Chapter 8: Materials for Exploration Systems

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8.1 Introduction

Progress has been made on materials to construct spacecraft and aerospace structures for rocket launches from Earth for exploration missions. These materials have enabled the development of a substantial satellite industry and the space probes beyond Earth orbit. However once we leave the sphere of influence of Earth or attempt to construct objects in space more massive than a space station, Earth based materials and processes become less important than space based materials and processes. The reason is simply that the Earth is physically a large planet with a large associated gravity relative to the propulsion energy that can be attained from oxidation of chemical fuels. Thus although the technology of the chemical rocket engine has reached maturity (the Space Shuttle Main Engine was the most efficient engine ever built and the Space Shuttle utilized reusable technology) the costs of space launch in the last 30 years has not decreased appreciably [1].

If we are to pursue the ambitious development of Earth-Moon space for space solar power, permanently occupy the Moon and send humans to Mars, then the basic laws of physics and economics dictate that we develop and use materials and processes in space to the exclusion, as much as possible, of Earth launch and resupply.

Since the costs of space infrastructure for a single mission to extract and process in-situ materials can be prohibitive, the temptation is to continue to design single missions based on the Apollo model of "planting a flag and foot prints," doing a survey, collecting samples and returning to Earth. However, this model has prohibitive recurring costs because it creates no in space infrastructure and has proved not to be sustainable even for human exploration. For the more ambitious (and arguably more important) goals of creating a space solar power industry and the human settlement of space, the Earth launch model does not scale up effectively [2] to enable a substantial program. Lunar and asteroid materials must be utilized.

Similar to our experience with industry on Earth, one must first invest in the mining and manufacturing infrastructure in space to attain a sustainable program of human exploration and development, and eventual human habitation of space. Analysis has shown [3] that for the large scale economic development of space three things are necessary. We must manufacture in space, we must use in-situ space resources, and we must have a work force that is living in space.

8.2 Development of a Technical Basis for Materials Processing in Space

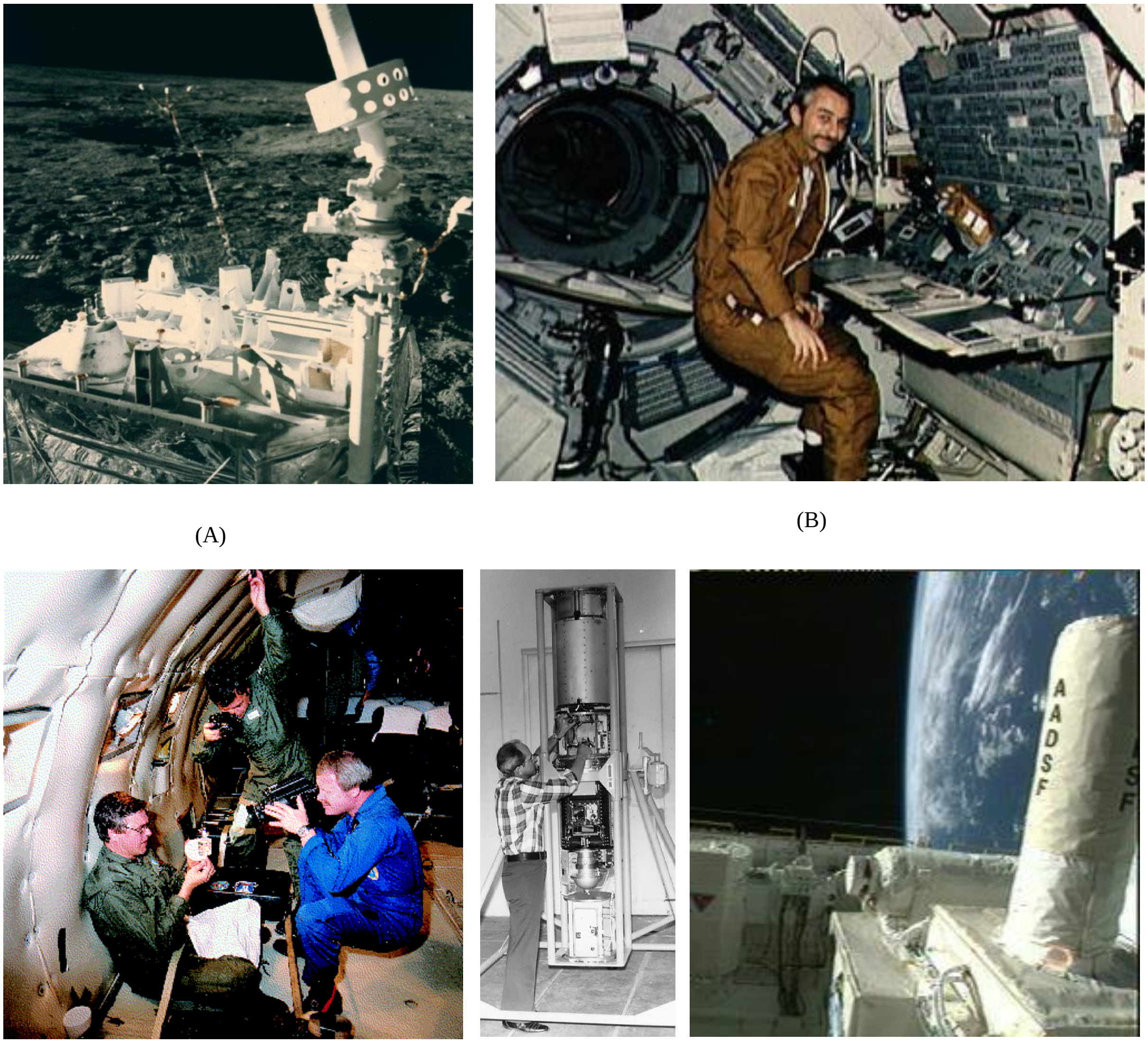
Much of the materials processing technology developed for use on Earth is applicable to material processing in space, but there are fundamental differences that the materials community must address. Chief among these differences is the difference in gravity which can have profound effects on materials processes and the resulting materials properties [4]. A fundamental scientific basis has been developed over the last 40 years by the low gravity materials science experiments on free fall platforms near Earth and on various space craft and laboratories in Earth orbit [5].

8.2.1 Materials Science and Processing in Space

The science of materials processing in microgravity provides a technical basis for the use of space resources for the exploration and development of space [6]. The Apollo flights to the moon and their robotic precursors emphasized the study of lunar geology, Figure 8.1 (A). Sample returns from lunar human and robotic missions have enabled extensive study [7] of lunar mineralogy. The near elimination of gravity during the flights to the moon enabled carry on experiments to study important materials processing phenomena such as surface driven convection. It was realized that the freefall conditions in low Earth orbit enabled, for the first time, materials science experiment in continuous microgravity. After the human lunar flights, excess hardware was utilized to loft the first large space station, Skylab, Figure 8.1 (B). Extensive materials science and processing experiments were performed during the months of human Skylab operations. The Skylab experiments included the microgravity solidification of metals and semiconductors. These experiments included the first results [8] showing that solidification in microgravity could reduce defect formation in semiconductor crystals. After Skylab research in microgravity solidification continued, first using free fall drop towers and parabolic aircraft flights, Figure 8.1 (C, D) and with the advent of the Space Shuttle and Spacelab experiments using both pressurized [9] and telescience manned orbital laboratories [10] in the Space Shuttle cargo bay, Figure 8.1 (E). Results from this materials science and processing in space studies were a main justification for the building and utilization of the International Space Station laboratories in which this science continues.

