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Utilization of Space Resources in the Space Transportation System

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Utilization of space resources (i.e., raw materials obtained from nonterrestrial sources) has often been cited as a prerequisite for large-scale industrialization and habitation of space. While transportation of extremely large quantities of material from Earth would be costly and potentially destructive to our environment, vast quantities of usable resources might be derived from the Moon, the asteroids, and other celestial objects in a cost-effective and environmentally benign manner.

Of more immediate interest to space program planners is the economic feasibility of using space resources to support near-term space activities, such as scientific and commercial missions in the 2000-2010 timeframe. Liquid oxygen for use as a propellant in a space-based transportation system appears to be the space resource that has the firmest near-term requirement for quantities great enough to be produced economically in a nonterrestrial setting. This paper identifies the factors most likely to influence the economics of near-term space resource utilization. The analysis is based on a scenario for producing liquid oxygen from lunar ore.

Analysis Methodology

The primary purpose of the parametric cost model developed as part of this study is to identify the factors that have the greatest influence on the economics of space resource utilization. In the near term, this information can be used to devise strategies for technology development so that capabilities developed will produce cost-effective results.

Predicting the actual costs of particular scenarios for space resource utilization is only a secondary objective of this analysis. Estimates are made and dollar values are assigned principally to allow comparison of options. Since the technologies for space resource utilization are in an early stage of development, it is premature to state conclusively whether mining the Moon, asteroids, or other celestial bodies makes economic sense. The parametric model is designed more for flexibility than for precision.

Although preliminary estimates indicate that production of oxygen from lunar ore is a project that is likely to yield an economic payback, this activity was selected as the "baseline scenario" primarily because its requirements can be relatively well defined. The major systems required to support this baseline scenario have been identified without much difficulty:

- A processing and storage facility to manufacture liquid oxygen (LO_2) from lunar ore and store it on the Moon
- A lunar habitat for a small, full-time crew
- A power system to support lunar LO_2 operations
- A transportation and logistics system to deliver and support the lunar base elements and to transport the LO_2 to low Earth orbit (LEO)

Systems Required To Support Production of Oxygen From Lunar Ore

This concept of a lunar base shows an oxygen plant in the foreground, habitats buried on the left, solar power systems for heat (at the plant) and light (for the habitats), ground transportation (trucks bringing ore and taking away products), and a surface-to-orbit ferry in the background. The same systems are pictured in the frontispiece, in the background on the right: reactors with their solar power, habitats being buried, a vehicle picking up products and transporting them to the launch area, a tanker just lifting off.

Once these major support systems were defined, fifteen key variables were identified as influencing the cost of developing and operating these systems (table 3). Cost variables were generalized so that the parametric model could be adapted to the evaluation of alternative scenarios. Next, equations were developed to calculate capital and operations costs as functions of these variables. Using the codes and units detailed in table 3, these equations are

$$\text{Capital cost} = (p \times c_p) + (n_t \times c_n) + (n_m \times c_u) + c_f + c_t \times [(p \times m_p) + (n_m \times m_m) + m_f]$$

$$\text{Operations cost} = c_t \times \{(n_r \times m_m) + [(1\text{-}d) \times 125\,000]\} + (n_b \times n_f \times \$100\,000)$$

where the capital cost is defined as the total cost of developing, building, and installing the lunar base elements (including transportation costs) and the operations cost is the annual cost of manufacturing 1 million kilograms (1000 metric tons) of LO_2 per year and delivering to LEO as much of this LO_2 as possible.

The term in square brackets [(1-d) x 125 000] in the operations cost equation reflects the assumptions that a portion (1-d) of the LO_2 produced on the Moon is used as propellant to deliver the remaining LO_2 (d) to LEO and that 1 kilogram of hydrogen must be delivered from Earth to the Moon for every 8 kilograms of oxygen used as propellant for the Moon-to-LEO leg (125 000 kg of hydrogen for the projected annual production of 1 million kg of oxygen). The higher-than-usual mixture ratio of 8:1 was selected for the baseline case after initial analyses showed that the resultant reduction in the hydrogen requirement offers substantial economic benefits.

The constant cost ($100 000) in the operations cost equation is the cost of ground support per provider per year. The variable that precedes this constant, n_f, is a ground support overhead factor which is multiplied by the labor cost to obtain total ground support cost.

