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The Moon-Gateway to the Universe

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ABSTRACT

A decision to exploit the extraterrestrial frontier gives man an infinite physical and resource environment in which to continue human development and growth. The off-planet expansion of the human resource base will be highlighted by several key technology steps: (1) the development of reusable space transportation systems, such as the Space Shuttle; (2) the establishment of manned space stations; (3) the development of space-based industries; (4) the creation of lunar bases and permanent manned settlements; and (5) the full exploitation of lunar and possibly asteroid resources. The Moon and its potential role as man's gateway to the Universe is discussed. Included are a summary of lunar facts, the history of lunar probes and exploration, and a look at Shuttle Era lunar base applications.

INTRODUCTION

The Moon is Earth's only natural satellite and closest celestial neighbor. Relative to its primary, it is extremely large and the Earth-Moon system might be regarded as a "double planet". [See Table 1]. (ref 1, 2 & 3) Not too long ago the Moon was only an inaccessible celestial object - but today, through the technology of the Space Age, it has become a "planet" to visit, explore and eventually inhabit.

The Moon was the first planetary body surveyed by spacecraft (ref 4) [See Table 2]. From evidence accumulated by the early unmanned missions (e.g. Ranger, Surveyor and the Lunar Orbiter spacecraft) and by the Apollo Program (ref 5) [See Table 3] lunar scientists have constructed a history of the Moon dating back to its infancy. Because the Moon has no oceans (i.e. free water) and no atmosphere appreciable erosion has not occurred there. The primitive materials that lay on its surface billions of years ago are in an excellent state of preservation. We know that the Moon was formed some 4.6 billion years ago and differentiated quite early - perhaps only 100 million years after accreting (ref 6 & 7). Tectonic activity ceased eons ago on the Moon. The lunar crust and mantle are quite thick, extending inward to more than 800 kilometers. The deep interior of the Moon is still however unknown. It may contain a small iron core at its center and there is some evidence that the lunar interior may be hot and even partially molten (ref 7). Moonquakes have been measured within the lithosphere and interior - most being the result of tidal stresses. Chemically, the Earth and the Moon are quite similar,though compared to Earth the Moon is depleted in the more easily vaporized materials. The lunar surface consists of highlands composed of alumina-rich rocks that formed from a globe-encircling molten-sea, and maria made up of volcanic melts which surfaced about 3.5 billion years ago. However, despite all we have learned in the past two decades about our nearest celestial neighbor, lunar exploration has really only just begun. Several puzzling mysteries remain, including an explanation for the remnant magnetism measured in the rocks despite the absence of a lunar dynamo - and the origin of the Moon itself.

To initiate the further exploration of the Moon, we can first send sophisticated machines in place of men. For example, an unmanned lunar orbiter could circle the Moon from pole-to-pole remotely measuring its chemical composition, gravity, magnetism, and radioactivity. This Lunar Polar Orbiter mission would continue the scientific tasks started by the Apollo Program and would produce extensive maps of the entire lunar surface. Other robotic spacecraft, like the Soviet Luna-16 and Luna-20 landers, could be used to return small soil samples from previously unvisited regions such as the far side and the poles.

Then, when man himself returns to the Moon, it will not be for a brief moment of scientific inquiry as occurred in the Apollo Program, but rather as a permanent inhabitant - building bases from which to explore the lunar surface, establishing science and technology laboratories, and exploiting the lunar resource base in support of humanity's extraterrestrial expansion (ref 8).

HUMANIZATION OF CISLUNAR SPACE

Human development at the start of the Third Millennium will be highlighted by the creation of man's extraterrestrial civilization. Man's progress depends on challenge and growth. As we enter the next millennium, expansion into space offers an untapped, almost limitless resource base for human progress (ref 8 & 9). Despite contemporary doomsday predictions that exaggerate the Earth's finite resource condition and increasing population density, technical progress can continue through the use of extraterrestrial resources (ref 8, 10 & 11). The key, of course, will be the skillful exploitation and "humanization" of space - an evolutionary process in which mankind learns to use cislunar space to improve the quality of life for those on Earth. (ref 8, 9 & 12) The dynamic growth of mankind depends on an ever expanding "open world" outlook --- its opposite, the "closed world" philosophy leads to evolutionary stagnation (ref 9 & 13). Simply stated, a decision to exploit the extraterrestrial frontier gives man an infinite physical and resource environment in which to continue human development and growth.

