



Figure 1: LEFT: Apollo 15 lander & launcher rockets, moon buggy, and astronaut more than 30 years ago
 RIGHT: NASA artist's depiction of a future lunar base.

PERMANENT – Chapter 2 – Lunar Materials Utilization

Excerpts from a website developed by physicist Mark Prado on issues related to space transportation and resources. [www.permanent.com]

1 Overview – of lunar materials and their Utilization

1.1 Why Lunar Materials?

Lunar materials are more economically attractive as feedstocks for large scale space-based industrialization than are materials blasted up from Earth, in the overall analysis. Whether lunar materials are more desirable than materials from asteroids near Earth is the subject of much debate. This website presents the merits of both cases. It would not be surprising to see both lunar and asteroidal materials used, in a synergistic manner.

1.2 Transportation Costs

The Earth is 81 TIMES as massive as the moon. As a result, it costs a whole lot more to get materials off the Earth than it does to get them off the Moon. In order to stay as nontechnical as possible, a visual example will be presented first. Remember the Apollo program, specifically the lunar module. The lunar module consisted of two parts – the lander and the launcher. The launcher, which returned the men from the moon's surface back into orbital space, was not much taller than a man. The fuel tank for it was set off in a corner, and smaller than a man – if you had one of those in your room, you could roll it over and sit on it. In contrast, the fuel and vehicle required to get a couple of guys and their bags of dirt off of the Earth would be huge and complex.

Indeed, imagine what would be required to LAND a launchable rocket onto the Earth from space (especially without the assistance of a braking atmosphere). We had to land the return rocket onto the Moon. This should give you an idea about how easy it is to get on and off the moon compared to get on and off of the Earth, assuming chemical rocket means. (Remember, we did that way back in 1969, just 12 years after the first successful launch of anything into space, *i.e.*, just 12 years after the Russian Sputnik unmanned satellite in 1957.)

Secondly, because of the Moon's low gravity and lack of atmosphere, engineers have decided that we don't even need rockets to get stuff into space. There are designs and laboratory prototypes of an electric "slingshot" called a "Mass Driver" which would need no fuel. (It is actually a launch tube, like a pea shooter.) The Mass Driver would shoot a steady stream of small fiberglass containers of lunar minerals into orbit to a "Mass Catcher", whereby the bags will have slowed down to almost zero speed due to gravity by the time they reach the catcher. The fiberglass containers encasing the minerals would be made from lunar material on the surface. In the long term, this may be the cheapest way to get materials into Earth orbit in very large quantities, quickly.

A prototype Mass Driver was developed for lunar duty by the Space Studies Institute (SSI). The Mass Driver and its initial power supply allegedly could be launched by one of today's existing rockets as one payload, though

additional launches would be necessary to deliver the fuel propellant, vehicle and general infrastructure required to deliver it from low Earth orbit to the Moon's surface. However, the Mass Driver may be a high risk device in the initial stages of space development, and one should consider conventional chemical rocketry for lunar launch in the first missions. Nevertheless, in the long run, the Mass Driver could make the Moon more competitive with asteroids as a source of material. (The Mass Driver is the antithesis of rockets. Unfortunately, an Earth-based Mass Driver is not very feasible due to the atmosphere – the payloads would burn and possibly break up like meteors in Earth's atmosphere, as well as be blown into unpredictable courses, especially at the speeds required to shoot stuff off of Earth.) In a private sector scenario, the lunar material might be processed mainly by industry based in orbital space, and not on the Moon. Why put the industry in space?

- 24-hour “noontime” sunlight in orbital space for electrical and thermal energy
- zero-gravity super-high temperature containerless processing in orbit, plus any desired gravity can be created in orbit by centrifuge
- costs and complexity of landing and deploying industrial equipment on the Moon's surface, including huge solar oven mirror arrays; and
- since sellable products will be used in orbital space anyway, and most systems in orbit will be huge, it may be better to manufacture them at the same place you assemble them.

Notably, like with the transport of asteroidal material, material delivered into space using a Mass Driver would dwarf the quantities that could be feasibly supplied from Earth, and at a cost per pound that would become trivial within a few years of completion of a serious first set of infrastructure.

1.3 What is Lunar Material?

Lunar material is pretty much like Earth's crust – silicate dirt – oxides of metals and silicon. Unlike asteroids, there are no big free metal ores on the moon (though there are some significant quantities of free iron granules in the soil, thanks mostly to asteroid craters and the lack of water to rust it). Oxygen is abundant and can be cooked out of the dirt, but other volatiles are in questionable supply in lunar soil with the exception of ice in super cold lunar craters. While metals can be extracted by space-based processing, the easiest things to make from semi-processed lunar materials are “lunarcrete”, fiberglass, various glass-ceramic composites, and oxygen. Notably, oxygen, which makes up roughly 40% of lunar soil (bound in molecular silicates and metal oxides), makes up 86% of the weight of fuel propellants in hydrogen-oxygen rocketry, with hydrogen making up the other 14%. Therefore, at least 86% of the fuel used in orbital operations could come from the moon. Notably, there are substitutes for hydrogen, such as atomized metal powder, such as is used for the Shuttle's two “solid rocket boosters”, and which can be readily made in space from lunar or asteroidal materials. Thus, fuel to transport the materials is another product of lunar material.

1.4 Mining the Moon

The moon is like a beach of fine powder. Mining this powder can be done by bucket-cable-reel draglines instead of heavy Earth-breaking machinery. The moon's powdery nature is due partly to the total lack of a protecting atmosphere which has allowed every meteor, micrometeor, and cosmic particle to bombard the surface and pulverize it over eons. This is combined with the fact that the Moon has been geologically dead (no reformation of rocks by sediment, crust folding, or volcanics) for the last 3 billion years. The Moon is small and cooled off quickly, in contrast to Earth, which explains differences in their geologic nature. Even the eons-ago pulverization by gigantic asteroid impact shocks has been preserved. Indeed, the Moon is so finely powdered that Apollo planners were concerned with sinkage of the lander and astronauts. Recall the fine bootprints, sunken yet every contour of the boot finely imprinted. Recall Neil Armstrong comparing the surface to charcoal ash. The moon's powdery nature is ideal for cheap mining and mineral processing.

2 The Origin and Composition of the Moon

It is important to first understand what the Moon is made of, and how it compares and differs from Earth and asteroids. To more fully understand this, it helps to know how the Moon came into existence and the general processes that occurred in its history. Astrogeology is also discussed in the section on asteroids, but this section does not require that you read the other astrogeology section, though it may be helpful to read the latter.

2.1 Mystery Solved – Where the Moon Came From

The mystery of the origin of the Moon has been solved by modern science. The first clue regarding the origin of the Moon is the fact that the Moon is getting further and further away from the Earth with each orbit. It's a very slow rate of escape and it will be billions of years before Earth will lose the Moon. It's a well understood and measured phenomenon. In fact, if you go backwards in time to see how far the Moon was from the Earth in the early days of the solar system, starting 4.6 billion years ago, you find that the Moon would be extremely close to the Earth if not part of the Earth at that time. The best way we can theorize this happening is if the Moon were made of material blown off of the Earth by giant asteroid impact(s), and that all the material floating around in low Earth orbits created a big cloud or ring around Earth (much like Saturn and Jupiter's rings). Eventually, the material stuck together by gravitational force, making the Moon.

