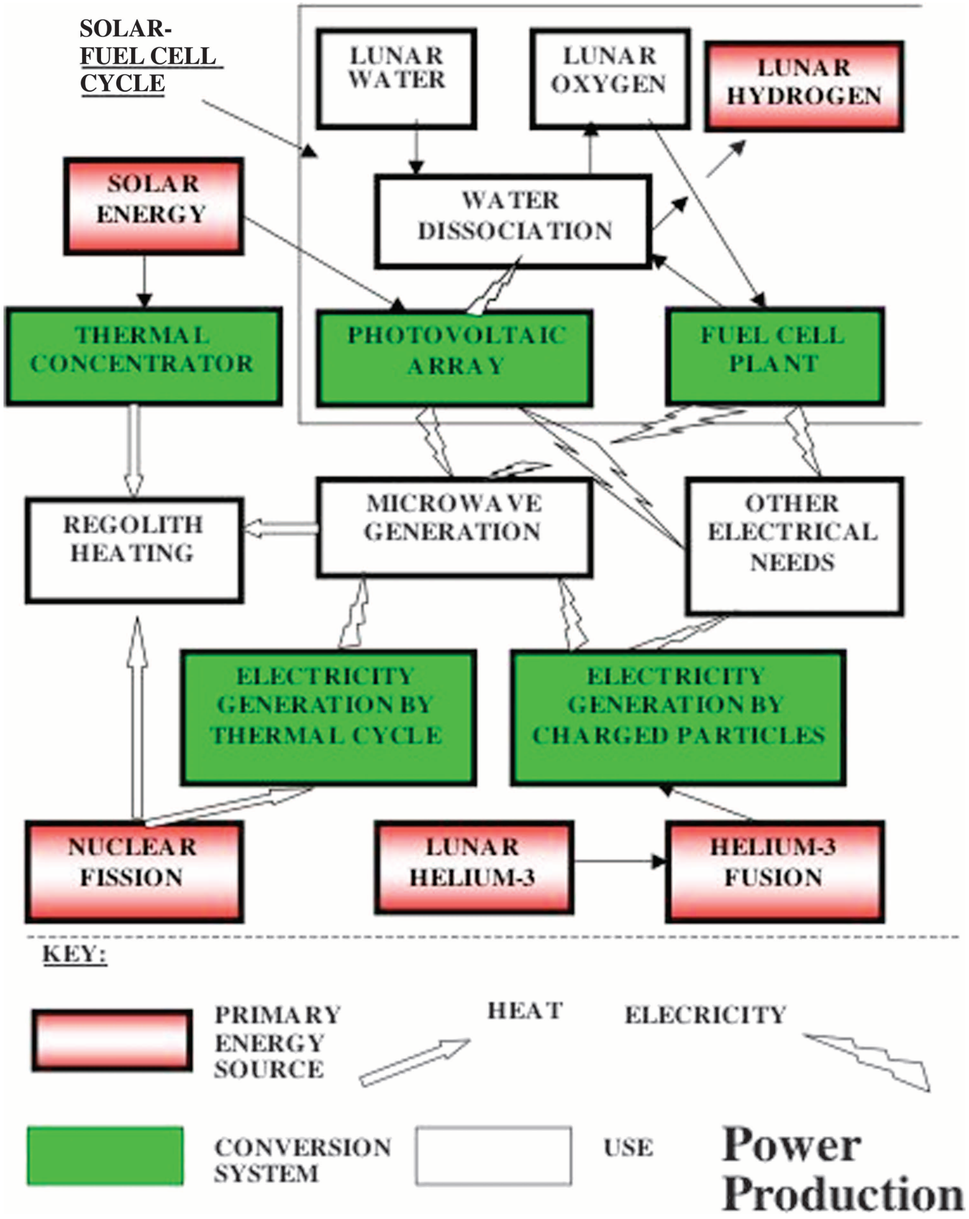


FIGURE 9. Conceptual flow diagram for thermal and electrical power production in support of lunar helium-3 production. Modified from Schmitt (2006).

hardware and facilities necessary to the success of the enterprise. Fortunately, a reasonable probability has developed in recent years that these investment tests can be met.

