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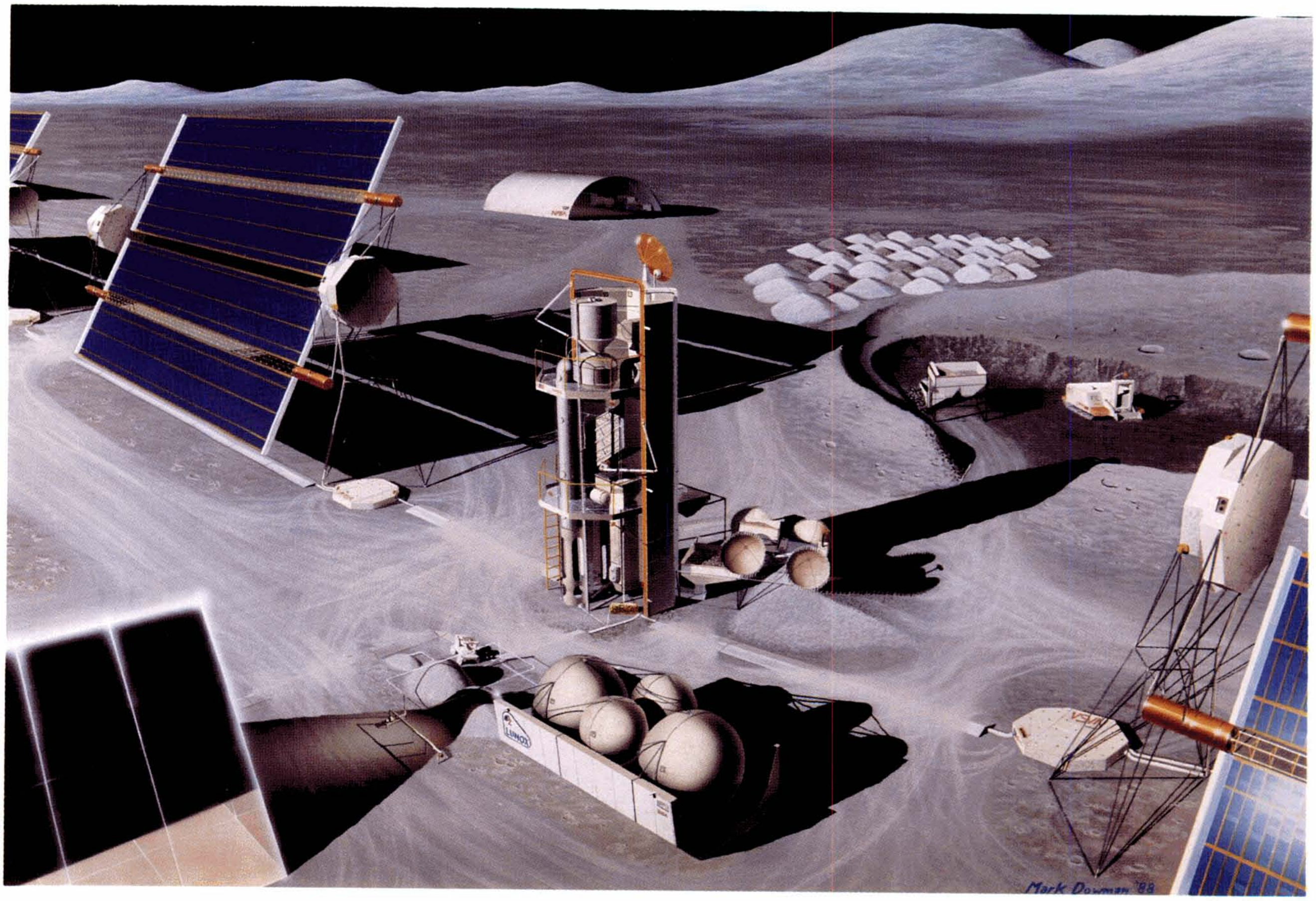
Using Space Resources



NASA Johnson Space Center
1991

Cover photo:

One of the most studied routes to produce oxygen from lunar materials involves the reaction of the mineral ilmenite with hot hydrogen. An early pilot plant to begin production of lunar liquid oxygen is depicted here, along with solar panels to power it and a small mining operation to supply it with raw material. This plant has been sized to fit inside the payload bay of the Space Shuttle.

Using Space Resources

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Mission Science and Technology Office
Solar System Exploration Division

sponsored by
Planet Surface System Office
New Initiatives Office

NASA Johnson Space Center
1991

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Reducing the Cost of Space Exploration

There is every indication that exploring the Solar System and expanding humanity's permanent presence to the Moon and Mars will provide significant benefits to America. Over the past three decades, America's space program has more than paid back its cost in a number of ways, both tangible and intangible. Even though it will continue to be an expensive undertaking, a far higher price would be borne by our nation in avoiding such a mission. However, the importance, the enormity, and the inevitability of the program require immediate focus on ways to lower its cost without reducing its scope or increasing its risk. What can we do to lower the price tag of this ambitious exploration program while still accepting its challenge?

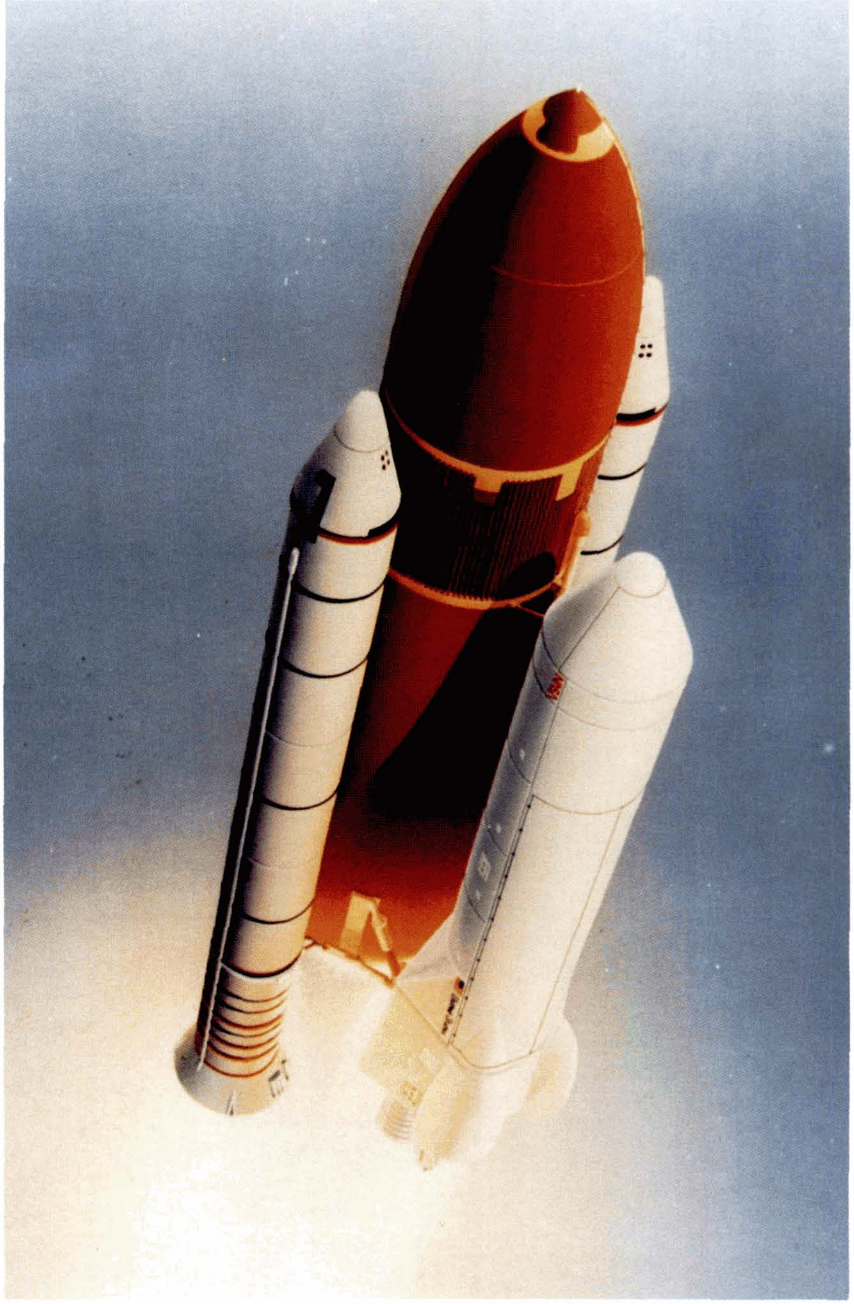
We can process natural resources on the Moon and Mars into products we need at an outpost, thus avoiding the need to bring them from Earth. These resources can provide us with oxygen and nitrogen to breathe and water to drink. We can produce propellants for our spacecraft. Carbon dioxide (CO_2) can be extracted from the lunar soil, or regolith, to support plant growth for food. We will learn to fabricate bricks and panels from local materials and use them for constructing habitats, workshops, and storage buildings. We will extract metals from local rocks and soil to make beams, wires, and perhaps even solar power cells. In short, many of the essential materials needed for life on the new frontier can be produced from local resources.

We can use materials that already exist on the Moon and Mars in an innovative approach to reduce the need (and thus the expense) to bring everything from Earth.

This program is ready to move from the concept stage into research and development. Indigenous Space Materials Utilization (ISMU — formerly called In-Situ Resource Utilization) can provide a reduction in cost and can increase our capabilities significantly as we develop and expand a lunar or Mars outpost. Our goal for the ISMU program is to free these outposts from total reliance on the Earth as soon as possible, thereby rapidly shifting the nature of our space transported cargo away from bulk materials, such as propellants and building materials, to additional people and complex equipment.

The High Cost of Shipping

As currently envisioned, a large part of the cost of a lunar outpost will be that of bringing supplies and propellant from Earth. The major component of this propellant is liquid oxygen (LOX). NASA's *"Report on the 90-Day Study on the Human Exploration of the Moon and Mars"* estimated that the amount of mass launched to low Earth orbit (LEO) could be reduced by 300 tons per year if LOX were produced on the Moon. This is equivalent to 10 Shuttle launches at a cost of a several billion dollars per year. Even if we develop a new heavy lift launch vehicle (HLLV), the price tag to launch this propellant will be huge. By producing the oxygen on the planet where it is actually needed, there is no shipping penalty. Thus, the amount required is much smaller.



