

Production and Use of Metals and Oxygen for Lunar Propulsion

Aloysius F. Hepp,* Diane L. Linne,† Geoffrey A. Landis,‡ and Mary F. Wadel†
NASA Lewis Research Center, Cleveland, Ohio 44135
and

James E. Colvin§
University of Arizona, Tucson, Arizona 85721

This article discusses production, power, and propulsion technologies for using oxygen and metals derived from lunar resources. The production process is described, and several of the more developed processes are discussed. Power requirements for chemical, thermal, and electrical production methods are compared. The discussion includes potential impact of ongoing power technology programs on lunar production requirements. This study also compares the performance potential of several possible metal fuels including aluminum, silicon, iron, and titanium. Space propulsion technology in the area of metal/oxygen rocket engines is discussed.

Introduction

UTILIZATION of resources available in situ is a critical enabling technology for manned space exploration. The ultimate success of a permanent lunar base will depend upon the use of available resources. The purpose of this article is to discuss in situ resources and processing options from the perspective of available power and propulsion technologies.

The topics of lunar resources¹ and processing of lunar resources²⁻¹² have been explored often in the recent scientific and technical literature. Two important products obtainable from available lunar resources are oxygen and metals. Oxygen can be used for both life support and as an oxidizer for rocket engines; metals can be used as power materials, as structural materials, and as fuels for rocket engines. Lunar samples returned from the Apollo and Luna missions indicate that approximately 45 wt% of the lunar surface material is oxygen.¹ Much of this oxygen is in the form of silicates and other mixed-metal oxides. Oxygen is the clear choice as an in situ oxidizer because of its prevalence on the moon and the accumulated experience in rocket engine combustion. The choice for a fuel, however, is less apparent. The most common elements used in rocket fuels, hydrogen and carbon, are not available in appreciable amounts. Because of this, interest has turned to lunar metals as a potential source of fuel.

There are many benefits to be realized by using indigenous materials for propellants. The most significant is the reduction in initial mass in low-Earth orbit (LEO). When launch costs to orbit are counted in thousands of dollars per pound of payload, a reduction in the mass required from Earth can translate to a significant cost savings. For lunar missions, if the return propellant can be manufactured at the moon; not only does this mass no longer need to be raised to LEO, but the propellant to transport it to the moon is also saved.²

Most propulsion systems used today operate at oxidizer to fuel ratios greater than 1; producing only oxygen at the moon will show significant reduction in initial mass in LEO. Mission analyses have predicted a 40–60% reduction in initial mass in LEO if oxygen is produced at the moon to operate with Earth-supplied hydrogen for all near-lunar and Earth return propulsive maneuvers.² Because almost all oxygen on the moon is in the form of metal oxides¹ the production of oxygen will necessarily produce metals as a coproduct. If these metals are used as fuel, then further reductions in initial mass in LEO can be obtained. While this additional reduction in initial mass in LEO may not be as significant as that obtained from in situ-produced oxygen, other benefits can be achieved when both propellants are obtained on the lunar surface. One of these benefits is a reduction in mission complexity because vehicle refueling can be performed in the one-sixth gravity environment of the lunar surface instead of the microgravity environment in lunar orbit. Another benefit is the establishment of true self-sufficiency of a lunar base.

Lunar Resources

A wealth of information about lunar resources was obtained between 1966–1976, the era of intensive lunar exploration. A recently published source contains much of the data presented in this discussion of lunar resources.¹ Table 1 lists the most important or potentially useful mineral structural types found on the moon. Specific mineral names are included for chemically pure compounds. These often represent end members or corners of phase diagrams. The actual minerals found are solid solutions of these compounds and may be doped with other metal ions of like charge or size. Lunar rocks and soils are composed of mixtures of silicates and mixed metal oxides (major phases) and metal sulfides and native metals (minor phases). The geological, mineralogical and chemical data, derived from over 2000 samples, are quite complex. The following discussion of resources focuses on applicability to propellant production.

Highland pristine rocks are of mainly three types.¹ Ferroan anorthosites are mostly plagioclase feldspar with small amounts of pyroxene and olivine. These rocks are quite rich in Ca and Al as expected from the chemical formula of both feldspars. Four other pristine rocks, gabbros, norites, troctolites, and dunites, are described as Mg-rich rocks and contain more pyroxene and olivine. Dunite, for example, is almost pure olivine, accounting for its high concentration of MgO. Troctolites are also composed of relatively higher concentrations

Received Dec. 2, 1991; revision received June 24, 1993; accepted for publication March 30, 1994. Copyright © 1994 by the American Institute of Aeronautics and Astronautics, Inc. No copyright is asserted in the United States under Title 17, U.S. Code. The U.S. Government has a royalty-free license to exercise all rights under the copyright claimed herein for Governmental purposes. All other rights are reserved by the copyright owner.

*Senior Scientist, Power Technology Division, M/S 302-1.

†Research Engineer, Space Propulsion Technology Division, M/S SPT-D4. Member AIAA.

‡Senior Engineer, NYMA Inc., M/S 302-1.

§Student, NASA Space Engineering Research Center.