We now have acquired the technical foundation for initiating the second phase of planetary development-expansion of the human resource base within our Solar System. The first phase of planetary development began with the origins of life on Earth and will culminate with the full use (and eventual depletion) of the terrestrial resource base. A third phase of planetary development, migration to the stars (ref 9 & 14), must await the successful exploitation of our own star system.

This extraterrestrial expansion of the human resource base will be accompanied by several key technology steps in the next few decades: (1) the development of reusable space transportation systems, such as the Space Shuttle; (2) the establishment of manned space stations, such as the proposed Space Operations Center (SOC), in low-Earth-orbit (LEO) and eventually in geosynchronous orbit or elsewhere as needed in cislunar space; (3) the development of space-based industries; (4) the creation of lunar bases and permanent settlements; and (5) the full exploitation of lunar and possibly asteroid resources. The Space Shuttle represents the U.S.commitment to the first step in extraterrestrial expansion. Firm national decisions for space stations and lunar bases are essential in the creation of a cohesive and coherent program of cislunar development for the benefit of all mankind.

MOON BASE APPLICATIONS

Many lunar base applications, both scientific and industrial, have been addressed in the technical literature since the Apollo Program (ref 15, 16, 17 & 18). Some of these concepts include: (1) a lunar scientific laboratory complex; (2) a lunar industrial complex to support space-based manufacturing; (3) an astrophysical observatory for Solar System and deep space surveillance; (4) a "fueling" station for cislunar cargo vehicles; (5) a nuclear waste repository for the very longlived radioisotopes (i.e. the transuranic nuclides) originating in terrestrial nuclear fuel cycles; and (6) the site of innovative political, social and cultural human developments-essentially rejuvenating man's concept of himself and his ability to change his destiny. All of these lunar settlement concepts are quite interesting and worthy of additional contemporary study, especially in light of the renewed interest in space that the Shuttle has stimulated.

This paper will limit detailed discussion to the use of lunar resources in support of space-based industries. The choice is predicated by the fact that the true stimulation for permanent lunar settlements will most probably arise from the desire for economic gain - a time-honored stimulus that has driven much terrestrial development.

Contemporary space systems studies involve the definition of major future large space systems in such areas as communications, manufacturing and energy for which the "stock" or building material must be transported from the Earth's surface to space for fabrication, construction and final assembly. These studies identify the major cost impact of transporting large quantities of materials from Earth and the potential environmental impact of large numbers of heavy lift launch vehicles ascending through the terrestrial atmosphere. A number of recent NASA studies (ref 19 & 20) and independent university efforts indicate the possibility that large space system material delivery and construction from lunar sources may be a potential economic and environmental advantage. This conclusion is based primarily on the fact that the energy required to transport lunar material into space is only some 4.5 percent of the energy required for transportation from the Earth (ref 19). One space industrialization scenario involves a lunar surface mining operation [Fig 1] which provides the required quantities of lunar material in a pre-processed condition to a space manufacturing facility that may be located at a number of possible locations in cislunar space, for example low-Earth-orbit or geosynchronous-Earth-orbit (ref 19). These delivered lunar materials would consist primarily of oxygen, silicon, aluminum, iron, magnesium, and calcium locked into a great variety of complex compounds. Table 4 presents the materials known to be available on the Moon as a direct result of the Apollo landings between 1969 and 1972. (ref 19) In time, lunar settlements could become the chief source of materials for space-based industries.

Numerous other tangible and intangible advantages of lunar settlements will accrue as a natural part of their creation and evolutionary development. For example, the high technology discoveries originating in a complex of unique lunar laboratories could be channeled directly into appropriate terrestrial economic and technical sectors as new ideas, techniques, products etc. The existence of "another human world" will obviously create a permanent "open world" philosophy for human civilization. Application of space technology, especially lunar base-derived technology, will stimulate a terrestrial renaissance, leading to an increase in the creation of wealth, the search for knowledge and even the creation of beauty by all mankind. Our current civilization - as the first to venture into cislunar space and to create permanent lunar settlements - will long be admired not only for its great technical and intellectual achievements but also for its innovative cultural accomplishments. Finally, it is not too remote to speculate that the descendants of the first lunar settlers will eventually become the interplanetary then starfaring portion of the human race. Perceived in the context of the Space Shuttle Era, the Moon and permanent settlements thereon could become man's gateway to the Universe.