The major cost driver of any planetary outpost is that of lifting its mass away from Earth. Even future heavy-lift vehicles, such as the proposed Shuttle-derived cargo vehicle shown here, will cost thousands of dollars to get each kilogram of material to the Moon. A major element in the case for Indigenous Space Materials Utilization stems from reducing this logistics train. By producing materials on the planet where an outpost is located, the cost, operations, and launch schedule of Earth-to-orbit vehicles can be reduced.

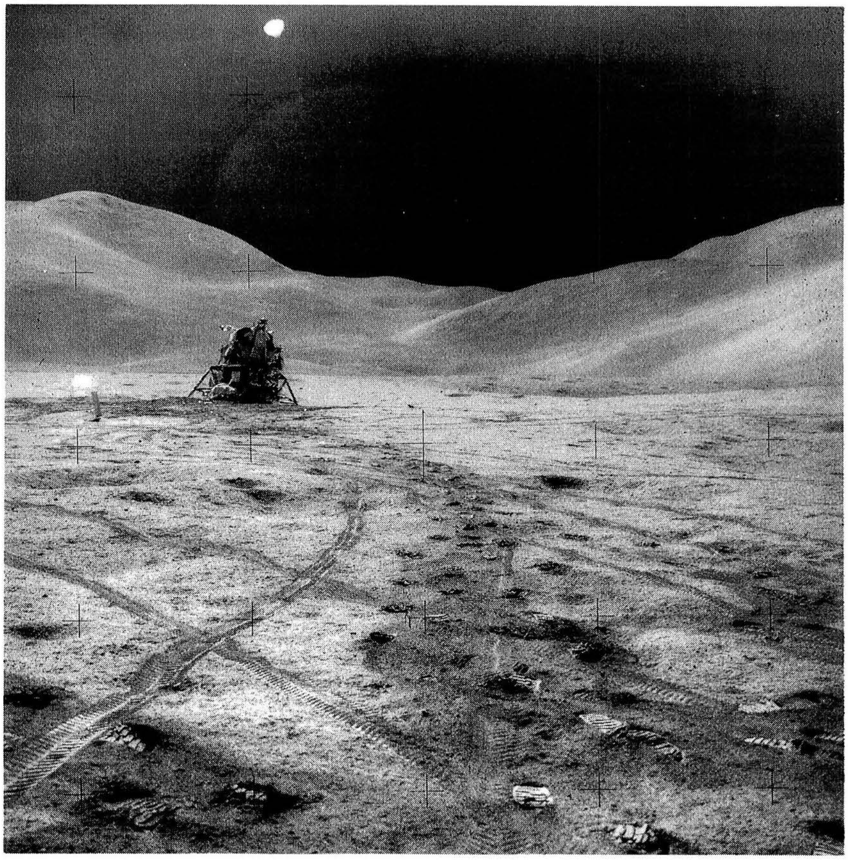
The use of lunar-derived LOX is thus a high-leverage item because it frees our space vehicles from the inefficient and costly exercise of shipping bulk propellants. The total cargo that must be shipped to the Moon will be reduced significantly. And for the remaining flights, instead of transporting large quantities of LOX to the Moon, more people, complex equipment, and scientific instruments can be shipped to provide additional capabilities at the lunar outpost. This effect can be increased dramatically when we also produce lunar-derived fuels, such as hydrogen or methane.

Perhaps as important as propellant production will be the use of the regolith for the manufacture of basic material. While it is true that much of the cargo arriving on the Moon will be extremely complex equipment, there is a real need for simple, basic infrastructure such as roads, rocket blast protection, and structures for habitats, storage, and equipment repair. If brought from Earth, the mass required for these uses would be enormous. For example, just for protection from solar particle radiation, the amount of mass that would have to be brought to the Moon represents several Space Shuttle launches. Based on present launch costs, the expense of transporting the hundreds of metric tons needed to protect an early habitat from this dangerous radiation would surpass a billion dollars.

Just as important as cost is the high flight rate which would be needed to support this effort. This would strain the capacity of our launch systems. When LOX is produced on the Moon, fewer flights to LEO will be necessary. On-orbit assembly and processing at Space Station Freedom (SSF) can also be reduced. Indeed, the additional facilities that would otherwise be required here on Earth and at SSF represent further cost savings made possible through an ISMU program.

Lunar Raw Materials

During the Apollo era we learned the detailed mineralogy and chemistry of lunar materials as well as the rock and soil compositions at various locations on the Moon. In addition to abundant oxygen — about 45 percent of the weight of lunar rocks and soils is chemically bound oxygen — these materials also contain considerable silicon,



This view of the lunar module Falcon from Apollo 15 shows the Moon to be barren. Whatever is necessary for people to survive and be productive on the lunar surface will have to be produced there or brought from Earth. Due to the absence of an atmosphere on the Moon, the only material to work with is the regolith. Thanks to the expedition style missions of the Apollo program, the mineralogy of the moon is well understood. Process development leading to products that will be required at a lunar outpost must begin.

Why bother making it there?

What does it take to bring a kilogram of anything to the surface of the Moon? First, you need to get the material to the launch pad at the Kennedy Space Center. Obviously, this means it must first be manufactured. The cost to make this item here on Earth will surely be lower than if we produce the same material on the Moon. From here on, however, the costs start to mount.

Launching an item to low Earth orbit (LEO) takes a great deal of energy. Most of what is launched is the propellant needed to accelerate it to more than 27,000 kilometers per hour and get it the first few hundred kilometers above the surface of the Earth. The cost in dollars depends on many bookkeeping assumptions, but we know that only a small percentage of what leaves the pad ends up in orbit. Estimates of the launch costs of items via the Shuttle range from $6,000 to $12,000 per kilogram.

A kilogram of material orbiting the Earth is not going to do you any good at a lunar outpost; you need to get it from LEO to the Moon. Leaving Earth orbit and going to lunar orbit — the path Apollo took — gets only about one-third of the original mass to the vicinity of the Moon. From there, another propulsive maneuver will be required to get to the surface, meaning another mass reduction of about 50 percent. Alternatives to this route exist, such as going directly to the lunar surface or using other transportation "nodes," such as an Earth-Moon libration point. These have some advantages and some disadvantages involving mass ratios, safety, operations, landing site flexibility, and commonality with other missions; it is not a simple analysis.

When all of this is factored together, only about one-sixth of what makes it to LEO can be payload for the lunar outpost — the rest is the propellant to get it there. Thus, the cost of a kilogram of material on the surface is six times the cost of getting it to LEO, or many tens of thousands of dollars. Even if future launch vehicles can lower the cost by a factor of ten, we are still faced with a large bill for shipping and handling.

And these figures all assume the best propellant combination available today — hydrogen and oxygen. It is not a given that we will

iron, calcium, aluminum, magnesium, and titanium which can be extracted as metals, possibly as coproducts of the same process which extracts oxygen.

We also learned that lunar soils have trapped a number of different kinds of particles from the solar wind over the geologic eons and therefore contain helium, hydrogen, nitrogen, and carbon from the Sun. These elements can be extracted as gases by heating the soil. These gases are found in most lunar soils, but their concentration varies from place to place.

Some Useful Space Products

The range of products that can be generated through the processing of lunar regolith or Mars resources is limited only by our ability to develop the necessary technology. The first step is to determine which products would be most beneficial choose this propellant mixture for any or all of the spacecraft involved in the transportation system. Handling liquid hydrogen on orbit is a technology we have yet to demonstrate. Long stay times on the lunar surface can cause loss of the extremely low-boiling hydrogen. Furthermore, the required volume of liquid hydrogen is very large owing to its very low density. To alleviate these problems, we may choose a more storable fuel, such as a hydrocarbon (like methane), or a hydrazine derivative. This could remove the negative impacts of hydrogen on the overall system. Because of the lower performance of these propellant combinations, however, the ratio of payload delivered to the lunar surface to the initial mass in LEO will be lower than the 1:6 determined above. This translates to an even greater Earth-launch mass to deliver that one kilogram to the Moon. During the Apollo missions, this ratio was around 1:10 because greater reliability dictated the choice of the less powerful hypergolic propellants. This difference would enter directly into any economic calculation. Indeed, making LOX on the Moon may make it more feasible to use these alternative fuels, benefiting from their favorable properties while ameliorating their effect on launch mass.

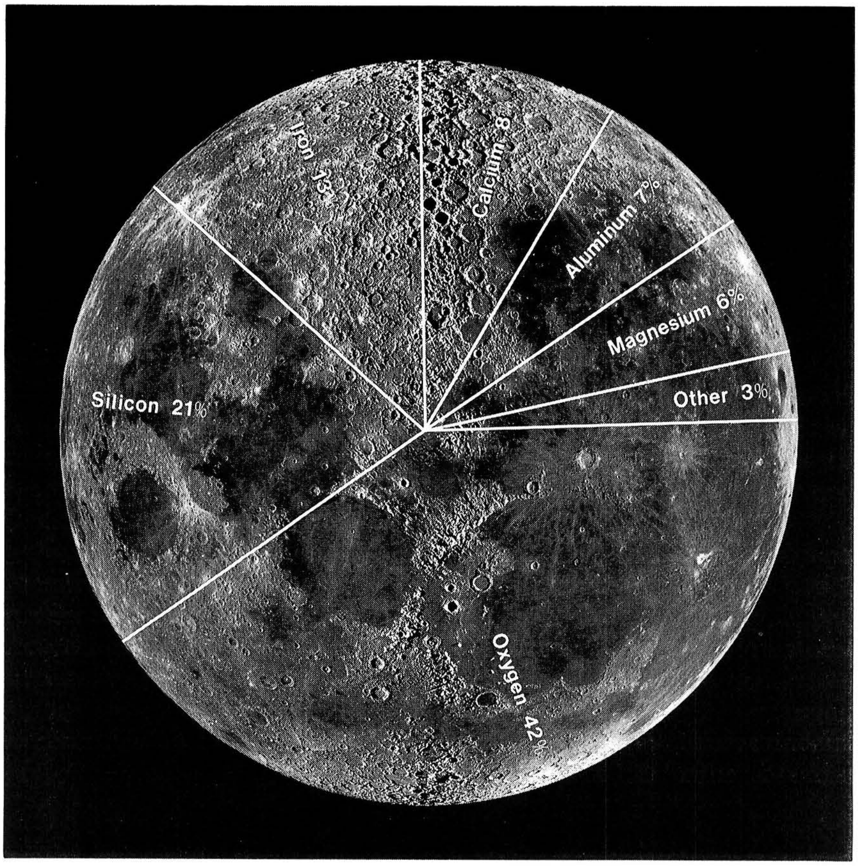
If materials could be produced on the Moon, rather than bringing them from Earth, all of the extra mass launched as propellant to get them there would no longer be required. For example, if the ascent of a lunar excursion vehicle from the lunar surface to lunar orbit requires, say, five tons of LOX, we would no longer need to take this propellant there at the cost of launching more than 30 tons to LEO. This is equivalent to the entire payload capacity of today's Shuttle. By making the material there, we are saving the cost, the logistics, and the risk of a launch.