TABLE 3. *Lunar Oxygen Production—Major Cost Variables*

Variable	Code	Units of evaluation
Power required	p	Megawatts of installed capacity
Cost of power	c_p	Nonrecurring cost ($) per megawatt of installed capacity
Number of types of lunar base modules	n_t	Number of types
Cost of modifying space station modules	c_n	Nonrecurring cost ($) for adapting each type of module
Number of lunar base modules	n_m	Number of units
Unit cost of lunar base modules	c_u	Recurring cost ($) of producing each lunar base module
Processing/storage facility cost	cf	Development and production cost ($)
Earth-to-Moon transportation cost	c_t	Cost ($) per kilogram delivered from Earth to the Moon
Power system mass	m_p	Kilograms per megawatt of installed capacity
Unit mass of lunar base modules	m_m	Mass (kilograms) of each lunar base module
Mass of processing/storage facility	m_f	Kilograms
Number of lunar base resupply missions/year	n_r	Number
Net lunar oxygen delivered to LEO	d	Fraction of lunar LO_2 produced which is delivered to LEO
Ground support labor	n_b	Number of people (full-time)
Ground support overhead factor	n_f	Multiplier of labor cost needed for total cost

After these cost equations had been set up, baseline values were assigned to each cost variable, using the ground rule that the technology having the lowest risk would be used for each system. Lunar base modules, for example, were assumed to be modified versions of the laboratory, habitat, and logistics modules that are being developed for NASA's LEO space station.

Another ground rule was that the costs of gathering the scientific data needed to select the lunar processing site would not be included in this model. It was further assumed that an initial lunar base would be in place prior to the LO_2 production activity and that this facility would be scaled up to meet the LO_2 production requirements. Thus, the cost included in this model is only the marginal cost of expanding this initial facility to produce LO_2.

Although some of these ground rules lowered capital and operations cost estimates, the specification of lowest-risk technology made these estimates higher than they might be if cost-reducing technologies are developed.

Results of the Analysis

Once baseline values were assigned to the cost variables, a simple calculation was made to obtain capital and operations cost estimates. These costs were determined to be

Capital cost: $3.1 billion
Operations cost: $885 million/year

An analysis of the performance of proposed lunar orbital transfer vehicles (OTVs) indicates that 49.2 percent of the LO_2 produced would be delivered to LEO. Consequently, the unit cost of LO_2 delivered to LEO, assuming 10-year amortization of capital costs, was determined to be $2430/kg ($1100/lb). This cost is one-quarter to one-third of the current cost of using the Space Shuttle, although it is somewhat greater than the cost that might be achieved with a more economical next-generation Earth-launched vehicle.

It should be reemphasized, however, that all cost estimates used in this analysis are based on a specific set of assumptions and are for comparative purposes only. The most important objectives of this analysis were the assignment of uncertainty ranges to each of the cost variables, the calculation of the sensitivity of LO_2 production costs to each of these variables, and the analysis of the technical and programmatic assumptions used to arrive at values for each variable. The data developed to support the sensitivity analysis are summarized in table 4. The baseline, best case, and worst case values assigned to each cost variable are shown, along with the impact of each variable's best case and worst case values on capital or operations cost. For example, as power requirements vary from a low value of 4 MW to a high value of 12 MW, with all other variables held at their baseline values, the capital cost for establishing the LO_2 production capability ranges from $2.30 billion to $3.90 billion. From this table it is evident that the principal driver of capital cost is the lunar base power requirement, while the Earth-to-Moon transportation cost is the most important operations cost driver. Since capital costs are amortized over a 10-year period, the Earth-to-Moon transportation cost has a much greater overall impact on the cost of lunar LO_2 in LEO. If this cost could be reduced from its