Since early 2000s, NASA has reemphasized plans to send humans again beyond Earth orbit to the moon, asteroids and Mars. Thus, in addition to the study of microgravity materials processing in ISS, the study of processing of lunar, Mars and asteroid resources to enable human exploration is also emphasized. Thus, there is a renewed interest in lunar, Mars and asteroid mineralogy, not only for astro geology but also for understanding their potential for in-situ processing to enable human presence and economic growth in space.

Studies of the moon have found [7] that the lunar geology differs significantly from Earth. The difference includes the relative abundance of elements. For example, relative to the Earth's surface, the abundance of hydrogen, carbon and nitrogen are scarce on the lunar surface. Although it is believed that the original source of the lunar materials was from the Earth's crust, the lack of atmosphere on the moon has changed this composition, for example to enable iron to exist in the reduced elemental state. This must be considered for example, when designing extractive metallurgical processes [11] for lunar materials. Extensive studies of solidification and processing in low gravity [4] have shown that the elimination of gravity induced convection and sedimentation can significantly affect microstructure and resulting materials properties. Orbital laboratories have enabled materials processes to be studied under long duration microgravity conditions; however, materials processes under the partial gravities of the moon (0.167g) or Mars (0.369g) have only been studied for durations of 10s of seconds during aircraft parabolic flights. Many phenomena, for example reaching a diffusion controlled steady state during metal alloy solidification, require minutes or hours duration in reduced gravity. Another aspect important to materials selection in reduced gravity is the hierarchy of materials in terms of specific mechanical properties [12], which is discussed next.



(A) (B)

(C) (D) (E)

Figure 8.1 (A) Apollo Lunar Dust Experiment, (B) Skylab Orbital Laboratory, (C) Low-Gravity Experiments during Parabolic Aircraft Flight, (D) Sounding Rocket Payload, (E) USMP Spacelab Furnace in Shuttle Cargo Bay (Courtesy NASA)

8.2.2 Important Considerations for using Non Terrestrial Materials

The discussion of "hierarchy of materials" in the context of non terrestrial materials presented in the next sections was first presented by Stefanescu, Grugel, and Curreri [12]. Materials processing in low gravity, however, can differ quite significantly from the same processes on Earth. The absence of buoyancy driven flow, for example, changes the solidification processes that are fundamental to most manufactured goods. In space, solidification can yield lower defects and more homogeneous crystals which could yield better semiconductors for computer chips, or conversely could increase the grain size and change phase composition of metal alloys which could yield poorer mechanical properties. Thus, just as terrestrial materials science has been essential for technological advance on Earth, it is expected that materials science in low gravity will enable cheaper, more robust, methods for manufacturing and hence extended human presence beyond Earth orbit. In this section the use of in-situ resources to produce metal alloys for use on Moon or Mars bases is discussed. The particular focus is candidate metallurgical extractive processes, new hierarchy of materials specific properties, and the effects of reduced gravity on microstructure and materials properties.

8.2.3 Hierarchy of Materials

Utilization of materials for specific applications is based on their mechanical properties. An example of such a hierarchy is given in Figure 8.2, where tensile strength is used as the main criterion. ADI is austempered ductile iron. Based on this criterion the best material is low-alloy steel and the poorest is magnesium. Other criteria such as yield strength, elasticity modulus, elongation or combinations of these can be also selected. This kind of hierararachization is acceptable when the weight of the part is not an issue. However, if weight becomes an issue as in aerospace applications, or even in today automotive applications, other criteria that take density or weight into account may be used (Table 8.1). Such a criterion may be the ratio tensile strength/density (specific strength), or maximum load/unit weight. The latter is preferable for this analysis since it includes the role of gravitational acceleration. Furthermore, it is nondimensional. The order will be changed, with titanium becoming the best and gray iron the least desirable material (Figure 8.3). Magnesium becomes more competitive.

The planetary bodies of interest for this discussion have significantly different gravitational accelerations than the planet Earth. The gravity level on the Moon is 0.167 g while on Mars it is 0.369 g. Because of the change in the g level, the numbers will change again. However, changing the g level alone will not alter the hierarchy, but only modify the numbers by a factor proportional with the gravitational acceleration.

Table 8.1 Quality criteria used to establish hierarchy of materials

Quality Criterion	Symbol	Units
tensile strength	TS	MPa
tensile strength/density	TS/ρ	m^2/s^2
load/unit weight #	$TS/(\rho \cdot g)$	-
cost/load/unit weight	$\$/(TS/\rho \cdot g)$	$

for unit length

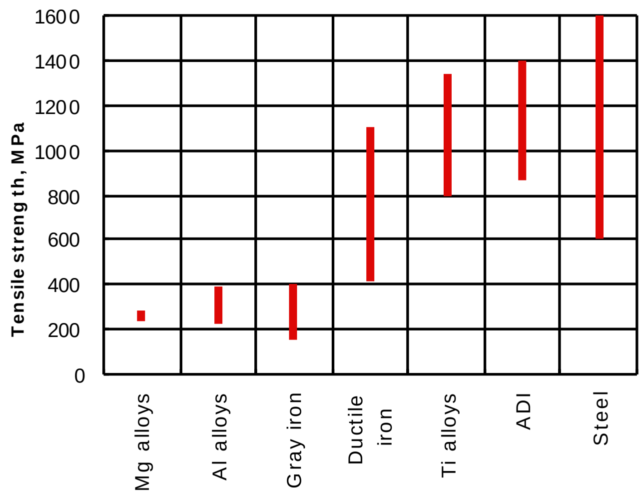


Figure 8.2 Hierarchy of materials based on tensile strength.

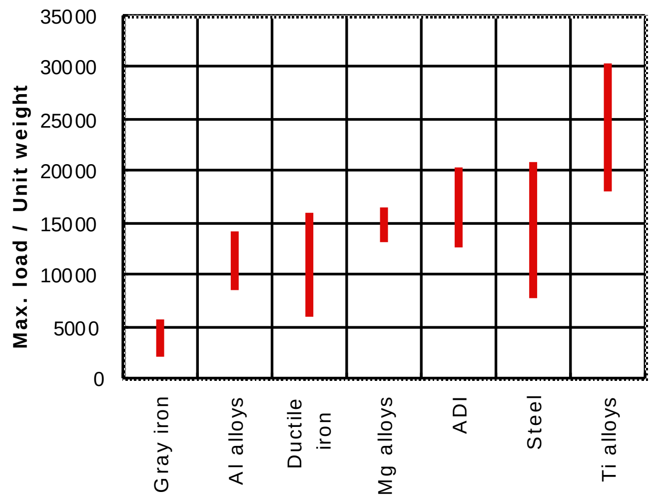


Figure 8.3 Hierarchy of materials based on maximum load/unit weight.