Table 1 Most common or potentially useful mineral types found on the moon (including specific mineral compounds)

Name	Chemical formula
Silicate minerals	
Pyroxene	(Ca, Fe, Mg) ₂ Si ₂ O ₆
Enstatite	MgSiO ₃
Wollastonite	CaSiO ₃
Ferrosilite	FeSiO ₃
Plagioclase feldspar	(Ca, Na)(Al, Si) ₄ O ₈
Albite	NaAlSi ₃ O ₈
Anorthite	CaAl ₂ Si ₂ O ₈
Olivine	(Mg, Fe) ₂ SiO ₄
Fayalite	Fe ₂ SiO ₄
Forsterite	Mg ₂ SiO ₄
Oxide minerals	
Ilmenite	(Fe, Mg)TiO ₃
Geikielite	MgTiO ₃
Ilmenite	FeTiO ₃
Spinel	(Fe, Mg)(Cr, Al, Ti) ₂ O ₄
Chromite	FeCr ₂ O ₄
Ulvöspinel	Fe ₂ TiO ₄
Hercynite	FeAl ₂ O ₄
Spinel	MgAl ₂ O ₄
Armcolite	(Fe, Mg)Ti ₂ O ₅
Ferropseudobrookite	FeTi ₂ O ₅
Karooite	MgTi ₂ O ₅
Other minerals	
Troilite	FeS
Iron/nickel alloys	(Fe, Ni)
Kamacite	(Fe, Ni)(Ni < 0.06)
Taenite	(Fe, Ni)(0.06 < Ni < 0.5)
Tetrataenite	FeNi

Note: Mare basaltic rocks and glasses found on volcanic plains are relatively rich in ilmenite, spinel, and armcolite. This explains the high concentration of iron oxide. Titanium oxide concentration is variable but generally much higher than found in highland regions.¹ The remaining composition of mare basalts (70–90%) consists of plagioclase and pyroxene. This accounts for the relatively lower abundance of SiO₂, CaO, and Al₂O₃ when compared to highland rocks and breccia. The relatively large amounts of oxides in mare basalts provides a potential source of both iron and titanium.

of olivine, accounting for 20% MgO. Finally, high concentration potassium (K) rare Earth element (ree), and phosphorus (P) rock (referred to as KREEP) rocks are basaltic lavas with relatively high concentrations (by lunar standards) of potassium, rare earth elements and phosphorus.

Breccias and impact melts form a class of materials that range in appearance from homogeneous to composite-like. This is due to the various impact, melting, and cooling processes that result in their formation. The breccias in general consist of clast (fragments) and the matrix that contains them.¹ The majority of the material in various breccias are similar to the pristine rocks, hence the similarities in composition. One potential use for breccias may be as a source of rare platinum-group metals derived from meteoric materials.

The lunar regolith, having been disintegrated by mechanical weathering, may be an important source of FeO and Al₂O₃ that requires a minimum of mechanical processing. Finally, lunar regolith (as well as some lunar rocks¹) is a source of metal powder and alloys (see Table 1). Though a minor component, reduced metals may prove to be an important iron source.

Representative oxide compositions for typical rock and soil samples collected on the moon are listed in Table 2. Examples listed are representative of material returned from the Apollo and Luna missions.

Geological exploration of the moon to date has sampled only a small fraction of the surface at a superficial level. Cratering has spread samples out over large areas at impact

Table 2 Approximate chemical composition of sampled lunar materials^a

Material ^b	SiO ₂	FeO	CaO	TiO ₂	Al ₂ O ₃	MgO
Mare basalts						
High-Ti	40	19	11	11	10	7
Low-Ti	46	21	10	3	9	10
Al low-ti	46	17	11	3	14	9
Very-low-Ti	46	22	12	1	12	6
Orange glass	39	22	8	9	6	14
Green glass	44	21	8	1	8	17
Highland pristine rocks						
Ferroan						
Anorthosites	45	3	17	0	31	3
Gabbros ^c	51	10	12	0	13	13
Norites ^c	51	10	9	0	15	13
Troctolites ^c	43	5	11	0	20	20
Dunites ^c	40	12	1	0	1	45
KREEP ^d	52	10	9	2	16	8
Complex breccias and impact melts						
Fragmental	45	3	17	0	30	3
Glassy melt	45	4	15	0	27	7
Crystalline	48	8	11	1	18	13
Clast-poor	47	7	13	1	22	8
Granitic	45	5	15	0	27	7
Lunar regolith						
Apollo 12 site	46	15	11	3	13	9
Apollo 14 site	48	10	11	2	17	9
Apollo 15 site	47	14	11	1	15	12
Apollo 16 site	45	5	16	1	27	6
Apollo 17 site	43	12	12	4	17	10

^aFrom text Ref. 1. The five most prevalent oxides generally account for >97% by weight; the remaining oxides are manganese, sodium, potassium, chromium, rare Earth oxides and other, generally at less than 1% abundance.

^bWeight fractions listed are composites of several samples from one site or from one mission.

^cExample of a rock-type referred to as magnesium rich.

^dAccounts for approximately 3–4%, by weight.

sites, and thus tended to homogenize the lunar regolith; nevertheless, further exploration may reveal mineral types, elements, and concentrations as yet unsuspected. Some authors indicate that differentiation processes may have produced ore deposits significantly enriched in certain components, and that further exploration of the moon may yet reveal surprises.³⁶

Processing Technology

Taking advantage of the abundance of metal oxides on the lunar surface as potential sources of in situ propellant compounds requires that areas where these raw materials are readily available be identified. The raw material must then be mined and often subjected to a beneficiation process to separate the desired feedstock to supply the particular process scheme to manufacture the propellant elements. Potential propellant elements include O₂, Al, Fe, Si, and Ti. Many processes have been proposed for the production of oxygen and metals from the lunar resources.^{3–12} While most of these have terrestrial counterparts, some have evolved to take advantage of unique characteristics of the lunar environment.

