FIRST STEPS TO LUNAR MANUFACTURING: RESULTS OF THE 1988 SPACE STUDIES INSTITUTE LUNAR SYSTEMS WORKSHOP

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Prior studies by NASA and the Space Studies Institute have looked at the infrastructure required for the construction of solar power satellites (SPS) and other valuable large space systems from lunar materials. This paper discusses the results of a Lunar Systems Workshop conducted in January 1988. The workshop identified components of the infrastructure that could be implemented in the near future to create a revenue stream. These revenues could then be used to "bootstrap" the additional elements required to begin the commercial use of nonterrestrial materials.

The concept of using nonterrestrial and, particularly, lunar materials for the construction of solar power satellites, free-flying space habitats, and other economically, scientifically, and politically interesting structures in space has been gathering momentum for almost 15 years. Favorable recommendations in the National Commission on Space Report, chaired by Dr. Thomas Paine, and the special NASA study prepared by Astronaut Sally Ride have accelerated national and international interest in this area.

Although the overall concepts first published by Dr. Gerard K. O'Neill in 1974 in his article "The Colonization of Space" (*O'Neill*, 1974) still represent current thought, the systems concepts involved in the use of lunar resources have evolved considerably. As observed from the vantage point of the Space Studies Institute, a nonprofit organization founded in 1977 to conduct critical path research on the use of nonterrestrial resources, this evolution has taken place in four phases. The initial period of systems studies on nonterrestrial materials systems took place between 1974 and 1977. In addition to three Princeton University conferences on the subject (AIAA), there were three major NASA-supported summer studies that took place during 1975, 1976, and 1977 (*Johnson*, 1979; *O'Neill and O'Leary*, 1977; *Billingham et al.*, 1979). Studies in this era generally assumed implantation of full-scale systems on the Moon and in space with costs commensurate with that of the entire Apollo program (on the order of $60 billion).

The second era of systems thinking took place during the years 1977 and 1978. Building on the successsful demonstrations of Mass-Driver I, a prototype electromagnetic launcher constructed at M.I.T. by Professor Henry Kolm, O'Neill, and a group of graduate students, O'Neill continued to look for ways to reduce the investment required to produce economic returns from a nonterrestrial materials scenario. This work culminated in an article entitled "The Low (Profile) Road to Space Manufacturing" (*O'Neill*, 1978). This article suggested that by taking a step-wise approach to the build-up of the space infrastructure, significant reductions in system cost could be obtained. This incremental building approach was coupled with the concept of using the shuttle external tank as reaction mass for a Mass-Driver reaction engine. The combination of this low-cost, high-tonnage, orbital transfer vehicle and an incremental build-up reduced the investment required to obtain "ignition point" from $60 billion to approximately $24 billion. Ignition point was defined as the point where revenues earned equal investment.

During this same time period, the Space Studies Institute was founded to guarantee the continuation of nonterrestrial materials research. The third systems evolution occurred as the result of a series of workshops sponsored by the Institute in 1979 and 1980. These workshops examined various scenarios in an attempt to minimize start-up costs and to maximize growth of the system's ability to throughput lunar materials. The results of these workshops were detailed in an article entitled "New Routes to Manufacturing in Space" (*O'Neill et al.*, 1980). Figure 1 shows the three prime scenarios considered by the workshop groups. The favored scenario involves placing 100,000 kg of equipment on the lunar surface and approximately the same amount of equipment in free space. This is distributed over three general components. The first of these is a small lunar base that operates a Mass-Driver launcher to transport lunar materials to a collection point in space and that also has the capability of making partial copies of additional Mass-Drivers. The second component is a mass catcher to collect the launch materials. The third component is a space manufacturing facility, or "job shop," that processes the lunar materials and makes parts for additional Mass-Drivers, mass catchers, and job shops. Although the workshop concluded that it does not make sense to try to replicate the labor-intensive computers and precision components of machine tools, it reported that such a system could manufacture 95% of its own mass in a 90-day timeframe. Assuming the existence of orbital transfer vehicles and lunar landers, the cost of implanting the first such seed for the exponential growth of space industry would be about $6 billion. This is of the same order as the Alaska Pipeline or a pair of Magnus-class North Sea oil rigs.

Between the 1980 workshops and the 1988 Lunar Systems Study, a wide range of research on the use of nonterrestrial materials has been carried out by the Space Studies Institute.