Further significant change in hierarchy will be brought about if cost is included in the criterion used. As illustrated in Figure 8.4, where the cost was assumed to be the processing cost on Earth, titanium becomes the least desirable. Since weight is included in the evaluation criterion the gravity level will affect the numbers. While, as indicated before, the hierarchy will not be altered, the difference between the various materials will change as a function of gravity level, as shown in Figure 8.5. A clear compression of materials properties is shown as the gravity level decreases. What this means is that on the moon, the decision to select one material over another may be based mostly on the availability of the material, since the differences on the cost/load/unit weight criterion are minimal. However, processing costs may be widely different than those on Earth, an issue that will be addressed in the next section.

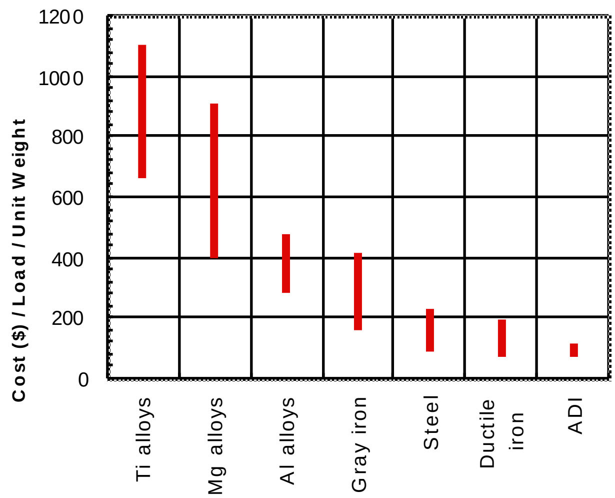


Figure 8.4 Hierarchy of materials based on cost/load/unit weight

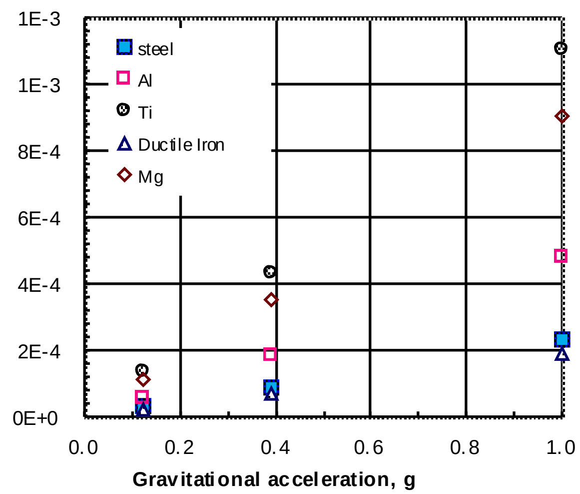


Figure 8.5 Influence of gravity level on the cost/load/unit weight criterion.

8.2.4 Materials Availability and Extraction

Naturally occurring “native” gold, silver, and copper were undoubtedly the first metals utilized by mankind. In a practical sense these elements were malleable and could be plastically deformed. Gold and silver took on ornamental roles, perhaps because of scarcity but more likely due to their inherent softness; copper, on the other hand, work hardened and could be hammered into useful, durable, tools. Unfortunately, most metals prefer to be combined with other elements such as oxygen, sulfur, or chlorine and are thus designated as ores. Subsequently, our prehistoric ancestors discovered smelting, the process by which an ore could be reduced in a wood fire to its base metal. This technically innovative process provided them with lower melting point metals such as lead, tin, and zinc; combining the latter two ores with copper and/or copper ore produced bronze and brass, alloys with improved properties. The bronze age succumbed to the iron age which then shaped civilization, set the stage for the Industrial Revolution, and arguably continues to this day.

Relatively tiny amounts of native iron were either formed under unusual conditions [13] or in some meteorites [14]. Iron, however, prefers to be combined with oxygen and its ores, e.g., hematite (Fe_2O_3) and magnetite (Fe_3O_4). These ores are well represented, although not uniformly distributed, in the Earth's crust. While the high temperatures required to reduce these ores precluded early man from producing pure metal, a spongy mass consisting of iron and slag was formed that could be hot-worked to useful shapes. The blast furnace eventually evolved in which the combination of ore, flux (limestone), coke (distilled coal) and air produced a high carbon "pig" iron. Today, in view of economy and properties, iron and its alloys are by far the most utilized metals.

The intent of this briefest introduction to iron production is to convey a sense of its long history and the associated trials and tribulations encountered and overcome in developing the science and technology to what it is today. Similar convoluted developments characterize production of other metals of interest, including aluminum, magnesium and titanium.

Earlier and recent space expeditions have found metal bearing rocks and soils, i.e., resources, on two of our nearest planetary neighbors, the Moon and Mars. A comparison of typical soil analysis [15] for the three celestial bodies of interest is given in Table 8.2.

Table 8.2 Typical soil analysis (wt.%) of celestial bodies of interest

Body	O	Mg	Al	Si	S	Ti	Mn	Fe
Earth	47	2.3	8	27	0.04	0.5	0.1	5.1
Mars	42-45	2-5.5	4.2-6.6	20-26	0.9-2.5	0.4-0.7	0.4-0.7	10-15
Moon	40-45	4.9-6.8	5.8-14	19-22	0.06-0.1	0.3-5.6	0.05-0.2	4-15

According to past surveys, the Moon has soils particularly rich in Al in its Highland regions, and in Ti in its Mare regions. Both the Moon and Mars have significantly higher levels of Fe than Earth. Thus, if the composition of the soil is any indication of the availability of these metals for extractive processes, and based on the analysis of the hierarchy of materials presented above, it might be anticipated that, iron and titanium will play a major role in the material competition to build the structures needed for extension of human civilization to the Moon and Mars.

As the Moon lacks an atmosphere its surface is subjected to exposure by hydrogen carried in the solar wind. This hydrogen reduces iron oxide (FeO) in the soil to fine iron particles [16] and, should sufficient quantities exist, would be an ideal source for raw material. Iron containing ilmenite ($FeTiO_3$) is also found in the lunar soil [17] but must be reduced, albeit by "non-traditional" methods. Some early suggestions follow terrestrial methods. Fe_2O_3 is a reaction product when ilmenite is subjected to molten sodium hydroxide [18], and iron can eventually be obtained through a carbochlorination process [19]. Silicon will reduce FeO to iron at 1300°C. Hydrofluoric acid can be used as a leaching agent after which iron can be recovered by electrowinning [20]. Other approaches attempt to utilize the unique environment of space for materials extraction. It has been suggested that the sun's energy could be focused to reduce Moon ores through vaporization [21]. More recent NASA sponsored research [22] has focused on lunar oxygen extraction for life support and propellant where metals and silicon might be a byproduct. The primary methods considered are hydrogen reduction and carbothermal reduction, and molten oxide electrolysis, the latter of which has been demonstrated in the laboratory as a viable candidate for extraction of metals and silicon from lunar regolith [23, 24]. Molten oxide electrolysis of lunar regolith has the advantage of being applicable to the known regolith compositions (ore independent) and not requiring the transportation of reagents from Earth. Some disadvantages of molten oxide electrolysis are high operating temperatures (1500 °C and higher) and development of suitable non reacting electrodes. Dissolution and electrowinning of lunar, Mars, and asteroid materials can be achieved with suitable Ionic Liquid electrolytes at near ambient temperatures [25]. The disadvantage is that the ionic liquids may have to be transported from Earth and must be reconstituted for continuous reuse.

