Humankind sought and attained galactic stature with the first explorations of the moon between 1967 and 1973. During these momentous years, our species took its first clear steps of evolution into the solar system and eventually into the galaxy. Now, as the Pueblo Indians of America relate the lesson of their ancestors, "We walk on the Earth, but we live in the sky."

Early explorers of the sky took their eyes and minds into space and became the eyes and minds of billions of other explorers on the starship Earth. They began the long process of transplanting human civilization into space. This fundamental change in the course of history occurred as humans also gained new insight about themselves and about their first planetary home. With the conclusion of the Apollo 17 mission and the Apollo Program in December 1972, humankind had reached the "end of the beginning" of its movement away from home.

The overall political backdrop against which new challenges in space will be addressed during the 1990s and early decades of the Third Millennium appears to be coalescing into three major themes: Empowerment of people, Stewardship of Earth, and, indeed, Settlement of Space.

Political debate concerning Empowerment has been part of history for thousands of years, at least since the exodus of the Israelites from Egypt, and knowing the human spirit, probably long before. Today and into the future, Empowerment of people involves finding an acceptable societal balance between individual freedom and individual responsibility.

Political concerns about Stewardship began to appear early in this century but sprang full blown into public consciousness only after World War II. Exploding populations, nuclear energy concerns, and the Apollo views of Earth thrust environmental issues onto the world political stage. Stewardship for the future embodies not only protection of Earth but improvement of the human condition.

Energy makes up the most significant component of the theme of Stewardship of Earth. The basic justification for a sense of urgency with respect to energy lies in the provision of abundant and environmentally acceptable energy resources. The need for an alternative to fossil fuels for the generation of electricity increasingly will become a global imperative.

Strong evidence now exists that the ever increasing and largely indiscriminate use of fossil fuels contributes significantly to the current rise in carbon dioxide in the atmosphere. Although the ultimate response of the Earth and its climate to this build-up remains unclear, prudence clearly demands that we find acceptable alternatives to fossil fuels as quickly as technically and economically feasible. If nothing else, the value of fossil chemicals to the feeding of more
billions of people on Earth will overwhelm their value as sources of electrical power.

Finally, as access to space near Earth became relatively routine in the 1960s, the theme of Settlement of Space moved from the pages of science fiction to the speculations of futurists and the reports of strategic planners. With former President Bush's Apollo 11 Anniversary speech of July 20, 1989, Settlement moved beyond speculations and reports into national policy considerations. Settlement of Space has reached a position of national visibility not unlike that reached by Stewardship during the 1950s.

Energy resources on the moon, specifically, a light isotope of helium known as helium-3, provide the link between Stewardship and Settlement (fig. 1). Fusion power plants on Earth, fueled by lunar helium-3, have the potential to produce essentially unlimited, environmentally acceptable electrical power. By-products from the production of helium-3 on the moon would provide the hydrogen, oxygen, water, and other consumable materials critical to sustaining the early settlers of Mars.

The time has come, then, to re-evaluate what we have learned about the moon in the context of these new imperatives.

One thing we learned in 1970 from the first lunar samples (Heiken et al, 1991), and which the Wisconsin workers re-discovered in 1985 (Wittenberg et al, 1985), was that the pulverized surface materials of the moon partially retain protons (96%), He (4%), and small amounts of other ions streaming from the sun as the solar wind (fig. 2). One of the solar wind volatiles is He or just He-3 (fig. 3).

The six Apollo landings on the moon have given us a first order understanding of the systematics of He-3 distribution in the lunar regolith (see Cameron, 1988, and fig. 4) as these surface materials are called. Fifty to sixty percent of the regolith down to depths of five to ten meters consists of particles less than 100 microns in average diameter, that is, it is dust. The He-3 and other volatiles have their greatest concentrations in this dust due to the large effective surface area it represents. Although we have limited data on the variations of volatile content with depth, the drill cores we have indicate no trends toward a decrease in concentration to depths of three meters.

