LUNAR RESOURCES UTILIZATION— AN ECONOMIC ASSESSMENT

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Abstract

In this paper, a solar power satellite (SPS) program scenario was analyzed to determine the economic viability of using lunar resources for manufacturing and constructing large structures in space. Three concepts featuring lunar resource utilization (LRU) were derived and compared with a NASA/JSC-furnished earth baseline concept. The economic assessment of the alternatives included cost determination, economic threshold sensitivity to manufacturing cost variations, cost uncertainties, program funding schedule, and present value of costs. It was found that LRU is potentially more cost-effective than earth-derived material utilization, depending upon such factors as the efficiency of the facilities and the manufacturing chain as well as the type of ownership and organization of the earth-based and lunar-based scenarios. Because of the uncertainties, cost-effectiveness cannot be ascertained with great confidence. The probability of LRU attaining a lower total program cost within the 30-year program appears to range from 57 to 93 percent.

I. Introduction

Space has often been called the new frontier. Its potential uses and benefits to mankind are without limit. In the last 20 years, the world has seen tremendous progress toward the conquest of space: the launching of the Sputnik in the fifties, men on the moon in the late sixties, and finally, the space shuttle era of today. Concepts of large orbiting space structures, such as communications platforms and solar power satellites, are presently in the concept definition stages. Such uses of space can potentially provide the same benefits to world users at a lower cost than do earth-based systems. An interesting parallel to the earth-based versus space-based alternative has been posed by NASA/JSC in the study, "Lunar Resources Utilization for Space Construction." That parallel is to determine if LRU is more cost-effective than earth resource utilization in the fabrication of very large space structures, and if so, at what threshold level, in terms of the number of satellites fabricated. The study was performed under contract NAS9-15560 by General Dynamics Convair Division, San Diego, California. The lunar alternatives were compared with an established earth baseline for fabricating solar-powered satellites. A discussion and description of the LRU alternatives are contained in a companion paper entitled, "Development of Space Manufacturing Systems Concepts Utilizing Lunar Resources," AIAA, paper No. 79-1411. The author, Mr. Edward H. Bock, addresses the technical issues of each concept.

The following is a brief description of each concept:

1. Earth Baseline (Concept A): Construction of 10 GW SPS at a rate of one per year for 30 years. All materials are earth-derived, and processing and manufacturing are earth-based. The heavy lift launch vehicle is used to transport finished material, parts, and assemblies to low earth orbit (LEO), where they are assembled into the basic modules of the SPS at the LEO construction facility. The modules are transferred to the geostationary earth orbit (GEO) construction facility for final assembly. Transportation elements include the heavy lift launch vehicle, space shuttle, expendable cargo orbital transfer vehicle (COTV), and reusable personnel orbital transfer vehicle (POTV).
2. LRU Concepts: Approximately 90 percent of the material required for each satellite is fabricated from lunar material that has been processed in space or on the lunar surface. All concepts require a shuttle-derived vehicle for earth-to-LEO material and personnel transfer, a fleet of reusable ion electric COTVs, and LH_2/LO_2 POTVs. Each concept contains lunar and space-based facilities for lunar soil extraction, processing, and manufacturing, as well as associated support facilities (i.e. habitats, power plants, and propellant depots). All oxygen propellant used in space is lunar-derived. The major differences between the LRU concepts are in the location of the processing facilities and the manner in which the lunar material is transferred to the space manufacturing facility (SMF).
   - In-Space processing and manufacturing (Concept B): Lunar-to-SMF material transfer accomplished with mass driver catapult and mass catcher.
   - Lunar processing and stock manufacturing (Concepts C & D): Construction material transported to low lunar orbit for COTV transport to the SMF for manufacture, structural fabrication, and final assembly; Lunar-to-space material transfer accomplished using a LO_2/LH_2 lunar transfer vehicle (LTV) for Concept C and LO_2/Aluminum lunar-derived rocket (LDR) for Concept D.

II. Methodology

The approach to the economic assessment began with the organization and definition of the costs within each concept alternative and includes an estimate of cost uncertainties, cost sensitivities, funding spreads, and, finally, a present value analysis. These factors were used to evaluate each alternative and served as a basis for comparison among alternatives. A discussion of each major area of economic assessment is contained below.