The existence of iron ore on the surface of Mars was confirmed by results from the alpha proton X-ray spectrometer within the Pathfinder rover. The Mars soil was determined to consist of 17.5 wt. % FeO and a given rock ("Barnacle Bill") contained 12.7 wt. %. The ready presence of this ore provides a processing advantage over processes that require ore beneficiation such as ilmenite reduction in the moon's stark environment. Furthermore, the carbon dioxide rich atmosphere of Mars provides a very important resource. In combination with hydrogen (which depending on the location may or may not have to be imported) several well known and well characterized reactions can be implemented [26]. Now, using well established technologies, carbon monoxide, water, and methane (CH_4) can be produced and collected. Carbon monoxide (CO) will reduce (solid) FeO at a temperature below 800°C. Thus, the atmosphere of Mars not only provides a basis for life support and fuel production but could well facilitate iron production.

Obviously there will be considerable technical and financial challenges before iron, steel, titanium, etc. components are produced on extraterrestrial bodies. However, this goal appears to be entirely attainable.

8.2.5 Solidification Processing

The main characteristics of the lunar and Martian environment that will impact on processing techniques are lower atmospheric pressure and lower gravity. It is difficult to anticipate at this time how the price structure of the materials of interest will be altered during processing on Moon or Mars. However, it is clear that significant changes are expected in the behavior of liquid metals during processing. This in turn will affect the cost of processing. Some of issues that must be addressed include melting and casting techniques.

8.2.5.1 Melting Techniques

Melt processing of metals on Earth can be done in ambient air environment, under inert gases or in vacuum depending on the reactivity of the molten metal. On both the Moon and Mars the atmosphere is extremely poor in oxygen, and thus it is anticipated that the price of melting of reactive alloys will be much closer to that of non-reactive ones. This will certainly benefit titanium and magnesium and further contribute to the compression of the specific properties data in Figure 8.5.

Melt containment is another relevant issue for reactive metals since they tend to react with most ceramics used in classic processes. Recent progress in magnetic containment melting (MCM) will find a much favorable environment on Moon and Mars. The reduced gravitational acceleration will impose significantly lower requirements on the size of the coils and the energy consumption. In particular a combination of cold-wall induction melting and MCM (Figure 8.6) may prove to be the method of choice for melting titanium and its intermetallics.

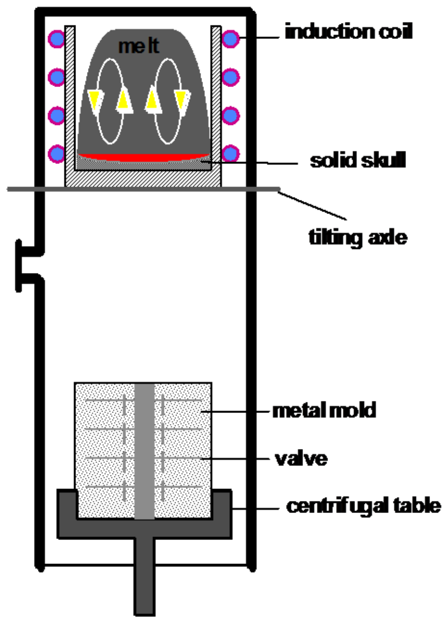


Figure 8.6 Cold-wall magnetic containment melting

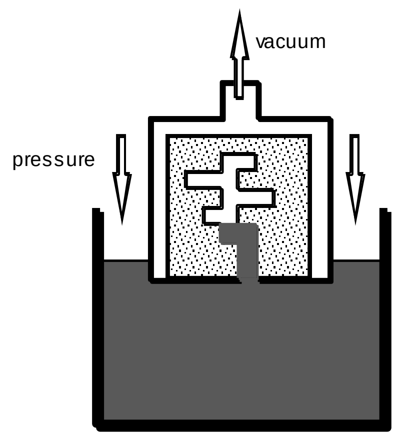


Figure 8.7 Principle of counter-gravity casting

8.2.5.2 Casting Techniques

Most casting processes on Earth rely on gravity to help fill the mold, hence the name "gravity casting". Gravity also imposes conveniently the position of shrinkage cavities in the upper part of the casting. The absence of gravity or very low gravity levels (μg) are known to create problems for scientist experimenting with solidification in space. Indeed, obtaining sound samples was invariably a problem in Space Shuttle experiments. Some pressurization during solidification may be required to improve casting soundness in the absence of gravity.

Gravity casting has a major disadvantage: metal flow is in the turbulent regime. This results in gas and solid inclusions being incorporated in the casting, which alters the quality of the cast material. To produce premium castings counter-gravity casting is used. In this process the metal is fed into the mold from the bottom by applying pressure on the liquid metal (Figure 8.7). The free vacuum on Moon and Mars will make counter-gravity casting a very competitive process.

8.2.5.3 Material Properties

Gravitational acceleration strongly influences solidification processes through Stokes flow, hydrostatic pressure, and buoyancy driven thermal and solutal convection. Microstructural development and therefore material properties, presently being documented through on-going research in microgravity science and applications, needs to be understood and scaled to the reduced gravity environments. Comparison of solidification data in microgravity on orbital platforms, 10^{-4} *g* on sub-orbital sounding rocket flights, and 10^{-2} *g* on parabolic aircraft trajectories with solidification data taken on Earth have documented gravity dependence in microstructure [4]. Convection has been shown to strongly influence solute redistribution. Continual buoyancy driven mixing of the liquid ahead of the solidification interface (for partition coefficient not equal to 1) in one-gravity causes alloy macrosegregation. In low-*g* a steady state diffusion controlled boundary layer can form resulting in sample solute homogeneity. Eutectic alloy microstructures, for example cast iron, are strongly dependent upon the magnitude of gravity during solidification. Spacings of eutectic fibers, flakes, and lamella, nucleation of graphite grains, spacing of primary dendrites can be quite different from that obtained on the laboratory or foundry on Earth when solidification occurs in low-*g*. Thus handbook values for alloy mechanical and electrical properties compiled in 1-*g* cannot be relied upon for in-situ resource processing on the Moon or Mars.

In summary the Moon and Mars offer rich sources of ores that can be exploited to produce metals for electrical conductors and structural materials. The new hierarchy of materials in terms of specific properties must be considered. Processing methods of choice are influenced by the low pressure atmospheres and lower gravity present on these worlds. The influence of gravity on the microstructures created by solidifying under reduced gravity must be understood and applied before the engineering properties of these in-situ produced materials can be accurately determined.

8.3 Development of an Economic Basis for Materials Processing in Space – In Situ Propellant Production

The costs to land a pound of payload on the lunar surface are about 6 to 10 times higher than the cost of putting a pound of mass into low Earth orbit. This is because for the trip from low Earth orbit to the lunar surface six tons of propellant must be used for each ton of mass landed on the Moon.