Amounts of He-3 and other volatiles also correlate closely with the concentration of titanium in the regolith (fig. 5), due to its strong retention by the iron-titanium oxide called ilmenite. This correlation fortunately gives us one technique to measure He-3's approximate distribution over the near face of the moon. Its property as a neutron absorber with the emission of a 22 mev gamma ray promises to provide a technique for more detailed resource mapping once a spectrometer of appropriate sensitivity can be placed in orbit.

Using remote sensing techniques from Earth, the regional distribution of Ti (Johnson et al, 1992) and, thus, of He-3 has been determined to a first approximation. The area of highest potential concentration or "grade" and of probable greatest initial interest will be in the northern half of Mare Tranquillitatis.

Even though present in the regolith in amounts less
than about 30 parts per billion, the total quantity of He-3 in
the first three meters of lunar regolith approximates one
million tonnes, including both mare and highlands (Wittenberg
et al, 1986). This quantity of He-3 would provide 10 times
more energy than that in all the economically recoverable
fossil fuels on Earth as defined by the U.S. Department of
Energy. Further, one tonne of He-3 can produce 10,000 MWe-yr
of electrical energy, or approximately that required by a U.S.
city with a population of 10 million, and the entire U.S.
electricity consumption in 1993 could be provided by 25 tonnes.

As indicated by the NASA Lunar Energy Enterprise Case
Study (1989), what really makes these numbers of economic
interest is He-3’s oil equivalent value on Earth today, if
commercial fusion plants existed to use it, of about three
billion dollars per tonne. Another way to look at this is that
He-3 at one billion dollars per tonne is equivalent to seven
dollar per barrel oil.

What is our energy and environmental imperative that
drives the search for an alternative to fossil fuels? First,
as summarized by Kulcinski and Schmitt (1990) worldwide energy
use per capita has increased steadily since 1960 and is
projected to reach 15 barrels of oil equivalent by 2050. For
reference, the U.S. per capita energy use is currently about 60
BOE. Second, world population will approach or exceed 10
billion by 2050. Projected cumulative energy use will exceed
seven trillion barrels of oil equivalent, potentially exceeding
recoverable supplies.

The production of one tonne of He-3 from lunar regolith
with a recoverable grade of 20 ppb requires the beneficiation
of about 50 million tonnes of material and the mining of about
100 million tonnes, equivalent to an area of about 20 km² mined
to a depth of three meters. This compares with the current
annual production of coal (without overburden removal and
replacement) of about 5 billion tonnes.

Simple heating to about 700 °C. (fig. 6) recovers over
90 percent of the He-3 and other solar wind volatiles present
in the fine-grained portion of the lunar regolith (Pepin et al,
1970). If the separation of fines, their solar thermal
heating, and heat recovery take place within the miner, very
little mechanical energy will be required for mining and
beneficiation relative to comparable large tonnage mining
operations on Earth.

The conduct of actual mining operations leads to a
number of possibilities, ranging from a traditional rectilinear
approach (Cameron, 1990), employing a semirobotic
self-contained miner and beneficiator (see Sviatoslavsky and
Jacobs, 1988, and fig. 7), to a spiral mining system that
includes a mobile base concept (see Schmitt, 1992, and fig.8).

Although the potential economic return on the
production of He-3 should attract considerable attention, the
return on the volatile by-products may be just as great (fig.
9), particularly for use in space. Hydrogen, water (a source
of oxygen), nitrogen oxides, and carbon oxides all have
important applications in space, not the least of which will be
the support of a lunar settlement and the initial support of
Mars settlements.
Mars appears to have have all the indigenous resources (Carr, 1984) necessary for permanent settlement, however, in the early start-up years, the moon may well be the low cost and necessary source of consumables supply.

The by-product volatiles have many uses (fig. 10). For example, hydrogen can be used to produce water, oxygen, and hydrocarbons as well as for propulsion and fuel cell electrical power. Water, a consequence of the reaction of hydrogen with oxides and silicates during heating, has many obvious applications for life support and agriculture. Carbon and nitrogen compounds probably will be most useful in the production of food and hydrocarbons. Helium-4 provides gas for fluid pressurization and propulsion enhancement.