The second major development challenge is to achieve significantly greater payload capability at much lower cost than Apollo did for launches from Earth to the Moon. In this regard, the Apollo Saturn V rocket (Figure 10) remains the benchmark for a reliable heavy-lift rocket for delivering large payloads to the lunar surface, as the author and 11 other moonwalkers can testify. Saturn Vs remain the largest rockets ever used, weighing 2.8 million kg (6.2 million lb) and developing 33.4 N (7.5 million lb) of thrust at liftoff. This huge booster reliably launched 40 to 50 t (80–110 tons) payloads to the Moon at a final marginal cost of about US $62,500/kg (US $28,400/lb) (2005 dollars). Competitive financial constraints on the required cost of helium-3 delivered to fusion power plants require that new modernized Saturn VI rockets should be capable of launching up to 100 t (220 tons) payloads to the Moon at a cost of about US $3000/kg (US $1360/lb) (Schmitt, 2006), that is, a factor of 21 less than at the end of Apollo. As competitive energy costs rise, that payload cost restriction becomes less onerous, of course, but it remains wise to target the lowest reasonable cost possible.

Vast technological advances have occurred in the more than 45 years since the Saturn V was designed and manufactured. These advances strongly suggest that the reduction in payload costs by a factor of 21 can be accomplished with an investment capital of

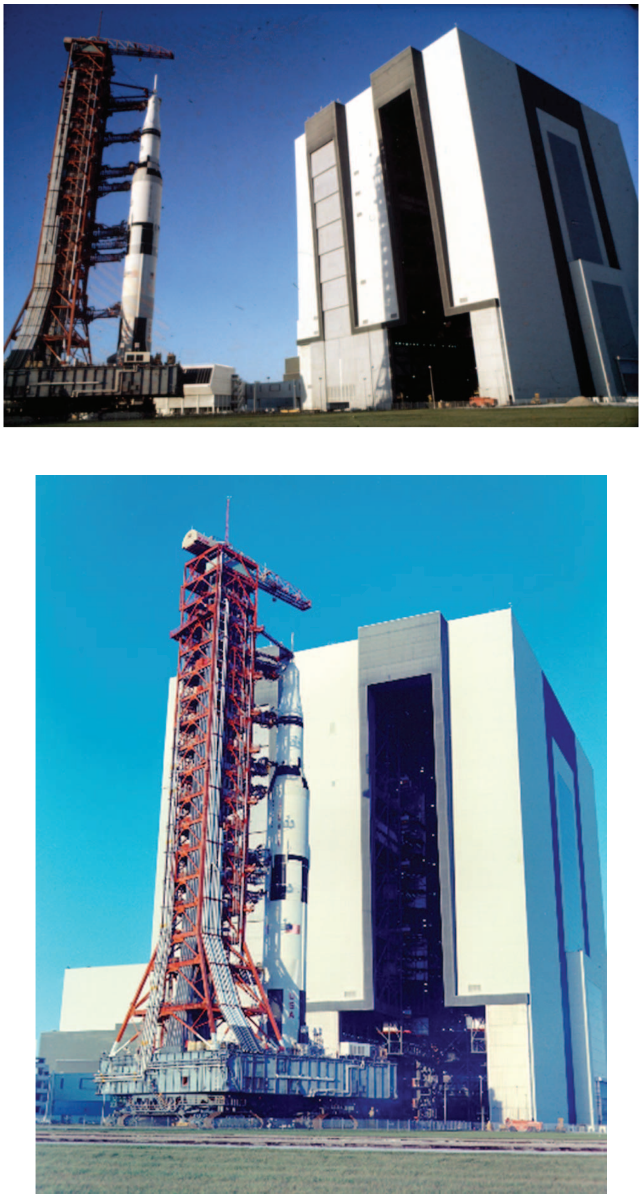


FIGURE 10. **Apollo 17 Saturn V launch system and spacecraft during transport to its launch pad on the mobile launch tower. The Saturn V is 109 m (364 ft) high. The Vehicle Assembly Building stands behind with a large fire engine at the right base (National Aeronautics and Space Administration Photograph KSC-72PC-426HR).**

about US $5 billion (Schmitt, 2006), including test flights. Although fusion development proceeds, a low-cost study of how to reduce the cost and increase the capability of the Saturn V toward an equally reliable Saturn VI would prepare investors for a critical concept review on which to base future decisions (Schmitt, 2006). Importantly, we know what we need to do to make this happen and in what technical areas potential improvements exist—a situation very unlike that in 1960 when President Eisenhower ordered NASA to initiate the Saturn project.

President George W. Bush and the Congress began the Constellation program to return to the Moon in 2004. If Congress provides adequate funding and NASA moves forward and succeeds in the development of the needed heavy-lift launch system, and associated lunar transfer vehicle and spacecraft, a trade study would be required to see if those systems can compete in cost and reliability with a conceptual Saturn VI, including redevelopment costs, and more specialized spacecraft appropriate to a lunar mining and settlement enterprise. At the earliest, that trade study would not be feasible until about five years after the conceptual design of a Saturn VI and the operational success of NASA's new heavy-lift booster.