TABLE 4. *Capital and Operations Costs—Sensitivity to Cost Variables*

Variable	Baseline case	Best case		Worst case	
	Most likely value	Value	Result	Value	Result
	Capital cost				
1. Power required	8 MW	4 MW	$2.30B	12 MW	$3.90B
2. Cost of power	$100M/MW	$50M/MW	$2.70B	$200M/MW	$3.90B
3. Number of types of lunar base modules	1	0	$2.80B	2	$3.40B
4. Cost of modifying space station modules	$300M	$100M	$2.90B	$500M	$3.30B
5. Number of lunar base modules	1	1	$3.10B	3	$3.90B
6. Unit cost of lunar base modules	$200M	$100M	$3.00B	$300M	$3.20B
7. Processing/storage facility cost	$500M	$300M	$2.90B	$1.0B	$3.60B
8. Earth-to-Moon transportation cost	$10 000/kg	$5000/kg	$2.45B	$15 000/kg	$3.75B
9. Power system mass	10 000 kg/MW	5000 kg/MW	$2.70B	15 000 kg/MW	$3.50B
10. Unit mass of lunar base modules	20 000 kg	15 000 kg	$3.05B	30 000 kg	$3.20B
11. Mass of processing/storage facility	30 000 kg	15 000 kg	$2.95B	50 000 kg	$3.30B
	Operations cost				
1. Number of lunar base resupply missions/yr	1	1	$885M/yr	3	$1.285B/yr
2. Net lunar oxygen delivered to LEO	49.2%	70%	$625M/yr	30%	$1.125B/yr
3. Ground support labor	20 people	10 people	$860M/yr	50 people	$960M/yr
4. Ground support overhead factor	25	5	$845M/yr	50	$935M/yr
5. Earth-to-Moon transportation cost	$10 000/kg	$5000/kg	$468M/yr	15 000/kg	$1.303B/yr
6. Unit mass of lunar base modules	20 000 kg	15 000/kg	$835M/yr	30 000 kg	$985M/yr

baseline value of $10 000 to its best case value of $5000 per kilogram delivered to the Moon, capital cost would drop from $3.1 billion to $2.45 billion, operations cost would decline from $885 million/year to $468 million/year, and the cost of lunar LO_2 would be reduced from $2430/kg to $1450/kg. Conversely, at its worst case value of $15 000/kg, the Earth-to-Moon transportation cost would drive capital cost up to $3.75 billion, operations cost to $1.303 billion/year, and the cost of lunar LO_2 to $3410/kg.

An alternative approach to showing the impacts of the cost variables is illustrated in table 5. It lists the effect of each cost variable in terms of percentage changes in the capital or operations cost and in the cost per kilogram of LO_2 produced (with a 10-year amortization of capital cost). In this table the variables are ranked in order of their impact on the LO_2 cost/kg. The influence of each variable is calculated as an "impact factor" equal to the average of the percentage changes in LO_2 cost/kg due to the best-case and worst-case values of the variable.

TABLE 5. *Sensitivity of Capital, Operations, and Oxygen Production Costs to Ranges of Cost Variables*

Variable	Sensitivity ranking	Best case: Change in total cost	Best case: Change in LO_2 cost/kg	Worst case: Change in total cost	Worst case: Change in LO_2 cost/kg	Impact factor
			Capital cost			
Earth-to-Moon transportation cost	1	-21%	-40%*	+21%	+40%	40
Power required	2	-26%	- 7%	+26%	+ 7%	7
Unit mass of lunar base modules	3	- 2%	- 4%*	+ 3%	+ 9%	7
Cost of power	4	-13%	- 3%	+26%	+ 7%	5
Number of lunar base modules	5	0%	0%	+26%	+ 7%	4
Processing/storage facility cost	6	- 6%	- 2%	+16%	+ 4%	3
Power system mass	7	-13%	- 3%	+13%	+ 3%	3
Number of types of lunar base modules	8	-10%	- 3%	+10%	+ 3%	3
Cost of modifying space station modules	9	- 6%	- 2%	+ 6%	+ 2%	2
Mass of processing/storage facility	10	- 5%	- 1%	+ 6%	+ 2%	2
Unit cost of lunar base modules	11	- 3%	- 1%	+ 3%	+ 1%	1
			Operations cost			
Net lunar oxygen delivered to LEO	1	-29%	-45%	+27%	+97%	71
Earth-to-Moon transportation cost	2	-47%	-40%*	+47%	+40%	40
Number of lunar base resupply missions/yr	3	0%	0%	+45%	+13%	7
Unit mass of lunar base modules	4	- 6%	- 4%*	+11%	+ 9%	7
Ground support labor	5	- 3%	- 3%	+ 8%	+ 6%	5
Ground support overhead factor	6	- 5%	- 3%	+ 6%	+ 4%	4

*Impact based on changes in both capital cost and operations cost.