Meanwhile, back on Earth, the critical question becomes how best to transition from an environmentally imprudent fossil fuel/fission energy economy to an environmentally sound economy based upon He-3 fusion.

For the purposes of comparisons, we have assumed that the penetration of fusion energy into the commercial market is somewhat faster than for fission in the U.S. and Japan but considerably slower than in France (fig. 11). If introduced in 2015, this would result in fusion capturing 50 percent of the U.S. electrical generation market in the year 2050 (fig. 12).

Based on this penetration rate, the production of He-3 would reach about 50 tonnes per year by 2050 (fig. 13), exceeding current coal production a few years prior to that. Mining an area the size of Washington, D.C. would not occur until about 2035.

At a very conservative $1 billion per tonne ($7 BOE), the cumulative market for He-3 would be over half a trillion dollars in current dollars for the first half of the 21st Century (fig 14).

The potential market value of other lunar volatiles also should not be ignored, although when there might be significant demand remains uncertain. For example, the total amount of volatiles required to support one person-year on the lunar surface exceeds 700 kg/yr (see Bula et al, 1992, and fig. 15). Once beneficiation of lunar regolith begins, the expansion of personnel at a lunar base could be tied to the rate of growth of volatile production, reaching about 150 people by 2020 under the He-3 penetration schedule assumed here (fig. 16). Eventually, the quantities of volatiles produced would be sufficient to meet the demands of a 21st Century space transportation infrastructure, including access to Mars and the Moon and return (figs. 17-20).

A near-term policy and budgetary commitment to a lunar base in support of He-3 mining appears consistent with an initial He-3 delivery date late in the first decade of the next century (fig 21). Such a commitment implies start-up costs in the range of 100 billion dollars for the base (roughly the cost of the Apollo Program in current dollars) and 30 billion for the mining infrastructure (currently a guess). These costs probably could be significantly lower if the private sector took responsibility for all or part of the enterprise.

As you can see (fig. 22), this mining schedule is consistent with the fusion development schedule suggested by
Kulcinski (1993), particularly if the Polywell™ concept proves commercially viable.

The rest of the world continues to move forward with fusion research (fig. 23), although most known programs focus on the D-T cycle, including the International Thermonuclear Experimental Reactor (ITER, 1989) effort. Only the Japanese appear to have a national eye on lunar He-3 as a future terrestrial energy possibility.

Conclusions

Clearly, enough environmental, economic, and practical potential exists for the application of lunar volatiles, He-3 in particular, that a rejuvenation of the nation's space program based on their access commands serious consideration. Lunar volatiles have broad relevance to the exploration and settlement of the solar system. Lunar He-3, He-4, hydrogen, and oxygen can be utilized in both conventional and fusion space propulsion. Lunar He-3 and lunar hydrogen and oxygen provide the option of both fusion and fuel cell electrical power generation for use in space. Most importantly, lunar He-3 offers possibly the only realistic global option for a near-term alternative to fossil fuels for the generation of terrestrial power.

It's time to take another look at the moon.

REFERENCES


Lunar Science Conference, 2, 1435-1454.
There are at Least 3 Areas That Could Benefit from Lunar Volatiles in the Near Term

- Life Support
- Transportation
- O₂, H₂ Propellant to Mars
SOLAR NUCLEAR FUSION REACTIONS
VIA THE PROTON–PROTON CHAIN

FIGURE 2
Solar Wind

• 96% Protons
  4% Helium

• Energy ~3 keV

• Total $^3$He Fluence
  500 million tonnes
  in 4 billion years
Measured Helium Content in Lunar Samples

![Bar chart showing Wt ppm Helium for US Apollo and USSR Missions, with categories for Highland and Basin Ejecta and Maria.]

FIGURE 4
Correlation of Helium Content With TiO2 in Lunar Regolith

FIGURE 5
Helium-3 Evolution from Lunar Regolith

% He3 Evolution

Regolith Temperature, °C

Pepin et al.