Many other business-related issues would be approached by a private enterprise effort in ways very different from an effort managed by a government agency. For example, a private company will immediately want lunar settlers as employees. Hiring committed settlers would eliminate the costs for their regular return to Earth except insofar as periodic return became an important employee retention benefit. In addition, the spacecraft will be specialized for the tasks of landing precisely at known resource-rich locations on the Moon instead of serving several masters, such as normally would be envisioned by NASA. A private initiative also will concentrate on lunar surface vehicles, highly mobile space suits, work facilities, and radiation-resistant habitats that provide highly reliable low-cost resource recovery during extended periods. All equipment will be designed for indefinite operational life, including embedded diagnostics, anticipatory component replacement, and ease of maintenance and refurbishment.

For investors, the primary advantage that lunar helium-3 fusion will have over other out-of-the-box energy sources in the pre-2050 time frame, such as space solar power (Criswell, 1996, 2002; Glaser, 1997), comes from a definable path into the private capital markets. The potential of several near-term applications of helium-3 fusion technology defines this path in existing markets before reaching breakeven power levels and a commercial plant demonstration (Kulcinski, 1998; Schmitt, 2006). Several such applications look as if they can provide early returns on investment as well as advance technology toward electrical power generation.

The development of side business lines in the longer term would improve profit margins and help retire debt once lunar operations commence. These potential businesses include sale of by-products from helium-3 production, such as hydrogen, water, and oxygen as well as food and other materials produced on the Moon. A lunar settlement's launch of consumables and other materials to space-based customers has a great competitive cost advantage over launch from the six times greater gravity of Earth. Furthermore, helium-3 fusion technology can contribute to efficient and long propulsion in space (Santarius and Logan, 1998) of interest for continuous satellite maneuvering and shortened transit times for deep space craft. Crews headed for Mars, for example, will appreciate and benefit from a shorter trip than possible with chemical propulsion. These additional launch and propulsion-related businesses include providing services for government-funded lunar and planetary exploration, astronomical observatories, national defense, and long-term on-call protection from the impacts of asteroids and comets. Space and lunar tourism also will be enabled by the existence of low-cost, highly reliable rockets.

Not all ancillary business opportunities from helium-3 fusion development lie in space. The development of fusion technologies will stimulate near-term business opportunities on Earth in medical diagnostics and treatment, transportation, weapons detection, and nuclear waste elimination (transmutation). The profit potential in the production of positron-emitting isotopes for medical isotopes grows yearly (Schmitt, 2006), for example, particularly now in the use of very short half-life isotopes of nitrogen, carbon, and oxygen (Kulcinski et al., 2009).

In summary, the rough boundaries of the economic envelope of concern to potential investors within which helium-3 fusion must fit as related to other 21st-century energy sources are as follows: total development cost approximately US $15 billion (including ~30% reserves), competitive coal costs US $2.50 or greater/million Btu (0.25×10^6 kcal), and payload costs to the Moon approximately US $3000/kg (US $1360/lb). A capital investment of US $15 billion in 2009 dollars would be about the same as was required for the 1970s TransAlaska Pipeline (Alyeska Pipeline, 2004). As competitive energy prices escalate and fusion power revenues increase, as is probable because of increased demand and regulatory costs, breakeven between gross revenues and recurring costs (including cost of capital) would occur earlier than the estimated activation of the 15th terrestrial fusion power plant and its supporting lunar miner-processor.

Estimates of the recurring costs for helium-3 production units suggest that those costs would approach breakeven relative to steam coal at US $2.50/million Btu ($0.25 \times 10^6$ kcal) after 15 production units were in place on the Moon (Schmitt, 2006). Clearly, many opportunities exist to reduce production costs. Alternatively, many current unknowns could increase those costs, including the inability to reach US $3000/kg (US $1360/lb) payload delivery costs. The next step will be to mature hardware designs to the point where more certain recurring as well as nonrecurring costs can be estimated more definitively.

The energy exploration industry commonly refers to the cost of developing access to a resource as the finding cost. For crude oil, finding costs are normally approximately US $1.00/bbl, and for natural gas, these costs are about US $3.50/mmcf (0.028 million m^3). Using 5.9×10^6 Btu (1.5×10^6 kcal) as the energy content of a barrel of oil (U.S. Department of Energy, 2004) and 5.6×10^{13} Btu (1.4×10^{13} kcal) as the energy content of 100 kg (220 lb) of helium-3 fused with D, Schmitt (2006) estimates the finding cost leading to helium-3 production by assuming the following:

- The first resource field is 10,000 km^2 (3900 mi^2) in area and to a depth of 3 m (9.8 ft) contains about 5000 100 kg (220 lb) units of helium-3 or the energy equivalent of 4.8×10^{10} bbl of oil. (A 10,000 km^2 [3861 mi^2] area is chosen somewhat arbitrarily as the amount of measured resources that clearly would be of interest commercially if fusion power customers existed on Earth.)
- The capital and operational costs necessary to initiate production from this field are estimated by Schmitt (2006) to be about US $15 billion.