Carter estimates [27] that transport from the Earth to the Moon would cost $25,000 per pound in 1984 dollars. This is inflated to about $50,000 in 2010 dollars, which is about twice the cost of gold in 2011.

The benefits of utilization of space resources are many. Some are beyond economic. For example establishment of self-sustaining human habitats beyond Earth are arguably essential for human survival [2]. From the economic point of view development of in-situ products individually and in combination must be analyzed for time to profitability. Since building the first materials processing and production facilities off Earth requires launch and transport out of the Earth's formidable gravity well, the initial costs are large. The payoff can be extraordinary (especially for space solar power satellite production from lunar or asteroid materials) [2]. However since a large investment is required before income, the cost of money can be an important financial lever.

Some products, for example lunar oxygen for propellant, have the potential to substantially lower space operations costs after the production capability is established. Other products, the best example are space collected solar power beamed for use on Earth, have the potential for extraordinary profits. These profits can be utilized to enrich investors or to dramatically accelerate the human settlement of space [28, 2].

There are a number of methods for economic analysis that have been utilized to study the financial feasibility of space resource utilization. To evaluate economic feasibility, often parametric analysis is performed. Simplified yearly costs of the major elements of the process are set up as parameters in an economic model. These models enable the time integrated net present value of the program to be assessed.

8.3.1 Production of Lunar Oxygen for Space Craft Propellant – a Paying Tenant for a Lunar Base

We will now discuss examples of economics analyses to determine the financial validity of space resource utilization for specific cases.

The production of liquid oxygen from lunar materials has received much attention in the aerospace community for several reasons. First oxygen, at about 40% by weight, is the most abundant element in the lunar surface regolith and rocks. Second oxygen in its elemental state has a ready market in that it can be utilized as a primary component (oxidizer) in rocket propellant. Third the processing methods for extracting oxygen from lunar surface materials have an experiential basis in the extractive metallurgical industry on Earth. Most importantly from the economic standpoint, the Moon is strategically located anchoring the Earth-Moon economic sphere and has only 1/6 the gravity burden to space that transportation from Earth has. For these reasons the space resources utilization focus at NASA in the recent decades has been lunar oxygen extraction for life support and propellants.

Economic analysis of a single product, oxygen, for commercial viability is not strictly valid, since for example the presence of in-situ derived electrical power, food production, metals and habitat production will change the economics substantially. To illustrate this we will first examine an economic parametric analysis for lunar oxygen production and delivery to Low Earth Orbit, LEO, and then discuss the sensitivity the analysis would have to other in-situ derived products.

Following Simon's parametric analysis of lunar oxygen production [29], we will consider the annual costs of producing 1000 metric tons of oxygen on the Moon and delivering as much of it as possible to LEO to supply a filling station for use by vehicles traveling from there to high Earth orbit, geocentric orbit and beyond.

A parametric economic model is designed more for flexibility than accuracy and is most useful for comparing relative costs and determining the best path to economic viability. Producing an element, oxygen, is relatively basic and thus allows easily modeled scenarios. The baseline scenario includes a lunar processing facility to manufacture oxygen, liquid oxygen (LO_2) storage, and lunar habitat for workers, the required power system for the plant and habitat, and a transportation system and logistics to support the lunar factory and deliver its product.

The costs are broken down into two categories, Capital Costs and Operations Costs. The capital costs include the development, emplacement, and installation of the lunar facility and transportation infrastructure. This cost is up front and then is amortized over 10 years. Operations costs include all the annual outlays needed to manufacture the 1000 Metric Tons of LO_2 and deliver as much as feasible to LEO.

The operations costs include shipping the lunar oxygen to LEO. Considering the case where our only lunar product is LO_2, if we assume the our fuel is liquid hydrogen (LH_2), then we must account for the costs of shipping one kg of LH_2 from Earth for each 8 kg of LO_2 used as propellant for the orbital transfer vehicle, OTV. Even though the OTV fuel is 80% lunar derived Simon's analysis found that the, 20% LH_2 shipped from Earth will dominate the economics because it must come "up hill" through Earth's steep gravity well.

Simon's analysis assumes that a lunar base is in place. That is, you have some basic infrastructure on the Moon onto which you can add the additional modules and power necessary to produce your product. This is a key assumption that makes oxygen production have the potential for economic viability. This analysis and others [30] indicate that lunar oxygen production, in association with a lunar base, may be commercially viable, if the lunar cost parameters are controlled. It speaks for the wisdom of a national or international effort to establish a lunar base as an anchor for the commercial development of Earth - Moon (cis lunar) space.

With these assumptions, a baseline estimate (2010 dollars) of $6.2 billion capital and $1.8 billion per year operations costs. Assuming that the OTV efficiencies allow 49% of the produced LO_2 to reach LEO and a 10 year amortization of the capital, and the middle range of cost parameter estimates the model estimates that LO_2 could be delivered from the Moon at about 1/3 the price that the Space Shuttle could ship it from Earth. If the worst case cost parameters are assumed then the costs from Earth to the Moon are about the same.

But the model is based on technical and programmatic assumptions. The strength of parametric analysis is that it allows assessment of the uncertainties of the cost estimates and the sensitivity of overall economics to each cost parameter. The result is that principal capital cost driver is the power system that needs to be added to the lunar base infrastructure to operate the oxygen production facility, and the principal operational cost driver is the costs of transporting consumables (particularly LH_2) from the Earth to the Moon. Thus, if low cost power and hydrogen were available commercialization of lunar LO_2 could become compelling.

Let's now extend the parametric analysis to include in-situ co-production of the most sensitive cost drivers of lunar LO_2 production. Lunar polar observations since the Clementine Mission have indicated relatively high concentrations of hydrogen in permanently shaded creators in the lunar Polar Regions. Methods are proposed [23] to produce solar arrays on the Moon from lunar materials that could result in base power 10 times cheaper then solar arrays transported from the Earth. If these were combined with a more self-sufficient lunar base, then the costs of lunar LO_2 to LEO could be well under 10 times less than supply costs from Earth. Thus, each additional space resource developed has a positive multiplier effect on the economic viability of the exploration and development of space.

In 1994 the U.S. Clementine spacecraft orbited the Moon [31] and inspected the Polar Regions for the first time. The space craft beamed radio waves into the Polar Regions which were then examined on Earth. The circular polarization ratio of the return radar was examined and the results indicated the possibility of water ice in the permanently shadowed regions in lunar polar creators.

The possibility of water ice existing in the lunar poles was hypothesized in the 1960 by Harrison Brown. Since the Moon's axis is stable within 1.5 % relative to the sun, permanently shadowed craters exist where water from comet impacts could be stable in a (cold trap) for long periods of time. The planet Mercury has an axis that is similarly stable relative to the sun and the presence of ice in permanently shadowed polar craters have been confirmed by NASA's Messenger mission 2011-2012..

A number of processes may be contributing to the presence of water ice in lunar polar crater cold traps. The possible sources include comets, meteorites, out gassing of the lunar interior, and water formation from the impact of the solar wind protons with the oxygenated lunar minerals. The water could form in the craters or it could migrate by ballistic molecular trajectories across the lunar surface until it is arrested in a permanently shadowed crater near the lunar poles.