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Table 1. Physical and Astrophysical Properties of the Moon.[1,2,3]

diameter (equatorial)	3476 km
mass	7.350 10^{22} kg
mass [Earth's mass = 1.0]	0.0123
average density	3.34 g/cm^3
mean distance from Earth (center to center)	384,400 km
surface gravity (equatorial)	1.62 m/s^2
escape velocity	2.38 km/s
orbital eccentricity (mean)	0.0549
inclination of orbital plane (to ecliptic)	5^{o} 09'
sidereal month (rotation period)	27.322 days
albedo (mean)	0.07
mean visual magnitude (at full)	-12.7

Table 2. Unmanned Lunar Probes and Spacecraft.[4]

Spacecraft	Launch Date; Nationality; Weight; Mission/Results
Pioneer 0	17 Aug 1958; USA; 38 kg; attempt to orbit Moon/launch vehicle exploded at an altitude of 16 km.
Pioneer 1	11 Oct 1958; USA; 38 kg; attempt to orbit Moon/ launch vehicle reached an altitude of 113,830 km then fell back into the South Pacific.
Pioneer 2	8 Nov 1958; USA; 39 kg; attempt to orbit Moon/ launch vehicle reached an altitude of 1550 km then fell back to Earth near Africa.
Pioneer 3	6 Dec 1958; USA; 6 kg; attempt to fly-by Moon/launch vehicle reached an altitude of 102,320 km then fell back to Earth over Africa.
Luna 1*	2 Jan 1959; USSR; 361 kg; attempt to impact Moon/partial success -- missed Moon by some 5000 kg, then entered solar orbit. [* Soviet data are from TASS bulletins]
Pioneer 4	3 Mar 1959; USA; 6 kg; lunar fly-by/successful--passed Moon at 60,500 km then entered solar orbit.
Luna 2	12 Sep 1959; USSR; 390 kg; impact Moon/successful--first lunar impact, struck 335 km from visible center.
Pioneer P-1	24 Sep 1959; USA; 170 kg; attempt to orbit Moon/launch vehicle and spacecraft destroyed in explosion during static test before launch.
Luna 3	4 Oct 1959; USSR; 435 kg; photography of far side of Moon/successful--returned pictures of 70 percent of lunar far side.
Pioneer P-3	26 Nov 1959; USA; 169 kg; attempt to orbit Moon/failure--launch vehicle shroud tore away during ascent, payload impacted near Africa.
Pioneer P-30	25 Sep 1960; USA; 176 kg; attempt to orbit Moon/failure--launch vehicle malfunction, payload impacted in Africa.
Pioneer P-31	15 Dec 1960; USA; 176 kg; attempt to orbit Moon/failure--launch vehicle climbed to an altitude of 13 km then exploded.
Ranger 1	23 Aug 1961; USA; 306 kg; high Earth orbit test of spacecraft/failure-- intended to climb to 1,102,850 km but remained in low Earth orbit.
Ranger 2	18 Nov 1961; USA; 306 kg; high Earth orbit test of spacecraft/failure--intended to climb to 1,102,850 km but remained in low Earth orbit.

Table 2. (--- continued ---)