These assumptions give a finding cost of about US $1.60/BOE for this size of helium-3 field or somewhere between the finding costs for oil and natural gas. Of course, the actual finding cost for helium-3 would be much lower because the resource field in Mare Tranquillitatis is significantly larger than 10,000 km^2 (3900 mi^2) in area—estimated to be about 84,000 km^2 (~53,000 mi^2) just for the region of highest helium-3 concentration near the lunar equator. Also, if deposits in the polar regions have significantly higher concentrations of helium-3, finding costs will decrease in direct proportion.

WHAT IS THE STATUS OF FUSION TECHNOLOGY?

After published verification of significant quantities of helium-3 in lunar soil in 1970 (Eberhardt et al., 1970; Hintenberger et al., 1970; Marti et al., 1970; Pepin et al., 1970 ; Funkhouser et al., 1971), interest remained purely scientific for about 15 years until, in 1985, researchers at the Fusion Technology Institute of the University of Wisconsin-Madison began investigating controlled D-^{3}He fusion as an alternative to D-T fusion and seeking potential helium-3 resources. They realized that the solar wind should have deposited helium-3 on the Moon and, while investigating how much may have been deposited, they became aware of the results of the previous Apollo analyses. They immediately realized the significance of the Apollo discovery in considering future energy resources (Wittenberg et al., 1986). The fusion of helium-3 with D and the production of protons and alpha particles had been demonstrated in 1949 (Wyly et al., 1949; Santarius, 1987; Crabb et al., 1994). This potential source of fusion energy, however, had been ignored as a practical option because of the absence of commercially significant quantities of helium-3 on Earth. In the absence of an economical terrestrial helium-3 supply and in view of the federal government's concentration on D-T fusion technology (weapons into plowshares) to the exclusion of potential alternatives, investor interest in technical development of helium-3 fusion has been minimal.

Historic progress has been made during the last two decades in the use of helium-3 to produce controlled fusion reactions. This has occurred through the advancement of inertial electrostatic confinement (IEC) fusion technology at the Fusion Technology Institute. Progress includes the production of approximately 1 W of steady-state power in the form of protons and alpha particles produced by D-^{3}He fusion. Steady progress in IEC research and understanding the basic physics of IEC fusion processes suggest that the helium-3 approach to fusion power has commercial viability in large-scale plants. Helium-3-based fusion, relative to other electrical plant options for the 21st century and beyond, can have inherently lower capital costs, higher energy conversion efficiency, a range of power from a hundred megawatts upward, and potentially no associated radioactivity or radioactive waste. Research and development costs to build the first helium-3 demonstration power plant are estimated to be about US $5 billion.

DO THE ENGINEERS EXIST TO UNDERTAKE GREAT NEW PROJECTS?

World War II and the Cold War brought government research funds into state and privately run colleges and universities and changed the face of learning for students entering these institutions in later years (Hutchins, 1936). The life-and-death necessities of that period left the country with little choice at the time. With those funds came increasing controls on not just how such funds could be spent but on unrelated institutional management. Reaction to Sputnik and the Cold War exacerbated the loss of state and private control over research institutions. The United States Great Society's Higher Education Act of 1965 instituted federal student loan guarantees and grants, bringing even greater federal regulation of how universities and colleges ran their institutions.

Clearly, a public interest exists in federal funding of research in qualified institutions in times of national security threats. Such funding can be justified under the joint legislative and executive powers for national defense enumerated in the United States Constitution's articles I and II. The reservation of educational powers to the states and the people by the Tenth Amendment, however, logically requires that, in contracting for research, the federal government cannot constitutionally regulate the management of the recipient institutions beyond that required for overseeing the successful and legal outcome of the funded research. Any coercion outside these bounds is on its face unconstitutional despite long-standing federal assumptions to the contrary.