The question then becomes: What does it take to produce useful products on the lunar surface? If the mass of a required item is small but the mass of the equipment to make it is large, then it clearly does not make sense to manufacture it there. If, on the other hand, the mass of the plant can be "paid back" in only a short operating time, we should consider making it there from those materials indigenous to the planet.

to the outpost and its support infrastructure. Since transportation costs are a major driver of the overall cost, this "marketing survey" generally focuses on mass as the selection criterion. We should note, however, that sometimes the product is really a service and that this service might be provided through a variety of means.

Next, we need to determine which of these products can reasonably be made at the outpost, considering the constraints both in the near term and in the long range capabilities. Obviously, as in an Earth-based marketplace, some products will have higher value and some will be easier to produce than others. The items described below represent products which we believe are appropriate for near- and mid-term programs. As study of the Space Exploration Initiative (SEI) in general and ISMU in particular proceeds, it is likely that the list will grow.

As a result of the six Apollo and two Luna missions, the general surface composition of the Moon is now known. While there are variations between mare and highland regions, the global average provides a basis for our plans to utilize the lunar resources.



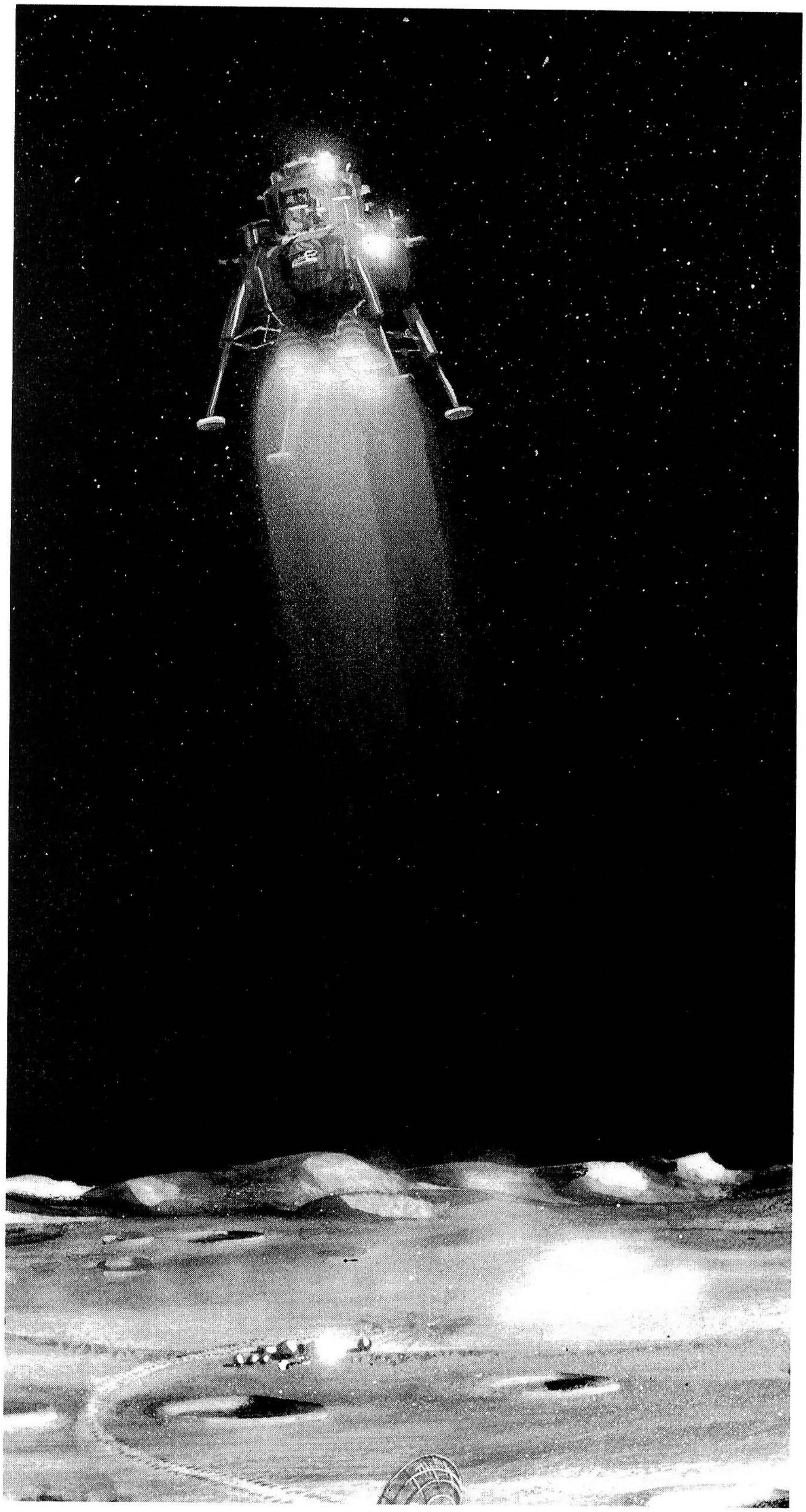
Lick Observatory Photo

Lunar oxygen

As discussed above, lunar-derived liquid oxygen is one of the big "carrots" in ISMU. Its main use, from a mass viewpoint, will be as a propellant to power the lunar lander up to lunar orbit (or some other transportation node such as a libration point) and back down to the lunar surface. Whether it would be used for the return-to-Earth-orbit leg of the journey would depend on further analysis and economic trades. Some engineers and scientists even envision its use in spacecraft bound for Mars.

Lunar oxygen could also be used in fuel cells to power rovers or to provide some of the power to the outpost. The amount of oxygen required to make up for losses in the life support system is likely to be smaller, but represents yet another market. It would be reassuring to have an operating plant and some storage tanks full of oxygen in case of a failure in the life support system or as a backup if a problem arose in a resupply mission. Large amounts of oxygen might even make it practicable to have less complex life support systems for habitats and extravehicular activities. The cost and maintenance of these systems may therefore be reduced.

Many chemical processes have been identified through NASA studies and workshops which can potentially extract oxygen from lunar rocks and soils. NASA, universities, and industry are all trying to understand these processes more fully to pick the best ones for plant design.



The propellant required to return both humans and scientific samples from the Moon to lunar orbit will be produced eventually from lunar minerals. For every pound of propellant thus off-loaded during descent, an equal amount of more valuable scientific equipment can be brought to the lunar surface.

It is not as if we are trying to develop an entirely new technology:

> *We have been building plants which extract oxygen from minerals on Earth for hundreds of years. The basic technology is very old.*

Metals — a primary product or a coproduct?

Iron and steel production from iron ore, practiced on Earth for hundreds of years, is really a process for extracting oxygen from iron oxides and other ores. In a typical iron smelting process, the ore is combined with carbon from charcoal or coke. The carbon extracts the oxygen by chemical reduction of the ore, forming carbon dioxide (CO_2) and leaving metallic iron behind. The iron is saved, and the CO_2 is thrown away into the atmosphere. In a lunar version of this process, we would process this CO_2 to break it into carbon and oxygen. The oxygen would be collected, and the carbon would be recycled back into the reactor. Other metallurgical processes are practiced here on Earth which use hydrogen to reduce an ore to the metallic state, generating water vapor as an off-gas.

The major metals present on the Moon are silicon, iron, calcium, aluminum, magnesium and titanium, all combined as compounds in a variety of minerals. As discussed above for iron, when oxygen is released from minerals, one or more metals is necessarily coproduced. Well-designed oxygen plants will take advantage of this fact and produce metals in useful quantities. The specific metal(s) produced would depend on the chemical process used. Silicon has been produced in the lab from simulated lunar soil (natural terrestrial anorthosite, similar to that found in the lunar highlands) at purities acceptable for solar cell production. Aluminum, magnesium, and titanium production could also be practical, as they represent important structural metals in the aerospace industry.

The production of metals, along with the production of oxygen, should be relatively easy. The next step, taking this metal and fabricating a useful product out of it, will require a fair degree of manufacturing capability. Some potential uses for locally produced metals at a lunar outpost or a Mars base might include

- structural beams, rods, and plates for construction
- cast shapes for foundation anchors, fasteners, bricks, tables and chairs, weights and flywheels for energy storage
- solar cells, bus bars, and wires for power generation and distribution
- pipes and storage vessels for fuel, water, and other fluids
- spray coatings or linings for buildings
- powdered metals for rocket fuels

Light gas recovery

Through the eons the solar wind has impinged upon the surface of the Moon, implanting hydrogen, helium, carbon, and other light elements at very low concentrations. Schemes to free these elements from the regolith have been conceived, and preliminary processes already exist.

The extraction of this hydrogen has considerable importance since, with lunar LOX, we would then have an entirely lunar-derived propellant system. We might choose, instead, to produce methane as a fuel. While methane is not as powerful a propellant as hydrogen, its liquefaction is much easier to accomplish and less regolith would need to be processed, perhaps resulting in a better system overall. Methane is also considered a storable propellant, which means we would lose less from boil-off during the lunar day. This option is especially attractive if we also choose to use the martian atmosphere as a resource to produce methane for operations at a Mars outpost. The choice of propellant is major driver of spacecraft design and needs to be considered from the start.