Spacecraft	Launch Date; Nationality; Weight; Mission/Results
Ranger 3	26 Jan 1962; USA; 330 kg; attempted TV reconnaissance of Moon and hard landing/partial success--spacecraft missed Moon by 36,808 km, no TV pictures or landed instruments.
Ranger 4	23 Apr 1962; USA; 331 kg; attempted TV reconnaissance of Moon and hard landing/partial success--timer failure, spacecraft fell on far side of Moon, no TV pictures.
Ranger 5	18 Oct 1962; USA; 342 kg; attempted TV reconnaissance of Moon and hard landing/partial success--power failure caused spacecraft to miss Moon by 725 km, entered solar orbit.
Luna (unannounced)	4 Jan 1963; USSR; 1400 kg (?); attempted soft landing on Moon/failure--spacecraft achieved only Earth orbit.
Luna 4	2 Apr 1963; USSR; 1422 kg; attempted soft landing on Moon/partial success--lunar fly-by at 8500 km, entered solar orbit.
Ranger 6	30 Jan 1964; USA; 365 kg; attempted TV reconnaissance of Moon and hard landing/partial success--impacted on target but no TV pictures returned.
Ranger 7	28 Jul 1964; USA; 366 kg; TV reconnaissance of Moon and hard landing/success--returned over 4300 high resolution images of Moon before impacting on target at Mare Nubium.
Ranger 8	17 Feb 1965; USA; 367 kg; TV reconnaissance of Moon and hard landing/success--returned 7,137 high resolution images of Moon before impacting on target at Mare Tranquillitatis.
Kosmos 60	12 Mar 1965; USSR; 1470 kg; attempted soft landing on Moon/failure--spacecraft achieved only Earth orbit.
Ranger 9	21 Mar 1965; USA; 366 kg; TV reconnaissance of Moon and hard landing/successful-- returned 5,814 high resolution images of Moon before impacting inside Crater Alphonsus.
Luna 5	9 May 1965; USSR; 1476 kg; attempted soft landing on Moon/partial success--retrofire failure caused spacecraft to crash land on Mare Nubium.
Luna 6	8 Jun 1965; USSR; 1442 kg; attempted soft landing on Moon/partial success--missed Moon by 160,000 km, entered solar orbit.

Table 2. (--- continued ---)

Spacecraft	Launch Date; Nationality; Weight; Mission/Results
Zond 3	18 Jul 1965; USSR; 890 kg(?); photography of Moon's far side/success--returned 25 pictures of lunar far side then entered solar orbit.
Luna 7	4 Oct 1965; USSR; 1506 kg; attempted soft landing on Moon/partial success-- retrofired early, spacecraft crashed in Oceanus Procellarum.
Luna 8	3 Dec 1965; USSR; 1552 kg; attempted soft landing on Moon/partial success--retrofired late, crashed in Oceanus Procellarum.
Luna 9	31 Jan 1966; USSR; 1583 kg; soft landing on Moon/ success-- first lunar soft landing, 100 kg capsule returned photographs from lunar surface at Oceanus Procellarum.
Kosmos 111	1 Mar 1966; USSR; 1600 kg(?); attempt to orbit Moon/ failure--spacecraft only achieved Earth orbit.
Luna 10	31 Mar 1966; USSR; 1600 kg; to orbit Moon/successful-- first spacecraft to achieve lunar orbit; returned physical data from lunar orbit.
Surveyor 1	30 May 1966; USA; 995 kg; soft landing on Moon/success-- touchdown north of Flamsteed, returned 11,237 pictures from lunar surface.
Explorer 33	1 July 1966; USA; 93 kg; attempt to orbit Moon/partial success--spacecraft failed to approach Moon at proper velocity, achieved Earth orbit instead.
Lunar Orbiter 1	10 Aug 1966; USA; 387 kg; to orbit Moon/successful-- photographic mapping of lunar surface (Apollo landing sites).
Luna 11	24 Aug 1966; USSR; 1604 kg (?); to orbit Moon/success-- spacecraft achieved lunar orbit but did not return lunar surface pictures.
Surveyor 2	20 Sep 1966; USA; 1000 kg; attempt to soft land on the Moon/partial success--stabilization failure, spacecraft crashed southeast of Crater Copernicus.
Luna 12	22 Oct 1966; USSR; 1625 kg(?); to orbit Moon/success-- spacecraft returned images of lunar surface.