A critical consequence of higher education's long dependency on unreliable federal research funds and burdensome student loans, added to the sad quality of precollege education in math and science, has been a steadily reduced interest in engineering studies. This cryptic crisis of science and technology education has caused multidecade erosion in the supply of young, well-prepared, American engineers available to serve in critical industrial, space, and defense projects (Augustine et al., 2007). This growing gap between the supply and the demand for highly educated talent undermines the nation's ability to compete internationally in the development of commercial and national security technology. A major initiative to develop and sustain a lunar helium-3 fusion power initiative requires that this gap be eliminated.

No matter what can be done to improve higher education, growth of the existing reservoir of young engineers and skilled workers requires restructuring of the elementary and secondary systems of education in math and science, as well as in the classic liberal arts. Unfortunately, in this regard, the government education system has failed. After World War II, our public education system for elementary and secondary grade levels gradually fell under the control of selfish special interests and away from the control of parents, contrary to the clear wording of the Tenth Amendment. This situation has reached a point of threatening the national security and long-term economic vitality of the United States and the liberty of its citizens, and presents even more of a threat to the development of new sources of energy.

HOW WOULD SETTLERS GET TO THE MOON?

To provide competitive returns on investment in its lunar endeavors, the private sector will want heavier payload capability and lower cost in Earth-Moon launch systems previously or currently envisioned by government (Schmitt, 2006). A private spacecraft will be specialized for the tasks of landing reliably and precisely at known resource-rich locations on the Moon instead of serving two or more masters, such as the International Space Station and a lunar base and sorties for science on the Moon and elsewhere in space (National Aeronautics and Space Administration, 2004).

A private initiative will need to concentrate on lunar surface vehicles and facilities that provide reliable low-cost resource recovery in addition to habitats for mine personnel. It also will require highly mobile and low-maintenance space suits that are less than half the weight and more than four times the mobility of Apollo suits and that have the glove dexterity close to that of the human hand. All vehicles, facilities, and space suits (Figure 11) will be designed for indefinite operational life, including embedded diagnostics, anticipatory component replacement, and ease of maintenance and refurbishment. Any required automated precursor missions to gather additional resource development information will use low-cost data-specific approaches instead of attempts to meet broad, higher cost, purely scientific objectives. Research and development costs for launch and lunar operations equipment are estimated by Schmitt (2006) to be between US $7 billion and US $10 billion.

FIGURE 11. **The author, using the Apollo A7LB space suit, beginning the examination of a large boulder near the base of the north wall of the Valley of Taurus-Littrow on the Moon, December 16, 1972 (National Aeronautics and Space Administration Photograph AS17 140 21497).**

WHO OWNS LUNAR RESOURCES?

International law relative to outer space, specifically the Outer Space Treaty of 1967, permits properly licensed and regulated commercial endeavors (Schmitt, 2006). Under the treaty, lunar resources can be extracted and owned, but national sovereignty cannot be asserted over the resource area. History clearly shows that a system of internationally sanctioned private property, consistent with the treaty, would encourage lunar settlement and development far more than the establishment of a lunar commons, as envisioned by the mostly unratified 1979 Moon Agreement. A somewhat different, but generally compatible, analysis of current international law has been made by Bilder (2010). Throughout history, designations of common access to resources have a notorious record of failure to sustain the productivity of a resource. Systems encompassing the recognition of private property have provided far more benefit to the world than those that attempt to manage common ownership.

HOW MUCH INVESTMENT IS REQUIRED?

The initial financial threshold for a private sector initiative is low: about US $15 million (Schmitt, 2006). This investment would initiate the first fusion-based bridging business, that is, production of medical isotopes for point-of-use support of diagnostic procedures using positron emission tomography. Ultimately, an estimated total of US $15 billion of investment capital would be required to deliver the first 100 kg of lunar helium-3 to the first operating 1000 MWe fusion power plant on Earth. This US $15 billion would include at least 30% as reserves but would be reduced by an as yet undetermined amount by retained earnings from precursor businesses.

THE FINAL FRONTIER?

Whenever and however a return to the Moon occurs, one thing is certain: that return will be historically comparable to the movement of our species out of Africa about 150 ka. Furthermore, if led by an entity representing the democracies of the Earth, a return to the Moon to stay will be politically comparable to the first permanent settlement of North America by European immigrants (Schmitt, 2006).

ACKNOWLEDGMENTS

I recognize the research team of the Fusion Technology Institute at the University of Wisconsin-Madison, led by G. L. Kulcinski, as having been primarily responsible for stimulating worldwide interest in the potential of lunar helium-3 resources and their by-products. Beginning in 1985, the state of Wisconsin and numerous private contributors have made possible the groundbreaking work of the Wisconsin team.

ADDITIONAL READING

American Society of Civil Engineers, 1988–2008, Proceedings of Engineering, Construction, and Operations in Space Conferences, Lunar Development Conferences 1988–2008, Space Frontier Foundation, American Society of Civil Engineers.