Other light gases, such as nitrogen and even oxides of carbon, could provide a life support system with critical material. The ability to provide these resources can act as a layer of redundency, thereby providing a level of safety, in addition to relieving a cargo burden from the transportation system. Helium has many uses, too, including as a pressurant gas, a heat exchange fluid, and perhaps as an important element in terrestrial energy production (see below).

It is important to realize that a process which aims to produce any particular gas will also release the remaining gases from the regolith. For example, a plant built to produce hydrogen or methane will also isolate helium and nitrogen. However, the amount of mining required to produce these gases is very large. Concentrations of the gases in the regolith vary from a few parts per million (ppm) to a few hundred ppm. Thus, before we can exploit this potential successfully, we must develop our ability to mine and process large amounts of regolith under the harsh lunar conditions. Only if we pursue these technologies in the laboratory and integrate them throughout the system will we know if it makes sense to pursue them on a larger scale.

Energy from the Moon

There may be an opportunity for lunar resources to play a role in the energy industry here on Earth. Power generation is a vast and growing market. Energy is a product that may legitimately be worth bringing back to the Earth's surface from the Moon.

How will we do this? In 1989, a NASA report concluded that, for the energy needs of the next century, we need to consider two alternatives enabled by a lunar outpost: solar energy collected on the lunar surface and beamed back to Earth via microwaves, and the return to Earth of a light isotope of helium, He-3. Both of these options would largely avoid the biggest problems of energy generation here on Earth: pollution, acid rain, ozone generation, carbon dioxide production with its potential for global warming, and large operations with highly radioactive fuels.

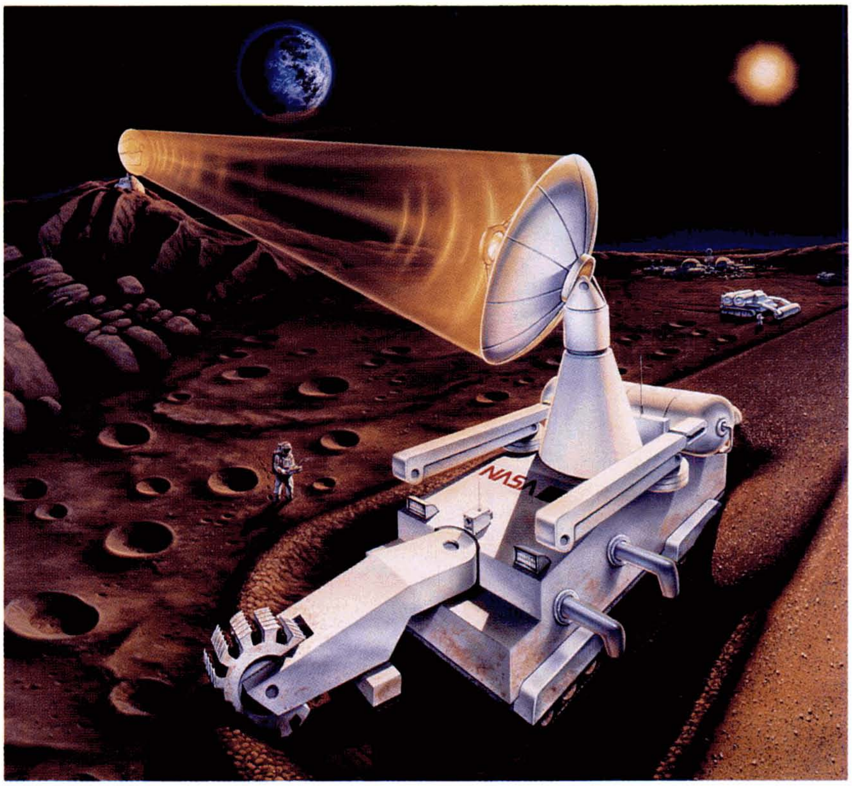
Helium-3

Along with the other light gases mentioned above, we can extract an isotope of helium from the regolith. He-3 has the potential to be used in fusion reactors here on Earth to provide electrical power. This technology, while still in the research stage, promises to be much "cleaner" than current, *fission*-based plants which consume uranium, and even cleaner than those fusion plants currently under development which would use radioactive tritium as a fuel. Why would we go to the moon for this material?

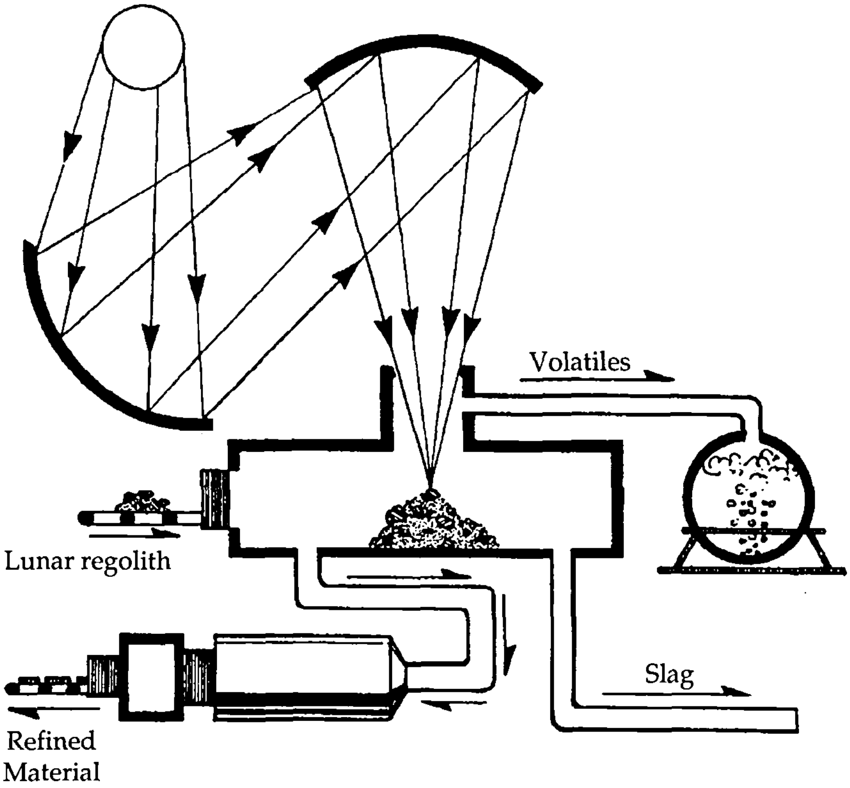
- It is nearly absent from Earth as a natural resource
- Millions of kilograms of it are present in lunar soil, albeit at very low concentrations.
- It may be the fuel for the next generation of electric power plants, providing nearly pollution-free power.
- It may, in the 21st century, replace our dwindling supplies of fossil fuels.
- It may be worth $2,000,000/kg.

Along with deuterium, which can be extracted from sea water, He-3 is the primary fuel of a clean nuclear fusion reactor currently being investigated by U.S., European, and Japanese fusion research scientists. Some of these scientists believe that a demonstration fusion power reactor using the He-3/deuterium reaction can be built within 10 or 15 years and a commercial power reactor within 20 years. It would generate only a very slight amount of radioactivity, equivalent in nature to that produced by hospitals in their nuclear medicine areas. When used in this plant, He-3 would have so much energy that it would require only 20 tons — less than one Shuttle load — to supply all the electricity used in the United States in a year. The current cost of fuel used to provide this electricity is tens of billions of dollars — and going up. We can estimate that the single Shuttle-load of He-3 might be worth about this same amount — or more when the environmental impact of fossil fuels is included.

Of course, this story depends on the successful demonstration that



Long-range strategies to use the Moon to produce Helium-3 call for large mobile miners, such as this one designed by the University of Wisconsin. This program would need to be preceded by smaller efforts such as schematized on page 11 to learn more about the chemistry and operation of such light gas recovery plant.



In addition to helium, the extraction of hydrogen, methane, nitrogen, and oxides of carbon would be possible using this technology. Thus, lunar-derived fuel for spacecraft and life support materials are potential coproducts.

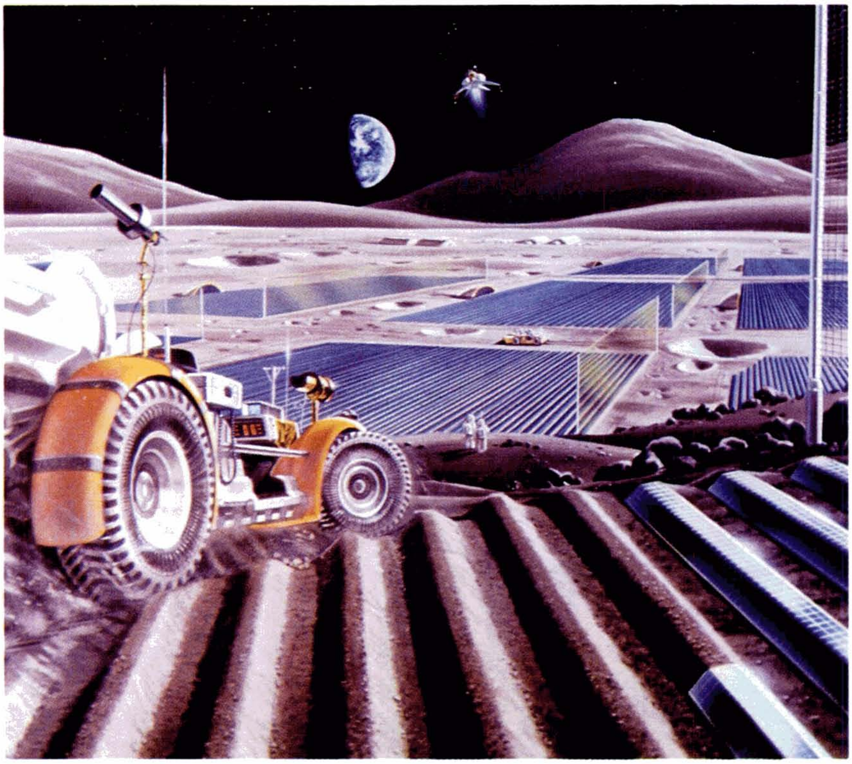
the He-3 reactor will work. It also depends on whether we can economically extract He-3 from the Moon and bring it back. But many believe that both the successful reactor and the economic recovery of He-3 are likely events in the early 21st century.