Cost — The purpose of the cost analysis was to compare the program costs of each LRU concept with the earth baseline concept costs provided by NASA/JSC. In order to obtain consistent comparisons, a work breakdown structure (WBS) was developed that was compatible with all concepts. The earth baseline costs were categorized into this WBS for comparison with the study-generated LRU concept costs. The approach to total program cost determination for the LRU concepts was to develop first the costs of the primary elements (i.e., processing and manufacturing, transportation and infrastructures) and then to assemble them into the WBS for comparison with the baseline. Comparisons were made to explain major cost differences and to identify areas of uncertainty. Finally, a determination was made of the nominal thresholds, where lunar resource utilization becomes more cost effective. Subsequent study tasks, including the cost sensitivity, uncertainty, and present value analyses, used the nominal costs determined in this task as a base.

Sensitivity — A major assumption used in determining LRU concept costs was a vertically integrated manufacturing chain, owned and operated by a single entity. This assumption resulted in a manufacturing cost savings equivalent to the expected transportation savings. This manufacturing cost saving may not have been found had the LRU manufacturing chain been more like the earth baseline chain — with its many owners and inefficiencies. The purpose of the sensitivity analyses was to determine the economic thresholds when manufacturing costs for each LRU concept were the same as the earth baseline. If the assumption regarding the LRU manufacturing chain is erroneous, this sensitivity analysis shows the effect on the economic threshold points.

Uncertainty — The uncertainty analysis complements and expands the cost and sensitivity analyses tasks. Nominal costs represent point cost estimates which are based on historical data, direct quotes, analyst judgment, and extrapolations of previous cost estimates. There is a great deal of uncertainty associated with these point cost estimates in the areas of supply/demand shifts, unknowns in the space/lunar based manufacturing chain, and the state of definition of the hardware and program characteristics. The uncertainty analysis attempts to quantify that uncertainty, providing a measure of confidence in our ability to accurately compare future conceptual projects. The consideration of uncertainties can significiantly affect the economic threshold point where the LRU concepts become cost effective.

Program Funding Schedule and Present Value Analysis — The timing of required expenditures and the present value of each program's total cost were determined to provide additional economic comparisons of the concepts. Nominal cost estimates consider the magnitude of cost but not the timing of the required expenditures. A funding requirements analysis allows timing to be considered. The present value analysis allows consideration of both the timing of cash flows and the time value of money.

III. Cost Analysis

A flexible and comprehensive cost WBS was established to ensure that valid cost comparisons could be made in the comparative evaluation process. The cost WBS assures that costs for each manufacturing scenario are organized under the appropriate cost elements and that like costs are compared with one another. A summary WBS is shown in Figure 1. The basic organization was derived from the categories in a NASA-furnished SPS earth baseline document with allowances for categories which arise under the lunar and space-based scenarios.

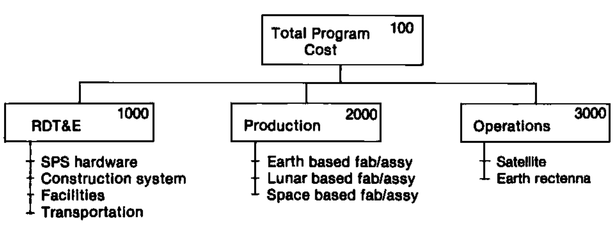

Figure 1. SPS summary work breakdown structure.

Costs from the SPS Baseline data were categorized into the WBS format and served as a basis for comparison with the LRU concepts. Costs were then developed for each LRU concept. Each of the three LRU concepts contain some elements which have never been analyzed or costed before. Other elements are similar to those of previous NASA studies. Due to this similarity, most of the LRU element costs were derived or scaled from those studies. Existing cost estimates for space stations, space construction bases, orbital transfer and launch vehicles were applied to obtain cost relations for propellant depots, habitats, facilities, vehicles and other LRU elements. Some LRU elements exhibit conceptual and innovative characteristics which are not similar to previously studied space systems. For these elements (e.g., mass driver catapult and manufacturing equipment) costs were based on direct analogies with similar industrial products or services, and with cost estimating relationships.

The primary ground rules and assumptions used in making economic estimates are outlined below.