This is called the "Collision-Condensation Theory" of the Moon, and is the generally accepted modern theory. (Notably, other moons in the solar system orbit around their planet's equator, just like the planets all orbit in the plane around the sun's equator. However, Earth's Moon is unique because it does not orbit around Earth's equator. It orbits in the plane of the Sun's planets, as you would expect from material blown off of a planet by asteroid bombardment coming from the plane of the other planets. Of course, this is fortuitous because it puts the Moon in the plane of present day asteroids in the solar system, thereby making it easy for the Moon to give gravity assists to asteroid payloads coming in from interplanetary space, as discussed in chapter 3.) The Apollo and Luna samples have further supported this theory.

2.2 The Structure of the Moon

The origin of the Moon has several fundamental effects on lunar geology. First, the Moon is made of lighter-weight material blown off of the Earth's surface, and is poor in materials from the Earth's mantle and core. We see this in the aluminum-rich lunar highland geologies. We also know by measuring the mass and density of the Moon by Apollo and other scientific instruments. Overall, the Moon is not very dense. The Moon does not have a large metal core, unlike Earth, as we know from seismic studies on the Moon, though later studies suggest it does have a small heavy, metal-rich core (if not pure metal). (In terms of percent, there's much more metal in asteroids on average than on the Moon.) The materials available from the Moon for building things in space are generally the lightweight silicate and metal oxide minerals of the lunar crust.

Second, the Moon is extremely poor in volatiles of all kinds, with the exception of permanently shadowed lunar polar craters. The Apollo soil and rock samples and various other scientific studies show that the Moon is deficient not only in water but also very deficient in compounds containing carbon, potassium, sodium and chlorine. That would be expected from a planet that formed late, after the Sun had already gotten big and started shining, and the clouds of interplanetary dust had already been gobbled up by planets so that the sun shined through. The infant sun would have caused the dust rings around Earth to lose much of their volatiles before they had a chance to accrete again to form the Moon.

Third, this lack of volatiles not only means deficient lunar supplies, but also means that certain ore forming processes that occurred on Earth could not have occurred as commonly if at all on the Moon. Certain volatile gases helped in the formation of ores on Earth, e.g., by dissolving and depositing certain minerals, and in making molten magmas more fluid.

Fourth, the Moon is small, the Earth being 81 TIMES as massive as the Moon. Hence, plate tectonic forces were not as strong on the Moon. Also, smaller bodies cool off quicker (in effect having less insulation). The Moon was molten when it first formed, but it cooled off quicker and underwent less metamorphosis than Earth. There's less chance for a diversity of deep layers to have been exposed on the surface. The lack of weather

means no sedimentary ores as on Earth, and no exposed ores due to weathering (though cratering can expose surface strata, too, albeit not nearly as deep as folding mountain geologies). The Moon has practically no folding mountains or volcanoes, and the landform geologic activity still active today on Earth's surface died out on the Moon billions of years ago. Many of the long, slow geologic processes that created many of the ores on Earth today did not occur on the Moon's surface. Lunar mountains were caused by material splashed up by giant asteroid impacts and the accretion phase.

2.3 Distribution and Density of Ores

In general, much less diversity of ores is expected on the Moon, according to the opinions of many geologists. On the other hand, it should also be noted that some of Earth's richest ores are from its oldest geologies, all lopped together under the name Pre-Cambrian, which means older than 0.5 billion years. Earth rocks are typically 10 million to 0.5 billion years old. (The "age" of a rock is the time since it last solidified from molten liquid.) The very oldest Earth rocks are 3.5 billion years old, and are rare specimens. In contrast, practically no Moon rocks are younger than 3.1 billion years old. The Moon rocks brought back to Earth are ALL quite old, well preserved rocks, with highlands rocks having solidification dates as old as 4.48 billion years ago.

The slow cooling of early molten planetary material generally causes separation of different elements and minerals at different temperatures as the magma cools slowly over time. The magma cooled much slower (due to nuclear radiation) and in a less disturbed way on the Moon, compared with Earth volcanism. This could possibly have created some special ores. While the oldest crustal ores on Earth have mostly been eroded, dissipated or buried on Earth eons ago, they're well preserved on the Moon. There's little physical evidence of an original Earth crust. Much more recent Pre-Cambrian rock layers have been exposed due to uplifts and erosion, and at some places at the continent's edge. However, these Pre-Cambrian rocks aren't as rich as the lunar highlands in aluminum and calcium, nor are the oldest known Earth rocks, on average. Of course, it's possible that some unusual and unpredicted ores could be discovered on the surface of the Moon, though we can't depend on that.

2.4 Extraterrestrial deposits of ores on Earth

The Republic of South Africa, the richest country in mineral wealth (non-fuel minerals), is largely a Pre-Cambrian geology. Witwatersrand ("the Rand") in South Africa is by far the single richest gold producer in the world. South Africa has half the world's platinum group metal resources, and most of the world's chromium resources. Deep gold mines in Brazil and India, and the extraordinary deposits of Kalgoorlie in Western Australia, are of Pre-Cambrian origin, as is Siberian gold. The two most important deposits of uranium-bearing minerals are found in the Pre-Cambrian rocks of the Belgian Congo and northern Canada.

Of course, the Sudbury Astrobleme in Ontario, the geology that produces more than half of the world's nickel and yields cobalt and platinum-group metals, is a well preserved Pre-Cambrian asteroid impact crater of massive size. It's possible that the slowly cooling magma oceans produced by asteroid impacts on the Moon could have concentrated exotic asteroid elements. But we won't know until we go there to investigate.

2.5 The role of water in ore formation – critical or optional?

Earth literature often suggests or implies that water is vital in ore-forming processes, even in igneous processes (those resulting from cooling of molten rock), because water dissolved in a magma increases fluidity (i.e., decreases viscosity) and encourages elements to move around and become concentrated. However, water is not necessarily vital for ore production. Besides asteroid crater deposits, the Moon has plenty of its own sulfur. Besides, atoms and minerals move around in a dry magma, albeit slowly, and an undisturbed magma that stayed molten for millions of years could produce some interesting results. Experiments still haven't been done on various "dry magma systems" to see what processes occur; such experiments haven't received support largely because they aren't seen as commercially relevant to Earth ores and magmas. But 3 billion year old preserved magma lakes exist only on the Moon. On Earth, they're long gone.