NASA is not a part of this fusion research, but the capability of recovering light gases implanted by the solar wind, if developed for smaller scale propellant or life support programs, can act as a "proof of concept" technology program to support future decisions made by the Department of Energy. The biggest hurdle is likely to be the extremely large mining requirement. Since He-3 comprises only 1 part in 2-3000 of the total helium, and since the total helium level is only 10 to 200 ppm, tens of millions of kilograms of regolith must be mined to obtain one kilogram of He-3. Of course, its value will be similarly large.

Complex products — Can we make solar cells?

The other option for returning power to Earth, collecting solar energy on the lunar surface and beaming it back to collectors on the Earth, requires a somewhat different capability at the outpost. In this proposal, large arrays of solar cells would be manufactured and emplaced on the Moon. The energy they collect would be converted into microwaves and transmitted to Earth using large antennae, which would also be produced on the Moon from indigenous materials. Previous studies have shown that it is not feasible to launch all of the material required for such a project from Earth.

We must ask whether we can make all the necessary items for such a large project from the resources available on the Moon. The products required include solar cells, wires, microwave reflectors,



Shown here is an array of solar collectors envisioned as part of a Lunar Solar Power System. This field would collect the energy from sunlight and convert it into electricity. This power would then be converted into microwave beams directed toward the Earth. Large rectennas on the Earth would collect this energy and direct it into existing and new distribution grids. There are many technologies and capabilities which need to mature before such an effort can be successful, but the development of scientific principles has already begun.

and metal, glass, or ceramic support structures. We have already demonstrated in the laboratory the ability to make pure silicon for solar cell manufacture, iron for structures and wires, fiberglass and iron for reflectors, and a variety of other individual products from simulated lunar materials. The vacuum and lower gravity present on the Moon may actually make it easier to produce many of the articles we need. It remains to be shown in a research and development program that large scale production of these materials and fabrication of such items can actually be carried out on the Moon, but a focused effort should accomplish many, if not all, of these goals. This "Lunar Power System" would then become largely an engineering program. The most "high tech" elements of this system would most likely still be imported from Earth, however.

After the development phase is complete, both of these enterprises could actually be run at a profit. The market for energy here on Earth will steadily increase as far into the future as we can see. Even if energy conservation programs are successful, the growing population of Earth and the increasing *per capita* use of energy, especially in developing countries, demand that we consider future energy needs in our lunar plans. The benefits to Earth's environment alone make these technologies worth exploring. We should remember that similar technology shifts in the past, such as the move from burning wood or coal to the use of petroleum products, took decades to evolve — this could be the next step to a benign energy source for an expanding population.

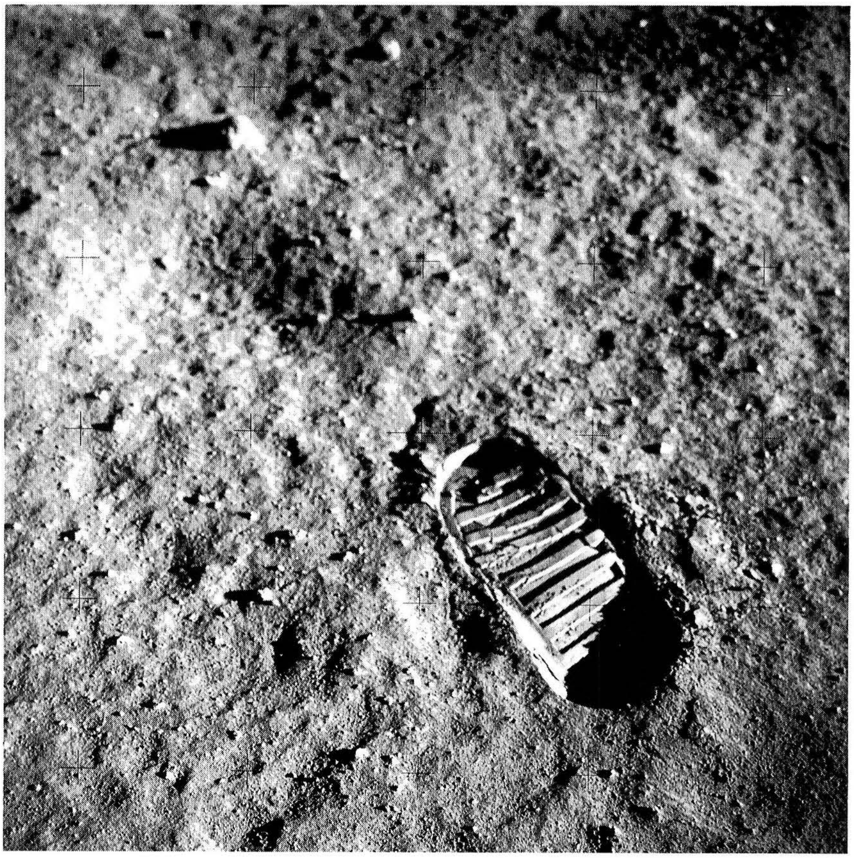
Ceramic, Glass, and Concrete Construction Materials

In 1986, the National Commission on Space proposed that "...NASA specifically include vigorous development of the technologies for robotic and teleoperated production of shielding, building materials, and other products from locally available raw materials." Since only physical processing is required, and not a chemical transformation, it is likely that this technology will be among the first to be practiced at a lunar outpost.

Radiation shielding

The Apollo astronauts only stayed on the Moon for a few days, so they did not need massive shielding from radiation. People staying for any length of time must be protected, however, not only from solar flares but also from galactic cosmic radiation. Advanced lunar habitats could be constructed underground in tunnels, giving natural protection. Early habitats, on the other hand, may be prefabricated Space Station Freedom-type modules or inflatable stuctures brought from Earth. One way to provide shielding for these habitats is to simply pile a large amount of regolith on them. This might be the first use of lunar material at an outpost. A thickness of several meters would be required for long stay times, so the mass savings of using local material rather than bringing it from Earth is obvious.

Burying the modules under a pile of soil has some drawbacks, however. It places constraints on the design of habitat modules and airlocks and may limit operations near the habitat. The soil could slide off, so it would have to be stabilized with supports or retaining walls. A thick layer of soil would make it difficult to add on rooms or



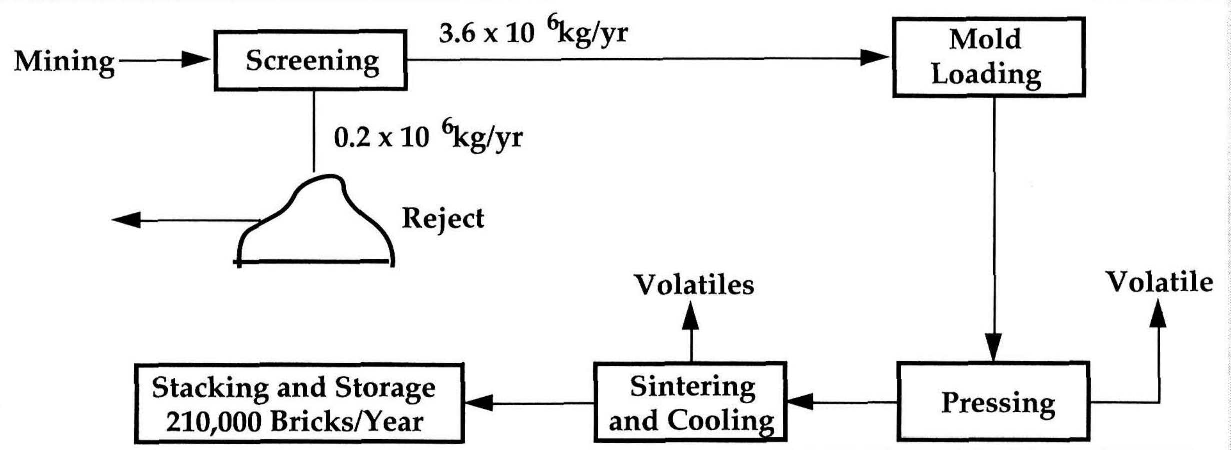
When humans return to the moon — this time to stay — we need to develop self-sufficiency. The material necessary to regenerate our life support systems, produce propellants, protect ourselves from the radiation of outer space, produce structures, and perhaps even provide clean, non-polluting energy to Earth, is already present in the lunar soil. We can choose to use them or ignore them. The goals and justification of the Space Exploration Initiative have been made clear by the President, the National Space Council, and NASA. The use of Indigenous Space Resources can extend our reach and lower the cost of our next step into the universe.

Lunar Brick Factory

The production of pressed and fused (sintered) bricks for use in a variety of applications was studied by Battelle-Columbus in 1988. Their design resulted in a 6-step process for the production of more than 200,000 bricks per year using only currently available ceramics processing technology. This is sufficient to cover six lunar habitat modules, as currently envisioned, with two meters of densified and stabilized regolith as shielding.

The first step after mining the raw feedstock is to screen it to remove the coarse stones which would interfere with the mechanical handling involved in the production process. Next, the fine material would be loaded into a mold and pressed to compact the regolith. Heating to 1100° C for a predetermined time is the key to allowing the compacted mass to achieve its strength. Controlled cooling allows the now solid bricks to retain this strength rather than fracture from internal stress. Finally, there must be a way of robotically removing and storing these bricks for use at the outpost.

Estimates for the mass of such a plant run from 25 to 40 metric tons. Its power requirement is about 375 kW. Both estimates depend on the desired strength of the bricks as well as the thermal properties of the starting material. More recently, other groups have suggested the use of microwaves to lower the power requirement and increase the heating rate. If feasible, this would decrease the processing time and thus greatly reduce the plant mass. Even without this improvement, such a plant would pay for itself by returning its own mass in 3 to 4 days of operation.



to connect new wires, antennae, or pipes as the outpost was improved. Putting soil in sand bags would solve some of these problems but not all of them.

An improvement over loose soil would be a radiation protection system constructed of cast basalt or sintered blocks made from regolith. These can provide much denser radiation protection compared to loose soil; therefore, the shield can be less thick. These blocks could be made in an automated block factory, formed into interlocking shapes, and moved and stacked by robotic arms. If access to the habitat wall is needed, the robotic arm could as easily remove the blocks. Later, when modules are added, the blocks can be removed easily and reused to accommodate expansion. Cast basalt has been used on Earth for years in many areas where hard, chemically resistant material is required. Much of the science and technology needed for lunar processing is already available in industry today.