1. Costs are expressed in constant year 1977 dollars. Current prices are assumed. No attempt was made to adjust costs for changes in future supply and demand.
2. Satellites will be produced at a rate of one per year for 30 years. Operations costs are limited to the 30-year period, starting with the operation of one satellite in the first year and ending with the operation of 30 satellites in the 30th year.
3. The following costs are the same for the earth baseline and LRU concepts: 1) SPS hardware development (satellite & rectenna); 2) Earth rectenna production; and 3) Development/fabrication of orbiting construction systems
4. No new earth-based SPS hardware manufacturing facilities are required for the LRU concepts, since only 10 percent of the satellite is constructed of components obtained from earth. The following earth-supplied production items were assumed to be purchased from existing earth suppliers: 1) Earth rectennas; and 2) any satellite equipment which cannot be fabricated in space or satellite material not obtainable from the lunar soil.
5. Earth-based support facilities, such as mission control, administration, and sustaining engineering, were assumed to be existing, and no charges were included for these facilities in either the earth baseline or the LRU concepts. The recurring cost of manning and operating these facilities in support of the lunar/space-based manufacturing is assumed to be three percent per year of the cost to fabricate the manufacturing facilities. The requirements for lunar and space-based launch facilities are assumed minimal, and no costs were included for their development or construction.
6. Lunar resources are not used to fabricate the lunar and space-based facilities. These facilities are fabricated on earth, transported to final location, and assembled during the facility activation phase.
7. The lunar and space-based facilities in all LRU concepts are owned and operated by a single entity that is in business for the purpose of selling power for profit. This entity uses the facilities to manufacture and construct the SPS fleet and purchases from earth only those materials not available from the lunar soil. The earth baseline costs are predicated on the normal way of doing business on earth (i.e., the entity purchases, rather than manufactures, the majority of SPS hardware from independently owned, earth-based firms).

Like the earth baseline, LRU element costs were categorized into the WBS in Figure 1 and program costs were obtained. A summary cost comparison is shown in Table 1. Costs are expressed in $/kW of installed capacity (300 GW). On a nominal basis, total costs of the LRU concepts could potentially provide a significant savings over an earth-based approach.

For further comparison, estimated construction costs for terrestrial nuclear and coal-fired generating plants are in the 500 to 1,000 $/kW range. SPS construction costs (RDT&E + Production) are 1,400 to 1,600 $/kW for the three LRU concepts and 2,400 $/kW for the earth baseline. All of the approaches require a much higher investment in facilities than do current terrestrial power plants. This is offset, however, by lower SPS operating costs. No fuel is required, and maintenance is low due to the passive generation system.

Data in Table 1 was used to compute the cost of delivering energy to the ground transmission system at the ground distribution system bus-bar. Assuming a 60 percent capacity factor, the bus-bar generation costs are approximately 7¢/kW-hr for the LRU concepts and 11¢/kW-hr for the earth baseline. This estimate includes all carrying charges and operating costs normally included in utility company estimates and assumes each satellite is used for 30 years. For comparison, today's bus-bar cost of a nuclear power plan, in 1977 dollars and at a 60 percent capacity factor, is about 13¢/kW-hr, and the cost of a coal-fired power plant is about 19¢/kW-hr.

Table 1. Summary SPS program cost comparison.

	Earth Baseline	LRU Concept B	LRU Concept C	LRU Concept D
RDT&E & startup ($/kW)	235.3	405.9	451.6	485.9
SPS hardware	21.0	21.0	21.0	21.0
Construction system	69.0	69.0	69.0	69.0
Facilities & equipment	55.7	229.3	253.0	277.7
Transportation	89.6	86.6	108.6	118.2
Production ($/kW)	2188.3	994.4	1127.2	1048.9
Earth-based fab & assy	2066.7	764.9	848.1	794.7
Lunar-based fab & assy	0	9.8	61.4	84.9
Space-based fab & assy	121.6	219.7	217.7	169.3
Operations ($/kW)	622.2	622.2	622.2	622.2
Total program cost ($/kW)	3045.8	2022.5	2201.0	2157.0

Breakeven curves were constructed to determine the threshold points where the LRU concepts become more cost-effective than the earth baseline. These are shown in Figure 2 in the form of average total cost curves. Without considering the time value of money and cost uncertainties, the threshold was found to lie between 3 and 5 satellite systems. If cost estimates were based on more detailed information, these results would be more significant. Due to the great deal of uncertainty associated with these estimates, the points are likely to vary from the nominals shown in Figure 2. This uncertainty is addressed in Section V.