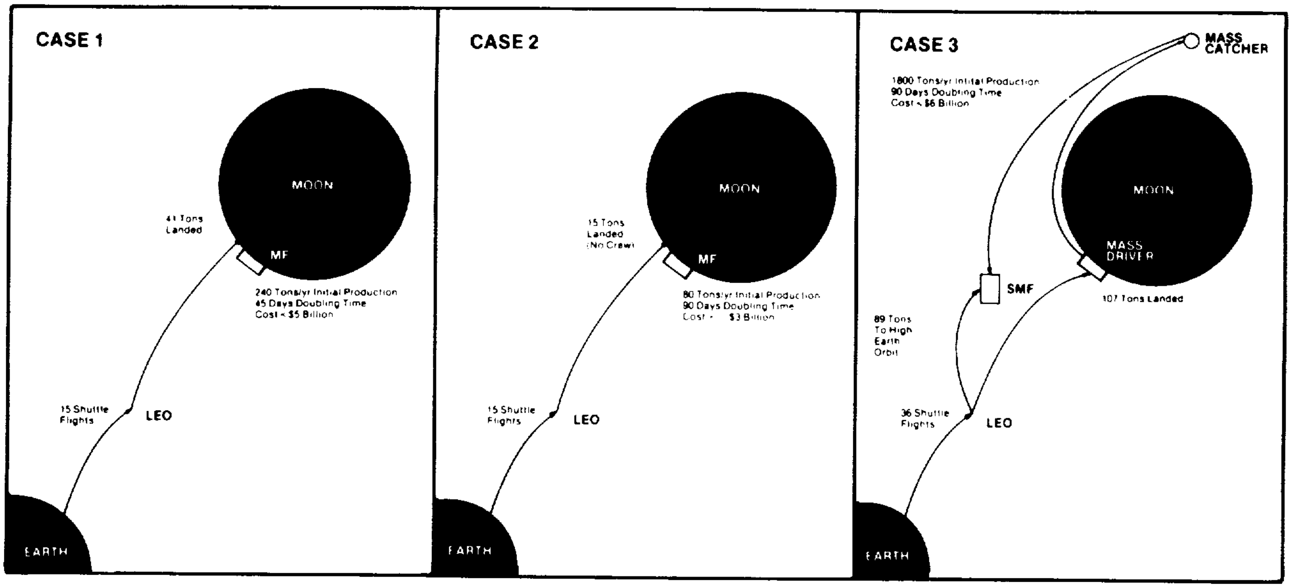

Fig. 1. "New Routes" Workshop Scenarios (1980). **Case 1.** Partially self-replicating system, with industrial operations only on the lunar surface. **Case 2.** Totally automated lunar-based system. **Case 3.** Partially self-replicating system on Moon and in orbit. Equipment on Moon used for replication of mass-drivers; equipment in space used for replication of wide range of components.

The results of these research projects can be found in the Proceedings of the SSI-sponsored conferences on Space Manufacturing held in 1974 and biennially since 1975. Table 1 shows the dates of the conferences and cosponsoring publishing organizations. Highlights of this research program have included a series of prototype Mass-Drivers constructed at Princeton University with accelerations ranging from 500 to 1800 *g*. A Mass-Driver with a 33-*g* acceleration (such as that exhibited in the first test of Mass-Driver I) would require an acceleration section of approximately 5 miles in length. With Mass-Driver III performance (1800 *g*), the length of the accelerator would be about 500 ft.

A hydrofluoric acid leach chemical processing technique has been demonstrated by SSI at a bench-scale level. Under Institute contract, Dr. Robert Waldron of Rockwell International conducted a series of experiments to determine upper limits to reaction times and impurity levels of the two most critical reagent elements, fluorine and hydrogen, in the output oxides produced by such a system. He produced a sizing analysis based on equipment and reagent inventory mass, and on power and cooling requirements necessary to the system. Key findings of this research include the determination that reagent replacement requirements appear to be less than 0.1% of the throughput mass of the system, and that by using the initial output of the system to manufacture additional plant equipment, a small starter plant made up of about 90% reagent material (by mass) could grow into a facility that would annually process about 500 times the original Earth import mass (*Waldron,* 1985).

TABLE 1. SSI/Princeton University conferences.

1974	AIAA	Vol. 1
1975	AIAA	Vol. 1
1977	AIAA	Vol. 2
1979	AIAA	Vol. 3
1981	AIAA	Vol. 4
1983	Published by AAS	
1985	AIAA	Vol. 5
1987	AIAA	Vol. 6

Conference proceedings for these years are available from the AIAA.

We have examined the use of the shuttle's expendable external tanks as a source of aluminum, hydrogen, and oxygen, in addition to applications as a structural element or pressure vessel.

We are developing the initial fabrication of glass and glass composite materials so that they can eventually be made entirely from lunar sources. In addition to requiring considerably less processing than metals chemically separated from lunar soil, these composites will have excellent thermal properties and may be used for structural beams as well as pressure vessels. A companion paper by principal composites investigator Brandt Goldsworthy was presented at this conference.

The Space Studies Institute has sponsored a design of the solar power satellite optimized for construction from lunar materials. The principal barrier to the development of large-scale space solar power systems for delivery of energy to the surface of the Earth is the cost of transporting construction materials from the surface of the Earth to construction sites in orbit. Although a Department of Energy and NASA study on implementing such an Earth-launched system was favorable (*U.S. Dept. of Energy,* 1980), a National Academy of Sciences overview study disagreed, largely on the basis of transportation costs (*National Research Council,* 1981). Studies performed by M.I.T. (*Miller and Smith,* 1979) and the Convair Division of General Dynamics (*Bock,* 1979) looked at substituting lunar material for terrestrial material in solar power satellite construction. However, both these studies were limited to using the Earth reference baseline for their design. Even so, the General Dynamics study suggested that 90% of an SPS could be lunar in mass, and the M.I.T. study indicated 96% of the mass could be lunar. A design study instituted by SSI was optimized not on low-launch weight but, instead, upon maximum use of lunar resources. Under contract to SSI, Space Research Associates of Seattle, Washington, designed a silicon planar solar power satellite that contained over 99% lunar materials. Figure 2 shows a mass comparison betwen the Earth baseline (Boeing) design, the General Dynamics lunar materials substitution design, and the Space Research Associates 1985 lunar design. The lunar design resulted in significant cost savings (97% less than the Earth baseline design) with a transport cost ratio assumed to be 50:1 for lunar materials. Furthermore, the lunar design was only 8% heavier than the Earth baseline (*Space Research Associates,* 1985).

The Institute also commissioned a study on the use of beamed power for space transportation (*Sercel,* 1986).

1988 WORKSHOP

In January 1988, a group of researchers convened at the GE Astro Space facility just outside Princeton, New Jersey, to reexamine the growth of a lunar systems infrastructure. The group agreed that its target would be to create one or more scenarios or business plans for the productive use of lunar materials. Our philosophy was that independent, profit-making space businesses could provide a robust, nonreversible course into space.