Table 2. (--- continued ---)

Spacecraft	Launch Date; Nationality; Weight; Mission/Results
Lunar Orbiter 2	6 Nov 1966; USA; 390 kg; to orbit Moon/successful--photographic mapping of lunar surface (Apollo landing sites and far side).
Luna 13	21 Dec 1966; USSR; 1595 kg(?); soft landing on Moon/successful--soft landing achieved on Oceanus Procellarum returned pictures of lunar surface, studied lunar soil density.
Lunar Orbiter 3	5 Feb 1967; USA; 385 kg; to orbit Moon/successful--photographic mapping of lunar surface (Apollo landing sites).
Surveyor 3	17 Apr 1967; USA; 1035 kg; soft landing on Moon/success--touched down in Oceanus Procellarum, returned images of surface, dug lunar soil with shovel.
Lunar Orbiter 4	4 May 1967; USA; 390 kg; to orbit Moon/successful--photographic mapping of large areas of Moon.
Surveyor 4	14 Jul 1967; USA; 1039 kg; attempted soft landing on Moon/partial success--signals ceased at lunar impact on Sinus Medii.
Explorer 35	19 Jul 1967; USA; 104 kg; to orbit Moon/successful--returned physical data from lunar orbit.
Lunar Orbiter 5	1 Aug 1967; USA; 390 kg; to orbit Moon/successful--photographic mapping of Moon, including much of far side.
Surveyor 5	8 Sep 1967; USA; 1005 kg; soft landing on Moon/success--soft landed on Mare Tranquillitatis and returned 18,006 pictures of lunar surface, performed first chemical analysis of lunar soil.
Surveyor 6	7 Nov 1967; USA; 1008 kg; soft landing on Moon/success--soft landed on Sinus Medii, returned 30,065 pictures of lunar surface, and performed chemical and mechanical studies of lunar soil.
Surveyor 7	7 Jan 1968; USA; 1040 kg; soft landing on Moon/success--landed near north rim of Crater Tycho, returned 21,274 images of lunar surface, and performed chemical analysis of lunar soil from trench it dug.
Zond 4	2 Mar 1968; USSR; 5800 kg(?); spacecraft test mission/partial success--flew to lunar distance but recovery in doubt.

Table 2. (--- continued ---)

Spacecraft	Launch Date; Nationality; Weight; Mission/Results
Luna 14	7 Apr 1968; USSR; 1615 kg(?); to orbit Moon/success--achieved lunar orbit, returned data on lunar mass distribution.
Zond 5	14 Sep 1968; USSR; 5800 kg(?); circumlunar flight/ successful--ballistic re-entry with biological specimens and pictures.
Zond 6	10 Nov 1968; USSR; 5800 kg(?); circumlunar flight/ successful-- lifting re-entry with biological specimens and pictures.
Luna 15	13 Jul 1969; USSR; 5800 kg(?); soft landing on Moon/ partial success--lunar orbit achieved, but crash landing occurred on Mare Crisium.
Zond 7	7 Aug 1969; USSR; 5800 kg(?); circumlunar flight/ successful--photographs of lunar far side taken and lifting re-entry accomplished.
Kosmos 300	23 Sep 1969; USSR; 5800 kg(?); soft landing on Moon/ failure--spacecraft only achieved Earth orbit.
Kosmos 305	22 Oct 1969; USSR; 5800 kg(?); soft landing on Moon/ failure-- spacecraft only achieved Earth orbit.
Luna 16	12 Sep 1970; USSR; 5800 kg(?); soft landing on Moon/ successful--landed on Mare Faecunditatis, performed automated lunar soil sample collection and returned it to Earth.
Zond 8	20 Oct 1970; USSR; 5800 kg(?); circumlunar flight/ successful--took photographs and accomplished ballistic re-entry.
Luna 17	10 Nov 1970; USSR; 5800 kg(?); soft landing on Moon/ successful--landed on Mare Imbrium, included Lunokhod 1 automated rover vehicle, which conducted long term exploration program.
Luna 18	2 Sep 1971; USSR; 5800 kg(?); soft landing on Moon/ partial success--spacecraft achieved lunar orbit,but crashed on landing at Mare Faecunditatis.
Luna 19	28 Sep 1971; USSR; 5800 kg(?); to orbit Moon/success--returned photographs and data.
Luna 20	14 Feb 1972; USSR; 5800 kg(?); soft landing on Moon/ successful--landed on Mare Crisium, made automated soil sample collection and returned it to Earth.