Mining techniques on the moon will be necessarily different from their terrestrial counterparts. On Earth, many mining techniques depend on the abundant water supply for cooling, lubrication, movement, and separation of materials, and solution and precipitation of metals. Another difference is the fact that the lunar surface has been subjected to a homogenization of the soils by repeated meteor impacts, making the regolith a mixture of many rock and mineral types.^{1,3} Because of this difference, the initial mining philosophy on the moon should involve mining the rocks and soil for their common elements.

On Earth most ores are recovered below the surface, whereas on the moon it is worthwhile to consider surface mining. This method would take advantage of the fact that the surface material is mostly pulverized, helping to reduce mechanical processing of rocks before beneficiation. Other advantages of lunar surface mining include totally visible operations, lower gravity relative to Earth (implying easier material transport), and lack of weather or a corrosive atmosphere. One disadvantage is that the moon experiences a 14-day sunlit period followed by 14 days of darkness. This could be a problem if considering solar-derived power for the operation. Additionally, extreme temperature contrasts accompany the day-night cycle, leading to problems with lubrication, friction, and equipment failure.³

Once raw materials have been mined, feedstocks for various processing techniques may need to be separated from the mined material. This process, called beneficiation, performs the function of concentrating the desired metal oxides. There are two major beneficiation techniques: 1) magnetic and 2) electrostatic.⁵ Magnetic beneficiation is accomplished by feeding the raw material through the field of one or more magnets, to separate magnetic minerals from nonmagnetic materials. The use of magnets with different field strengths further separates the magnetic minerals. Electrostatic separation is more complex, but has the advantage of being able to separate nonmagnetic minerals. This process is used to separate materials with respect to their conductive properties: conducting, semiconducting, or insulating. Most minerals will show some difference in conductive properties. But homogenized regolith may not separate well if many minerals are melted together.¹

There is a variety of propellant processing schemes proposed for potential use on the lunar surface. Table 3 lists

several of the more studied processes.³⁻¹² Although lunar processing methods will model terrestrial modes of operation, there are several concerns that must be considered when processing operations are conducted on the moon.⁶ First, there is no air or water, thus depriving the plant of heat sinks provided by these fluids. Traditional energy sources are absent (i.e., coal, oil, or gas). Basic processing chemicals are absent (i.e., ammonia, salt, chlorine, soda ash, carbon dioxide etc.). Finally, since initially there may be no local human operators, the plant will have to be autonomous or tele-operated.

One conclusion that may be drawn from Table 3 is that titanium production from lunar materials is quite difficult, requiring large amounts of energy. Production of iron, aluminum, or silicon can be optimized by proper choice of processing method and is dependent upon the feedstock. When anorthite is the feedstock, silicon and aluminum are obtained similarly from this aluminosilicate.^{16,17,20} Iron may be obtained from reduction of ilmenite,^{13,14} FeO in glasses, or pyroxenes. Separation of the reduced iron from the process materials may prove challenging, however.

The four example metals were chosen because they are relatively abundant on the moon, can be obtained by a known terrestrial process, and are candidates for lunar-derived propellants. The particular method(s) and metal(s) chosen will be a function of the feasibility of the process on the moon (processing materials and power requirements), potential utility of the metal as a propellant (and other applications), and mass tradeoffs between the plant requirements and terrestrial-derived substitutes.

Processing methods in Table 3 are listed in order of technology readiness.⁷ Methods that are most developed have

Table 3 Lunar processing methods^a

Process	Feedstock	Electrical power, kW/t fuel/yr ^b	Thermal power, kW/t fuel/yr ^b	Temperature, °C	Products ^c (fuel)
Hydrogen reduction ^{7,13,14}	Ilmenite (FeTiO ₃) or pyroclastic glass	0.72	0.18	900	O ₂ , Fe, FeO, TiO ₂ (Fe)
Carbothermal ^{6-10, 15, 16}	Enstatite (MgSiO ₃)	0.82	3.28	1625	O ₂ , Si, MgO, SiH ₄ (Si)
Carbochlorination ^{4,12,16,17}	Anorthite (CaAl ₂ Si ₂ O ₈)	1.33 1.38	2.46 2.57	675-770	O ₂ , CaO, Al, Si (Si) (Al)
HF acid leaching ^{6,8,10,12}	Mare regolith	8.85	8.85	110	O ₂ , Al (Al)
Reduction by Li or Na ^{5,18,19}	Mare regolith	2.15 3.30 14.55	2.15 3.30 14.55	900	O ₂ , Si, Fe, Ti (Si) (Fe) (Ti)
Reduction by Al ^{5,7,12,20}	Anorthite (CaAl ₂ Si ₂ O ₈)	2.56 2.64	0.64 0.66	1000	O ₂ , Si, Al, Ca (Si) (Al)
Direct fluorination ^{3,4,11,21}	Anorthite (CaAl ₂ Si ₂ O ₈)	15.52 16.16	3.88 4.04	900	O ₂ , Al, Si, CaO (Si) (Al)
Magma electrolysis ^{4,22,23}	Silicate rock or regolith	0.26	0.26	1000-1500	O ₂ , Fe (Fe)
Fluxed electrolysis ^{6,8,24}	Silicate rock or regolith	6.40 9.95 19.15	6.40 9.95 19.15	1000-1500	O ₂ , Al, Si, Fe (Si) (Fe) (Al)
Vaporization/fractional distillation ^{7,12,25,26}	Regolith	1.77 5.28	4.13 12.32	2700	O ₂ , Al, Si, Suboxides (Si) (Al)
Selective ionization ^{4,5,12,25}	Regolith	7.90 12.20 23.60 52.00		7700	O ₂ , Al, Si, Fe, Ti, Mg (Si) (Al) (Fe) (Ti)

^aMethods ranked in order of technical "readiness" as defined by Ref. 7, with the most mature technologies at the top. Normal text indicates terrestrial-derived processes; highlighted text indicates space-derived processes.