Under the direction of Dr. O'Neill, the group established a series of assumptions. All necessary political and regulatory approvals were assumed as given. Each business, or business stage, would have to reach revenue in five years from its first substantial investment, with profits within an additional two years. Although full cooperation of governments was assumed, no subsidies other than those already built into standard launch fees would be assumed. No launch vehicle not already developed could be used for planning purposes; however, any launch vehicle, including the Soviet Energia, could be specified. The existence of a fully reusable vehicle (or cooperating pair of vehicles) capable of transferring cargo and, if necessary, people between low Earth orbit (LEO) and the lunar surface was assumed. Viable businesses must produce at least 20% per year compounded return on investment.

Dr. Peter E. Glaser advised the group to think of space as being no different from the surface of the Earth in terms of economics. In effect, all terrestrial economic ground rules will still hold true on the high frontier. Further, he suggested that each new step that we take should not only provide economic return but should also provide a foundation for the next development step. That is, we should use a "terracing" approach to space development.

The workshop team was unanimous in the long-range goals of the space infrastructure system. Ultimately, such a system should be capable of processing sufficient lunar materials to enable the construction in free space of solar power satellites and eventually space habitats. However, it was also clearly understood that while the creation of such a system is technically possible, from a financial standpoint, the risks are presently too great and the payback period too long to make such a system fit our study criteria if accomplished in one effort.

Although the supply of lunar-derived oxygen has been widely discussed (*Andrews and Snow,* 1981) and appears to be a particularly attractive option for supplying exploration missions beyond cislunar space (*Woodcock,* 1988), it will require considerable infrastructure building to initiate and could not, in and of itself as a stand-alone enterprise, fall within the limits set by our study assumptions. We therefore decided to look at the subcomponents of our ultimately desired, nonterrestrial materials manufacturing scenario to identify the locations of critical nodes. We then created subteams to explore business plans for operations that could profitably develop at each of the nodal locations prior to the operation of the eventual total system.

Teams were created in each of the following areas: LEO node, space transportation, space power development, lunar surface operations, and space manufacturing.

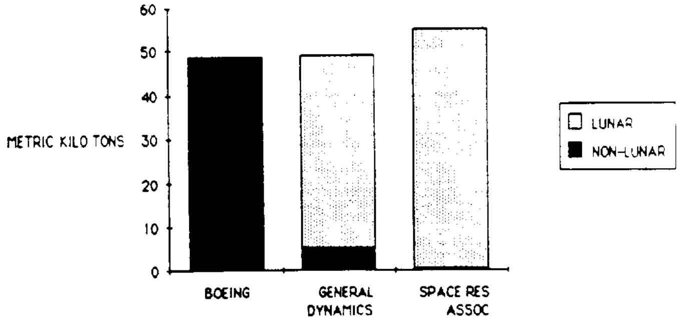

Fig. 2. 5 GW to Earth.

LOW EARTH ORBIT NODE

One of the underlying assumptions of the study was the existence of an orbital transfer vehicle and a lunar landing system to connect the surface of the Moon with LEO. These space transportation system components will require an LEO node for fueling payload integration and servicing. The LEO node group (F. Bailiff, D. Andrews, and A. Gimarc) looked at markets that could be serviced from an LEO facility, which could also service the lunar transportation system and return early revenues.

Several assumptions were made by the group. First, external tanks of the space transportation system are available for salvage. (This assumption was made approximately two months before the White House National Space Policy announcement that external tanks would be made available to corporations in orbit.) Second, residual propellants are assumed to be available for scavenging at cost. Also Orbiting Maneuvering Vehicle (OMV) sorties as well as Expendable Launch Vehicle (ELV) and shuttle sorties are assumed available at cost. Payload insurance is also assumed to be available at a price of 30%. The LEO group also defined two categories of markets. The first was a group of early markets. These included a storage facility for experiment racks and equipment for the U.S. and other space stations, a waste management facility, again assumed to be colocated with a space station, a volatiles storage facility, primarily for the storage of propellants, and a man-tended facility for experiments that could provide communications, power, and waste heat radiation.

Later markets that could be serviced by this node include a cryogenic storage and a refueling facility for OTV/OMV, a construction facility for the outfitting of additional external tank-based equipment, and a payload rescue capability to recover space equipment that had been placed in improper orbits or that required propellants or other servicing to extend their lifetime. Other possible markets are the rental of volume to commercial users, payload mating and launch to higher orbits, and training for commercial customers.

Growth of this type of commercial enterprise is expected to occur in three phases defined as follows. Phase I involves the buildup of a man-tended external tank plus a services module to provide internal storage, volatiles storage, waste management facility, and external support of commercial/scientific experiments. Phase II involves the buildup of a manned construction facility/commercial floor space and support, payload integration, OMV servicing and support, ELV payload support, shelter, and training of commercial crews. During Phase III a large, tethered cryogenics storage facility will be constructed and OTV support established.

Phase I would be a man-tended, single external tank and services module that would consist of a modified external tank with a services module and solar array located in a 28.5° orbit along the velocity vector of the space station. External tank modifications include internal hatches, tankage for propellants in the intertank section, external mounting in brackets, modification of the external tank tip for orbital maneuvering vehicle docking, and internal hardware in the hydrogen tank for storage of equipment racks. Additional support equipment includes the service module, teleoperators, a docking system, an electolysis reboost system, waste management, micrometeorite bumper, thermal shielding, communications, power, and miscellaneous support equipment. Start-up costs and potential market costs for Phase I are listed in Tables 2 and 3.

Phase II is a manned construction facility. The purpose of this unit would be the refitting of surplus external tanks for other commercial users. This phase would also include the introduction of the propellant scavenging operation and the development or purchase of a free-flying scavenger that could double as a manned OMV/OTV. Phase II would also involve the attachment of a space station logistics model to the second external tank, preparation of the hydrogen tank interior for shirt-sleeve environment, outfitting of the logistics module for manned habitation, and design and preparation for the launch of a future construction platform.