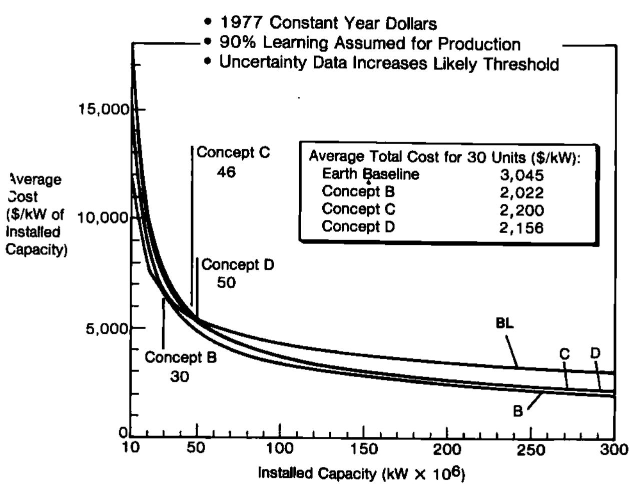

Figure 2. Nominal economic threshold of LRU concepts.

The final portion of the cost analysis task was to examine major differences between earth baseline and LRU concept costs. Major differences exist in development, transportation, and satellite production costs. Table 2 provides a breakdown of the cost differences between each LRU concept and the earth baseline. Since satellite operations costs are the same in both cases, they were omitted from the table. The remaining costs are in the RDT&E and Production Phases. They were allocated between the major categories of transportation and manufacturing. Included is the cost of facilities, vehicle and RDT&E amortization, vehicle production and maintenance, facility operation and maintenance, startup operations, and propellants. Also included is the cost of purchased parts and material. The LRU concepts are lower in the transportation area by $117.8 to $158.5 billion. This result was expected due to the large reduction in earth launch vehicle payload requirements and the smaller energy requirements to launch the same amount of material from the moon as from earth. Table 2 shows the LRU concepts to be lower in manufacturing costs by a similar amount; $18.6 billion of this manufacturing cost is due to a difference in the number of space construction systems required for satellite assembly. Thus, the LRU concept cost to manufacture SPS hardware, up to the point of on-orbit assembly, is lower than the earth baseline by $129.8 billion for Concept B, $117 billion for Concept C, and $102.8 billion for Concept D. This result was surprising since intuitively space manufacturing would cost the same, if not more, than earth manufacturing. The large manufacturing cost differences actually result from a combination of factors. These are discussed next in order of importance.

Table 2. Comparison of costs between the earth baseline and LRU Concept B.

	Cost Difference between Earth Baseline and LRU Concepts ($B)		
Category	**B**	**C**	**D**
Transportation	158.5	117.8	145.2
Earth Based	186.4	158.4	173.7
Lunar Based	-2.3	-2.0	-7.4
Space Based	-25.6	-38.6	-21.1
Manufacturing	148.4	135.6	121.4
Earth Based	235.2	235.2	235.2
Lunar Based	-8.0	-36.8	-48.2
Space Based	-78.8	-62.8	-65.6

1. Earth Manufacturing Chain Influences
   The earth-based manufacturing chain introduces additional, significant costs which are not present in the LRU scenarios. These are (1) the cost of middlemen and (2) the addition of profit (and the presence of profit pyramiding) by the middlemen, mining companies, processors, and manufacturers. This difference is a direct result of Assumption 7: LRU scenarios assume a vertically integrated manufacturing chain owned by a single entity. The entity makes no profits until power is sold. It requires no profit on the SPS hardware fabricated in space. Only the 10 percent portion of the SPS which is purchased on earth includes middlemen costs and profits. The earth baseline concept, on the other hand, relies heavily on purchased parts from independent manufacturers. Profit pyramiding in the earth-based manufacturing chain, and the presence of the middlemen's labor, overhead and profit, add to the cost of purchased hardware from earth.
2. Manufacturing Facilities
   A second factor which contributes to lower LRU concept costs is in the facilities area. The manufacturing facilities and equipment for the LRU options are specifically designed to turn our hardware for a single end product. This results in a smoother, more efficient manufacturing flow than is achievable by a group of earth-based firms who have diverse interests. LRU concept space facilities are also optimally sized to produce the required output, whereas existing earth facilities may (1) have excess capacity that may result in higher overhead charges to buyers or (2) be too labor-intensive due to insufficient investment in plant/equipment. Finally, LRU facilities which house manufacturing equipment are less costly than earth-based facilities. Although