^bProcess power requirements dependent on desired metal product.⁷ Some thermal power estimates may not include the power needed to reach processing temperature, such as selective ionization.

^cProducts produced by the listed method include the major metal-containing species and oxygen.

terrestrial counterparts. These methods are compatible with the use of solar thermal heating, discussed below, and solar- or nuclear-generated electricity. Unfortunately, these methods often involve the use of terrestrial-derived materials such as HF, Na, Li, C, F₂, or Cl₂. Methods that are compatible with space processing involve very high temperatures and relatively large amounts of power.

Power Technology

Priorities for a power system are reliability and absence of dangerous failure modes. Due to the high cost of transporting cargo to the moon, an additional priority for a surface power system will be low weight. For resource processing, two types of power are needed: 1) thermal and 2) electric energy. Depending on the processing technology chosen, the relative amount of thermal and electrical process power required can vary considerably. It is much more efficient to use a primary thermal energy source than to produce thermal power from electricity.

There are two main power choices: 1) solar and 2) nuclear. (A third alternative, use of lasers to beam power to photovoltaic arrays,^{27,28} will not be discussed.) The 354-h lunar night requires that a solar power system either shut down during the night, or include a large energy storage system.²⁷ In general, power levels needed for resource processing are so high that energy storage for night operation is not likely to be practical.

Thermal power can be produced either from a solar furnace, by the direct use of nuclear core heat, or from electrical power. Concentrator mirrors designed for solar thermal power on Earth have demonstrated the high temperatures needed for most of the thermally demanding processes proposed. A solar concentrator designed for space solar dynamic power systems produces a working temperature of about 750°C.^{10,11} For mirror concentrator systems, the hot region is at the focus of the mirror, and typically moves as the mirror tracks the sun. Since resource processing equipment is likely to be heavy, a system designed for the moon might require a separate tracking mirror (or "heliostat") to reflect the sun to the concentrator mirrors, or an active secondary mirror system to redirect light to the processing site.

If a nuclear reactor is used for electrical power, reactor heat could possibly be used directly. To date, little mention has been made of this possibility. The SP-100 nuclear reactor has a working-fluid operating temperature of about 1000°C.²⁹ (Higher temperatures can be produced internally, depending on the materials used, e.g., nuclear thermal rockets operate at temperatures of several thousand degrees.) Radioactivity from the reactor means that the reactor is likely to be located at least 1 km from human-occupied locations. If the reactor is to supply thermal processing energy, either the processing must be autonomous or remotely operated, hot working fluid must be piped over relatively long distances to a site compatible with man-tended operation, or significant additional shielding must be added to the reactor.

Use of electrical power to produce heat is inefficient. However, a base will require an electrical power system in any case, and it may be more convenient to scale an existing power system up to high powers than to design a separate system. Electrical power may be produced either by a nuclear reactor or by solar panels. A nuclear power system based on the SP-100 reactor would deliver 100 kW of electrical power from a 2.5-MW thermal reactor for a baseline system.²⁹ Replacing the low-efficiency thermoelectric converters by high-efficiency Stirling engines would result in a power level of 825 kW from the same reactor. The mass of this reactor system would be about 20,000 kg, resulting in a specific mass of 24.5 kg/kW. Less conservative designs incorporating further technological advances may have lower mass.

An alternative source of electrical power is solar panels. Photovoltaics provide power with high reliability and no moving parts. Design considerations for photovoltaic power sys-

Table 4 Specific power of solar arrays (Earth orbit solar intensity)

System	Specific power, W/kg
Best flight tested array solar array flight experiment (SAFE)	66
Best currently built array advanced photovoltaic solar array (APSA)	130
Best array combining existing technology APSA with 20% CLEFT GaAs cells	300

tems for a lunar base are discussed in recent references.^{30,31} For an advanced system, it may be possible to manufacture the solar cells on the moon.³²

Existing spacecraft use planar photovoltaic arrays. The conversion efficiency of standard-technology silicon cells currently flown is about 14% under space conditions. Up to 20% efficiency has been demonstrated for cells not yet space qualified. (Note that for calculating operational power, efficiency numbers must be adjusted for the array packing efficiency and corrected for intensity and temperature effects.) An advantage of silicon cells is that large-area cells are available and the array technology is well-developed and characterized. Gallium arsenide (GaAs) cells currently available on the market have conversion efficiency of 18.5%. Efficiency over 22% has been achieved in the laboratory. GaAs cells are smaller, more brittle, and heavier than silicon cells, but development is underway to increase the size and reduce the mass.

An alternative approach is to use thin layers of photovoltaic material on a flexible substrate. Thin-film solar cells have lower conversion efficiencies, but potentially higher specific power.³⁷ This has not yet been demonstrated in space, although thin-film solar cells have been developed for terrestrial use. A third approach is to concentrate the light onto small, extremely efficient solar cells. This approach has been tested in space only in small-scale experiments. In the laboratory, conversion efficiency over 30% has been demonstrated.

