Lunar Helium-3 Fusion Resource Distribution[1]

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Introduction

Settlers of space face a remarkable and diverse spectrum of challenges, whether on the Moon, Mars or some other distant outpost. 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 directly benefit the cost and feasibility of many future activities in deep space. Accessing, producing, marketing, and using those lunar resources, and doing so efficiently, requires imaginative planning and execution and a full understanding of the lessons of Apollo lunar exploration. Such requirements become particularly relevant if a primary economic objective of future lunar 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 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).

Defining the distribution and concentration of this resource on the Moon and making it available to humankind, as well as to a successful space settlement, will require use of the lessons of what has worked and has not worked during fifty years of human activities in space. The Apollo Program constitutes a critically relevant case study. Particularly important lessons from Apollo relative to future complex space endeavors are (1) employing well-educated engineers and technicians in their twenties and

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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 insure 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.

What Will Be 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 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 ten to twelve billion earthlings that will be on this planet by 2050 (Bartlett, 2004; Weisz, 2004). Current per capita use of energy is equivalent to about twelve barrels of oil per year for a global total equivalent of about seventy-two billion barrels of oil equivalent (BBOE) per year (Edwards, 2001), or about 410 quads (quad = 10^{15} BTU or 0.25 x 10^{15} kcal) per year.

It can be argued, conservatively, that more than a nine-fold increase in annual energy production needs to be made available by the middle of the 21st Century. That increase includes a two-fold increase to account for world population growth from 6.5 to twelve billion and a five-fold 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 five-fold “aspiration” increase barely brings the rest of the world to the 2006 average per capita energy use in the United States of about 62 barrels of oil per year equivalent. These estimates do not include, however, the increased energy consumption demanded by new consumer technologies or by climate change mitigation.

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 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 ten to twelve 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. International competition deserves special emphasis in this context as China, India, and Russia have advocated accessing lunar energy resources for many years. Noticeably absent from this advocacy has been the government of the United States. The contribution of the total standard of living "aspirations" to future global growth in per capita electricity demand only can be roughly estimated today. If it is as great, however, in the next forty 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.

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. Research efforts have focused almost entirely on fusion of deuterium (D) and tritium (T). The fusion products consist of high-energy neutrons and alpha particles (^{4}He ions) with a total kinetic energy of 17.6 MeV (million electron volts). DT fusion potentially can produce electrical power by extracting the kinetic energy of the neutrons as heat after they have been captured in reactor blankets, and then use that heat to create steam or hot gas to drive turbine generators. This heat cycle limits any future DT fusion plant's efficiency to around 40% or no more than the best coal and nuclear power plants.

Many practical roadblocks will prevent DT fusion power from being commercialized in 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 plasmas with extremely large, super-conducting magnets and dealing with radioactive tritium 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 and blanket structural materials that must extract heat from the kinetic energy of 14 MeV neutrons and still withstand the destructive power of those neutrons for several years. 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.

The "second generation" approach to controlled fusion power involves combining deuterium and helium-3. Helium-3 is a light isotope of helium, most of which is helium-4 (^{4}He). 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. Only a few percent of the energy released by the D-^{3}He fusion reaction involve neutrons via side reactions of D-D. Dealing only with charged particles (vs. neutrons) as fusion fuels and products inherently simplifies engineering design and construction. Electrostatic fields rather than large magnets can control D-^{3}He fusion fuel ions as well as the charged reaction products. At high power levels, some confinement concepts require the stabilization of electron cloud cathodes that will require the use of configurations of relatively small magnets. On the other hand, magnetic confinement could serve D-^{3}He fusion as well and eventually, trade studies will be require to make a final reactor choice.

Fusion protons, as positively charged particles, can be converted directly into electricity. Potential conversion efficiencies of close to seventy percent may be possible. Some side D-D fusion reactions result in minor low energy neutron production (2.45 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 of 40-50 years or more.

The "third generation" approach to fusion power fuses helium-3 with itself, producing only protons and alpha particles with total energy of 12.9 MeV, eliminating all neutron producing reactions and also eliminating all radioactive waste at the end of plant life. Nuclear power without nuclear waste therefore becomes the ultimate promise of pure helium-3 fusion.

The fusion of D and ^{3}He has been demonstrated for several years in 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 has followed, recently (Kulcinski, et al, 2009).

Helium-3 fusion power promises much lower capital and operating costs than its Twenty-first Century competitors due to greatly reduced materials damage and radioactive waste production, no tritium breeding, higher energy conversion efficiency, smaller size, no radioactive fuel, no air and water pollution, a major reduction in cooling water requirements, and at worst only low level radioactive waste disposal requirements. Recent estimates suggest that about $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, pp. 68-73). 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 ~$0.05 per kilowatt-hour could occur after five, 1000 megawatt plants were on line, replacing old conventional plants or meeting new demand. [$0.05 per kilowatt-hour reflects the 20 day moving average minimum with maximum at ~$0.14 in the 2005-2009 period (Perry, 2009).]

How Important Could Helium-3 Be to Future Energy Supply?

Lunar helium-3 fusion power represents a relatively new entrant into the Twenty-first Century energy sweepstakes (Wittenberg, et al, 1986; Kulcinski and Schmitt, 1987; Kulcinski and Schmitt, 1992**;** Schmitt, 1997; Schmitt, 2006). Access to lunar helium-3 at competitive costs potentially offers an environmentally benign means of helping to meet an anticipated nine-fold or higher increase in energy demand by 2050.