A second STS sortie will be purchased for delivery of the external tank, logistics module, and scavenger to the Phase I platform. A second 25-kW solar array would be attached. The interior of the second external tank would be made habitable for an initial crew of 8, which can be expanded to 24. A medium-lift ELV sortie (a Titan 4 or Proton class vehicle) would be purchased to deliver the construction platform, tools, and support equipment to the facility. If an external tank Aft Cargo Carrier (ACC) were available at reasonable cost in this timeframe, it could be purchased in place of the logistics module. (Phase II start-up costs were also computed and can be found in Tables 4 and 5.)

Phase III of the buildup of this node is a cryogenic storage depot. This requires the addition of a third external tank and module combination to the construct. This addition enables the node to service OTVs and lunar operations. The support module is configured for the reliquification of delivered oxygen and hydrogen and is used initially for the refueling of reusable OTVs. It is tethered below the initial Phase I and Phase II components. Estimated Phase III start-up costs and revenues are computed in Table 6.

The assumption that the tankage will be necessary at the rate of six OTV sorties is consistent with space station planning. Every traffic model that assumes a reasonable growth of activities in space requires some sort of cryogenic storage and servicing facility.

In summary, the commercial operation of an LEO services complex can, in its early stages, provide valuable warehousing, housekeeping, and other services to the space station, and in later phases it can service Earth and orbit lunar OTVs and show

TABLE 2. Start-up costs for Phase I.

Facilities	Cost ($ million)
Modified External Tank	1.00
Orbital Mods/Bumper	5.00
Logistics Module	20.00
Docking Adapter	0.25
Thermal/Comm/GN&C	1.00
Power 0.25 kWe	2.50
Electrolysis Reboost	10.00
Teleoperators (2)	10.00
Shuttle Launch	120.00
Insurance	15.00
Total	185.00

TABLE 3. Potential market costs for Phase I.

Market	Cost ($ million)
Garbage/Waste disposal- $1000/lb	15.00
Equipment storage- $1 m/rack/year	25.00
Volatiles storage- $1000/lb/yr at 10,000 lb/OMV sortie	10.00
Payload attach services- STS pallets flat - $2m/variable - $10m/(×2)	24.00
ELV grab - $3m/OMV sortie & Flat & Variable (Note: OMV sortie is additional charge) (×2)	24.00
Power Supplied- $0.5m/kWe/yr	4.00
Big LDEF facility- $1 m/experiment/yr	10.00
Total	112.00

TABLE 4. Start-up costs for Phase II.

Facilities	Cost ($ million)
Modified External Tank	5.00
Scavenger - Manned*	75.00
MLI/Bumpers/Attachments/Docking Adapters	5.00
Logistics/Service Module	25.00
Power (25 kWe)	2.50
Totals (approx.)	115.00
ELV Launch	50.00
Shuttle Launch	120.00
Insurance (30%)	35.00
Total	320.00

* Capacities: 30,000 lb LOX, 2000 lb LH_2, 1540 lb N_2O_4, and 960 lb MMH.

TABLE 5. Low Earth orbit node operations.

	Costs ($ million)	Sales ($ million)
Outfitting 4 ET/Yr	590.00	1180.00
ET & Module & Misc.		
Assembly - EVA $20K/hr	5.00	75.00
Assembly - IVA $3K/hr	5.00	6.00
10 Scavenger Flights	20.00	
Payload Rescue	10.00	60.00
6 OMV Refuelings		18.00
Totals	630.00	1339.00

TABLE 6. Start-up costs for Phase III.

Facilities	Cost ($ million)
Modified External Tank	5.00
Service Module Plus Equipment	55.00
Tanker DDT&E & 2 Copies	50.00
Totals (approx.)	110.00
Shuttle Launch	120.00
Insurance (30%)	33.00
Total	263.00

significant profit potential. An investment of $770 million in equipment facilities, sorties, and insurance could lead to a yearly profit in excess of $1 billion.

Figure 3 shows a drawing by Eagle Engineering artist Pat Rawlings of the LEO node after addition of the tethered Phase III cryogenics handling capability.

SPACE POWER

The space power subgroup (W. C. Brown and L. Snively) investigated means of bootstrapping space power utility systems. Given the relatively low cost of generating electrical power on the surface of the Earth in comparison to the cost of solar electric power in orbit, the group concluded that initial space power utility markets might be serviced by beaming terrestrial power from the surface of the Earth via microwaves or lasers. Markets for these services could include industrial facilities in LEO (*Brown,* 1987a) and might include powering electric propulsion orbital transfer vehicles from LEO to geosynchronous orbit (GEO) (*Brown,* 1987b). The cost required to build the terrestrial infrastructure network needed to support LEO-to-GEO OTVs is high (on the order of $1 billion), although the resulting transportation costs are very competitive with other proposed OTV systems. An alternative concept, recommended for further study by the group, would use terrestrially generated beams via a laser tuned to the optimum frequency for conventional solar cells. This method appears to be optimal from the point of view of low initial costs and acceptable overall transmission efficiences.

A logical progression from these initial systems would be the construction of a small-scale SPS, whose output would be transmitted via laser to users in GEO, LEO, and possibly for Earth-to-Moon OTVs. The size of such a platform (approximately 10 MW) would provide useful amounts of power as well as a test of solar power satellite construction and deployment. This size is consistent with proposals for the creation of a test SPS as an International Space Year project. The key uncertainty for space solar power is the size of the market for transmitted power.

LUNAR SURFACE NODE AND PRECURSOR MISSIONS

Lunar surface activities were explored by the workshop at two different levels including long-term lunar operations, e.g., permanent facilities and equipment, and precursor missions that would enable exploration, technology, development, and sortie mission activity prior to permanent lunar settlement.