The presence of water ice in polar craters was also consistent with neutron spectrometer data from the Lunar Prospector orbiter which also indicated higher hydrogen composition at the lunar poles. However, the first definitive measurement of lunar ice was made by the Lunar Reconnaissance Orbiter (LRO - 2009) and its impactor payload. The experiment included an impactor which utilized the LRO's spent Centaur transfer stage which yielded a 2300 kg kinetic payload that produced on impact 200 times the energy of the previous experiment conducted when the Lunar Prospector was crashed into the lunar polar region at the conclusion of its mission. The shepherding space craft first helped guide the impactor to its target and then measured the contents of the resulting cloud using imaging and spectroscopy at a distance of 5 km from the lunar surface.

NASA's Lunar Reconnaissance Orbiter (2009) included the LCROSS experiment in which two lunar impacts were made in the Cebeus crater near the Moon's South Pole.

The significance of the presence of ice in craters at the lunar poles is twofold. First the energy that would be required to make water on the moon is about 100 times less then water derived from solar wind hydrogen. Second, the presence of nitrogen, carbon, and other light elements from comets that supplements the deficiencies in the equatorial composition that was reported by Apollo missions.

Stone describes [32] a commercial venture; "Shackleton Energy Co." which was formed to try to economically extract water from the lunar pole permanently shadowed craters to provide rocket fuel depots for cis-lunar operations. Water can be provided from the moon to low Earth orbit depots for 1/14 to 1/12th of the fuel needed for Earth launch. He estimates that about $20 billion (2009 dollars) would be necessary to set up mining operations on the Moon. Financial viability assumes that inflatable structures are used for habitats and tanks, multi pass aero capture for the Moon Earth leg used to minimize transport fuel percentage, and the return propellant (even for the first trip) is produced on the Moon. With this strategy the costs can be kept comparable with large oil development ventures on Earth. When inexpensive, lunar derived fuel is available in depots in Earth-Moon space, many ventures, such as lunar tourism, and cleanup of orbital debris become financially viable.

8.3.2 Mars In Situ Propellant Production – Making a Human Mars Mission Practical

To see the value of utilizing space resources for a Mars mission, one needs to only examine the exponential nature of the rocket equation [33] (also see Chapter 9) the energy available from chemical rocket propulsion to escape the Earth's substantial gravitational field and the resulting payload to fuel ratios. A rocket can have a gross weight to payload ratio in LEO as much as 40 to 1. A trip to Mars surface could require about another 5 to 1 reduction [34]. Thus the gross lift off weight to payload ratio to travel from Earth to Mars surface would be about 200 to 1. Thus, the manufacture of a needed item, for example return propellant, in situ has a very high leverage for mission cost reduction. For example a human Mars reference mission [35] was designed in which the return propellant was manufactured from the Martian atmosphere which is 90% carbon dioxide (CO_2) at less then 1% the atmospheric pressure on Earth.

Utilizing CO_2 from Mars atmosphere along with hydrogen feedstock brought from Earth (and in later scenarios extracted from Mars sources) was found to be technically feasible and provided a definitive cost and safety advantage. The technology required was found to be available and could be employed for the mission after a few years development.

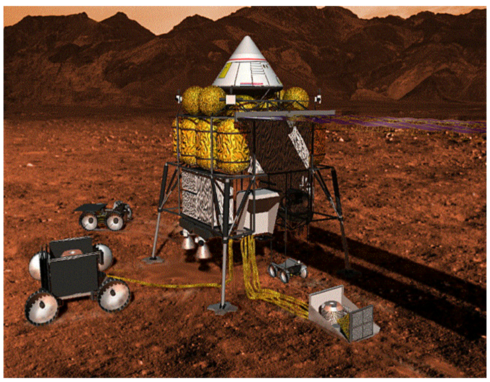
The concept relies on a "split mission" in which a propellant production plant is landed in a Mars landing opportunity two years prior to crew launch from Earth. When the plant produced the required methane propellant and oxygen for crew return to Mars orbit, the crew would be given the "go" for launch from Earth. In addition to the cost savings from in situ propellant production, the capability would enable the production of fuel for Mars surface transportation, and provide a safety supplementation to oxygen life support. The Mars in situ propellant production facility can produce 30 metric tons of LOX/CH4 propellant which can provide the 5.6 km/sec delta-V that is necessary to enable the crew to ascent to Mars orbit and rendezvous with the return vehicle.

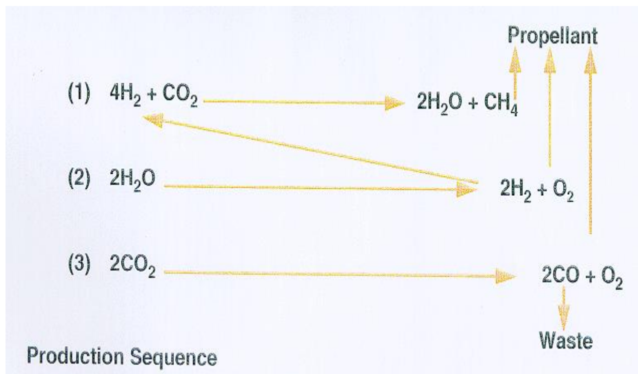
An additional advantage of a "split mission" using producing propellant on Mars surface is that it assures a "safe haven" on Mars surface before the launching of a crew from Earth. This safe haven is also available for a Mars surface abort in case of mission problems in Mars vicinity. The alternative without Mars resource production is a six month trip back to Earth. Of the three environments that a crew will experience, Earth orbit, deep space and Mars surface, deep space is the most hazardous due to radiation and microgravity conditions. Orbit mechanics for a Mars mission impose a 2 to 3 year duration, once a crew is launched from Earth, before return to Earth is possible. Thus, because the transport costs of supplies to Mars is so high, the ability to produce air, water and other life support on the Martian surface is a practical necessity.

The technologies required to produce propellant from Mars CO_2 are currently available, and have been demonstrated in NASA laboratories. In general the In Situ Resource Utilization, ISRU, technologies for Mars mission scenarios reduce the size and number of required Earth launches, provide dual purpose infrastructure on Mars surface that support crew activities and reduce risk.

The NASA Mars Exploration Study Team (referred to above) lists Resource Utilization as an important technology for humans space transportation, living in space and planetary surfaces. These technologies include extraterrestrial mining, resource extractive processes, material preparation and handling in reduced gravity and extraterrestrial manufacturing.

The cost saving of a human Mars mission using Mars resources is only about 1/10 that estimated for the Mission using only Earth launched materials . This dramatic cost savings (from about $30 Billion to about $3 Billion per year) makes a human mission to Mars practical within contemporary NASA budgets [35].