Embedded continuously in particles of the lunar dust over almost four billion years of time, and in spite of losses due to thermal cycling and micro-meteoroid impact, helium-3 concentrations have reached levels that can legitimately considered to be of economic interest (Schmitt, 2006, pp. 77-108). Helium-3 comes to the airless Moon largely as part of the "solar wind." It also may be contributed by cosmic ray and meteoritic sources and particularly helium-3-rich solar flares. Stirred continuously by meteoroid impacts, the nearly four billion year old rocky debris layer, referred to as "regolith," 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 they 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 other samples collected on later missions, have shown that helium-3 concentrations in many lunar soils are at least thirteen parts per billion by weight. Detailed analyses of lunar soil samples and other evidence indicate that in situ helium-3 concentrations probably range between twenty and thirty parts per billion in undisturbed, titanium-rich soils (Schmitt, 2006, pp. 86-92). Schmitt concludes that helium-3 averages about 20ppb in the titanium-rich impact commutated basalt 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, S., et al, 2004) indicate that helium-3 may triple in average abundance at latitudes above 70° due to cold trapping (Schmitt, et al, 2000; Cocks, personal communication, 2009).

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 2010-2020, estimated conservatively at \$2.50 per million BTU (0.25 x 10^6kcal) will be almost \$1400 per gram (\$40,000 per ounce)! This compares with about \$28 per gram (\$800 per ounce) for gold at the beginning of 2009. At \$1400 per gram, one hundred kilograms (220 pounds) of helium-3 would be worth about \$140 million. One hundred kilograms constitutes more than enough fuel to potentially power a 1000 megawatt electric plant for a year when fused with deuterium, the terrestrially abundant heavy isotope of hydrogen.

The production of a hundred kilograms (220 pounds) of helium-3 per year would require annual mining and processing of about two square kilometers (1.6 sq. mi.) of the lunar surface to a depth of three meters (9.8 ft.) (Schmitt, 2006, pp. 92-98). In turn, that annual rate requires hourly mining of an area about twenty-eight meters square (92 ft.) and three meters (9.1 ft.) deep along with the hourly processing of the finest fifty percent of the mined soil (about 2000 tonnes/hour or 4400 ton/hour) 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, ten-hour mining shifts per day, twenty days out of each lunar month (about twenty-seven 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-processor are estimated at an average of eight, including operations, maintenance and support crew (Schmitt, 2006, pp. 134-137).

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 \$2.5 billion dollars of investment capital over about five years. Financial breakeven at a sales price of \$140 million per hundred kilograms (220 pounds), 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 years from the start of initial production with the activation of the 15th miner-processor (Schmitt, 2006, pp. 135-142).

Extrapolation of the Apollo 11 sample data by remote sensing indicates that the 84,000 square kilometers (~53,000 sq. mi.) of the highest grade regolith on Mare Tranquillitatis contains at least 5000 tonnes (5500 tons) of recoverable helium-3 (Cameron, 1990; Schmitt, 2006, 92-95). That amount would provide 50 years supply (assumed plant life) for 100, 1000 megawatt helium-3 fusion power plants on Earth. Near the lunar poles, 84,000 square kilometers (~53,000 sq. mi.) may supply three times the above number of power plants. Future direct remote sensing and/or sample data from high latitude regions of the Moon may positively influence the calculation of inferred helium-3 reserves as well as the production costs. Where deep permanent shadow exists, helium-3 also may be contained in clathrates and non-lunar fullerenes.

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, consumers in earth orbit, during Mars transit, on the Mars surface, 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 (methane, for example). 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).

A largely privately financed initiative to utilize lunar helium-3 for terrestrial fusion power, with a primary focused on business rather than 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 over 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.

With respect to a lunar regolith miner-processor a few detailed efforts to design have been undertaken (Sviatoslavsky, 1993; Muff, et al, 2002; 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, Gajda has refined this design (Gajda, 2006). Gajda's Mark III miner-processor (Figure 6) has a launch mass of about 10 tonnes (11 tons) and can produce about 66kg (145 pounds) of helium-3 per year, two-thirds of that required for a 1000 megawatt fusion power plant. Refinement of this design to provide higher production rates will come as part of preparation for lunar operations following demonstration of the viability of commercially viable helium-3 fusion power.

Exporting lunar helium-3 to Earth and its by-products to elsewhere in space constitutes a relatively small challenge compared to 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 about $140 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 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, a reaction that had its own long history of investigation within the fusion community, as an alternative to D-T fusion, and seeking potential helium-3 resources. The fusion of helium-3 with deuterium 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.

Historic progress has been made over the last two decades in the use of helium-3 to produce controlled fusion reactions. This has occurred through the state and private advancement of inertial electrostatic confinement (IEC) fusion technology at the Fusion Technology Institute. Progress (at funding levels of only a few million dollars, total) includes the production of approximately one watt of steady-state fusion power in the form of protons and alpha particles produced by D-^{3}He fusion. Research and development costs to build the first helium-3 demonstration power plant are estimated to be about five billion dollars.

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, pp. 275-286, 295). 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 largely un-ratified 1979 Moon Agreement. 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.

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 150,000 years ago. Further, 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, pp. 8, 318-319).

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