Building with blocks

Such blocks might also be useful for paving the launch and landing area to prevent engine exhaust from sandblasting the outpost. Simple walls made from these blocks can provide shade for outside equipment such as thermal radiators and protect them from some of the direct sunlight. Similarly, simple garages made of blocks can provide thermal protection during the cold lunar night for critical equipment such as rovers. In these and other ways, the ability to produce simple, lo-tech construction material may significantly improve outpost operation.

Another possible use of cast basalt blocks might be as a storage mass for thermal energy. By simply heating these blocks using solar concentrators during the day, and then withdrawing this energy at night, heat engines might become competitive with other forms of power generation. Because of the long lunar night, power storage devices brought from Earth would be massive. By using materials indigenous to the Moon, even with an inefficient technology, a more efficient system (defined as kilowatts per *imported* kilogram) based on thermal energy storage may be possible. This is a case where the true product is a service, namely energy storage, rather than a one-for-one replacement.

Other related products include glass blocks, glass windows, fibers for reinforcement, and even fiberglass mats and fabrics which can be produced by melting and processing soil. In the extremely dry lunar environment, these glass products may rival metals as strong construction materials. In the longer term, the production of cement and concrete is also under consideration. The manufacture of these materials presents the opportunity to expand the inhabitable volume of the outpost with minimal support from Earth.

Mars Atmospheric Resources

Upon reaching Mars, we again have a world with resources that can be used to expand our capabilities. The martian atmosphere, consisting mostly of carbon dioxide, can be processed to release oxygen for life support or propellant use. Carbon monoxide, which could be a moderate performance rocket fuel, is the coproduct. By combining this oxygen with a small amount of hydrogen, water for a variety of uses could be produced for only a fraction of its mass if brought from Earth. One good aspect of atmosphere utilization is that no mining is involved. Simple gas handling equipment can be used, providing a much more reliable system.

Life support technologies routinely deal with the conversion of CO_2 to other compounds, including methane. This process was discovered nearly one hundred years ago and is still used in many chemical plants today. A direct application of this technology to the martian atmosphere would allow for the production of oxygen,

Carbon Dioxide as a Raw Material

The carbon dioxide (CO_2) that makes up 95 percent of the atmosphere of Mars can be a valuable starting material for the manufacture of critical products. Unlike lunar resources, CO_2 can be had by merely compressing the atmosphere. Carbon dioxide itself can be used to support plant growth at an advanced outpost. Both carbon and oxygen are important elements which have many possible uses at an outpost. There are several well understood chemical reactions that we can use to produce oxygen, methane, water, and perhaps other materials.

Oxygen can be produced by passing CO_2 through a zirconia electrolysis cell at 800 to 1000° C. Twenty to thirty percent of the CO_2 dissociates into oxygen and carbon monoxide. Separation is accomplished by electrochemical transport of oxide ion through a membrane. A prototype reactor using this chemistry has been run for over 1000 hours. Using such a scheme, we could bring a small unit to the surface of Mars which would then continuously make oxygen for life support, propellant use, or further processing. The only additional item we would need to supply is the power to run it: a 12kW unit would produce about one metric ton of oxygen per month.

This oxygen can be converted into water if we also bring a small supply of hydrogen. Since the molecular weight of hydrogen is 2 and the molecular weight of water is 18, we can leverage 2 kilograms of hydrogen into 18 kilograms of water. The mass savings would, at some manufacturing rate, pay back the mass of the oxygen production unit. After that, we would get water for only the price of getting the hydrogen to Mars.

$2\,CO_2 \rightarrow 2\,CO + O_2$
zirconia electrolysis

$O_2 + 2\,H_2 \rightarrow 2\,H_2O$
combustion of hydrogen

If we choose to import hydrogen, there are other things we can do with it in addition to making water. A chemical reaction which converts CO_2 into methane (CH_4) was discovered in 1899. This is known as the Sabatier reaction. Along with the CO_2, hydrogen is passed over a finely divided metal catalyst at an elevated temperature. Methane and water vapor are produced. By taking this water vapor and splitting it to obtain

methane, and water by bringing only a small amount of hydrogen. Thus, large quantities of propellant could be leveraged from minimal import mass. As described earlier, a rocket engine using methane and oxygen could be developed for use in both lunar and martian spacecraft. This could enable another large cost savings for the SEI by utilizing those materials available at the Moon or Mars.

Planetary scientists agree that water is available at the poles of Mars in the form of ice. It is likely, but not certain, that water is available elsewhere on the planet, perhaps as a permafrost layer or bound as a mineral hydrate. If the robotic missions in the early stages of the SEI provide evidence of water, there is every reason to believe that a process can be developed to make it available for human use. It is likely that one could even extract oxygen and hydrogen (which is recycled), we can completely convert the imported material into 4 times its mass of fuel. We also get the oxygen we need to burn this fuel in a rocket engine, fuel cell, or internal combustion engine. When combined with the production of additional oxygen via the zirconia process described above, only 4 kilograms of hydrogen can be converted into 72 kilograms of a rocket propellant mixture.

$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$
Sabatier Reaction

$2\,H_2O \rightarrow 2\,H_2 + O_2$
Electrolysis

$CO_2 + 2\,H_2 \rightarrow CH_4 + O_2$
Net Reaction

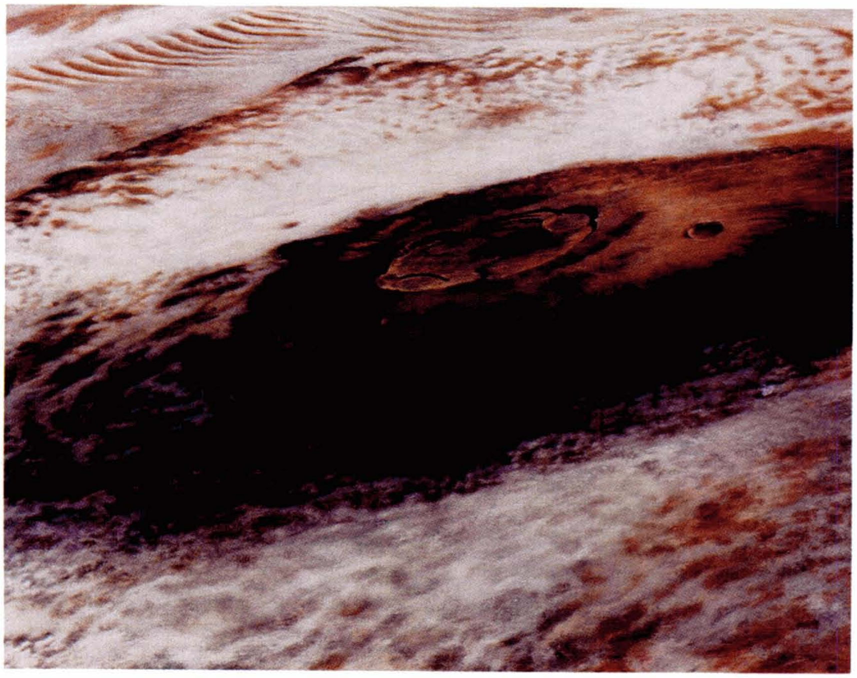
Other well known reactions have been practiced for decades which can also accomplish similar conversions. Fischer-Tropsch chemistry is practiced in the petrochemical industry in a variety of ways. It converts carbon monoxide and hydrogen into methane and water. The Bosch reaction can convert CO_2 and hydrogen into carbon and water. The carbon could, perhaps, be used for advanced material production at an outpost once fabrication facilities are available.

Eventually, we will obtain water from the environment of Mars. We would then not need to make water from imported hydrogen. Indeed, we could turn the situation around and use this water as a source of hydrogen, thus continuing to utilize the chemical processing capabilities we have developed. For instance, it would be even more favorable to produce methane from the atmospheric CO_2 and water-derived hydrogen. This would require the production of much less water than if we switched the space transportation system to a hydrogen-oxygen propellant system. It is also much easier to liquefy methane than hydrogen.

With a large amount of hydrogen available, and a ready supply of CO_2, we may consider going the next step and developing the ability to produce a large variety of products. If ethylene were produced from hydrogen and a carbon source, polyethylene can be made using technology available today. This material, or other carbon-based polymers, can then be extruded or molded to form habitats, furniture, pipes, and a variety of useful items. The petrochemical and natural gas industries can contribute a great deal of expertise in this area.

enough water to produce both hydrogen and oxygen propellant for the launch back to orbit and even the return trip to Earth, thus reducing the size of the spacecraft leaving Earth for Mars. Telerobotic mining at distances as far as Mars is not practical, however, and totally automated systems would need to be developed. And, at the more accessible latitudes near the equator, any water is likely to be found at a lower depth, compounding the problem.

The two moons of Mars, Phobos and Deimos, may also be rich in water. Processing at the extremely low gravity present on these bodies will require some innovative equipment. While early exploration scenarios suggest it would be difficult to bring this promise to fruition, future operations on or near Mars could easily make use of the potential within these bodies. Many asteroids are believed to be of similar composition and are also likely targets for utilization once we have



Olympus Mons, a volcano on Mars, is 15 miles high and 375 miles across at its base, dwarfing all other known volcanoes in the solar system. This view shows the caldera protruding through a cloud layer in the northern hemisphere of Mars. The presence of an atmosphere provides a Mars program with a resource unavailable at the Moon. Chemical procedures exist to convert carbon dioxide, which is 95 percent of the atmosphere, into products such as oxygen, water, and methane.

honed our ability to operate highly complex equipment at distances so remote that teleoperation is not feasible. For the near term, however, the SEI requires the development of an ISMU program which focuses on the Moon and Mars.

Relationship to Space Exploration Initiative (SEI)

On the 20th anniversary of the landing of Apollo 11, President Bush committed the United States to going "...back to the Moon, back to the future, and this time, back to stay...And then a journey into tomorrow, a journey to another planet, a manned mission to Mars." This Space Exploration Initiative builds on the successes of the past and gives NASA a definite direction for the future.