95%

86%

75%
Spiral Mining System for Lunar Volatiles

VR: Volatile refining subsystems
HS: Habitat and crew work section
LP: Launch and landing platform
PS: Power subsystems
SA: Mobile Miner support arm

FIGURE 8
Process for Extracting Helium-3 from Lunar Regolith

FIGURE 9
Applications of Lunar Volatiles

- **Helium-3**
  - Fusion Energy (Propulsion, Electric Power, ...)

- **Helium-4**
  - Pressurization, Cryogenics, ...

- **Hydrogen**
  - Water, Fuel, Hydrocarbons, Reagents, Oxygen

- **Water**
  - Life Support, Oxygen

- **Nitrogen**
  - Food, Atmosphere, Pressurization, Reagents

- **Carbon Dioxide**
  - Food, Atmosphere, Pressurization Hydrocarbons

MOON
The Assumed Penetration of Fusion Energy Into the Commercial Market is Somewhat Faster Than For Fission in the U.S. and Japan But Considerably Slower Than in France

% of Total Annual Electricity Generated

Year After Introduction of New Technology

FIGURE 11
The Introduction of Fusion in the Year 2015 Could Result in the Capturing of 50% of the U. S. Electrical Generation Market in the Year 2050

![Graph showing the growth of energy production from 1980 to 2050 with a peak in 2030, indicating the potential impact of fusion energy on the market share.](image-url)
Under Conservative Penetration Scenarios, the Mining of He3 Would Not Approach 50 Tonnes per Year Until 2050

Figure 13

Cumulative Tonnage of Helium-3 Mined, or, Cumulative Billions of 1992 Dollars

Start Helium-3 Mining
The Total Amount of Volatiles Required to Support 1 Person-Year on the Lunar Surface Exceeds 700 kg/ year

- Carbon Dioxide: 77 kg
- Water: 142 kg
- Oxygen: 150 kg
- Nitrogen: 347 kg

kg per Person-Y Assuming Efficient Recycle (Replacement Only)
The Availability of Lunar Volatiles For Life Support Could Allow More Astronauts to Live and Work on the Lunar Surface
There Could Be a Substantial Need For Lunar Oxygen and Hydrogen Propellants

- Mars Mission From L2 (Chemical)
  - Hydrogen: 100 tonnes
  - Oxygen: 400 tonnes

- Moon-LEO-Moon (With Aerobraking)
  - Hydrogen: 60 tonnes
  - Oxygen: 340 tonnes

- Lunar Surface to LEO
  - Hydrogen: 0 tonnes
  - Oxygen: 20 tonnes

![Bar Chart](chart.png)

FIGURE 17
The Demand for Lunar Volatiles Could Be in the 1000's of Tonnes per Year Range in the Next 20 Years

- **Tonnes of Volatiles Required/y for Mars Trips**
- **Tonnes of Volatiles/y for Propellants Moon-LEO-Moon**
- **Tonnes of Volatiles for Life Support**

**FIGURE 18**
The Potential Demand For Lunar Volatiles Could Exceed 9,000 Tonnes Over the Next 30 Years

- Cumulative Tonnes of Volatiles Req'd For Mars Transportation
- Cumulative Tonnes of Lunar Propellants Needed For LEO-Moon Transport
- Cumulative Tonnes of Volatiles For Life Support

FIGURE 19
The Mid Term Market For Lunar Volatiles From 2000 to 2020 Could Exceed 350 Billion Dollars

Mars From L2
LEO-Earth Transportation
Life Support

Billions of 1992 Dollars

$5,000 $10,000 $20,000 $40,000

Landed Cost on Lunar Surface, $/kg

FIGURE 20
Commercial DHe3 and Lunar Resource Recovery Schedules are Very Compatible

TPX
ITER
FUSION
SPACE

1990
2000
2010
2020

Construction Operation

Construction Operation

Add Power Modules

Breakeven & Ignition

Construction Operation

Commercialization

Robotic Return

Human Outpost

Pilot Plant Volatiles

100's tonnes Volatiles/year

FIGURE 21
Success With the Polywell™ Concept Could Require Lunar $^3$He by 2015
Worldwide Effort in Helium-3 Fusion and Lunar Recovery Research