We should guard against being overly biased by Earth ores. Only a substantial post-Apollo survey will tell us for sure whether there are any special ores on the Moon. If aliens sent half a dozen small Apollo-style scouting

expeditions to Earth, it would be extremely unlikely that they would find any of our great ores. A post-Apollo survey could possibly find fantastic ores that have no equivalent on Earth. Ore formation processes have been unveiled and understood usually by hindsight after discovery and analysis, not by prediction. Many ores are still not well understood, e.g., in Pre-Cambrian South Africa deposits. Indeed, the Apollo and Luna samples have given us many surprises, and lunar geology has turned into a very complex field with many mysteries. However, we can't count on finding any special ores when it comes to investing to establish the initial space based infrastructure, building solar power satellites, etc..

Every major study into mining and processing lunar material assumes that we will use only what Apollo samples offer. Nonetheless, the Apollo samples show that there are minerals abundant in the common lunar soil which are fairly easily processible to produce major quantities of fiberglass, ceramics, clear glasses, aluminum, calcium, iron, magnesium, titanium and chromium, as well as other materials – the basic building blocks of space development. For the basics of space development, we don't need anything exotic.

However, bulk supplies of volatile elements, e.g., hydrogen, carbon, sulfur, will probably need to come from asteroids. One exception is that hydrogen could come from the permanently shadowed lunar polar craters based on the discovery of ice by the Clementine and Lunar Prospector probes, as discussed later.

2.6 Highlands Versus Lowlands Geology

Like on all planetary crusts and the dirt under your feet here on Earth, lunar material consists predominantly of silicate minerals, i.e., silicon and oxygen molecularly bonded to various metal atoms. However, the lunar highlands differ from the lunar lowlands mainly in their concentrations of the metal oxides. The early lunar crust formed a “magma ocean” which solidified into a crust of the lightest minerals which had floated to the top, predominantly aluminum calcium silicates (“anorthositic material”) about 4.5 billion years ago. In fact, this crust is quite rich in aluminum and calcium compared to Earth's crust. (Earth's crust is split into two layers, the top being richer in aluminum silicates, “SiAl”, with an underlying layer of magnesium rich silicates, “SiMg”.) However, the period between 4.5 and 4.0 billion years ago was marked by heavy bombardment by meteors and asteroids, causing intense cratering.

The highlands geology is mostly composed of overlapping layers of material ejected from craters, predominantly the initial anorthosite (aluminum rich) crust. Rocks brought back from the highlands vary in age between 3.84 and 4.48 billion years old.

Today's flat lowlands “mare” regions (“mare” is Latin for “sea”) formed about 4 billion years ago when immense asteroid impacts fractured the crust, allowing the lavas from 300 kilometers deep (200 miles) to erupt through the impact fractures and form vast seas of lava. (For comparison, Earth's crust today is 50 kilometers, or 30 miles, thick in most places.) This material was poor in aluminum and calcium, but rich in iron and magnesium. However, the lavas melted preexisting aluminum-rich surface materials and mixed with them. The lava was rich in the heavier radioactive elements which had initially settled well below the crust, and the radioactivity kept the molten seas of lava hot for millions upon millions of years. Mare rocks have been measured to be between 3.15 and 3.77 years old. The last molten lakes are thought to have finally solidified about 3 billion years ago. The resulting material which makes up the surface of these ancient lava seas is rich in iron and magnesium minerals, with a remarkably high content of titanium minerals. When you look at the moon, the mares are the darker areas, and tend to be circular in shape because they formed in giant asteroid impact spots.

2.7 The Apollo and Luna Landings

The USA had six Apollo landings, the last three having electric powered dune buggies to transport samples and astronauts considerable distances from the landing site. Russia had seven Luna missions of unmanned robots, some of which took samples at the landing site and a few of which used a robot vehicle to drive around a little. The Apollo samples are biased to the flat lowlands because it was safer to land there.

Apollo 11 and 12 were cautious missions landing on the flat lava plains of Mare Tranquillitatis (“The Sea of Tranquility”) and Oceanus Procellarum. The Apollo 13 mission was aborted. Apollo 14 landed on the ejecta blanket around the vast Mare Imbrium impact basin. Apollos 15, 16 and 17 used a “roving vehicle”, that is, an electric powered car to transport samples and the astronaut for much longer distances than feasible on foot.

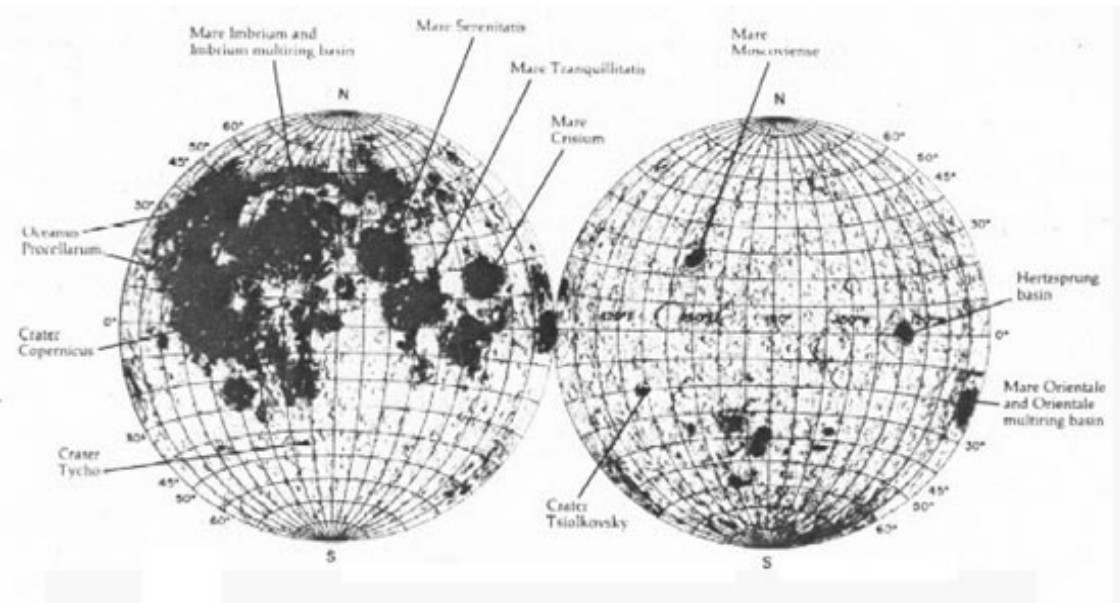


Figure 2: The near side (left) and far side (right) of the Moon.

Apollo 15 landed at the edge of the lava plane inside Mare Imbrium, taking samples of both the Mare and the foot of the Apennine Mountains which form the rim of the Imbrium Basin (and which straddle the intersection of Mare Serenitatis and Mare Imbrium).

Apollo 16 was the only real highlands landing of the U.S., albeit close to and surrounded by mares. The lunar module landed on a slope at a harrowing 15 degree angle. Apollo 17 was sent to the edge of Mare Serenitatis, where scientists had misinterpreted an unusually dark area as possible recent volcanic deposits. Instead, they were 3.8 billion year old lava deposits. The seven Soviet landings were all in either the mares or in mare rim mountains.