From these impact factors it is clear that two of the cost variables are far more important than all the rest: net lunar oxygen delivered to LEO and Earth-to-Moon transportation cost. The percentage of lunar-produced oxygen delivered to LEO is important because of its double impact. As the percentage of LO_2 delivered declines, LO_2 cost/kg increases not only because less LO_2 is delivered but also because more hydrogen must be transported from the Earth to match the LO_2 used as propellant from the Moon to LEO.

The six operations cost variables are among the nine most important, largely because the impact of capital cost is spread out over the 10-year amortization period. The relative significance of the operations cost leads to the important observation that LO_2 production costs may be reduced substantially by increasing capital expenditure on technologies that can reduce operations cost. One such technology is Earth-to-Moon transportation, which has a tremendous impact on operations cost. Capital cost factors, such as the mass and cost of the power system and of the processing/storage facility, have much less impact on LO_2 cost/kg.

Technology Development Required To Improve Performance

It is not possible to conclude, on the basis of this analysis, that production of liquid oxygen from lunar materials is justifiable on economic grounds. Although the cost estimates for the baseline scenario are encouraging, a number of technologies with significant impact on LO_2 production costs must be explored. The performance and cost of space-based orbital transfer vehicles is the most critical technology issue. Developing a low-cost OTV is a fundamental requirement for cost-effective utilization of space resources because the OTV is the single most effective means of reducing Earth-to-Moon transportation cost.

Another key issue is the cost of hydrogen used for launching payloads from the Moon. Production of lunar LO_2 would be far more cost-effective if a capability for the co-production of lunar hydrogen could be developed (even though capital cost might increase substantially). Although relatively large quantities of lunar ore would need to be processed, the additional cost of lunar hydrogen production could be offset by a savings of over $600 million/year in transportation cost. Production of some alternative propellant constituent, such as aluminum, also might offer an opportunity for reducing or eliminating costly import of fuels from Earth. However, this example would require the development of an aluminum-burning space engine.

A third category that seems to have substantial impact on the economics of lunar resource utilization is the technologies influencing lunar base resupply requirements. Increasing lunar base automation, closing the lunar base life support system, and other steps to reduce the frequency and scale of resupply missions appear to have a high likelihood of providing economic benefits and should be given particular emphasis in future studies.

If all three of these objectives were met to the greatest extent possible (i.e., if Earth-to-Moon transportation cost were reduced to its best case value, if hydrogen transportation requirements were eliminated, and if lunar base resupply requirements were eliminated), the cost of lunar LO_2 delivered to LEO would be reduced from $2430/kg to $600/kg, or about $270/lb. These figures assume no change in capital cost; but, even if capital cost were doubled to achieve these capabilities, LO_2 cost would be reduced to approximately $1100/kg—less than half the baseline cost.

Twenty-five key technology issues influencing these and the other cost variables in LO_2 production are presented in table 6. In this table, a dark square indicates a stong impact of that technology issue on the cost variable, a light square indicates a moderate impact, and no square indicates little or no impact. The selection and evaluation of these technology issues was made by a panel of experts convened for the purpose, not by a quantitative analysis. The fifteen cost variables ranked as in table 5 are listed across the top of table 6 in descending order of importance. Hence, table 6 is a graphic representation of the relative importance of the technologies based on three considerations: total number of squares, number of dark squares, and distribution of squares to the left of the chart (i.e., toward the most important cost variables).

TABLE 6. *Impact of 25 Key Technology Issues on Cost Variables in Space Resource Utilization*