Table 2. (--- continued---)

Spacecraft	Launch Date; Nationality; Weight; Mission/Results
Luna 21	8 Jan 1973; USSR; 5800 kg(?); soft landing on Moon/ successful--landed near Le Monnier, included Lunokhod 2 automated rover vehicle.
Explorer 49	10 Jun 1973; USA; 328 kg; to orbit Moon/successful-- performed radioastronomy experiments from far side of Moon.
Luna 22	29 May 1974; USSR; 5800 kg(?); to orbit Moon/success-- achieved lunar orbit, took photographs and collected data.
Luna 23	28 Oct 1974; USSR; 5800 kg(?); soft landing on Moon/ partial success--soft landing in southern part of Mare Crisium, but drill damaged so no soil sample returned to Earth.
Luna 24	9 Aug 1976; USSR; 5800 kg; soft landing on Moon/ successful--performed automated soil sample collection in Mare Crisium and returned to Earth.

Table 3. A Summary of the Apollo Program Missions.[5]

Apollo 7	Dates: 11-22 Oct 1968 Crew: Schirra, Eisele, & Cunningham Mission Duration: 260 hours; 9 minutes Results: tested Apollo Command Module in Earth orbit.
Apollo 8	Dates: 21-27 Dec 1968 Crew: Borman, Lovell & Anders Mission Duration: 147 hours; 01 minute Results: first manned Saturn V launch; 10 manned orbits of the Moon.
Apollo 9:	Dates: 3-13 March 1969 Crew: McDivitt, Scott, Schweickart Command and Lunar Module Names: Gumdrop and Spider Mission Duration: 241 hours; 01 minute Results: Earth orbital mission; first manned flight of the Lunar Module; two extravehicular activities (128 min).
Apollo 10	Dates: 18-26 May 1969 Crew: Stafford, Young & Cernan Command and Lunar Module Names: Charlie Brown and Snoopy Mission Duration: 192 hours; 03 minutes Results: 31 manned orbits of the Moon; Lunar Module descended to within 14.5 km (9 mi) of the lunar surface.
Apollo 11	Dates: 16-24 Jul 1969 Crew: Armstrong, Aldrin & Collins Command and Lunar Module names: Columbia and Eagle Mission Duration: 195 hours; 19 minutes Results: first manned lunar landing: Sea of Tranquility; one lunar extravehicular activity (168 min); returned 20.9 kg (46 lb) of lunar samples.
Apollo 12	Dates: 14-24 Nov 1969 Crew: Conrad, Gordon & Bean Command and Lunar Module Names: Yankee Clipper and Intrepid Mission Duration: 244 hours; 36 minutes Results: manned lunar landing: Ocean of Storms; two lunar extravehicular activities (total 7 hours: 46 min); returned 34 kg (75 lb) of lunar samples.
Apollo 13	Dates: 11-17 Apr 1970 Crew: Lovell, Haise, & Swigert Command and Lunar Module Names: Odyssey and Aquarius Mission Duration: 142 hours; 55 minutes Results: lunar landing aborted after oxygen tank ruptured; safe recovery of crew.

Table 3. (--- continued ---)

Apollo 14	Dates: 31 Jan - 9 Feb 1971 Crew: Shepard, Roosa, & Mitchell Command and Lunar Module Names: Kitty Hawk and Antares Mission Duration: 216 hours; 02 minutes Results: manned lunar landing: Fra Mauro; two lunar extravehicular activities (total: 9 hrs; 23 min); returned 42.6 kg (94 lb) of lunar samples.
Apollo 15	Dates: 26 Jul - 7 Aug 1971 Crew: Scott, Irwin & Worden Command and Lunar Module Names: Endeavour and Falcon Mission Duration: 295 hours; 12 minutes Results: manned lunar landing: Hadley Apennine; three lunar extravehicular activities (total: 18 hrs; 35 min); returned 76.7 kg (169 lb) of lunar samples.
Apollo 16	Dates: 16-27 Apr 1972 Crew: Young, Mattingly & Duke Command and Lunar Module Names: Casper and Orion Mission Duration: 265 hours; 51 minutes Results: manned lunar landing: Descartes highlands; three lunar extravehicular activities (total: 20 hrs; 14 min); returned 93.9 kg (207 lb) of lunar samples.
Apollo 17	Dates: 7 - 19 Dec 1972 Crew: Cernan, Evans & Schmitt Command and Lunar Module Names: America and Challenger Mission Duration: 301 hours; 52 minutes Results: manned lunar landing: Taurus-Littrow; three lunar extravehicular activities (total: 22 hrs; 4 min); returned 110.2 kg (243 lb) of lunar samples.