All samples come from the lunar nearside, in and around the mares, due to communications problems with Earth from the far side. The far side is almost all highland material. The lava flows forming the mares occurred almost exclusively on the side of the Moon facing the Earth. The Moon has kept one side facing the Earth from nearly the time of its formation due to gravitational tidal forces, and the Earth's gravity may have contributed to the flows of lava on the nearside. The Moon is pictured below. The highlands are the bright areas, the lowlands dark. Note the huge size of the asteroid craters which created the mare. The Moon is a 3000 kilometer (2000 mile) wide planet, so some of those craters and resultant lava plains are hundreds of kilometers wide.

The average composition of the Moon's highlands and lowlands based on the average Apollo samples are also given below, and for comparison are set alongside the average composition of Earth's crust. Keep in mind that we have limited highlands samples since the Apollos landed in and around the safe, flat lowlands areas, except for Apollo 16 which landed in a semi-highlands place as discussed above.

Chemical analysis in weight parts per million.

2.8 Major Lunar Minerals

Before we discuss materials processing in Chapter 3, we need to discuss the minerals we are mining. As always, if this section gets too technical for you, please skip it and continue on with the following one. In a planetary crust, mines for the base metals like iron and aluminum do not dig out pure iron or aluminum from the ground. For example, for aluminum they dig out minerals whereby atoms of aluminum are bonded to atoms of oxygen and silicon, called "silicates". This material must be processed by heat, chemicals and/or electrical current to

Lunar highland vs. lowland compositions and comparison to Earth Avg

Element	Highland	Lowland	Earth	Rank	Issues	Applications
Oxygen	446,000	417,000	466,000	1		Fuel propellant, life support
Silicon	210,000	212,000	277,000	2		Glasses, ceramics, solar cells
Aluminum	133,000	69,700	81,300	3	highlands rich	Electrical conductor, structures, mirrors
Iron	48,700	132,000	50,000	4	lowlands rich	Structural steel
Calcium	106,800	78,800	36,300	5	highlands rich	Ceramics, electrical conductor
Sodium	3,100	2,900	28,300	6	adequate?	Chemical processing
Potassium	800	1,100	25,900	7	adequate?	Chemical processing
Magnesium	45,500	57,600	20,900	8		Metal alloying element
Titanium	3,100	31,000	4,400	9	lunar rich	High strength metal
Hydrogen	56	54	1,400	10	lunar poor	Fuel propellants, life, chem.
Phosphorus	500	660	1,050	11		
Manganese	675	1,700	950	12		
Carbon	100	100	200	17	lunar poor	Life, chemical process, fuel?
Chlorine	17	26	130	20		
Chromium	850	2,600	100	21	lunar has	Metal alloys

separate the metal from its oxide or silicate. The industrial facility to process the material is often called a “smelter”.

For example, the lunar highlands mineral “anorthite” is similar to the ore “bauxite” from which aluminum is produced on Earth. Anorthite is a mineral consisting of aluminum (chemical symbol Al), calcium (Ca), silicon (Si) and oxygen (O), with a chemical formula of $\text{CaAl}_2\text{Si}_2\text{O}_8$. The smelter’s job is to split all that up to produce pure aluminum metal, and optionally calcium metal, free oxygen, “silica” glass (SiO_2), and perhaps pure silicon. Alternatively, anorthite could be processed to produce ceramics like “calcia” (CaO , aka “lime”) and “alumina” (Al_2O_3) instead of the metals, or silica glasses with various properties depending upon the metal oxides existing in the final glass product and any other impurities added.

Metals are generally found as metal oxides. (When manmade pure iron rusts, it is returning to its natural oxidized state.) These metal oxides usually bond to silica to produce various minerals, though sometimes they can be found in their metal oxide state without silica. For example, magnesium oxide combines with silica to make a greenish mineral called “olivine”: $\text{MgO} + \text{MgO} + \text{SiO}_2 = \text{Mg}_2\text{SiO}_4$.

Chapter 3 includes a section on mechanical, electrical and/or magnetic techniques called “beneficiation” to roughly separate bulk lunar regolith into its component minerals. NASA studies into lunar materials utilization using Apollo soils which are then beneficiated have come up with the following feeds for a materials processing facility (after bulk beneficiation). There are many other minerals which occur in lunar material in lower abundance, and some are exotic, but a more expansive coverage of this topic is beyond the scope of this book. The above is intended mainly to give the reader an understanding of the basics of lunar materials so that they understand the main issues related to lunar resources and materials processing.

It has also been speculated that there are probably beds of nearly pure ilmenite, anorthite and other minerals which would not need to be beneficiated to produce the above or better purity of minerals. These are much more likely to exist a few meters down, under the crater splashed surface. The reader can now understand that oxygen is the most abundant element on the Moon even though there is no air on the Moon. Making air to breathe is no problem (within an enclosed capsule, of course). The reason oxygen is the most abundant element is that it bonds to so many things. Since oxygen-bonded minerals are lightweight, they float up to form the crust of a planet. On the other hand, metals like nickel, gold and platinum stay shiny because they don’t like to bond to oxygen. For that reason, they usually sink to the core of a planet and hence they’re rare in the crust and precious to surface dwellers. In some of the tables and in the following text, the names of additional minerals are mentioned. There’s no need to memorize anything, as I redundantly remind the reader what the minerals are, and keep clear what the main points of the discussion are.

2.8.1 For Aluminum

Aluminum (spelled/pronounced “aluminium” by non-Americans) is a particularly interesting lunar resource. It’s a good electrical conductor, indeed the most widely used conductor material on Earth, even more than copper. It’s a lightweight structural material, which helps when building large structures rotating for artificial gravity. Aluminum mirrors are good reflectors and could compete with those plated from asteroidal nickel. Atomized aluminum powder also makes a good fuel when burned with oxygen. Indeed, it’s the fuel source of the Space Shuttle’s solid boosters. On the Moon, it could become the primary fuel source for chemical rocketry of material to and from orbit (though we would need a different kind of rocket since the Space Shuttle solid boosters use aluminum in a kind of rocket we can’t make from lunar materials).

The main disadvantage of aluminum is that it expands and contracts with temperature much more than most common metals, which could be an issue with large exposed structures on the Moon which are exposed to the extreme day/nite temperature variations, or equipment which operates over a wide temperature range. Iron (steel) is better used on the Moon and other such places for metal structures. We are fortunate that the Moon has concentrations of aluminum in an attractive mineral form, anorthite. As McKay and Williams conservatively report:

“Anorthite can be considered to be a potential aluminum ore in the sense that it is a naturally occurring concentration of aluminum from which it may be economically feasible to extract the metal. Bauxite [, a sedimentary Earth ore,] which contains about 25 percent aluminum [compared to 20% in anorthite], is currently the major terrestrial aluminum ore. However, terrestrial anorthite has been used in some countries as a commercial aluminum ore. The United States Bureau of Mines recently studied the economics of extracting aluminum from anorthite ... They concluded that the cost of extracting aluminum from anorthite was within a factor of 2 of the cost of extracting aluminum from bauxite and would become even more competitive as the cost of bauxite increased [with depletion]. The Bureau of Mines is currently planning to build a pilot plant to extract aluminum from anorthite. Alcoa Corp., which recently purchased a large area in Wyoming estimated to contain as much as 30 billion tons of recoverable anorthosite

“If anorthite is becoming attractive as a terrestrial aluminum resource, it is even more attractive as a lunar aluminum resource. The lunar crust contains a much higher proportion of anorthite than does the Earth’s crust and the lunar highlands are particularly rich in anorthite.” Only one of the Apollo missions landed on the rugged lunar highlands (albeit at the junction between two lowland areas). The average anorthite concentration was 75 to 80%, and varied up to 98%. There are many other highland areas which are thought to have even better anorthite concentrations than the Apollo 16 site. Raw anorthite is also a good material for making fiberglass and other glass and ceramic products.