Of importance to power system analysis is the specific power (power per unit mass). It is possible to measure specific power at the cell, blanket, array level, or power system level. Specific power at the photovoltaic array level (including array structure) for the best arrays developed to date are shown in Table 4. For currently designed space power systems, the photovoltaic blanket is only about a quarter of the total power generation system mass (excluding batteries used for electrical storage). The array plus structure accounts for half of the power system mass. The power management and distribution (PMAD) system accounts for the remaining half. This provides a powerful incentive to develop new and more efficient PMAD systems and to design new array structures to take advantage of ultralight blankets.

Propulsion Technology

Choice of production methods will depend greatly on the selection of the most useful products. The theoretical performance of several metals burned with oxygen was determined using a one-dimensional chemical equilibrium computer code.³³ This code predicts specific impulse assuming the maximum energy release possible in the combustion chamber less chamber dissociation losses. Figure 1 shows this predicted performance for aluminum, titanium, silicon, and iron as a function of mixture ratio, chamber pressure, and expansion area ratio.

Figure 1a shows the effect on specific impulse for aluminum/oxygen at a chamber pressure of 3000 psia as area ratio increases from 10 to 500, and as mixture ratio increases from 0.3 to 4.0. The results for a chamber pressure of 200 psia are shown only for an area ratio of 10 as a representation of the small effect that chamber pressure has on ideal specific impulse. The maximum predicted impulse of aluminum/oxygen

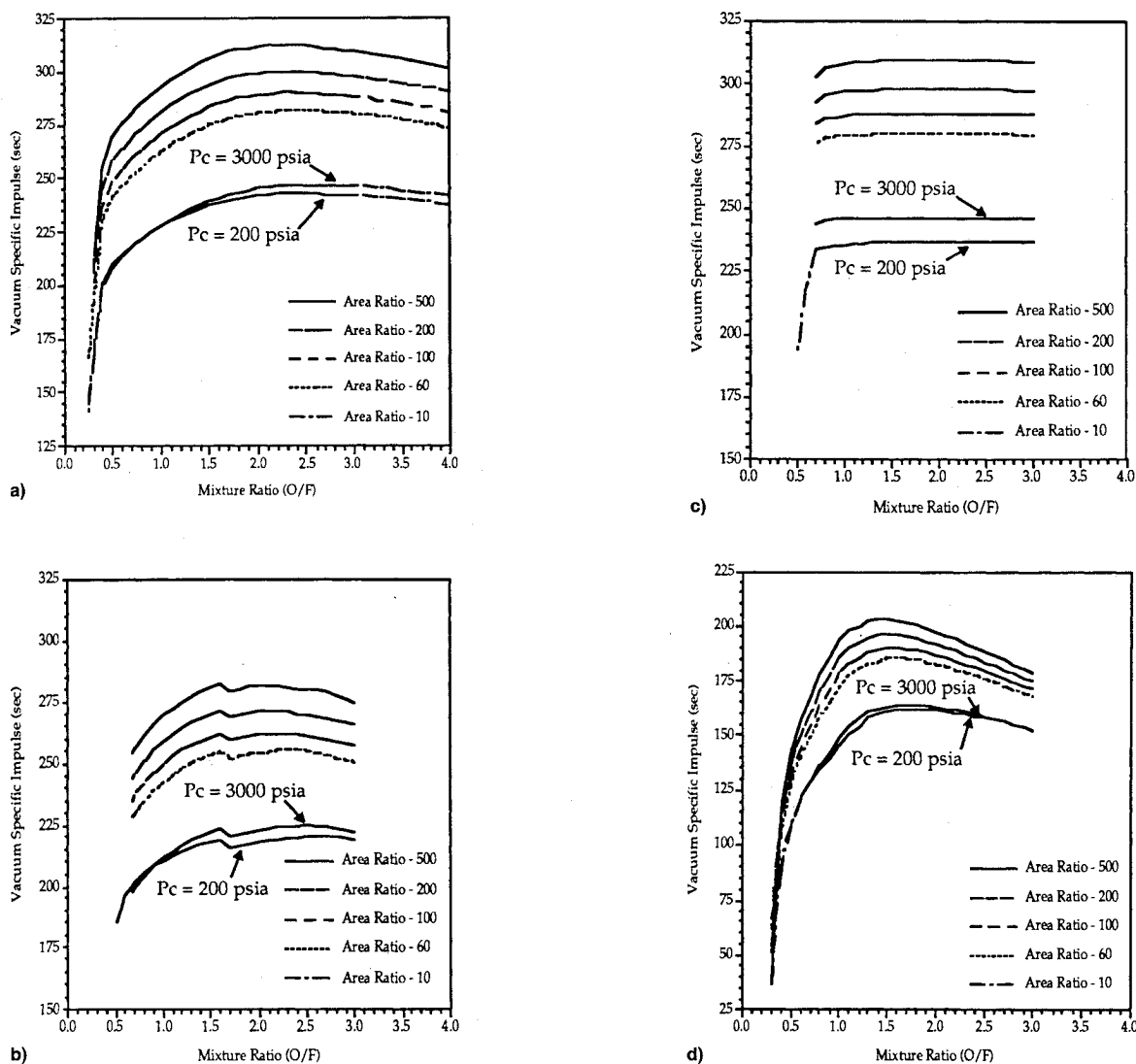


Fig. 1 Theoretical vacuum specific impulse performance of indigenous lunar propellants assuming one-dimensional equilibrium: a) aluminum/oxygen, b) titanium/oxygen, c) silicon/oxygen, and d) iron/oxygen.

is approximately 315 s at a chamber pressure of 3000 psia and an area ratio of 500.