(A) (B)

Figure 8.8 (A) Artist's Rendition of Propellant Processing Plant on Mars, (B) Production Sequence for Propellant Production from Mars Atmospheric Carbon Dioxide (Courtesy NASA)

A processing plant was designed, Figure 8.8, that would land on Mars prior to the crew and make 17 times its weight of methane and liquid oxygen. Not having to carry the return propellant from Earth to Mars had the effect of allowing for smaller launch vehicles and reduced the total mission costs by a factor of 10. This savings allowed NASA to plan for human Mars missions, after the completion of the Space Station, without substantial increases of the agency's budgets.

The costs of human Mars missions could be reduced further if hydrogen were recovered from Mars water ice. Thermodynamic calculations and orbital measurements from spectrometers on the Mars Reconnaissance and the Mars Express orbiters indicate that abundant water ice is present in the higher latitudes of Mars. This has been confirmed in situ by the NASA JPL and University of Arizona Phoenix Lander mission which landed 25 May 2008 at a reocentric latitude 68.22 degrees in the northern arctic polar region of Mars.

The presence of water ice was graphically illustrated by photographs (Figure 8.9) from the Lander's arm camera of the Mars surface where the landing thrusters had blown away the surface regolith. The Lander was designed to confirm the existance of subsurface water ice. The Phoenix 2.35-m robot arm with its associated Soil Acquisition Device was used to excavate 12 trenches that uncovered an apparent water ice table under 5 – 18 cm of regolith.

Figure 8.9 Mars Phoenix Mission Lander arm camera of decent thruster blast area showing apparent sub regolith ice (NASA JPL).

8.3.4 Outposts versus Settlements

The degree of criticality for utilizing space resources depends on the strategic structure of the campaign to explore and develop space. We usually term these campaigns into new living spaces, human bases or human settlements. A space base can be defined [35] as an "outpost" or "base" where human crews stay for six months to two years and then leave or are rotated with a relief crew. The base is historically associated with a military occupation where a short term expensive presence is required. A settlement on the other hand historically is a natural result from the proximity of a wealth producing entity, for example a mine, fertile land, or a commercial confluence of waterways. A settlement nominally is then a place where people stay for two years to an indefinite time. A base relies on expensive supply from a sponsoring organization or government but a settlement must be economically independent relying on indigenous resources and trade. A base has by economic necessity the minimum of personnel, while a settlement grows more or less freely by procreation of its citizens and immigration of others to share in the wealth production. A base is ultimately unsustainable while a settlement is self-sustainable. A base is often deliberately placed in an inhospitable place, while settlement occurs naturally and spontaneously around places of opportunity. Thus the economics of space (lunar, Mars, asteroid, or free space) settlements are much less burdensome to its sponsors than long term bases would be. Sherwood and Woodcock analyze the economic input output linear algebraic matrix for the case of a 100 ton per year lunar oxygen production facility that is operated under an 18- person base mode or a more self sufficient settlement mode. For financial viability the settled lunar habitats and infrastructure must also be constructed in situ with local resources. They conclude that the resupply needed for the oxygen production facility is a factor of 6 less when operated by a settled workforce. The small crew required to produce 100 tons of oxygen would not justify the infrastructure needed for settlement; however, if other projects (for example the extraction of He_3) were occurring and the productivity kept very high through advanced automation, the financial case for a settled lunar workforce becomes compelling.

8.3.4.1 Processing Space Materials on a Grand Scale – Energy to Earth and Space Habitation

Two of the main themes that this section builds upon are that space labor and space resources are cheaper than Earth based labor and resources to achieve large scale monetization of space. The use of space resources is imperative to enable economically reasonable space exploration [35], settlement [37], and space industrialization and solar power development [15]. Launching advanced lightweight solar power satellites from Earth can be cheaper than using space resources when few units are launched [38]; however, Earth launched solar power satellites, even using advanced technologies, are not economically competitive [39] unless Earth launch costs can be greatly reduced. Space solar power satellites might be constructed autonomously from Earth, but only with significant advancements in technology [40]. Using space resources, such as metals from the Moon as construction materials, has a high initial cost but a much lower cost per unit produced and transported into space. This is shown graphically in Figure 8.10 in which the difference in cost when bringing just 50 kilotons per year to fifth Earth-Moon Lagrangian point, L5, from the Earth or Moon.

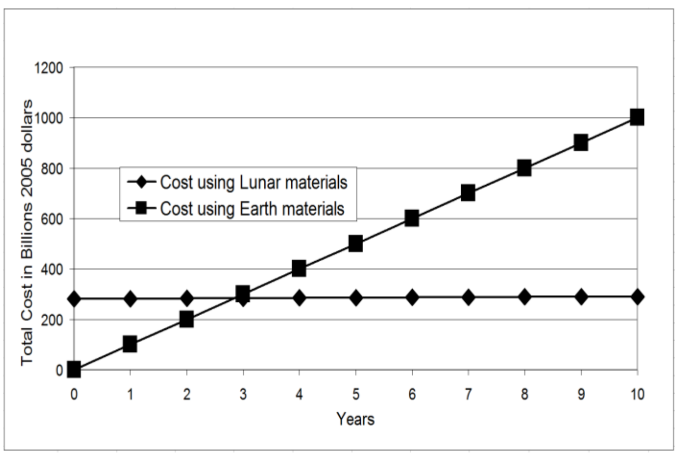


Figure 8.10 The economics of using space resources relative to Earth launch is compared by showing the cumulative cost for sending 50 kt/yr of material from the Earth or from the Moon. The cost from the Moon includes the $283 billion required to build a lunar base and other necessary infrastructure.

Detweiler and Curreri [41] analyzed the economics of space workers in outposts versus in settlements for the large scale manufacturing needed to build solar power satellites to supply energy to Earth. The calculations show that for large space endeavors space based labor is far cheaper than Earth based labor. Space labor in this case is the labor of people living in habitats in free space. The habitats are shielded and rotated to provide near Earth normal radiation and gravity. The community in space creates its own products and grows its own food. The Earth based workforce uses terrestrial supplies and bears the exorbitant costs of transporting them from Earth to space. Because of the high costs the outpost (Earth based) workers live in Spartan conditions and must be rotated back to Earth every six months, and their salary must also be supplied from Earth. Workers living in a near independent and moderately comfortable permanent space habitat are paid mostly using goods constructed in space. Each settlement habitat could have a large agriculture section, in which food is grown. Living in permanent settlement habitats also has the added benefit of attracting individuals who are betting their future on the project. The economic consequence of this can be seen in Figure 8.11. The cost of Earth based workers is obtained by multiplying 614 workers by their wages of $38,420 and the cost of buying and sending 1.67 tons (at $19.11 per kilogram) of resupply material from Earth. The cost of Space based labor is obtained by the cost of building and maintaining one space habitat for 614 workers, and paying each space settler the equivalent to launching 100 kg from Earth.