2.8.2 For Calcium

Interestingly, production of aluminum from anorthite would create calcium as a byproduct, since anorthite is a calcium-aluminum silicate ($\text{CaAl}_2\text{Si}_2\text{O}_8$). Calcium is the fourth most abundant element in the lunar highlands. Calcium oxides and calcium silicates are not only useful for ceramics, but pure calcium metal is an excellent electrical conductor. Calcium metal is not used as a conductor on Earth simply because calcium burns spontaneously when it comes in contact with oxygen (much like the pure magnesium metal in camera flashbulbs). But in vacuum environments in space, calcium becomes attractive.

Calcium is a better electrical conductor than both aluminum and copper. Calcium’s conductivity also holds up better against heating. A couple of figures mining engineer David Kuck pulled out of the scientific literature: “At [20C, 68F], calcium will conduct 16.7% more electricity than aluminum, and at [100°C, 212°F] it will conduct 21.6% more electricity through one centimeter length and one gram mass of the respective metal.” Compared to copper, calcium will conduct two and a half times as much electricity at 20°C, 68°F, and 297% as much at 100°C, 212°F. Like copper, calcium metal is easy to work with. It is easily shaped and molded, machined, extruded into wire, pressed, and hammered.

As would be expected of a highland element, calcium is lightweight, roughly half the density of aluminum. However, calcium is not a good construction material because it is not strong. Calcium also sublimates (evaporates) slowly in vacuum, so it may be necessary to coat calcium parts to prevent the calcium from slowly coating

other important surfaces like mirrors. In fact, calcium is sometimes used to deoxidize some metal surfaces. Calcium doesn't melt until 845°C (1553°F). Utilization of lunar materials will see the introduction of industrial applications of calcium metal in space.

2.8.3 For Titanium

Titanium is a “titan”-like high strength metal, offering more strength per unit weight than aluminum. Titanium is used for military aircraft and missiles. The Apollo 11 and Apollo 17 sites were surprisingly rich in an economically attractive titanium mineral, ilmenite, FeTiO_3 (iron titanium oxide). Note that it's not a silicate. Ilmenite grains of high purity make up more than one fifth of the Apollo 17 mare samples, on average. These ilmenite grains average 53% TiO_2 , 44% FeO , 2% MgO and 1% of various impurities. McKay and Williams note: “Although rutile [*i.e.*, the mineral of pure TiO_2 found in some places on Earth] is more desirable, ilmenite is also considered to be a commercial ore for producing titanium. Dupont Corp., for example, has used ilmenite ores on a commercial basis and the United States Bureau of Mines has recently reviewed the feasibility of replacing imported rutile with domestic ilmenite as a source for U.S. titanium.” Ilmenite minerals also trap solar wind hydrogen very well, so that processing of ilmenite will also produce hydrogen, a rare element on the Moon. Ilmenite was found in significant quantities on the surface of two of the five Apollo lowland sites. Since it's not so common in Earth's crust, it's a big lesson in lunar geology and the differences between Earth and the Moon.

2.8.4 For Iron

Iron is most abundant in lowland minerals, and fairly easy to extract, *e.g.*, from ilmenite (above, same as for titanium). Small quantities of free iron also exist. In the above section, I stated that the main industrial metals don't exist in free form in planetary crusts. However, free iron metal is abundant in asteroids, and asteroids have impacted the Moon and spread their vaporized material far and wide. With the lack of water and air on the Moon, this metal has not rusted into iron oxide. Small grains of free iron exist in lunar soil. Free iron averages about half of one percent of average lunar soil. The grain sizes are generally less than a few tenths of a millimeter. (For the curious, there is also a trace of free iron from solar wind hydrogen atoms stealing the oxygen from iron oxide. This kind of free iron is microscopic.) The free iron metal is extractable by simple magnets after grinding. This produces a supply of iron powder. This powder can be easily handled to make parts using a standard technique on Earth called “powder metallurgy”. On Earth, the metal handled this way must be powderized, whereas on the Moon and with many asteroids it's already powder. Free iron metal from the Moon probably could not compete well with asteroid-derived iron due to the abundance and cheapness of asteroidal iron. However, it would be valuable for use on the Moon's surface. The free iron metal is naturally alloyed with nickel and cobalt.

2.8.5 Lunar Polar Volatiles

In 1998, the Lunar Prospector (LP) probe discovered hydrogen at the lunar poles in large quantities and high concentrations, presumably in the form of water ice, located in craters that are permanently shadowed from the sun and extremely cold. Existence of carbon and other volatiles is unknown, as LP sensors are designed to detect hydrogen. Volatiles will be useful for rocket fuel propellant, industry, and life support. The challenge will be mining this extremely cold material, at -220 Celsius / -370 Fahrenheit / 50 Kelvin.

2.8.6 Origins of Lunar Ices

Craters exist at the lunar poles which are never sunlit in their interior. This is because the Moon's axis of rotation is nearly the same as its orbit around the sun – 1.6 degrees – so that the Moon doesn't have “seasons”. The insides of these craters are extremely cold, at roughly -220 Centigrade (50 K), or -370 Fahrenheit. Over the eons, comets and asteroids rich in volatiles such as water, hydrogen, carbon and nitrogen have bombarded the Moon. Each impact resulted in vaporization of these volatiles and a temporary, extremely thin gas around the Moon. Some of this gas would have impinged on these polar craters, which served as “cold traps”. The amount of vapor captured per impact is small, but it has added up over the eons and countless comet and asteroid impacts.