Figure 1b shows similar curves for the titanium/oxygen combination. The discontinuity in the curves is caused by a change in the predominant oxide formed in the combustion chamber. For titanium/oxygen, the maximum predicted impulse is approximately 285 s at a chamber pressure of 3000 psia and area ratio of 500.

Figure 1c shows the same curves for the silicon/oxygen combination. While the maximum specific impulse of 310 s is nearly as high as that predicted for the aluminum/oxygen, the curve shown for a chamber pressure of 200 psia and an area ratio of 10 indicates increased sensitivity to chamber pressure. For this propellant combination, there is a difference of more than 10 s in predicted specific impulse at chamber pressures of 200 and 3000 psia. This is an indication that the silicon dioxide product has a high rate of dissociation at lower pressures. The high dissociation rate could become a significant problem when finite-rate kinetics are considered in the calculations.

Figure 1d shows the same curves for the iron/oxygen propellant combination. The maximum impulse predicted for the iron is only 210 s at a chamber pressure of 3000 psia and area ratio of 500. While lower engine performance can be tolerated from an in situ propellant combination because of the benefits of obtaining the propellant at the destination, mission analyses

have shown that 210 s is too low for iron fuel to be seriously considered as an alternative.

While one-dimensional equilibrium predictions provide adequate comparisons when evaluating potential propellants, a more rigorous theoretical analysis would need to be performed to accurately predict the specific impulse that an actual engine would deliver. Factors that may degrade performance from the ideal values discussed above include incomplete energy release in the chamber due to incomplete mixing of fuel and oxidizer or incomplete burning of the metal particles, finite-rate chemical reactions, growth of a viscous boundary layer in the chamber and nozzle, and thermal or velocity nonequilibrium between the solid and gaseous combustion products. Some losses, such as finite-rate kinetics, cannot be changed or reduced. Other losses, such as incomplete mixing in the chamber and boundary-layer growth, can be reduced by proper hardware design. Finally, losses such as incomplete burning of the metal particles and two-phase flow effects can be reduced by proper fuel design. Technology efforts have been initiated to reduce those loss mechanisms that can be affected by hardware or fuel design.

A program is underway to establish the technology base needed for the development of engines that use resources indigenous to the moon. The metal and oxygen propellants can be used as either a monopropellant—with powdered metal suspended in the liquid oxygen, as a bipropellant—with a

conventional liquid oxygen feed system and a pneumatic feed system for the powdered fuel, or as a hybrid rocket—with liquid oxygen feed and a solid metal fuel. A monopropellant could be potentially hazardous; a hazards assessment and propellant formulation must be completed before any combustion experimentation can begin. Meanwhile, single particle ignition studies offer insights into the ignition mechanism of the metal particles.

The objective of the hazards assessment activity is to assign an explosive classification to the monopropellant so that the associated safe handling procedures can be used. A preliminary goal of the hazards assessment is to test small, laboratory-scale quantities for explosive hazards such that formulation research can begin with assurances of safety. To accomplish this preliminary goal, two phases of the hazards assessment program have been completed.

The first phase consisted of mixing tests, where small amounts of the metal powders and liquid oxygen were combined and then stirred at low speeds (approximately 600 rpm) while being monitored for any signs of chemical reaction. A total of 63 tests were performed with aluminum, titanium, silicon, and iron powders, with and without a gellant; no chemical reactions were observed.³⁴

The second phase consisted of mechanical impact tests, where a weight was dropped into a small sample of the monopropellant from various heights to determine the necessary energy to cause a reaction. The results were reported in terms of a 50% height, which is the height at which a reaction occurred 50% of the time. PETN, which is a solid Class A explosive known to be impact sensitive, was used as a reference material in the test apparatus. The 50% height of the PETN was 51.0 cm (impact energy of 45.4 J). The 50% height of the titanium/oxygen mixture was less than 15.2 cm (13.6 J), which was the lowest height available in the test apparatus. The 50% height of an 80% Al/20% Mg alloy in oxygen was 67.6 cm (60.1 J). The 50% heights of the aluminum, silicon, and iron mixtures with liquid oxygen were all greater than 123.0 cm (109.4 J), which was the highest height available in the test apparatus. For all metal powders except titanium, the results of the mechanical impact tests indicated that it is safe to handle the powders in the quantities and manners necessary to begin formulation and characterization of the monopropellant.³⁵

The objective of the monopropellant formulation task was to determine the minimum amount of gellant required to stably suspend the metal particles in the liquid oxygen, while maintaining acceptable flow properties. Preliminary efforts have indicated that this can be accomplished with as little as 2% by weight of the gellant (amorphous fumed silica). A secondary objective of the formulation and characterization task was to determine the burn rate of the monopropellant. If the monopropellant burns faster than the injection velocity into the chamber, then burning could propagate into the feed lines and the propellant tank, causing catastrophic failure. The burn rate tests were conducted with the monopropellant submerged in a liquid nitrogen bath to prevent boil-off of the liquid oxygen before the start of the test. During the test, this nitrogen acted as a heat sink, absorbing the energy created by the combustion of the monopropellant. Because of this rapid heat transfer, the monopropellant combustion was unable to sustain itself after the solid propellant ignition charge was removed. Therefore, the ambient pressure burn rate of monopropellants at liquid nitrogen temperatures approaches zero, assuring that the flame will not propagate into feed lines.