With the help of outside inputs, NASA is defining possible strategies to be used to work toward the goals of the SEI. Some paths make extensive use of ISMU to build up our presence in the solar system quickly. Others take a more restrained approach, relying almost completely on bringing material from Earth as part of an overall attempt to lower the cost of the program by trading off scientific and operational capabilities. As the program develops over the next several years, the interplay of capabilities and investments will be more completely understood for the program as a whole. A near-term focus of the SEI is on technology development, with a search for innovative ideas that have a high leverage impact on cost, schedule, and performance. Since the ISMU program affects all these measures of performance, it is sure to play a major role in this effort.

An Evolutionary Approach to Using Space Resources

In 1987 the "Ride Report" stated that, "Exploring and prospecting the Moon, learning to use lunar resources and work within lunar constraints, would provide the experience and expertise necessary for further human exploration of the solar system." It went on to assert that, "There is no doubt that exploring, prospecting, and settling Mars should be the ultimate objectives of human exploration. But America should not rush headlong toward Mars; we should adopt a strategy to continue an orderly expansion outward from Earth."

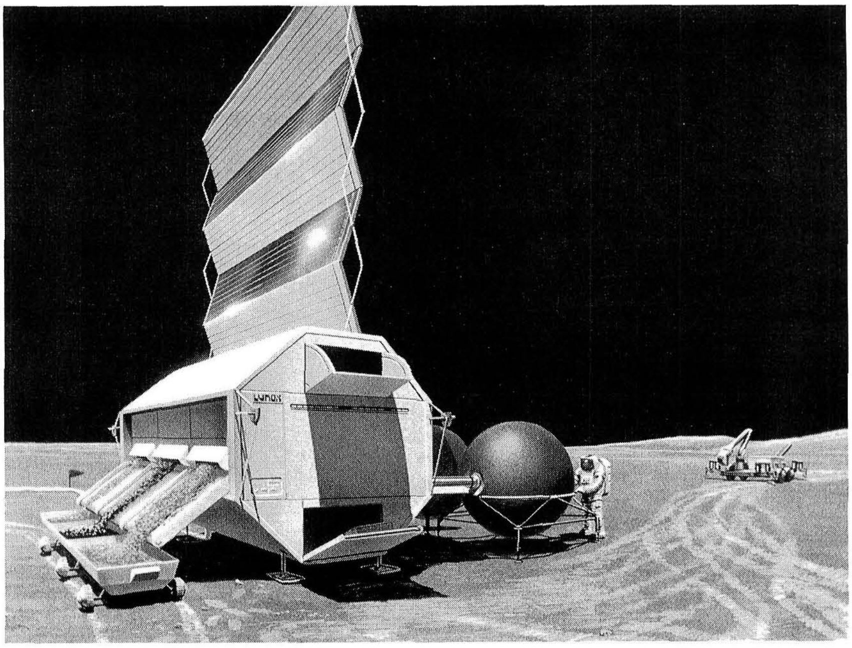
When we return to the Moon and proceed to Mars, we are not going there solely to utilize the resources. We are going

- to satisfy our need to explore, to strive, to seek, to find,
- to increase the pool of scientific knowledge,
- to enhance our understanding of life in the universe and to find out if life once existed on Mars,
- to ignite the human spirit and enhance our national pride,
- to keep our country competitive in economic, political, and technology areas,
- to improve the Earth's political and economic condition, and
- to invigorate science and engineering for our children's education, and countless other reasons.

However, using lunar and Mars resources can have a major effect on the way we proceed, the cost of the program, its timetable, milestones along the way, and ultimately on whether the program is successful or not.

This view of Earth rising over the Moon, brought back by Apollo 11, inspires us to once again accept the challenge of space exploration. This quest for an understanding of the universe in which we live can stir our children to learn more and so fulfill their potential. It will stimulate American industry by developing technology which will also provide benefits to Earth. It will allow us to unfold the mystery of how planets evolve and help us to understand our own planet better — a planet which is a fragile oasis in the vastness of space.

An early pilot plant to begin production of LOX is depicted here. It may require electric power, or it can be designed to provide its own power independent of the outpost. A small mining operation will supply it with raw material. The mining vehicles may be the same ones used for other operations at the outpost. These same vehicles will remove the tailings and replace them in the mine, thus minimizing the impact of such an operation on the lunar environment.



> *The real test of whether a program to put people permanently into space is successful is whether they stay. And people will only stay on the Moon and Mars if they learn how to use local resources to make their settlements permanent. Otherwise, the continual cost of supplying everything from Earth will become too great a burden, and these settlements will be abandoned.*

The timing, or phasing-in, of ISMU will be a natural evolution of productivity as power levels and capabilities increase. As in any market, the needs of the outpost will dictate what products are produced. Many technologies already exist and need only be modified for use in space. Robotic units sent ahead of crews will perform critical experiments. These units will be followed by engineering prototypes for the demonstration and verification of technologies and products. Each level will justify itself in terms of enhanced capabilities or cost benefit to the SEI. Each step forward will provide minimal risk and will have graceful upgrades and safe fallbacks. As pressurized living space is expanded, the material necessary for radiation protection shall, of necessity, be produced. This will also provide material for other uses at the outpost. The technology and vehicles used for mining this material will later be used to mine feedstock for a lunar LOX plant and perhaps burrow under the surface for the creation of inhabitable tunnels. As the reusability of landing vehicles is demonstrated, the manufacture of propellant (such as LOX) will be brought on-line: enough for ascent back to lunar orbit at first, but eventually enough to make a round trip. During this time the technology necessary for metal and light gas production will be developed, providing the flexibility for whatever avenues we choose to follow in our exploration of space, with little support required from Earth.

By mastering the details of this type of operation in an extra-terrestrial environment, we will be using the Moon to learn how to operate with minimum dependence on Earth, a skill necessary to control the cost of expanding our presence in the solar system. In addition to the hard engineering technologies required to accomplish this task, the use of teleoperation, automation, and robotics will increase the capabilities of the outpost without a large cadre of astronauts.

This timing of the use of lunar and Mars resources must fit into the overall mission of a lunar and Mars program. In some mission "architectures," only simple products will be possible because of the limited power, mass, and logistics available to produce them. Other schemes can be envisioned where the first flights bring large numbers of robotic processing plants so we can build up the outpost from local materials. A scaled-back, man-tended base would provide the core for this bootstrapping activity. Only after we can refuel landing vehicles and build structures would we attempt to bring down large payloads or increase stay times. The propellant for the Mars voyages might also be produced on the Moon, thus saving the enormous expense of lifting it from Earth. A number of similar concepts of varying complexity exist.

Once LOX has been produced at the lunar outpost, certain operations will be required to utilize it. Still to be determined is whether humans will be involved in propellant transfers to a lunar vehicle, as shown here, or whether this task will be performed robotically.

On Mars we will again develop the capability to extract those things from the local environment which we need for survival. The martian atmosphere can be used to provide oxygen for life support and eventually for propellant. Methane and water will be produced for a variety of uses. Schemes incorporating these concepts into robotic missions can provide an early demonstration of the technology and greatly increase the mass of a returned sample, while lowering the mass launched from Earth.

Developing the Technology — Who can contribute?

The timing and likelihood of the products described above are not equal. Oxygen and cast basalt are two products which, we feel, are relatively easy to produce. The greater amount of mining for light gas collection puts these products further into the future and also requires robust mining systems. While the production of refined materials such as silicon and aluminum has already been demonstrated, the fabrication of solar cells, wires, and structural beams from these feedstocks requires a fair degree of manufacturing sophistication.

The development of new technologies will thus be necessary to accrue the benefits of ISMU. Thermal control, cryogenic engineering, and space power sources are cross-cutting technologies that are well understood, but chemical processing, teleoperated mining vehicles, and manufacturing are new to NASA.

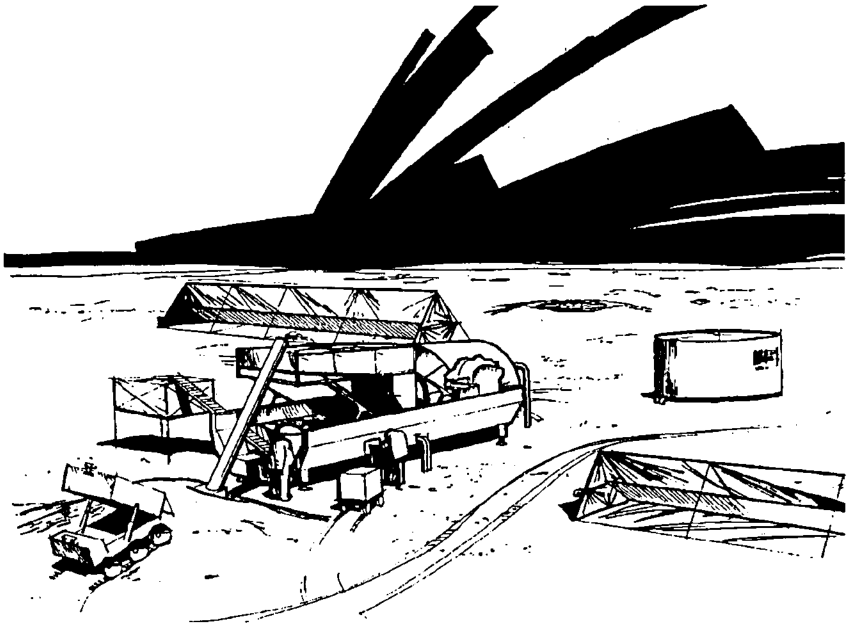
In their 1986 report, the National Commission on Space recommended the formation of "a continuing program to test, optimize, and demonstrate chemical engineering methods for separating materials found in space into pure elements suitable as raw materials for propellants and for manufacturing." This directive was based on lab results from preliminary tests of oxygen extraction using electrolytic and chemical processes. The Commission continued with the following recommendation: "Research to pioneer the use, in construction and manufacturing, of space materials that do not require chemical separation, for example: lunar glasses and metallic iron concentrated in the lunar fines." The development of many of the technologies in each of these disciplines will be synergistic. As in any development program, time and effort will be necessary to bring these possibilities to fruition. How will we acquire the necessary expertise to accomplish our goals?