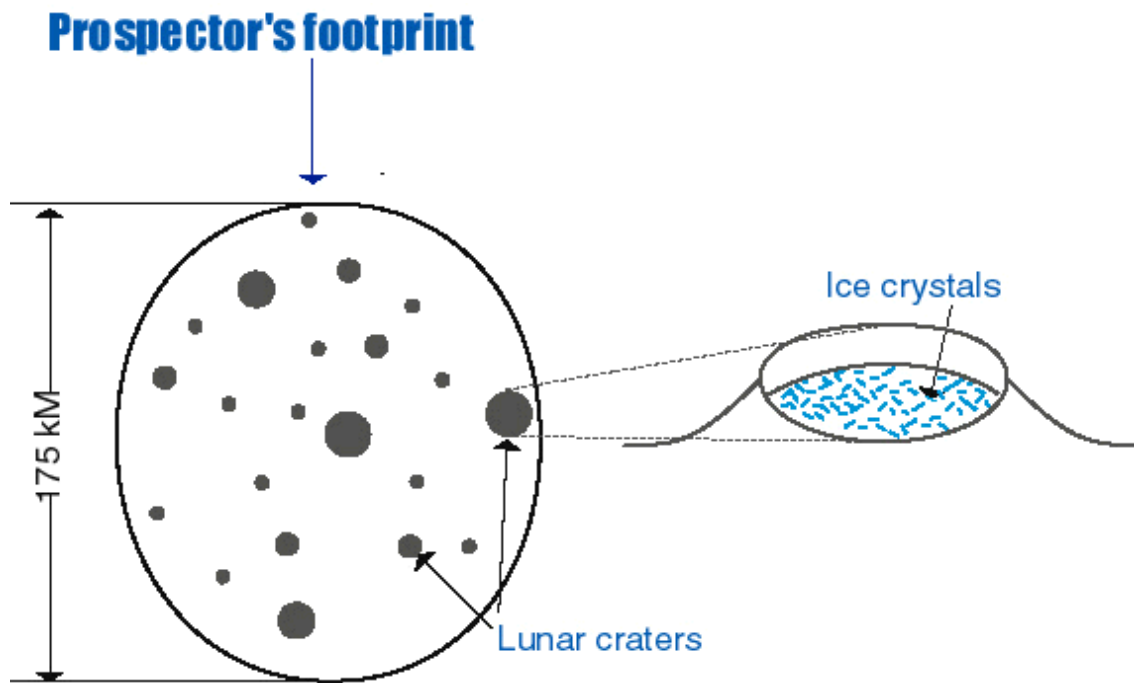


Figure 3:

2.8.7 History of Discovery

The US Department of Defense's probe Clementine, funded by the Strategic Defense Initiative Organization (SDIO, aka "Star Wars") in conjunction with NASA, sent a probe into a lunar polar orbit in 1994 to map the Moon before heading off for an asteroid near Earth. Data from Clementine's radar indicated the existence of concentrations of water ice at the lunar south pole, though other interpretations were possible albeit less likely. (Mission cost was \$75 million, with multiple other purposes as well.) In response, NASA funded the Lunar Prospector spacecraft, based on a preliminary design due to SSI's previous private sector support, and built by Lockheed Martin Astronautics in Denver, Colorado. Data from Lunar Prospector confirmed the existence of hydrogen and gave a vastly better measurement, using a neutron spectrometer. The hydrogen is inferred to be in the form of water ice. (Total mission cost: 63 million dollars.)

2.8.8 Quantities and Concentrations of Lunar Ices

Hydrogen exists in craters at both the north and south poles. Total ice at the north pole totals about 50% more than ice at the south pole. The sensor on Lunar Prospector can detect water up to a depth of 0.5 meters, so that's what the data reports on. It's possible that there's more water, since the lunar surface has been covered with layers of crater ejecta to an average depth of 2 meters, though the depth varies by location. Practically all the water ice is thought to come from comet and asteroid impacts. There's little mention of hydrocarbons in the NASA analyses released to the public, as the equipment was not designed to measure carbon abundance or certain other volatiles. The location of the ice has not yet been pinpointed. This is because the LP spacecraft's sensors have a wide field of view, or "footprint" – roughly 150 kilometers by 175 kilometers. At any good viewing time, there are several permanently shadowed craters in the sensor's field of view, as illustrated in the first figure following. The second figure shows the footprint of the prospector against a real image of the lunar poles and their larger craters.

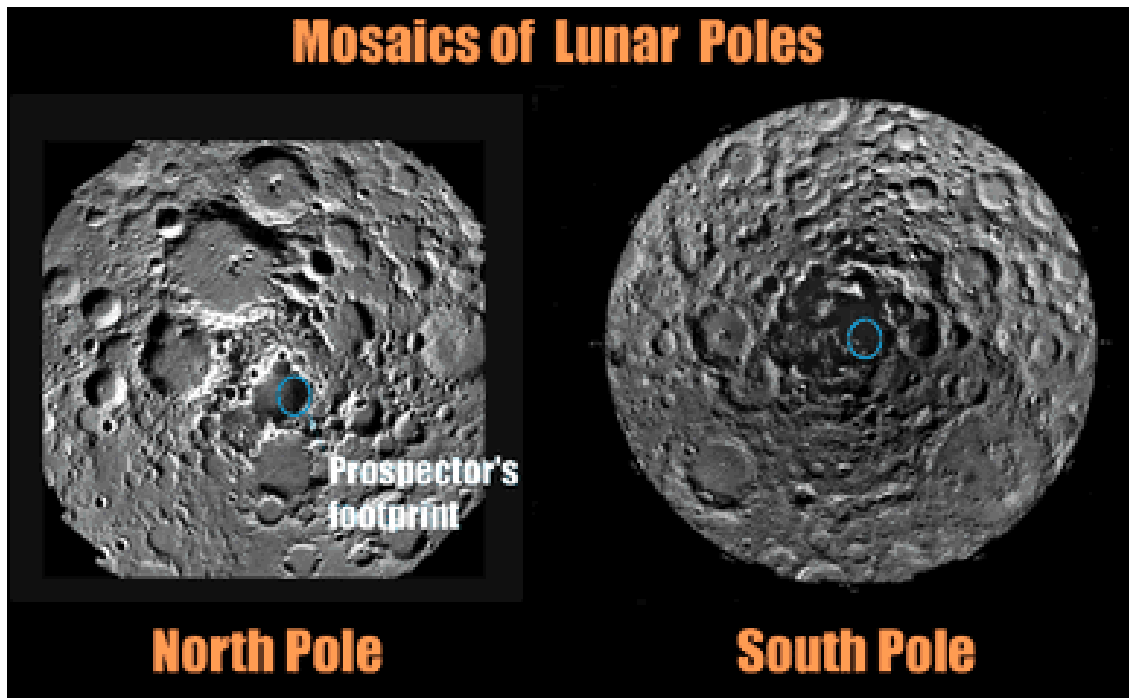


Figure 4: Source: NASA.

The initial estimates of water ice in March, 1998, were awesomely high. However, upon further collection and analysis of data, these estimates were dramatically increased by a factor of about 10 times by the time the next major report was published in September, 1998. It was initially thought that the hydrogen exists in the form of small crystals of water ice in concentrations of 0.3% to 1%, dispersed over a large surface area of 5,000 to 20,000 square kilometers at the south pole and 10,000 to 50,000 square kilometers at the north pole. However, as of the time of this writing in December 1998, the most recent data, analysis and predominating theory suggests a total of six billion metric tons of water are concentrated in a small number of lunar polar craters. As explained by Dr. Alan Binder, the Lunar Prospector principal investigator, “if the main source is cometary impacts, as most scientists believe, our expectation is that we have areas at both poles with layers of near-pure water ice” in the form of “discrete, confined, near-pure water ice deposits buried beneath as much as 18 inches (40 centimeters) of dry regolith”, which is around the 50 centimeter maximum depth that Lunar Prospector can detect water.