operating environments differ considerably, the earth environment is actually more severe than space, due to winds, moisture, snow loads, etc. The more passive environment in space eliminates the need for protective enclosures in many cases, and expended shuttle external tanks can be employed in the fabrication of pressurized facilities. Since the primary use of the external tanks is transportation, the only costs charged to the manufacturing category for their use was in transporting them to the space manufacturing facility location and converting them to facilities.

3. Labor and Overhead
A highly automated manufacturing scenario and extensive use of industrial robots in the manufacturing process result in lower labor costs for LRU concept production. In the LRU options, only 1,500 to 1,600 personnel were required for the entire mining, processing, manufacturing, and assembly process. On earth, these processes would require many times that number of workers for the same output. Not only are costs incurred for the direct labor costs of these workers, but they are also incurred in the direct labor of supporting groups and the overhead associated with them.

The above differences in manufacturing cost are actually a result of a difference in the study assumptions between LRU and the earth baseline. If the same manufacturing chain and ownership assumptions had been made for the earth baseline scenario, manufacturing costs similar to those of the LRU concepts would have resulted. Alternatively, the manufacturing chain in space could have been assumed to be like that on Earth, with many independent owners. Either assumption was felt to be unrealistic. If such a project were undertaken on Earth, it would be difficult to imagine a single entity owning the entire chain (i.e., the mines, the processing facilities, and manufacturing facilities) without involving other enterprises. From the standpoint of space-based manufacturing with lunar supplied material, this approach would be entirely reasonable; thus, the assumption was used in the present study. To determine the effects of this manufacturing assumption on the economic threshold, a sensitivity analysis was performed. The results are documented in the next section.

IV. Threshold Sensitivity to Manufacturing Costs

For the purpose of the sensitivity analysis, it was assumed that LRU scenarios included independent firms and middlemen, which resulted in increased manufacturing costs. This increase would occur not only because of profits and additional overhead, but also because of lost efficiencies in the manufacturing process. To test the sensitivity of the economic crossover points to such a scenario, it was assumed that the manufacturing costs of LRU concepts are the same as those in the earth baseline. From the cost analysis results, the total differences in manufacturing between Concepts B, C, and D and the earth baseline are $129.8 billion, $117 billion, and $102.8 billion respectively. If these amounts are added to the LRU concept costs, the effects on the crossover point can be determined.

The differences in manufacturing costs were allocated to the lunar and space-based manufacturing costs, using ratios of element costs to totals. Costs were further allocated to RDT&E and Production by cost ratios. Economic thresholds were then determined in a similar manner as in the previous analyses. The nominal threshold, in terms of average total cost per kilowatt of installed capacity, is provided in Figure 3. The figure indicates that, even with the added costs, the LRU concepts are still more cost-effective than the earth baseline with crossovers at 11.1, 12.0 and 13.4 units.

V. Cost Uncertainty Analysis

The nominal costs previously derived are only point estimates which lie within a range of potential future costs. Our current ability to predict those costs with a great deal of certainty is limited. Uncertainties exist in several areas which can contribute directly to actual program costs being higher or lower than nominal.

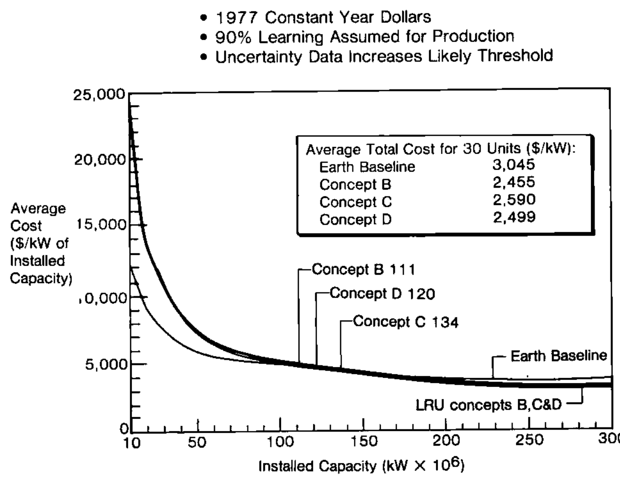

Figure 3. Nominal economic threshold for LRU concepts, assuming earth baseline and LRU concept manufacturing costs are equal.