NASA and the aerospace community

NASA and many of the aerospace firms have begun considering how we can develop the potential of ISMU so that we can incorporate it with confidence into plans for the SEI. One realization is that many of the skills which will be required are not ones which they have traditionally embraced.

The chemical process industry

Many of the aerospace firms have thus formed links with companies whose main function is chemical processing. Firms that construct chemical plants or engage in the actual operation of these plants have decades of experience which can be brought to bear on the tasks which lie ahead.



Another candidate for the production of oxygen from lunar regolith is depicted here. This process involves electrolysis to release oxygen from the silicates present in the soil. While this technology has some similarity to the aluminum industry here on Earth, much research remains to be done before such a process can be developed for lunar conditions.

The energy industries

Likewise, industries that work in the many aspects of energy here on Earth can bring their expertise to many of the hurdles we face in methane production and handling, power generation from stored thermal energy, lunar power systems, or helium fusion. Additionally, the power requirements of most ISMU processes can be quite high, so energy conservation — also being pursued by industry — will play a role.

The steel-making and non-ferrous metal-making industries

As described earlier, many of the routes to oxygen are similar in nature to the production of metals from ores. The processing of regolith for metal and oxygen production can benefit from the knowledge and experience of metallurgical firms.

The mining industry

Before we can hope to process the soil of the Moon into other materials, we will most likely need to dig it up and feed it into our processing plants. There are many concepts of how to do this, but all will need to resolve many of the same issues that have been faced by mining companies for centuries. While there are problems on the Moon that are not a factor here on Earth, the mastery of this skill will require NASA to include the lessons of this segment of industry in its planning. The U.S. Bureau of Mines and several universities have already begun to consider the requirements and options for lunar mining equipment.

The construction and materials transport industries

The skills and technologies engendered in these industries will be critical to many aspects of a lunar outpost. Excavation and materials transport, like mining, will teach us how to prepare a site for a habitat module as well as how to bring regolith to our feedstock pile. Larger scale production will require larger processing plants. These plants may exceed the size and mass we can bring down on a single vehicle, thus construction will be required at some level. Since many of these

Oxygen and Metal Coproduction

Because many minerals consist of metal oxides, we can utilize them to produce both oxygen and metals. This scheme, first explored in 1971, passes an electric current through a molten silicate to release oxygen at the anode. Metals, both iron and silicon, are produced at the cathode. This metal layer can be tapped off into ingots for a variety of needs. There may also be a layer of slag which can be used for the production of bricks. Thus, three separate products can be made in one unit. This process is performed at high temperatures, and the stability of the materials used in many of the components of the plant requires further research before a viable process can be claimed. As in most other proposed routes to oxygen, the electric power requirements for such a unit are considerable.

The actual chemical mechanisms that occur are quite complex; however, the reactions can be written as

$$SiO_2 \rightarrow Si + O_2$$

$$FeO \rightarrow Fe + {}^1/_2\, O_2$$

Thus, an alloy of iron and silicon is produced as a coproduct. An alloy of aluminum and silicon has also been produced in a laboratory investigation of a related process aimed at the production of metals from lunar materials. Alloys such as these can be further processed to provide construction materials for structures or interior articles.

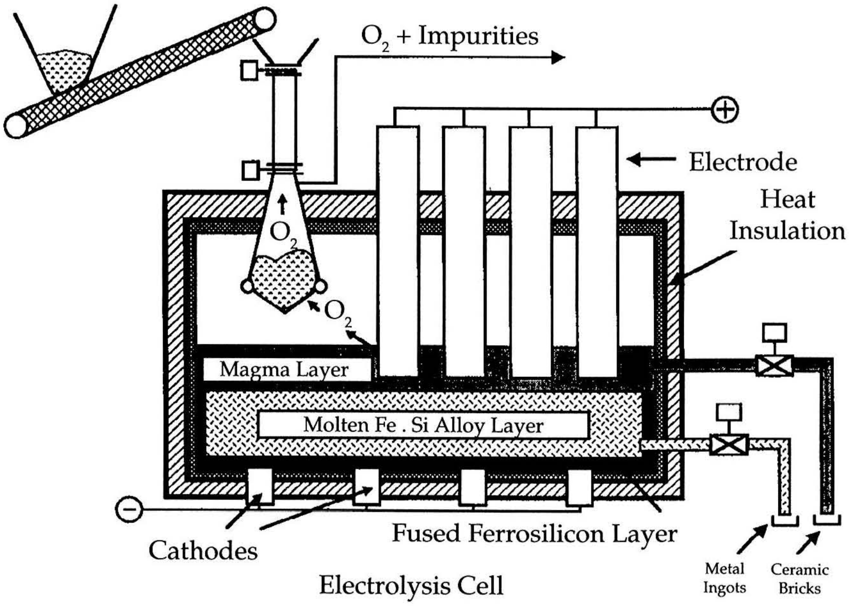


Illustration courtesy Rockwell International Corporation

Another route to oxygen by electrolysis of the lunar regolith is shown here. This involves processing molten soil to release oxygen, iron, and silicon. A slag which can be used for brick fabrication is also produced. The amount of mining required to produce each ton of oxygen is lower for this route than for many other potential processes. Much development work will be required to take this chemistry from the research stage to that of a reliable process.

capabilities will be needed in the fabrication of larger habitats, whether they are derived from ISMU products or brought from Earth, there is a great need for adaptable construction equipment.

Designing for Space — Constraints

While the advantages of incorporating an ISMU program into man's expansion into the solar system are clear, they must be weighed carefully against the requirements such an effort will impose.

Many traditional engineering disciplines are represented in several functions at an outpost. Technology developed for one area can solve many other problems. Commonality is present at many levels in a program as large as the SEI. Some equipment will have evolving uses as time goes on, such as vehicles used to transport cargo later being used to mine regolith. Also, the technologies and procedures developed in an ISMU effort on the Moon would serve to bring us up the learning curve for similar operations on Mars. As shown in the table below, these technologies run the gamut of specialties. The lead time to develop these skills can be many years. We need to begin now.

Since the benefits of ISMU present themselves, in part, in the form of reduced mass launched from Earth, the mass of the plants and equipment needed to provide these benefits must be low. The availability of everything we normally use to manufacture

Commonality for Moon and Mars:
ISMU Technologies and Procedures

Tasks	Moon	Mars
Mining	yes	yes
Telerobotic Operation	yes	no
Conveying	yes	yes
Atmosphere compression	no	yes
Chemical Processing	yes	yes
Automatic control	yes	yes
Expert systems	yes	yes
Liquefaction	yes	yes
Closed loop processing	yes	yes
Operations	yes	yes
Maintenance	yes	yes
Deployment/construction	yes	yes
Cryogen transfer	yes	yes
Material handling	yes	yes
Fabrication technology	yes	yes
Physical processing	yes	yes
Product usage	yes	yes
Interface with program	yes	yes
Space transportation	yes	yes
Planetary surface systems	yes	yes
Demonstration and Verification	yes	yes

materials on Earth will be limited on the Moon and Mars. Power, mining capacity, spare parts, and especially manpower, will be in short supply. Hence, their usage comprises the criteria against which all processes must be judged. All elements of every space effort must be concerned with these limitations. The ISMU plants must operate at reduced gravity and, unless enclosed in a structure, will be exposed to vacuum, solar radiation, and severe temperature variations. They will be subject to the Moon's day/night cycle of two weeks each. Thus, reliability and operability will be extremely important. Complex systems that require frequent maintenance and spare parts must be avoided whenever possible. Systems which can be teleoperated or supervised from Earth will relieve the operations burden from the outpost. Automation similar to that used in present-day chemical plants, enhanced by expert systems now in the development stage, and supervised by Earth-based engineers and scientists, are planned for these robotic factories.

Benefits to America and the Earth — Everyone may benefit

Historically, technology development programs carried out by NASA have been an excellent investment in America. Whenever we explore new technologies, there are spinoffs and benefits in areas where we didn't anticipate them. We now have a unique opportunity to have a much greater impact on direct terrestrial applications. In developing the capabilities for manufacturing in the severe environment of the Moon and Mars, we can expect that technology

As we continue to push outward, we will reap the benefits of our efforts here on Earth. Areas in which we can expect break-throughs due to R&D in ISMU include pollution control, manufacturing, engineering, robotics, and other areas with direct terrestrial benefits. America has a unique opportunity to use this challenge to improve life on Earth.

improvements and inventions will occur in several areas important to our life on Earth, including chemical engineering, mining, pollution control, computer programming, manufacturing, and other fields. We can also expect that improvements to the environment will result. The impact of our efforts in these areas should also be felt throughout our educational system as research programs mature.

In their 1986 report, the National Commission on Space predicted that 21st century America would receive the following types of benefits from the space program:

- Scientific and technological advances of critical importance to the nation's future economic strength and national security.
- Direct economic returns from space-based enterprises capitalizing on broad, low-cost access to space.
- New worlds to explore on the space frontier, with vast resources that can free humanity's aspirations from the limitations of Earth.

Embodied within the SEI program, ISMU affects all of the aforementioned goals. We expect to be able to expand the capabilities of people and equipment at our outposts on the Moon and Mars, while the American taxpayer will benefit through the overall decreased cost of the SEI program.

Conclusions and Recommendations — What do we do next?

We have in hand a good understanding of the opportunities where an ISMU program can provide vast savings to the SEI. Without such a plan, it is uncertain that America would choose to bear the expense of such a push into the solar system. The specific products outlined in this report define the areas where we must develop further technology to bring these promises to fruition.

What do we need to do next?

- We must rapidly develop and expand the technologies that would make possible the early use of available resources when we send people to the Moon and Mars.
- We must develop small, early robotic ISMU experiments to send before we send people. These systems will demonstrate the production of useful products in the actual environments of the Moon and Mars. We will learn from them, and they will influence the design of the production plants which will follow. This is a low risk approach.
- We must include strategies that aim toward maximum self-sufficiency as major goals of the SEI. This should include designing other elements of the outposts and spacecraft to maximize these benefits.
- We must implement the recommendations of the National Commission on Space and the Ride Report, which include continuing research and technology development programs focusing on processing indigenous raw materials into propellants and construction materials.

Only by learning to live off the land will we be able to take the next "giant leap for mankind" and continue our journey to Mars and beyond.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1991—561-653

National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center