2.8.9 Mining Challenges

The main challenge in recovering these volatiles is handling the extremely cold material, at -220 Celsius / -370 Fahrenheit / 50 Kelvin. We’ve never mined anything near that temperature. Thus, a valid question is “What’s the scoop?” To successfully scoop up material without breaking our machinery, we would probably warm the surface material to be mined, *e.g.*, using microwaves or infra-red heaters in front of the mining equipment and scraping up the warmed surface. We would mine the material slowly, limited by the heat transfer properties of the material. The vehicle and any appendages would also need to be warmed. Another option is to put a hood over an area and heat the material underneath, bringing in the water as vapor through pipes and into tanks. On the plus side is the likely prospect that some places on the rims of polar craters may be permanently sunlit. If so, they could provide continuous solar power. This is one geographical issue that has yet to be resolved at the time of this writing. The south pole has bigger, permanently shadowed depressions. The north pole has a larger number and more interspersed permanently shadowed areas, which may give more choices of places to mine, *e.g.*, near a crater rim that is always sunlit to produce electrical power. However, the exact layout in detail has yet to be determined. More information on the Lunar Prospector discovery of water ice can be found here at the NASA Ames Research Center.

2.8.10 For Other Minerals

The main minerals on the Moon are “plagioclase” minerals (aluminum silicates of which anorthite – calcium aluminum silicate – is the most common plagioclase mineral), “olivine” (predominantly magnesium and iron silicates – Mg_2SiO_4 and Fe_2SiO_4), ilmenite (discussed above, $FeTiO_3$), and pyroxenes ($MgSiO_3$, $CaSiO_3$, $FeSiO_3$). However, there are many other minerals and glasses mixed in. Covering lunar geology in detail is beyond the scope of this website.

2.9 Powdery Texture (Helps in Mining and Processing)

One of the benefits of dealing with lunar material is that it’s powdery on the surface. Indeed, the astronauts compared it to ash. Look at how fine the imprints of their sunken footprints are. The reason for this is the lack of any shielding atmosphere, which has allowed meteorites, micrometeorites and solar and cosmic radiation to bombard the surface over the eons, pulverizing it into powder. Typically, the thickness of the powder is 2 to 10 meters in the lowlands, and 100s to 1000s of meters (kilometers) in the highlands, the highlands consisting of piles of crater ejecta. Since the surface of the Moon has been unchanged by any geologic activity for 3+ billion years, we see the accumulated effects of 3+ billion years of meteorite bombardment and pulverization. As a NASA report summarizes: “The fragmented material consists of as much as 25% by weight under 20 micrometers in diameter [*i.e.*, one fiftieth of a millimeter!], and more than 70% under 150 micrometers in size [*i.e.*, one seventh of a millimeter]. Approximately 90% by weight of the lunar soil consists of particles under 1 millimeter in size.” It’s more powdery in some places than in others. The material properties of lunar soil are discussed further in the section on mining.

3 Mining the Surface

The fine, powdery material that makes up the lunar surface is most commonly called “regolith” in the scientific and engineering literature, so that tradition will be followed here. The earliest studies had conventional equipment strip mine the moon’s surface, *e.g.*, “front loader” vehicles to scoop up the regolith and drop it into “haulers” which would bring it back to the materials processing site. In these scenarios, the vehicles would be launched from Earth and need to be assembled after landing on the lunar surface. The haulers would not be as structurally massive as Earth haulers due to the Moon’s one-sixth gravity. However, the loaders would be nearly the same, since they need a counterweight when scooping up regolith. Simple counterweights would be produced from lunar materials, not launched from Earth. Application of terrestrial mining experience and technology to the lunar environment, with emphasis on teleoperated and automated systems, is covered in a U.S. government (public domain) paper presented at the 1993 AIAA/SSI conference by E.R. Podnieks (Senior Staff Scientist) and J.A. Siekmeier (Civil Engineer, Twin Cities Research Center) of the U.S. Bureau of Mines, entitled Terrestrial Mining Technology Applied to Lunar Mining (paper reference). A significantly improvement may be to replace the front end loaders with a simple bucket-and-reel system, called a “flail” or “slusher”, as shown below, as put forward by mining engineer Robert Gertsch (ref. 3). It pulls the dirt up a ramp and into the hauler.

Since the surface material is powdery, a flail may handle the job of collecting bulk lunar material. The above are methods used on Earth and adapted to the Moon. Other methods have been proposed which have no precedent on Earth, but they may be considered too new and unproven to be considered by a private venture in the near term. For most of the Moon, the top few meters of the lunar surface consists of a mix of minerals, whereas lower depths probably offer more uniform mineralogy from the old magma oceans. The mix on the surface is due to all the splashes of asteroid impacts which has mixed materials from distances. Also, the surface is glassier due to the superheated nature of the asteroid ejecta and the subsequent quick cooling.

Many proposed methods for materials processing call for processing just one particular mineral, *e.g.*, ilmenite. This would require either separating the desired mineral from the regolith mix, or mining underneath the



Figure 5: NASA artwork by L. Ortiz showing Richard Geitsch's slushr mining system.

surface where the mineral may be found in a fairly uniform state. Which mining method is used, and which mining site exploited, depends upon which products are desired, the processing methods employed, and the amount of investment that financiers are willing to put forth.

3.1 Various Issues in Lunar Mining

The Apollo missions were surprised by the difficulty of extracting subsurface samples. While the top was powdery and soft, attempts to drill into the surface and extract subsurface material resulted in seizing of drill tubes which could not be removed and had to be abandoned. It is now thought that underneath the very top layers, lunar soil is actually more dense than equivalent Earth soils at the same depth. Due to small, repeated vibrations by distant meteor impacts over the eons, the soil particles have settled down by shifting relative to each other into ever more dense geometrical orientations. Thus, it is now recommended that any experiments in mining lunar simulants first settle the material by vibration, not by compressing the material. Indeed, it's been found that compression is not nearly as effective as vibration (within nondestructive compression pressures). (Asteroids are probably the opposite - they don't have the strong gravity to cause settling, and in fact meteor impacts may serve to make asteroids fluffier.)

Another issue is rubbing friction in vacuum. The U.S. Bureau of Mines found that exposing lunar simulant to vacuum long enough for nearly complete outgassing caused increased friction between the tool and lunar simulant – from 1.5 to 60 times more friction! On the lunar surface, it will probably be even higher due to incompletely oxidized minerals and total absence of moisture. Tools should be made from (or coated with) materials which will minimize friction, and experiments should be performed on simulants that have been sitting in vacuum. (This applies to asteroids as well.)