The first area is related to supply and demand shifts and their effect on prices. Two factors that contribute to uncertainty in this area are the dwindling supply of the earth's natural resources which will increase future costs, and the effects of SPS program demand on facilities, material, and labor prices. Had these factors been considered, they would have a greater cost impact on the earth baseline than on the LRU concepts. Such assessments would certainly be appropriate in future studies. In fact, the scarcity of earth's natural resources and the resulting increase costs are major reasons for considering LRU.

A second major area of uncertainty is the number of unknowns associated with the space and lunar-based manufacturing chain. Man's efficiency in and adaptability to space could have major effects on space crew productivity. The amount of earth-based support required along with associated facilities have not been defined. Operation and maintenance costs of space-based manufacturing equipment are based on earth experience and could vary significantly from the nominal estimates.

Cost uncertainties are also present due to the state of hardware definition and operational characteristics for the optional programs. The scope of the current study was much too limited to define many of the LRU elements in detail; this is especially true of enclosure facilities for the space and moon manufacturing equipment, space-based launch and recovery facilities, and earth-based support facilities. It is also true for advanced state-of-the-art systems. The final source of uncertainty is in the development cost of advanced elements. Since problems in technology and hardware development cannot be foreseen, costs could be higher than predicted.

Due to the potential effects of the unknowns on predicted program costs, an uncertainty analysis was performed in an attempt to quantify uncertainties and determine the effect on economic thresholds. The approach to estimating cost uncertainties was one of combining analyst judgment with quantitative techniques. In this study, standard deviation was used as a measure of cost uncertainty, and all cost distributions were assumed to be normal for ease of data analysis. Although cost distributions tend to be skewed, this should have little effect on the results, since, for large numbers of samples (cost elements), the total distribution will approach normality. The objective was to define an interval around the nominal point cost estimates that represent a $\pm 3\sigma$ standard derivation spread from the nominal estimate.

This interval theoretically includes 99.7 percent of the possible variation in costs.

Confidence intervals about the nominal were determined in three distinct steps: (1) cost elements were ranked according to degree of certainty of the estimate; (2) rankings were converted to $\pm 3\sigma$ confidence intervals, based on a percent of nominal costs; and (3) percentages were applied to nominal costs to obtain dollar value $\pm 3\sigma$ confidence intervals for each program phase.

Once the $\pm 3\sigma$ confidence intervals were developed, the effect of uncertainties on economic threshold points was determined. Uncertainty ranges were plotted for each concept. Figure 4 shows the results of the LRU Concept B comparison with the earth baseline in terms of average total cost. A 90 percent learning curve was applied to production costs. The ranges are too broad to ascertain the presence of a crossover. To determine the presence of an economic threshold within the 30-unit production phase, the maximum limit of the LRU Concept B range must cross the minimum limit of the earth baseline range. This does not occur. The crossover in the comparison between Concept B and earth baseline could occur at any point in the overlap area of the two ranges, or at some greater production quantity. Thus, for confidence intervals which include 99.7 percent of possible outcomes, it cannot be determined which concept is more cost effective. Similar results were obtained for Concepts C and D.

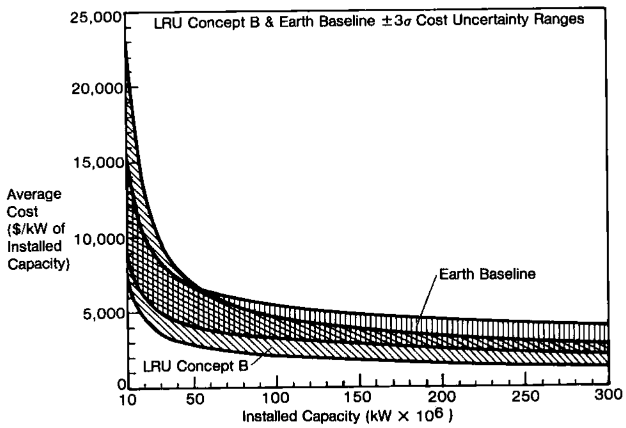

Figure 4. Economic threshold for concept B if cost uncertainties are included.