REFERENCES CITED

Akasofu, S. -I., 2009, Natural causes of 20th century global warming: Recovery from the Little Ice Age and oscillatory change: Heartland Conference on Climate Change 2, New York, March 9–10, 2009, http://climateconferences.heartland.org/syun-akasofu-iccc2/ (accessed June 17, 2012).

Alyeska Pipeline, 2004: http://www.alyeska-pipe.com/pipelinefacts.html (accessed December 19, 2011).

Augustine, N. R., et al., 2007, Rising above the gathering storm: Energizing and employing America for a brighter economic future: Washington, D.C., The National Academies Press, 592 p.

Bartlett, A. A., 2004, Thoughts on long-term energy supplies: Scientists and the silent lie: Physics Today, v. 57, no. 7, p. 53–55, doi:10.1063/1.1784303.

Beattie, D., 2001, Taking science to the Moon: Baltimore, John Hopkins University Press, p. 28–57.

Bilder, R., 2010, A legal regime for the mining of helium-3 on the Moon: U.S. policy options: Fordham International Law Journal, v. 33, p. 3.

Boucher, D. S., and J. Richard, 2004, Report on the construction and testing of a bucket wheel excavator (abs.), *in* Space Resources Roundtable VI: Lunar and Planetary Institute (LPI) Contribution No. 1224, #6004: http://www.lpi.usra.edu/meetings/roundtable2004/pdf/6004.pdf (accessed June 17, 2012).

Bradley, R. S., M. K. Hughes, and H. F. Diaz, 2003, Climate in medieval time: Science, v. 302, p. 404–405, doi:10.1126/science.1090372.

Broecker, W. S., 2001, Was the medieval warm period global?: Science, v. 291, p. 1497–1499, doi:10.1126/science.291.5508.1497.

Cameron, E. N., 1990, Geology of Mare Tranquillitatis and its significance for the mining of helium, Technical Report, Wisconsin Center for Space Automation and Robotics, Madison, Wisconsin, 65 p: http://fti.neep.wisc.edu/pdf/wcsar9006-1.pdf (accessed June 17, 2012).

Clark, R. N., 2009, Detection of adsorbed water and hydroxyl on the Moon: Science, v. 326, p. 562–564, doi:10.1126/science.1178105.

Crabb, J. C., S. W. White, L. P. Wainwright, S. E. Kratz, and G. L. Kulcinski, 1994, Fifty years research in helium-3 fusion and helium-3 resources: Madison, Wisconsin, Fusion Technology Institute, WCSAR-TR-AR3-9312-1.

Criswell, D. R., 1996, World and lunar solar power systems costs, *in* S. W. Johnson, ed., Engineering, construction, and operations in space V: 5th International Conference on Space 96: American Society of Civil Engineers, p. 293–301, doi:10.1061/40177(207)40.

Criswell, D. R., 2002, Solar power via the Moon: The industrial physicists: American Institute of Physics, p. 12–15.

Dino, J., and Lunar Crater Observation and Sensing Satellite Team, 2009, LCROSS impact data indicates water on the Moon. NASA: http://www.nasa.gov/mission_pages/LCROSS/main/prelim_water_results.html (accessed December 19, 2011).

Duke, M. B., L. R. Gladis, G. J. Taylor, and H. H. Schmitt, 2006, Development of the Moon, *in* B. Jolliff, B. L. Jolliff, M. A. Wieczorek, C. K. Shearer, and C. R. Neal, eds., New views of the Moon: Mineralogical Society of America and The Geochemical Society, p. 597–656.

Easterbrook, D. J., 2008, Evidence for predicting global cooling for the next three decades: Global Research, Centre for Research on Globalization: http://www.globalresearch.ca/index.php?context=va&aid=10783 (accessed December 19, 2011).

Eberhardt, P., J. Geiss, H. Graf, N. Grogler, U. Krahenbuhl, H. Schwaller, J. Schwarzmuller, and A. Stettler, 1970, Trapped solar wind noble gases, exposure age and K/Ar-are in Apollo 11 lunar fine material: Apollo 11 Lunar Science Conference, v. 2, p. 1040.

Eckart, P., ed., 1999, The lunar base handbook: An introduction to lunar base design, development, and operations: New York, McGraw-Hill Companies, Inc., 851 p.

Edwards, J. D., 2001, Twenty-first century energy: AAPG Memoir 34, p. 21–34.