Consensus of the group was that the primary product from precursor missions is information. Examples of this type of activity include small lunar-orbiting spacecraft that would provide a resolution of the question of the existence of water trapped as ice in the permanently-shadowed regions near the Moon's poles. Figure 4 shows a simple surface rover that would follow orbital surveys to provide high-resolution chemical, mineral, and perhaps isotopic ground truth in areas mapped by the orbiter as promising for resources. Because a small machine is likely to be upset by obstacles, the vehicles are designed to be self-righting in the manner suggested in the background of the picture. At this stage of development, it is likely that the primary customer for information produced in this manner would remain government entities.

In a sense, information gained from these missions could "bootstrap" other missions, especially if volatiles are located. (While the average man in the street would probably not quit his job because of a rumor of "ice in them thar hills," if water is located in abundance, it will dramatically reduce the costs of lunar transportation beyond initial prospecting missions.) The workshop sought private ventures that could be economically self-

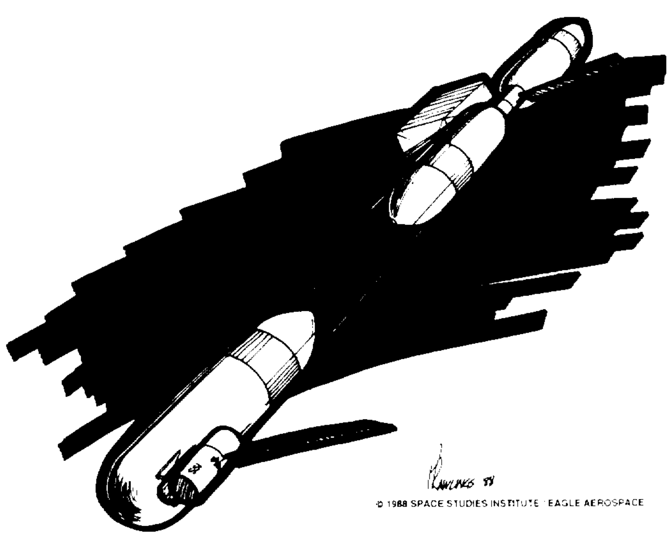

Fig. 3. LEO services node.

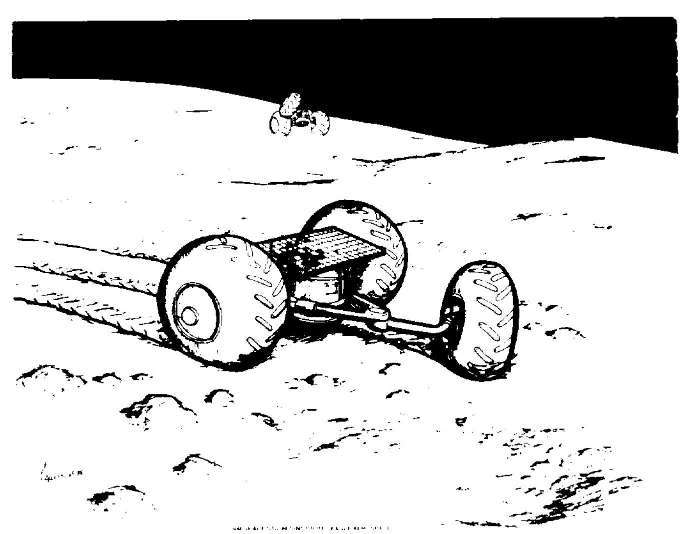

Fig. 4. Early lunar rover for geochemical "ground truth" surveys.

supporting and could provide information, material samples, and technology development without government support.

"A quick payback" subgroup (E. Bock, G. Maryniak, R. Temple, B. Tillotson, and R. Tumlinson) proposed a three-mission scenario of automated landers for an investment of approxiamtely one order of magnitude lower than that required for piloted systems.

The premise of the first mission is that a lunar landing stage is expended by a one-way trip with 10,000 kg of payload to the lunar surface. The payload is made up of six small teleoperated lunar rovers weighing 10,000 kg in aggregate. Two tonnes are devoted to a pilot LOX production plant, 3000 kg are core payload structure in avionics, and 1000 kg is comprised of TV cameras and transmitter, a robot arm and hand, and a demonstration electrostatic or electromagnetic beneficiator. Figure 5 is a drawing of a teleoperator being deployed from the landing stage. The overall cost of the first mission was estimated at $200 million with half that figure devoted to transportation at $11,000/kg predicted on a heavy-lift vehicle of the Energia class.

Most novel of these scenarios is sponsorship for a lunar surface race between some or all of the teleoperated vehicles. Development cost for the vehicles is assumed to be zero to the enterprise, as it is envisioned that these would be constructed by sponsors such as automobile manufacturers in order to obtain promotional consideration (Fig. 6). It was pointed out that the recent solar electric automobile race conducted in Australia was an approximately $20 million venture, just one order of magnitude below the cost of this mission. The rovers can also be used for performing a traverse of a scientifcally interesting region of the Moon, including a possible traverse from Copernicus to Kepler to Aristarchus and Gruithuisen. Tables 7 and 8 detail potential cost and income for such a mission. In addition to the entertainment and advertising aspects of the mission, which would provide consciousness-raising benefits for space development, this first mission would also include a pilot-scale LOX production plant that would process surface materials directly underneath the lander, or possibly those delivered by one of the teleoperators. In addition, one or more of the teleoperators would test magnetic and electrostatic beneficiation pilot models and could cache quantities of beneficiated feedstocks at the landing site throughout the equipment lifetime.