Research into the ignition and burning of single metal particles in a hot oxygen environment has been started in an effort to reduce potential performance losses. From experience with metal fuels in solid rocket motors and from theoretical calculations, it is known that two keys to reducing performance losses are quick ignition of the metal particles and vapor phase or explosive combustion that minimizes the size of the solid products. To achieve these goals, various

aluminum/magnesium alloys are being tested in a shock tube. It is expected that magnesium in an alloy will ignite more quickly than aluminum; differences in boiling temperatures will help promote the vapor phase or explosive combustion. Results from these experiments can be used in future design of rocket engines that use metal/oxygen propellants. Although metals have not been used before as the sole fuel element, the technology work being performed indicates that a metal/oxygen monopropellant or bipropellant may make a suitable propellant combination for indigenous use at the moon.

Conclusions

The case for in situ propellant production is a powerful one. Reference 38 (published while this article was in the process of review) has a good review of the advantages of in situ propellant production, as well as discussions of lunar resources and processing. Lunar resources are available to provide the necessary metals and oxygen. While our knowledge of the lunar surface and its geology, mineralogy, and chemistry is extensive, further exploration will be required to fully exploit lunar resources for manned exploration and colonization.

Production technology must be developed to deal with, or even take advantage of, the lower gravity, sunlight, and vacuum environment. Lunar production processes must depend as little as possible on nonrenewable Earth-derived chemicals. The power must be obtainable from solar or nuclear sources and be compatible with the intended use of the energy, thermal or electrical. The power source itself could be derived from local resources.³²

By obtaining all of the propellants for near-lunar operation on the moon's surface, significant benefits for future manned lunar missions can be realized. It is also expected that mission architectures will include plans for lunar-derived propellants to fuel further exploration to Mars.

References

- ¹Lunar Sourcebook, edited by G. Heiken, D. Vaniman, and B. M. French, Cambridge Univ. Press, Cambridge, England, UK, 1991.
- ²Wickman, J. H., Obert, A. E., and Mockenhaupt, J. D., "Lunar Base Spacecraft Propulsion with Lunar Propellants," AIAA Paper 86-1763, June 1986.
- ³Burt, D. M., "Mining the Moon," *American Scientist*, Vol. 77, No. 6, 1989, pp. 574-579.
- ⁴Steuer, W. H., "Extraterrestrial Materials Processing," Jet Propulsion Lab., JPL Publication 82-41, Pasadena, CA, April 1982.
- ⁵Christianson, E. L., "Conceptual Design of a Lunar Oxygen Pilot Plant," Eagle Engineering, Inc., Rept. 88-182, Contract NAS9-17878, Houston, TX, July 1988.
- ⁶Criswell, D. R., and Waldron, R. D., "Chemical Processing of Lunar Materials," 30th International Astronautical Federation Congress, Paper IAF-79-116, Munich, Germany, Sept. 1979.
- ⁷Stancati, M. L., Jacobs, M. K., Cole, K. J., and Collins, J. T., "In Situ Propellant Production: Alternatives for Mars Exploration," Science Applications International Corp., SAIC-91/1052, Final Rept. for NAS3-25809, Schaumburg, IL, Oct. 1991.
- ⁸Waldron, R. D., Erstfeld, T. E., and Criswell, D. R., "Overview of Methods for Extraterrestrial Materials Processing," *Space Manufacturing 3*, edited by J. Grey and C. Krop, AIAA, New York, 1979, pp. 113-127.
- ⁹Phinney, W. C., Criswell, D. R., Drexler, E., and Garmirian, J., "Lunar Resources and Their Utilization," *Progress in Astronautics Aeronautics*, Vol. 57, AIAA, New York, 1977, pp. 97-123; also *Space Manufacturing 2*, edited by J. Grey, AIAA, New York, 1977, pp. 171-182.
- ¹⁰Waldron, R. D., and Criswell, D. R., "Materials Processing in Space," *Space Industrialization, Vol. 1*, edited by B. O'Leary, CRC Press, Boca Raton, FL, 1982, pp. 97-130.
- ¹¹Research on the Use of Space Resources, edited by W. F. Carroll, Jet Propulsion Lab., JPL Publication 83-36, Pasadena, CA, March 1983.
- ¹²Teeter, R. R., "Lunar Surface Base Propulsion Study," Vol. 1, Astronautics Corp. of America, Madison, WI, Feb. 1992.
- ¹³Gibson, M. A., and Knudsen, C. W., "Lunar Oxygen Production

from Ilmenite," *Lunar Bases and Space Activities of the 21st Century*, edited by W. W. Mendell, Lunar and Planetary Inst., Houston, TX, 1985, pp. 543–550.

¹⁴Williams, R. J., "Oxygen Extraction from Lunar Materials: An Experimental Test of an Ilmenite Reduction Process," *Lunar Bases and Space Activities of the 21st Century*, edited by W. W. Mendell, Lunar and Planetary Inst., Houston, TX, 1985, pp. 551–558.

¹⁵Cutler, A. H., and Krag, P., "A Carbothermal Scheme for Lunar Oxygen Production," *Lunar Bases and Space Activities of the 21st Century*, edited by W. W. Mendell, Lunar and Planetary Inst., Houston, TX, 1985, pp. 559–569.

¹⁶Rosenberg, S. D., Guter, G. A., and Miller, F. E., "The On-site Manufacture of Propellant Oxygen from Lunar Resources," *Aerospace Chemical Engineering*, Vol. 62, No. 61, 1966, pp. 228–234.