Table 4. Available Lunar Materials.[19]

Elements	Percent By Weight		
	Mare	Highlands	Basin Ejecta
Oxygen	39.7 - 42.3	44.6	42.2 - 43.8
Silicon	18.6 - 21.6	21.0	21.1 - 22.5
Aluminum	5.5 - 8.2	12.2 - 14.4	9.2 - 10.9
Iron	12.0 - 15.4	4.0 - 5.7	6.7 - 10.4
Calcium	7.0 - 8.7	10.1 - 11.3	6.3 - 9.2
Magnesium	5.0 - 6.8	3.5 - 5.6	5.7 - 6.3
Titanium	1.3 - 5.7	0.3	0.8 - 1.0
Chromium	0.2 - 0.4	0.1	0.2
Sodium	0.2 - 0.4	0.3 - 0.4	0.3 - 0.5
Manganese	0.2	0.1	0.1
Potassium	0.06- 0.22	0.07 - 0.09	0.13 - 0.46
Hydrogen, Carbon, Nitrogen, Fluorine, Zirconium, Nickel		100 ppm	
Zinc, Lead, Chlorine, Sulfur, Other Volatiles		5 to 100 ppm	

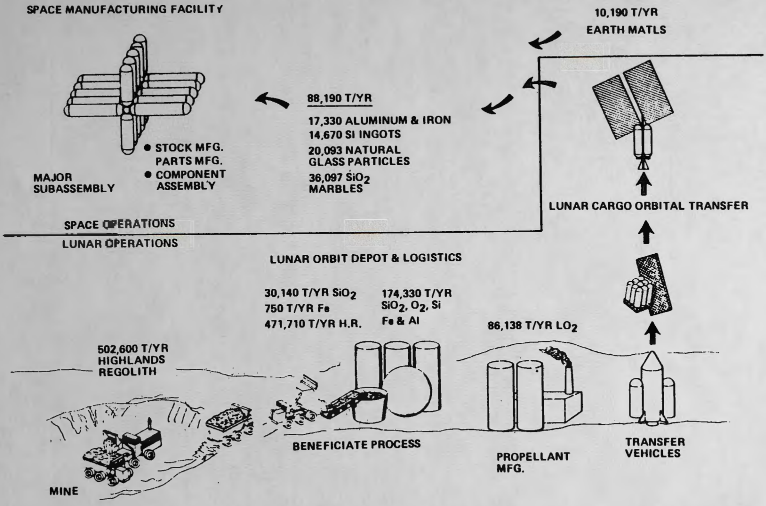
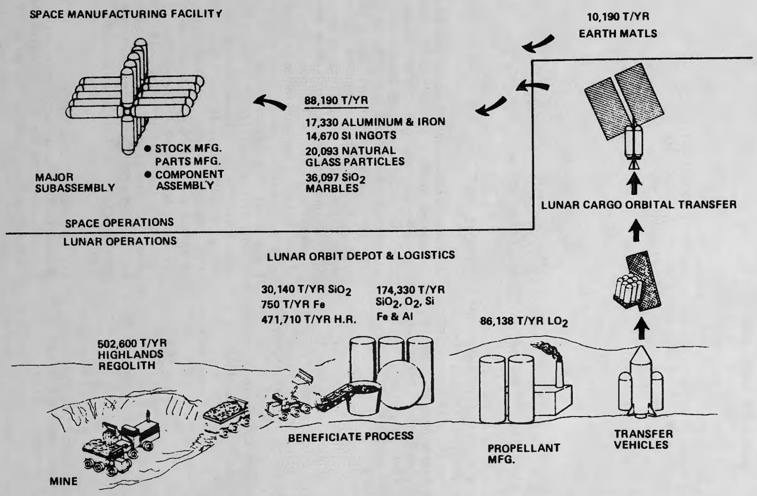


Figure 1. General processing and space-based manufacturing flow using lunar materials. (ref 19)



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