On the Moon, temperatures vary from approximately -170°C (-275°F) at night (due largely to the long, two week lunar night) to around 140°C (280°F) in the day. Significant differences in temperature occur between shadows and sunlit areas. Either surface mining equipment must be designed to operate in high temperatures, or a partial sunscreen should be put over the mine, possibly complimented with foil mirrors to eliminate shadows. Various schemes may be employed to regulate the temperature of areas being mined. At night, surface mining equipment will need to be sheltered, *e.g.*, a tunneled garage or a canopy with heaters. (The temperature extremes are much less with asteroids, which typically rotate roughly four times a day though rotation period can vary over a wide range from asteroid to asteroid.)

Gravity on the Moon is one sixth that on Earth, and the mining and processing equipment must be designed accordingly. This does not pose a major challenge, but like working in vacuum with electricity instead of petrol,

the Moon will require design of new equipment, even if it's based on Earth mining conventions. (For asteroids, the mining processes need to be radically different from most mining processes on Earth.) One of the best sources of expertise on lunar mining can be found at: The Center for Space Mining Colorado School of Mines Golden, Colorado 80401

4 Lunar Bases

The objective of the early lunar base is to get material into orbit so that products and services can be sold to support space development. Some studies have the lunar base making components on the surface of the Moon and blasting them up. However, it may be better to send a minimal lunar base to collect semi-processed minerals, and to locate most of the processing industry in orbital space. There are advantages to industry located in orbit – continuous solar energy with no nights for power and thermal energy, huge solar ovens, gravities from zero to whatever a centrifuge will provide, saving the costs of landing and deploying processing equipment on the Moon's surface, and the capability to use the same industry in orbit for processing both asteroidal and lunar material. It seems that beneficiation (discussed in the industrial section) will produce material of high enough quality to launch into orbit. In the early years, waste is generally usable for things ranging from radiation shielding to melt-cast bulk "lunarcrete" walls and light duty structural elements and outfittings. It's likely that we will adopt space-based industrial processes which will be able to convert almost all of the lunar minerals delivered into very useful final products without much waste.

Surface manufacturing capabilities for the purpose of building up the lunar base using local materials would be quite worthwhile, *e.g.*, for making steel and glass-ceramic structural items. A mobile solar reflector oven could make the landing/launch pad, road surfaces, dome roofs, etc. Most of the base, in terms of weight, will be produced on-site from local materials, not blasted up from Earth. The lunar base will need a landing/launch pad, a power plant (perhaps a solar cell array for daytime "peak" energy and a small nuclear power plant for nighttime), base construction equipment, a spare parts and maintenance garage, a central control and communications center, housing for the people on-site, and life support systems. Of course, it will also need the mining and beneficiation equipment discussed in other sections. The mining equipment (flail and haulers) and a solar oven would be used in building the initial lunar base before being employed for supplying material for industry in orbital space.

5 Other's web pages on Lunar Materials and Utilization

The following links either don't fit in elsewhere in the lunar section or are particularly noteworthy for their broadbased information.

- One of the best and most reliable sources of current information on lunar development is the Lunar Enterprise Daily, an electronic newsletter from Space Age Publishing, which has been putting out news reliably back into the 1980s (when it was a nice paper newsletter in the mail). Over time, they've compiled a Lunar Enterprise Directory of organizations and individuals which is instantly accessible on the web. With that kind of service comes a significant price for an individual, though it should be standard fare for an organization. For more information, see www.spaceagepub.com
- Artemis Society International and the Lunar Resources Company are two important and closely related private sector operations which are discussed in section 8 on Mission Scenarios.
- The International Lunar Exploration Working Group (ILEWG) was founded in 1995 at a meeting in Europe, and seemingly developed mainly in European settings. It's supported with government money, and is heavily established for international cooperation between governments. The ILEWG home page is sponsored by the Mission from Planet Earth Study Office at NASA Headquarters, Washington DC, and is maintained by researchers at the Johnson Space Center in Houston, Texas, now contracting with USRA (Universities Space Research Association) for web curatorial support, but European activity has been rising. Strengths include the Lunar Explorers Register, the sponsored ICEUM conferences (Int'l Conference

on Exploration and Utilization of the Moon) and LUNEX (the Lunar Explorer's Society). One weakness is that the information is a bit dated now. If the government money stops flowing, would it continue?

- The Lunar and Planetary Institute (LPI) runs an excellent website which includes lunar base and space resources related materials, among a bunch of other planetary stuff. Of particular interest within this site are the excellent lunar base documents prepared by NASA and contractor employees at the NASA Johnson Space Center, several issues of the Beyond LEO Newsletter, and the Lunar Explorer's Digest reviews of books on the moon.
- The Lunar Base Quarterly is a well done resource which, if you go through the text, reveals good supplementary coverage of current activity, progress and prospects in the international arena. It's a good, active site whereby one can get involved and contribute to their process, which includes their "Lunar Database" concepts. You'll at least want to revisit them for their substantive quarterly newsletters. The emphasis is on government sponsorship around the turn of the century, with little on purely commercial initiatives, however. The materials are compiled and produced by Dr. H. H. Koelle, Technical University of Berlin, Chairman of the Subcommittee on Lunar Development of the International Academy of Astronautics, and longtime participant and enthusiast for lunar materials utilization. Dr. Koelle has edited an interesting paper from the International Academy of Astronautics entitled Prospects and Blueprints for Future Lunar Development with an emphasis on government funding. See also his 100 kilobyte report entitled The Lunar Laboratory, another 100K report analyzing a lunar settlement, and a 60K report on an Earth heavy launch vehicle and lunar landing, launch and interorbital vehicles. All are impressive. For all this and more from this energetic 72-year-old veteran, keep in touch with the home page of Professor Heinz-Hermann Koelle, which is also where you can FTP his main documents.
- A current proposal within NASA, Icebreaker One, to fund a surface lander mission to the lunar pole to verify ice at the pole, as a follow-up mission to Clementine and the Lunar Prospector.
- The Lunar Rover Initiative is a joint venture between Carnegie-Mellon University (CMU) and LunaCorp of Arlington, Virginia, to develop and land two entertainment robots on the Moon by year 2000, which would return live video for audiences of theme parks, TV networks and educational media, as well as allow people to teleoperate the exploring vehicle. LunaCorp has, among other books on outer space, authored and published Return to the Moon, which has sold more than 22,000 copies to date, and authored and published Mission: Planet Earth
- An excellent article, "Using Space Resources", by Dr. Thomas A. Sullivan and Dr. David S. McKay, NASA Johnson Space Center, New Initiatives Office, Planet Surface System Office, and Solar System Exploration Division, Mission Science and Technology Office.
- The Space Studies Institute has many research reports on elements of lunar materials utilization which would be useful for a private sector initiative. SSI belongs at the top of any list of established and quality organizations to contact for a private sector venture, having a breadth of active research members in industry and government, and has led much of the research in this field as a private organization for more than 20 years.
- The NASA National Space Science Data Center (NSSDC) makes available on the internet data from NASA (e.g., Apollo samples, Lunar Prospector, others), U.S. Defense Department (Clementine) and Soviet missions to the Moon. Their Moon pages start at <http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html>
- For images and good pictures of the Apollo missions, go to the NASA Johnson Space Center Public Affairs Office's Apollo Pages