Eke, V. R., L. F. A. Teodoro, and R. C. Elphic, 2009, The spatial distribution of polar hydrogen deposits on the Moon: Icarus, v. 200, p. 12–18, doi:10.1016/j.icarus.2008.10.013.

Fagan, B., 2000, The Little Ice Age: New York, Basic Books, p. 10–15.

Feldman, W. C., S. Maurice, A. B. Binder, B. L. Barraclough, R. C. Elphic, and D. J. Lawrence, 1998, Fluxes of fast and epithermal neutrons from Lunar Prospector: Evidence for water ice at the lunar poles: Science, v. 281, p. 1489–1500, doi:10.1126/science.281.5382.1496.

Funkhouser, J. G., O. A. Schaeffer, D. D. Bogard, and J. Zahringer, 1971, Active and inert gases in Apollo 12 and Apollo 11 samples released by crushing at room temperature and by heating at low temperatures: Lunar Science Conference 2, v. 2, p. 1181–1396.

Glaser, P., 1977, Solar power from satellites: Physics Today, v. 30, no. 2, p. 30–38, doi:10.1063/1.3037410.

Goldberg, F., 2010, Some historical ice observations and future possible ice conditions in the Arctic: Heartland Conference on Climate Change 4, Chicago, May 17, 2010, http://climateconference.heartland.org/fred-goldberg-iccc4/ (accessed June 17, 2012).

Gujda, M. E., 2006, A lunar volatiles miner: M.S. thesis UWFDM-1304, University of Wisconsin-Madison, Wisconsin, 112 p.

Hansen, B., S. Østerhus, D. Quadfasel, and W. Turrell, 2004, Already the day after tomorrow?: Science, v. 305, p. 953–954, doi:10.1126/science.1100085.

Harris-Kuhlman, K. R., 1998, Trapping and diffusion of helium in lunar minerals: Ph.D. dissertation, University of Wisconsin-Madison, Madison, Wisconsin, p. 234–237.

Hintenberger, H. H., W. Weber, H. Voshage, H. Wanke, F. Begeman, and F. Wlotzka, 1970, Concentration and isotopic abundances of rare gases in lunar matter: Apollo 11 Lunar Science Conference, v. 2, p. 1269–1282.

Hutchins, R. M., 1936, The higher learning in America: New Haven, Connecticut, Yale University Press, 119 p.

Idso, C., and S. F. Singer, 2009, Climate change reconsidered: Chicago, Illinois, Heartland Institute, 856 p.

Khilyuk, L. F., and G. V. Chilingar, 2006, On global forces of nature driving the Earth's climate: Are humans involved?: Environmental Geology, v. 50, p. 899–910.

Koelle, H.-K., and H.-N. Mertens, 2004, Conceptual design of a lunar base: Aachen, Germany, Shaker Verlag, 114 p.

Kulcinski, G. L., 1998, Nonelectric applications of fusion energy: An important precursor to commercial electric power: Fusion Technology, v. 34, p. 477.

Kulcinski, G. L., and H. H. Schmitt, 1987, The Moon: An abundant source of clean and safe fusion fuel for the 21st century: 11th International Scientific Forum on Fueling the 21st Century, Moscow, USSR, 38 p.

Kulcinski, G. L., and H. H. Schmitt, 1992, Fusion power from lunar resources: Fusion Technology, v. 21, p. 2221–2229.

Kulcinski, G. L., et al., 2009, Near-term applications of inertial electrostatic confinement fusion research: Fusion Science and Technology, v. 56, p. 493.

Lambright, W. H., 1995, Powering Apollo—James E. Webb of NASA: Baltimore, Maryland, Johns Hopkins, 271 p.

Marti, K. K., G. W. Lugmair, and H. C. Urey, 1970, Solar wind gases, cosmic-ray spallation products and the irradiation history of Apollo 11 samples: Apollo 11 Lunar Science Conference, v. 2, p. 1357–1367.

Maurice, S., D. J. Lawrence, W. C. Feldman, R. C. Elphic, and O. Gasnault, 2004, Reduction of neutron data from Lunar Prospector: Journal of Geophysical Research, v. 109, no. E7, p. E07S04, doi:10.1029/2003JE002208.

Mendell, W. W., ed., 1985, Lunar bases and space activities of the 21st century: Houston, Lunar and Planetary Institute, 860 p.

Mendell, W., ed., 1992, The Second Conference on Lunar Bases and Space Activities of the 21st Century: NASA Conference Publication 3166, 706 p.

National Aeronautics and Space Administration, 2004, The vision for space exploration, NP-2004-01-334-HQ, 32 p.: http://history.nasa.gov/Vision_For_Space_Exploration.pdf (accessed December 19, 2011).