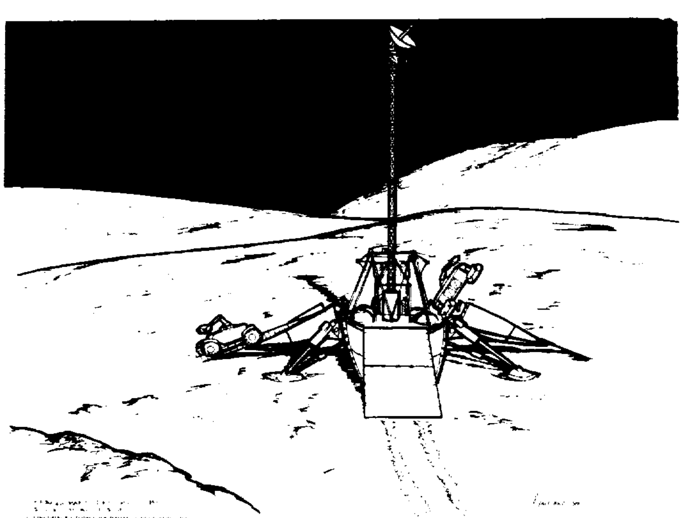

Fig. 5. Lunar lander deploying teleoperated rover.

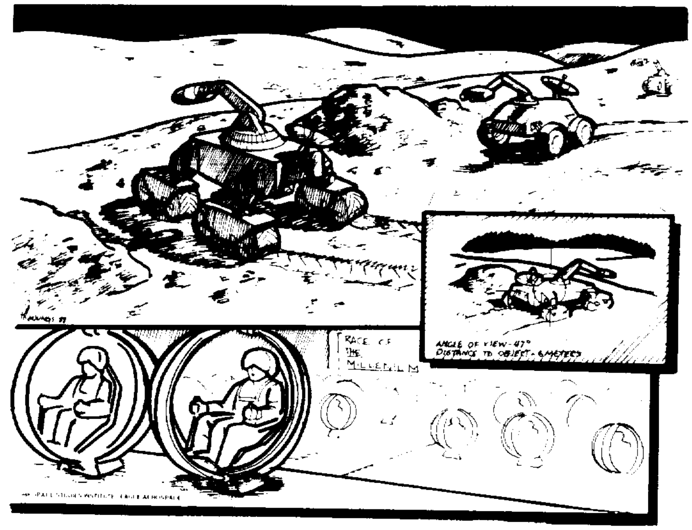

Fig. 6. Lunar teleoperated rover race.

The second mission is also unmanned, but the payload includes a small rocket that can return 1500 kg of selected lunar material to Earth. The automated payload also includes a second-generation LOX production plant to process small amounts of lunar iron and glass into high-value products for sale on Earth, such as lunar iron "coins" and lunar glass jewelry. After landing, adjacent to the first mission payload, iron, glass, and peculiar lunar surface samples collected by the six Mission I rovers are deposited in the Mission II lander. The unprocessed samples and processed coins and jewelry are returned to Earth, recovered, packaged, and sold to the public. The value of this lunar material is dependent on demand, but we have estimated that a price of $300-500 per carat is feasible. This provides rapid mission payback plus significant profits. Table 8 depicts the cost and potential income of the second mission.

The third automated mission demonstrates the ability to use lunar-produced oxygen as propellant to return an OTV lander to LEO with 8000 kg of lunar material payload. The payload to the Moon for this third mission is a much larger LOX propellant production plant and the LH_2 fuel and an aerodynamic braking shield for the return flight to LEO. Table 9 shows the third mission's activities. Although the revenues for these missions are derived largely from entertainment and trinket sources, if adequate markets exist, such missions could prove critical technologies, including lunar teleoperation, chemical and physical processing, and lunar propellant handling. The permanent lunar surface node group (E. Bock, J. Burke, L. Snively, and B. Tillotson) explored a range of private activities that could produce goods and services at a profit at that location. These could include provision of a turnkey lunar base or support for an existing base with life support, power, communications, teleoperations, landing facilities, storage, propellant supply, or food and supply cache and placement. Off-base markets could also include construction services to build private facilities, large antennas, scientific arrays, and rescue and emergency support services. The group also assessed the required components for such a lunar surface node and estimated current development stages for each (see Table 10).

TABLE 7. Mission I scenario.

Expend (soft land) OTV second stage on lunar surface.	
Leave OTV first stage in lunar orbit.	
Assume 10-tonne payload (direct from LEO).	
Payload (tonnes)	
Pilot LOX production plant	2.00
Six teleoperated lunar rovers	4.00
TV cameras and transmitter	
End effector	
Mech/electrostatic beneficiator	
Core TV and Earth transmitter	1.00
Core payload structure/avionics	3.00
	10.00
Cost ($ million)	
Development	
Payload core	20.00
Pilot LOX plant	20.00
Lunar rovers	0*
OTV/Lunar lander (expended)	40.00
Insurance	20.00
Total development	100.00
Transportation ($11,000/kg)	100.00
Total	200.00
Mission	
Lunar rover race (entertainment)	
Lunar product advertising	
Surface survey (materials)	
Iron and glass collection	
LOX production demonstration	
Collect unusual lunar surface samples	
Income ($ million)	
Sponsorship of lunar rovers by major automobile company ($20m × 6)	120.00
Subsponsor of rovers by auto equip. suppliers ($2m × 3 × 6)	36.00
Exclusive TV rights to race	20.00
Advertising during race	20.00
Marketing franchises	20.00
Filming rights	50.00
Fee to drive rovers on survey trips	2.00
Survey TV coverage	2.00
Advertising during survey coverage	5.00
Doc. of project (book/movie rights)	1.00
Gambling commission on lunar race	10.00
Total income	286.00
Schedule (years)	
Development	1-3
Production	3, 4
Launch	5
Payback	5

*Funded by sponsors.