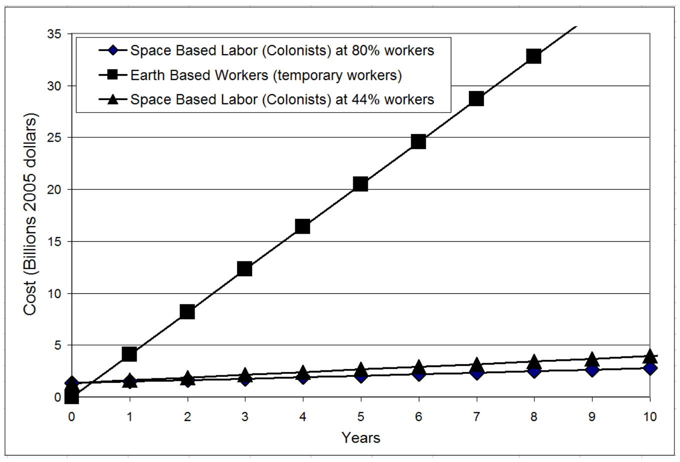


Figure 8.11 Cost for 614 Earth based labor versus space based labor.

In the habitats for the space settlers only a fraction of the inhabitants work in construction. The habitat in which only 44% are workers will be larger than the habitat in which 80% are workers. Examining Figure 8.11, it is apparent that the costs of using Earth based personnel (salary, transportation, and resupply costs) quickly exceeds the cost of using space based labor housed in the space habitats after less than a year of operation. Using space settlers instead of temporary workers not only begins the human settlement of space, but also provides much cheaper, more comfortable and dedicated workers for large scale development of space.

<u>8.3.4.2 Economic Comparison of Earth Launched and Space Derived Solar Power Satellites (SPS)</u>

Studies [39, 42] since Glaser's have attempted to achieve a viable financial model for Earth launched SPS. For comparison to O'Neill-Glaser, Detweiler-Curreri found that the most comprehensive and best documented financial model was a NASA led study in the 1990's called the "Fresh Look Study" [38]. That study employed more advanced technologies (than Glaser's) that included remote robotic assembly, phase array microwave pointing, state-of-the-art solar cells, and high temperature superconductor bus lines. Figure 8.12 shows artist's renditions of the leading design concept the "Solar Disk," and "Sun Tower" Earth launched SPS compared to a Glaser era satellite being constructed in the vicinity of an O'Neill habitat. In order to keep the initial costs as low as possible, the Fresh Look Study did not consider lunar materials and the number of humans in space were kept as low as possible. It was found that with these advanced technologies SPS might be financially viable even if Earth launch costs could be aggressively reduced.

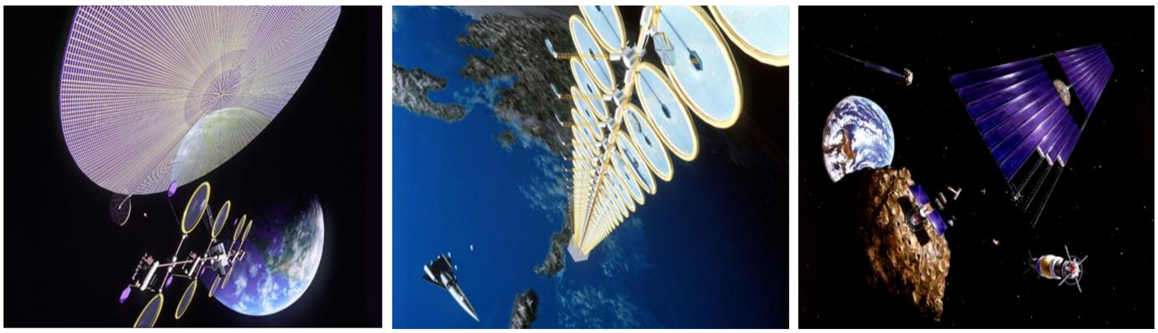


Figure 8.12 Artist's conceptions of Solar Disc (left) and Sun Tower (center) Earth launched, and a Glaser era space derived SPS (right) with O'Neill habitat and near Earth asteroid miner (NASA).

The evolution of the economics of the two Earth derived (Sun Tower and Solar Disc) models and the space derived Optimized O'Neill – Glaser model is shown in Figure 8.13. The Earth launch models after six or seven years of relatively low cost research and development the SPS launching begins. However, even assuming the optimistic launch costs of $400/kg, the 78 GW Sun Tower program requires 30 program years to break even after which there is only a modest projected profit. The 30 GW Solar Disc program is even less favorable economically, with financial outlays of over $100 Billion and projected financial break even after 37 years.

The space derived (optimized O'Neill – Glaser) model requires an investment of $300 Billion to build the infrastructure on the Moon and in space to allow utilization of lunar materials and space based labor. Once the infrastructure is in place, however, the SPS are constructed more than an order of magnitude cheaper than by Earth launch. These inexpensive SPS have a very large profit margin even when selling electricity below Earth market values. The peak investment of about $460 Billion is paid back at program year 24 and by program year 27 the project is projected to realize $600 Billion in profits.

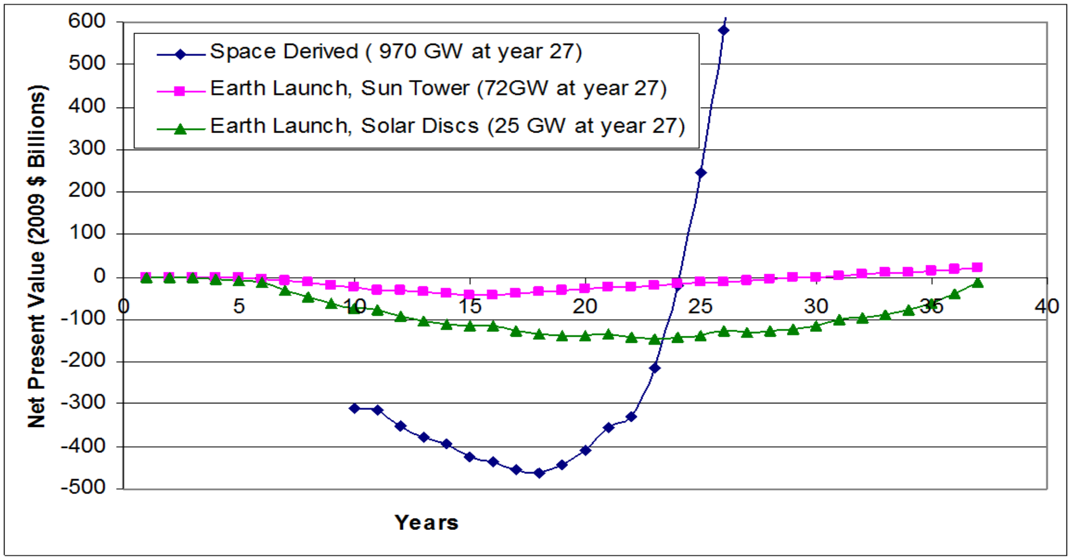


Figure 8.13 Economics versus time for proposed Earth Launch and Space Derived SPS construction models.

8.4 Summary and Conclusions

Materials science and processing research in space can be thought of as a field of study that began with the sounding rocket experiments in the 1950s. Material science studies of the lunar surface materials returned during the Apollo missions enabled the study of lunar resource utilization. The study of materials science and processing in space continued with over 30 years of microgravity materials processing research which continues today in the International Space Station. These studies are the technical foundation that could enable lower cost human exploration through the use of in-situ propellant production, the production of energy from space resources, and the eventual establishment of a substantial portion of humanity living self sufficiently off Earth.

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