No crossover can be detected within the 30-unit production program using a $\pm 3\sigma$ confidence band; however, as the uncertainty range is narrowed, maximum crossover points can be detected, first at very high production quantities and then at lower and lower quantities as the uncertainty band becomes smaller. Due to the overlap of the earth baseline and LRU option uncertainty bands, the crossover points are of a cumulative nature, that is, they represent the number of units at or below which the LRU options become cost effective. The initial uncertainty bands shown in Figure 4 represent ranges of cost within which 99.7 percent of the actual costs would fall. As these bands are narrowed, it becomes less and less probable that actual future costs would fall within their smaller ranges. The process of narrowing down the bands was performed to determine the probability intervals associated with a crossover at 30 production units or less. This exercise allows the probability of crossover at or before 30 units to be determined for each concept. These probabilities are shown in Table 3. Even with the reduced confidence intervals, the probabilities of attaining a crossover within 30 production units is quite high. Concept B shows the highest probability of reaching a crossover with a 92.8 percent probability. Concepts D and C have probabilities of 88.5 percent and 86.3 percent respectively.

The uncertainty analysis was repeated for the case where manufacturing costs for the baseline and LRU concepts were assumed to be equal. The increased LRU manufacturing costs have a significant effect on the width of the uncertainty range. The added costs more than doubled the original nominal costs for space and lunar facilities and equipment and their operation. This, in turn, increased the dispersons and resulted in a much wider 3σ confidence band. The conclusions reached are the same as before. With the 99.7 percent probability interval, the bandwidths are too wide to determine if an economic threshold would be reached within the 30-unit production run. The probability of a crossover at or before 30 units for each concept is shown in Table 3. The probabilities of achieving a crossover are significantly lower than in the original analysis, where satellite manufacturing costs are different for the baseline and LRU concepts.

Table 3. Probabilities of crossover within 30 units of satellite production (percent).

	Different Manufacturing Costs	Same Manufacturing Costs
Concept B	92.8	64.4
Concept C	86.3	57.0
Concept D	88.5	63.9

The major implication of the uncertainty analyses is that an economic threshold will be reached within the 30-unit production run. Even if LRU concept manufacturing costs are grossly understated and, in fact, are more like those of the earth baseline, the probability is still high that LRU concepts would be more cost-effective than the earth baseline. In this case, the LRU advantage is due primarily to the savings in transportation alone, rather than in both transportation and manufacturing.

VI. Program Funding Schedule and Present Value Analyses

Program funding schedules were generated for each alternative. Funding requirements are always important on a program, primarily because they assure that there are no unreasonable peaks in spending and that annual expenditures are consistent with the available budget. The funding schedules also provide a basis for the present value analysis performed. The present value analysis is a useful tool in the selection of alternative investments, because it considers not only the magnitude of the program costs but also the timing of expenditures and the time value of money. In effect, the present value analysis removes the time variable; consequently, projects can be compared on an equivalent basis.

Figure 5 shows the results of the program funding schedule analysis. The nominal LRU Concept B spread is superimposed upon the earth baseline spread for comparison. Spreads for Concepts C and D were of similar shape and magnitude. In general, the expenditure profiles are indicative of the relative costs of the alternatives. Annual costs were highest for the earth baseline, peaking at $25.6 billion in the year 2004 and gradually decreasing to $18.7 billion by the end of the program. When the first SPS becomes operational in the year 2000, cumulative expenditures are approximately 31 percent of total program cost. Annual costs for the LRU options are in the order of $15 billion per year, beginning in about 1990. Cumulative expenditures are approximately 34 percent of the total when the first SPS becomes operational in the year 2000. Based on the lower annual funding requirements, the LRU concepts appear to be better alternatives than the earth baseline. The annual costs of any one of the programs, in light of the present NASA budget, appear excessive and cast doubts on the capability of a single enterprise to undertake such a program. For a program of this magnitude, a large single entity would probably have to be formed to provide the required funding. To demonstrate the immense size of the SPS program, analyzed in terms of energy output as well as dollars, the energy capacity growth is shown in Figure 5. The 300 GW maximum reached in the year 2030 compares with a total United States electrical energy capacity of 500 GW in 1977.