TABLE 8. Mission II scenario.

Expend (soft land) OTV on lunar surface.	
Assume 10-tonne payload (direct from LEO).	
Payload (tonnes)	
Second generation LOX plant	3.00
Iron coin sintering equipment	1.00
Glass processing equipment	1.00
Return rocket for high value payload	5.00
	10.00
Cost ($ million)	
OTV/lunar lander (expended)	40.00
Development	
Payload core	10.00
LOX plant	20.00
Iron minting	5.00
Glass processing	5.00
Insurance	20.00
	100.00
Transportation ($11,000/kg)	100.00
	200.00
Mission	
Coin production from lunar materials	
Lunar glass jewelry production	
LOX production	
Return coins and jewelry to LEO	
Return unusual lunar samples	
Income ($ million)	
Return 1.5 tonnes of lunar material with value (when properly packaged) of $500/carat	750.00

TABLE 9. Mission III scenario.

Payload (tonnes)	
(UP) third generation LOX plant	6.00
LH_2 propellant and tankage	2.00
Aerobreak	2.00
	10.00
(Down) aerobreak	2.00
Lunar material/products	8.00
	10.00
Cost ($ million)	
OTV (expended)	30.00
LH_2 payload	2.00
Aerobreak	8.00
Third generation LOX plant	40.00
Insurance	20.00
Transportation	100.00
	200.00
Income	
Return 8 tonnes of lunar material with value of $200/carat	1600
Mission	
Land OTV with payload that includes	
Aerobrake for return to LEO	
Hydrogen propellant and tankage	
Third generation LOX production plant	
Transfer third generation LOX production plant to first OTV	
Fill newly landed OTV with LOX from earlier OTV/propellant plants	
Return newly landed OTV with 8 tonnes of lunar material payload to LEO	

Subsequent missions ready to supply LOX for manned missions.

LUNAR RESOURCES AND MANUFACTURING

The lunar processing and manufacturing subgroup (J. Burke, A. Cutler, R. Ness, S. Vetter, and G. Woodcock) examined products that could be manufactured at the lunar surface or at a space manufacturing facility, assumed for purposes of this study to be colocated with a mass catcher at libration point L2. Table 11 shows six classes of initial products that could be made from lunar resources. This figure also shows the feedstock materials necessary to produce them. Woodcock proposed that an examination of a LOX LH_2, fuel cell-based power storage system, which would

TABLE 10. Lunar surface node requirements.

Component	Intitial Source Earth	Space	Lunar	Later Source Earth	Space	Lunar	Development Stage*
Mass Driver	x			x		x	D
Construction/Assembly							
Crew (2+ for safety)	x			x			M
Intermittent Habitat							
Shielding (Dirt)			x			x	E
Consumables	x			x	x	x	D
Waste Reuse	x			x		x	D
EVA Suits	x			x			C
Vehicles	x			x			D
Landing Site							
Landing Pad			x			x	C
Beacon	x			x			E
Blast Shield			x			x	D
Refueling	x					x	C
Teleoperations	x			x		x	M/E
Spare Parts	x			x	x	x	—
Recharger	x			x		x	M/E
Comm links	x			x			M
Garage	x		x			x	E
Service and Repair	same requirements as assembly, above						
Power							
SP-100 or equiv.	x			x			D
Solar	x		x		x	x	C
Storage	x			x	x	x	C
Material Collector	x			x		x	D

* Key to development stages: Mature (M): production hardware is available off-the-shelf; Engineering (E): preproduction prototypes tested and in use; Development (D): operational prototype underway; Conceptual (C): idea with some theoretical support.

This table shows the parts needed for manned operations on the lunar surface. It shows the source of the initial supply of the component, and estimates where the later supply source. The final column gives an estimate of the state of the engineering for the component.

double as an oxygen production plant, would be a key production component (Fig. 7). The consensus of the group was that a good analysis of solar power and power storage options is an important tool for decision making about nuclear, solar, or other power generation options. Woodcock outlined the design and buildup sequence of a production facility that could produce 250,000 kg of LOX per year (Table 12). The ground rule for the facility was to run the production plant at at least 50% of its rating at night to avoid shut-down and attendant system damage. This equated into a 2-MW daytime power requirement for the plant and a 500-kW night requirement. To store the requisite 10^5 kWhr of energy would require approximately 40,000 kg of O_2 and 5000 kg of H_2 as fuel cell reactants. A 2-MW photovoltaic power array would provide 1 MW of power for daytime use and 1 MW of storage charging power. The mass budget for the plant would be 140,000 kg made up of solar collectors (40,000 kg), power conditioning (10,000 kg), storage tanks (45,000 kg), and reactants (45,000 kg). Since 40,000 kg of the reactant mass is O_2 and may be lunar derived, this requires a 120,000-kg delivery from the Earth. Table 12 depicts a buildup sequence for this facility and assumes that a Mass-Driver is used to export the oxygen to a libration point tank farm for eventual delivery to LEO.

TABLE 11. Initial lunar product categories.

	Iron	O_2	Soil	Glass
Power Generation		x		
Radiators	x	x		
Pressure Vessels	x			x
Propellant		x		
Shielding	x		x	
Structures	x			x

TABLE 12. Buildup sequence for LOX facility (at 20 tonnes per delivery).

1:	125 kW power module (no storage)
2:	Deliver 1/2 of reactant tanks
3:	Pilot O_2 production module (capacity 0.6 tonnes/week = 30 tonnes/year)
4:	Deliver 300-kW power module
5:	Deliver O_2 production module
6-9:	Four trips to grow to 250 tonnes/year
10-17:	Deliver lunar base (government option)
18-20:	Deliver 150 tonnes/year Mass Driver
21-22:	Deliver 200-tonne capacity tank farm to 1.2

During steps 1-5 spent landers provide 25 tonnes of storage capacity.