■ heavy impact

□ moderate impact

(blank) little or no impact

		d Net lunar oxygen delivered to LEO	c_t Earth-to-Moon transportation cost	p Power required	n_r Number of lunar base resupply missions/yr	m_m Unit mass of lunar base modules	c_p Cost of power	n_b Ground support labor	n_m Number of lunar base modules	n_l Ground support overhead factor	c_l Processing/storage facility cost	m_p Power system mass	n_l Number of types of lunar base modules	c_n Cost of modifying space station modules	m_l Mass of processing/storage facility	c_u Unit cost of lunar base modules
		71	40	7	7	7	5	5	4	4	3	3	3	2	2	1
Power	Lunar base power source (nuclear vs. solar)						■					■				
Power	Scalability of small (<100 kW) power systems						■									
Power	Electrical vs. thermal energy						■				□	■			□	
Power	Power consumption of processing technique(s)			■												
Power	Complexity of power system installation						■									
Power	Maintainability of power system				□		■					■				
Operations	Pressurized volume required for lunar operations				□	■			■					□		□
Operations	Duration of lunar base crew shifts				■				□				■	□		□
Operations	Degree of automation of lunar base operations			□	■	□	■	■	■	■	■	□	□	■	■	■
Operations	Size of lunar base crew			□	■	■		■	■				■			
Operations	Self-sufficiency of lunar operations			□	■	■		■	■	□	□		■		□	
Operations	Ground support approach							■		■						
Base	Commonality of lunar base module w/ space station modules													■		■
Base	Lunar base shielding requirements					■								□		□
Base	Space station interfaces													□		
Base	Scalability of initial lunar research facilities			□			□		□			□	□			
Base	Degree of closure of lunar base life support system				■	■		■	□	□			□	□		□
Factory	Complexity of lunar factory processes			□	□	□		□	□		■		□	□	■	□
Factory	Number of lunar factory processes			□	□	□		□	□		■		□		■	
Factory	Commonality of processing facility w/ space station lab modules										■				□	
Factory	Commonality of LO_2 storage unit w/ OTV propellant depot										■					
Factory	Availability of lunar hydrogen	■		■				□			■				■	
Transport	Performance and cost of SDLV/HLLV (if available)		■													
Transport	Performance and cost of OTV (if available)	■	■		□			□								
Transport	Availability of aerobrake for LO_2 delivery	■														

To quantify the impact of these twenty-five technology issues on the economics of the baseline scenario for space resource utilization, a technology weighting factor of 3 was assigned to each dark square and a factor of 1 to each light square. These technology weighting factors were then multiplied by the impact factor (table 5) for each cost variable that the technology issue affects. The sum of the products across each row was calculated as the total economic weighting factor for that technology issue. For example, the lunar base power source has a heavy impact on cost of power and power system mass for an economic weighting factor of (3 x 5) + (3 x 3) = 24.

The ten most important technology issues, according to their total economic weighting factors, are listed in table 7.

TABLE 7. *Major Technology Issues in the Cost-Effective Production of Lunar Oxygen*

Issue	Economic weighting factor*
1. Performance and cost of OTVs	345
2. Availability of lunar hydrogen	254
3. Availability of aerobrake for LO_2 delivery	213
4. Performance and cost of Shuttle-derived launch vehicle (SDLV) or heavy lift launch vehicle (HLLV)	120
5. Degree of automation of lunar base operation	119
6. Self-sufficiency of lunar operation	94
7. Size of lunar base crew	85
8. Degree of closure of lunar base life support system	71
9. Complexity of lunar factory processes	51
10. Number of lunar factory processes	48

*Each of 25 key technology issues was assessed with respect to its influence on the 15 cost variables. Weights were assigned on the basis of the subjective judgment of a panel of experts. These weights were multiplied by an "impact factor" for each cost variable (based on the sensitivity of the cost of lunar LO_2 to the variable) affected by the technology issue.

Finally, it is important that parametric cost analyses such as this one be used to assess a variety of space resource utilization scenarios. Use of lunar ore for production of construction materials is one such option, although to be cost-effective this type of enterprise would probably require a dramatic increase in space activity. Another option that merits careful consideration is the development of asteroidal resources. Both rocket propellants and construction materials could be derived from asteroids; and, while the up-front cost of asteroid utilization would probably exceed the capital expenditure required for lunar development, operations cost could be substantially lower. Further analysis of all these opportunities needs to be carried out over the next several years before a commitment is made to any particular plan for space resource utilization.

As new technologies are developed, the reliability of cost estimates for space resource utilization will improve. Eventually, it will be possible to generate cost estimates of sufficient fidelity to support detailed definition of space utilization objectives. An important step in this process will be the adaptation of this parametric model and similar techniques to the evaluation of a broad range of space resource development options.