¹⁷Rao, B. D., Choudary, U. V., Erstfeld, T. E., Williams, R. J., and Chang, Y. A., "Extraction Processes for the Production of Aluminum, Titanium, Iron, Magnesium, and Oxygen from Non-Terrestrial Sources," *Space Resources and Space Settlements*, edited by J. Billingham and W. Gilbreath, NASA SP-428, 1979, pp. 257–274.

¹⁸Sammells, A. F., and Semkow, K. W., "Electrolytic Cell for Lunar Ore Refining and Electric Energy Storage," 2nd Symposium on Lunar Bases and Space Activities in the 21st Century, Paper LBS-88-017, Houston, TX, April 1988.

¹⁹Semkow, K. W., and Sammells, A. F., "The Indirect Electrochemical Refining of Lunar Ores," *Journal of the Electrochemical Society*, Vol. 134, No. 8, 1987, pp. 2088, 2089.

²⁰Anthony, D. L., Cochran, W. C., Haupin, W. E., Keller, R., and Larimer, K. T., "Dry Extraction of Silicon and Aluminum from Lunar Ores," 2nd Symposium on Lunar Bases and Space Activities in the 21st Century, Paper LBS-88-066, Houston, TX, April 1988.

²¹Burt, D. M., "Lunar Mining of Oxygen Using Fluorine," 2nd Symposium on Lunar Bases and Space Activities in the 21st Century, Paper LBS-88-072, Houston, TX, April 1988.

²²Kesterke, D. G., "Electrowinning of Oxygen from Silicate Rocks," U.S. Bureau of Mines Report of Investigations 7587, 1971; also, *Proceedings of the 7th Annual Working Group on Extraterrestrial Resources*, 1970, pp. 139–145 (NASA SP-229).

²³Du Fresne, E., and Schroeder, J. E., "Magma Electrolysis," *Research on the Use of Space Resources*, edited by W. F. Carroll, Jet Propulsion Lab., JPL Publication 83-36, Pasadena, CA, March 1983.

²⁴Rao, G. M., Elwell, D., and Feigelson, R. S., "Electrowinning of Silicon from K_2SiF_6 -Molten Fluoride Systems," *Journal of the Electrochemical Society*, Vol. 127, No. 9, 1980, pp. 1940–1944.

²⁵Steurer, W. L., and Nerad, B. A., "Vapor Phase Reduction,"

Research on the Use of Space Resources, edited by W. F. Carroll, Jet Propulsion Lab., JPL Publication 83-36, Pasadena, CA, March 1983.

²⁶Sparks, D. R., "Vacuum Reduction of Extraterrestrial Silicates," *Journal of Spacecraft and Rockets*, Vol. 25, 1988, pp. 187–189.

²⁷Landis, G. A., "Solar Power for the Lunar Night," *Space Manufacturing 7*, edited by B. Faughnan and G. Maryniak, AIAA, Washington, DC, 1989, pp. 290–296; also NASA TM-102127, May 1989.

²⁸Landis, G. A., "Moonbase Night Power by Laser Illumination," *Journal of Propulsion and Power*, Vol. 8, No. 1, 1992, pp. 251–254.

²⁹Mason, L. S., Bloomfield, H. S., and Hainley, D. C., "SP-100 Power System Conceptual Design for Lunar Base Application," NASA TM-102090, Jan. 1989.

³⁰Landis, G. A., Bailey, S. G., Brinker, D. J., and Flood, D. J., "Photovoltaic Power for a Lunar Base," *Acta Astronautica*, Vol. 22, 1990, pp. 197–203; also 40th IAF Congress, Paper IAF-89-254, Torremolinos, Spain, Oct. 1989.

³¹Hickman, J. M., Landis, G. A., and Curtis, H. B., "Design Considerations for Lunar Base PV Power Systems," *Proceedings of the 21st IEEE Photovoltaic Specialists Conference* (Orlando, FL), Vol. 2, 1990, pp. 1256–1262; also NASA TM-106342, May 1990.

³²Landis, G. A., and Perino, M. A., "Lunar Production of Solar Cells: A Near-Term Product for a Lunar Industrial Facility," *Space Manufacturing 7*, edited by B. Faughnan and G. Maryniak, AIAA, Washington, DC, 1989, pp. 144–151; also NASA TM-102102, May 1989.

³³Gordon, S., and McBride, B. J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations," NASA SP-273, March 1976.

³⁴Woods, S. S., "Liquid-Oxygen/Metal Gelled Propellants Hazards Analysis (Phase I)," NASA JSC White Sands Test Facility, NASA TR-625-001, Las Cruces, NM, Jan. 1990.

³⁵Rathgeber, K., and Beeson, H., "LOX/Metal Gel Mechanical Impact Test Special Test Data Report," White Sands Test Facility, WSTF 90-24223-28, 90-24490-91, Las Cruces, NM, Jan. 1991.

³⁶Gillett, S. L., "Lunar Ores from Magmatic Processes," *Engineering, Construction, and Operations in Space II*, American Society of Civil Engineers, New York, 1990, pp. 88–97.

³⁷Landis, G. A., and Hepp, A. F., "Thin Film Photovoltaics: Status and Applications to Space Power," *Proceedings of the European Space Power Conference*, European Space Agency, 1991, pp. 517–522 (ESA SP-320).

³⁸Lewis, J. Matthews, M. S., and Guerrieri, M. L. (eds.), *Resources of Near Earth Space*, Univ. of Arizona Press, Tucson, AZ, 1993.