Pepin, R. O., L. E. Nyquist, D. Phinney, and D. C. Black, 1970, Rare gases in Apollo 11 lunar material: Apollo 11 Lunar Science Conference, v. 2, p. 1435–1454.

Perry, M. J., 2008, Wholesale electricity prices fall by 51 to 77%: http://seekingalpha.com/article/105000-wholesale-electricity-prices-fall-by-51-to-77 (accessed December 19, 2011).

Revelle, R., and H. E. Suess, 1957, Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO_2 during the past decades: Tellus, v. 9, p. 18–27, doi:10.1111/j.2153-3490.1957.tb01849.x.

Santarius, J. F., 1987, Very high efficiency fusion reactor concept: Nuclear Fusion, v. 27, p. 167, doi:10.1088/0029-5515/27/1/017.

Santarius, J. F., and B. G. Logan, 1998, Generic magnetic fusion rocket model: Journal of Propulsion and Power, v. 14, p. 519.

Schmitt, H. H., 1992, Lunar base activation scenario, *in* W. W. Mendell, ed., The Second Conference on Lunar Bases and Space Activities of the 21st Century: National Aeronautics and Space Administration Conference Publication 3166, p. 667–672.

Schmitt, H. H., 1997, Interlune-Intermars business initiative: Returning to deep space: American Society of Civil Engineers: Journal of Aerospace Engineering, v. 10, no. 2, p. 60–67, doi:10.1061/(ASCE)0893-1321(1997)10:2(60).

Schmitt, H. H., 2006, Return to the Moon: New York, Copernicus-Praxis, 345 p.

Schmitt, H. H., 2008, Lunar resource mining, processing and refining: AAPG Annual Meeting.

Schmitt, H. H., G. L. Kulcinski, J. F. Santarius, J. Ding, M. J. Malecki, and M. J. Zalewski, 2000, Solar-wind hydrogen at the lunar poles: American Society of Civil Engineers, SPACE 2000, p. 653–660.

Schrunk, D., B. Sharpe, B. Cooper, and M. Thangavelu, 1999, The Moon: Resources, future development and colonization: Chichester, Wiley-Praxis, 432 p.

Segalstad, T. V., 1996, The distribution of CO_2 between atmosphere, hydrosphere, and lithosphere: Minimal influence from anthropogenic CO_2 on the global "greenhouse effect," *in* J. Emsley, ed., The global warming debate: The Report of the European Science and Environment Forum: Bournemouth, Dorset, United Kingdom, Bourne Press Ltd., p. 41–50.

Segalstad, T. V., 1997, Carbon cycle modeling and the residence time of natural and anthropogenic atmosphere CO_2: On the construction of the "greenhouse effect" global warming dogma (abs.): Oslo, Norway, Mineralogical-Geological Museum, University of Oslo, p. 11.

Skirrow, G., 1975, The dissolved gases—Carbon dioxide, *in* J. P. Riley and G. Skirrow, eds., Chemical oceanography, 2d ed.: New York, Academic Press, v. 2, p. 1–192.

Spencer, R., 2009, Satellite evidence for global warming being driven by the Pacific decadal oscillation: Heartland Conference on Climate Change 2, New York, March 9–10, 2009, http://climateconferences.heartland.org/roy-spencer-iccc2/ (accessed June 17, 2012).

Sviatoslavsky, I. N., 1993, The challenge of mining He-3 on the lunar surface: How all the parts fit together: Wisconsin Center for Space Automation and Robotics, WCSAR-TR-AR3-9311-2, 12 p.

U.S. Department of Energy, 2004, Annual energy outlook forecast evaluation 2004: http://www.eia.gov/oiaf/analysispaper/pdf/forecast_eval.pdf (accessed December 19, 2011).

Weisz, P. B., 2004, Basic choices and constraints on long-term energy supplies: Physics Today, v. 57, no. 7, p. 47–52, doi:10.1063/1.1784302.

Wittenberg, L. J., J. F. Santarius, and G. K. Kulcinski, 1986, Lunar source of He-3 for commercial fusion power: Fusion Technology, v. 10, p. 167–178.

Wyly, L. D., V. L. Sailor, and D. G. Ott, 1949, Protons from the bombardment of He-3 by deuterons: Physical Review, v. 76, p. 1532–1533, doi:10.1103/PhysRev.76.1532.

Zurmühle, R. W., W. E. Stephens, and H. H. Staub, 1963, Gamma rays from neutron capture in helium-3 and deuteron capture in deuterium: Physical Review, v. 132, p. 751–754, doi:10.1103/PhysRev.132.751.