Another major emphasis of the production group was the utility of using iron from lunar regolith as a feedstock for space manufacturing. Iron exists in relatively pure form as a result of meteoric bombardment. Work by Agosto (*Agosto,* 1981) and others indicates that magnetic and electrostatic beneficiation may be suitable to provide fine iron powder without chemical processing. In addition to powdered metallurgy, common terrestrial iron processing techniques can be employed to make a wide variety of useful products from this common metal.

MISCELLANEOUS AREAS

In addition to the nodes previously described, Dani Eder outlined an air-launched system that could launch material into LEO for approximately $1000/kg. He also showed a tethered spaceport consisting of a landing platform at orbital altitude, but at less than orbital velocity. This is made possible by connecting the platform to a balast mass made of nonterrestrial materials (Fig. 8).

OVERALL IMPLEMENTATION

Figure 9 details the overall implementation scenario. Emphasis is on automated or teleoperated systems wherever possible, with the expectation that repair and maintenance will be performed with some on-site human assistance (E. Bock and B. Tumlinson).

CONCLUSION

The 1988 Lunar Systems Workshop continued the trend followed in the 1978 and 1980 evolutions of nonterrestrial materials system design toward smaller and less expensive implementations. Economic viability is the key to the growth and health of space systems, just as in terrestrial projects.

Market information is critical to economic analysis of space systems. Our group found that assessing market values of the systems was actually more difficult than addressing technical issues. Not surprisingly, market figures for activity closer in distance to the Earth and closer in time to the present are more accurate than those for lunar surface systems or those systems that will follow lunar systems operations.

Government can do two important things to accelerate the growth of space manufacturing systems. The first of these is to develop the required transportation infrastructure. Government

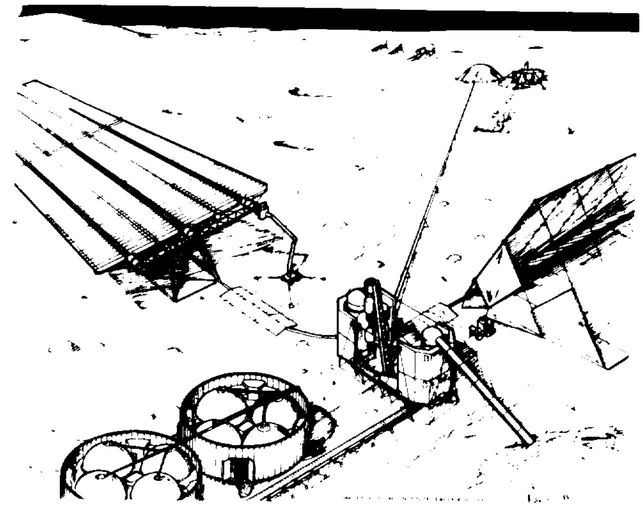

Fig. 7. Lunar oxygen production facility.

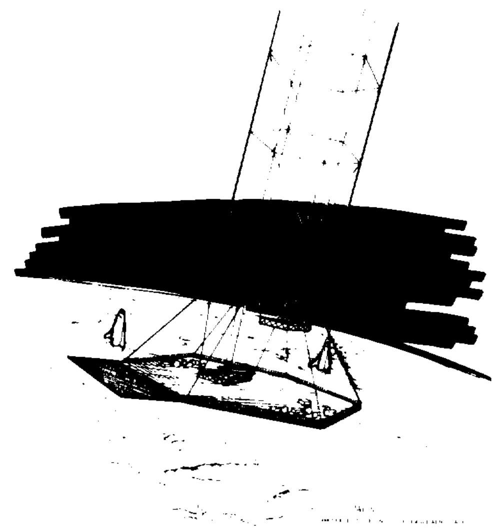

Fig. 8. Tethered LEO spaceport.

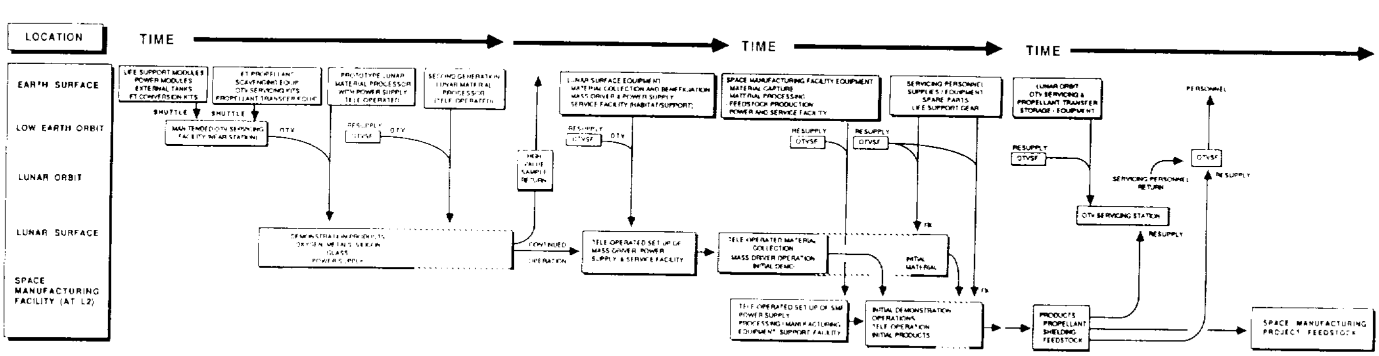

Fig. 9. NTM infrastructure timeline. This implementation scenario was authored by E. Bock and drawn by R. Tumlinson.

can also guarantee markets for commodities and manufactured products. If the markets are there, technical expertise and capital funds exist to address market needs.

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