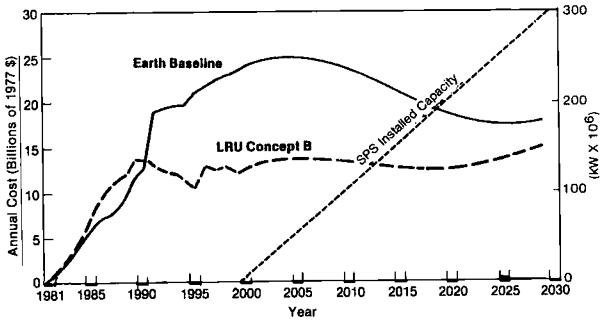

Figure 5. Estimated annual expenditures.

The appropriate discount rate for determining present values is in the order of 10 percent. To allow for uncertainty in the discount rate, three rates were actually chosen for the present study: 7 percent, 10 percent and 15 percent. Discounted dollars were determined using each of the three rates and the results are shown in Table 4.

Table 4. Present values of the alternatives (billions of 1977 dollars)

Billions of Dollars	Present Value Of Costs Discounted At		
	7%	10%	15%
Earth Baseline	191.7	118.0	61.9
LRU Concept B	139.1	90.9	52.5
LRU Concept C	152.8	100.1	58.0
LRU Concept D	153.7	101.6	59.4

The present values indicate the same relative ranking regardless of discount rate. LRU Concept B has the lowest present value, followed by Concept C, Concept D, and then the earth baseline. This ranking supports the earlier cost analysis and indicates that, on a nominal basis, all LRU concepts are superior to the earth baseline.

VII. Conclusions

(1) The use of lunar materials in the fabrication of large structures in space can potentially be more cost effective than the use of earth-derived materials. Whether or not this cost effectiveness is realized is dependent upon such assumed factors as the efficiency of the manufacturing chain and its facilities as well as their form of ownership. Uncertainty also plays a role. Uncertainty factors that affect costs include earth support requirements, effects of future supply/demand on prices, man's adaptability to space, final hardware/facility definition, and operational characteristics of each program. Even with these uncertainties, the probability of the LRU concepts being more cost effective than the earth baseline is quite high, ranging from 89 to 93 percent.

(2) The major economic benefits of LRU are in lower transportation costs and a more efficient manufacturing chain. If it is assumed that the efficiencies in the manufacturing chain do not exist and manufacturing costs are the same, the LRU concepts are still more cost effective. The probability of achieving this economic threshold, however, is significantly lower than for the more efficient manufacturing case and ranges from 57 to 64 percent.

(3) Although cost differences among the LRU concepts are not significant, Concept B was found to be the lowest cost alternative. This is due primarily to the use of the mass driver/mass catcher for transporting material from the lunar surface to space. The mass driver requires no propellants, as do the lunar vehicles in the other concepts. Thus, the lunar material requirements for propellant manufacture are less for Concept B, resulting in lower facility, processing, and logistics support costs.

Q. Was there any consideration given to using the mass driver to return materials to Earth for sale, to offset the costs of Lunar Resource Utilization (LRU) plant development?

A. No. All materials launched from the Moon were assumed to be for use in SPS construction.

Q. In your uncertainty analysis for supply and demand, were you referring to the demand for power on Earth?

A. I referred to the supply and demand effects on the material used to fabricate the satellite itself. The costs of Earth material used in the fabrication of the SPS were based on resource costs under today's economic conditions. In 20 or 30 years the lower availability of Earth resources will tend to drive costs up. This point was not considered in deriving the nominal cost estimates, which leads to uncertainties in the final results.

Q. In the Earth baseline case did you look into the environmental impact of the pollutants dumped in the atmosphere?

A. No, we did not consider environmental, social, or political factors.

Q. How much of the lunar orbital transfer vehicle costs were included in the LRU concept?

A. All of the costs. It was assumed that these vehicles were developed specifically for the program.

Q. Why does Option C, the chemical rocket case, cost $100/kw more than Option B? We know much more about chemical rockets than mass drivers.

A. The processing plant is considerably larger. The propellants themselves are cheap, but the relatively low efficiency of the chemical rocket makes the plant costs high.

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