A COST BENEFIT ANALYSIS OF SPACE MANUFACTURING FACILITIES*

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Abstract

The paper updates the author's previously published economic model by incorporating the results of the 1976 NASA/Ames summer study of space manufacturing facilities (SMF's) as well as other data which have recently become available. The analysis reveals that the economics of SMF's are substantially better than the favorable results found for space settlements (colonies) using this model in previous studies. The DDT&E costs are $75.8 billion and the benefit cost ratio is 2.1. After some discussion, it is decided that the funding organization should be the government during the DDT&E phase of an SMF program and, for the most part, private enterprise during the commercialization phase. Comparisons are made with the ongoing ECON, Inc., study of earth-launched satellite power stations (SPS's). It is found that the SMF option for producing SPS's may be less risky than building them on and launching them from earth.

I. Introduction

The model employed in this paper was originally developed for the NASA/Ames 1975 summer study of space settlements (colonies)[7]. It is discussed in detail there and also in an article by the present author which will appear in a forthcoming issue of the Journal of the British Interplanetary Society (JBIS)[6]. A summary of the results of the JBIS article is currently in print[5].

The following section examines some questions concerning the funding organization. This topic is addressed at considerable length in response to a specific request for information on the subject. Next, Sections III through VII briefly discuss the model, incorporate new data mainly from the '76 summer study, and present comparisons between the JBIS results, those of the '75 summer study, and the new results. Sections VIII and IX discuss comparisons with the ECON study and risk, respectively.

II. Funding Organization

The costs incurred by and the benefits accrued to the funding organization of a given program will in general depend on the nature of that organization. In this paper we will only consider potential American organizations. Some of the pro's and con's of international organizations are discussed briefly in the JBIS paper. There are two major candidates for an American organization--the government and private enterprise. The following discussion of their relative merits will consider only economic factors. It is recognized that noneconomic factors play an important role, but these fall outside the author's expertise.

Government funding has three major advantages. First, the government is larger than any practical private organization and thus is better able to absorb risks. Secondly, many of the benefits to Americans that would result from the program cannot be captured by private enterprise. Contrarily, since the government represents the interests of the people, these benefits should be counted toward its total. Examples of such benefits are spinoffs and any lowering of the price of electricity that occurs as a consequence of the program. Finally, the government requires a minimum rate of return in order to invest, which is lower than that of private enterprise. This is due to several

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factors. Two of the most important are that the government does not have to pay taxes nor, because of its superior ability to deal with risk, does it have to buy insurance. The advantage of a private organization is that it is more efficient: it can perform most tasks at lower costs.

The DDT&E phase of an SMF program is a classic example of a situation in which the economic factors indicate that the government should provide any necessary funds.

This phase is risky. It has numerous benefits to society other than those which could be obtained by private investors. And it will last a long time. The last point needs some further elaboration. Assume that a private organization requires a real rate of return of 15%, and the government 7.5%, in order to engage in a program. Further, ignore differences in efficiency. Then for a one-year program, private enterprise requires that the benefits be 7% larger than they need be in order to interest the government. In contrast, if we have a program which lasts for 20 years and (to take a simple case) is characterized by having all of its costs in the first year of the program and all of its benefits in the last year, private enterprise will require the amount of benefits in the 20th year to be 285% larger than the amount required by the government. The point is that differences in the required rate of return are much more important for long-run programs such as the one we are concerned with in this paper, than they are for short-run programs.

The situation is different for the commercialization phase of the program. By this time the likely costs and benefits of building more SPS's can be assessed with relative accuracy. As a consequence, assuming that the estimated benefits which can be obtained from the sale of electricity are reasonably above the estimated costs, then risk will be greatly reduced. The benefits of the additional SPS's which are not obtained by private investors can be counted toward paying back the costs of government DDT&E. The length of a private enterprise investment in additional SPS's will be considerably shorter than the length of investment if a private enterprise had undertaken the entire program itself. In fact, the length will be comparable to that of current investments in electricity generating plants.

Because of these differences it is likely that private enterprise's superior efficiency will be sufficient to warrant its undertaking of the commercial phase.

An organizational approach of this type where the government funds the DDT&S while private enterprise handles commercialization has been used with success in past programs which had similar economic characteristics. Examples include nuclear power and communication satellites.

To the above general conclusions should be added some qualifications. The statement that private enterprise has higher efficiency than the government depends to a considerable extent upon the previously implicit assumption of a high degree of competition. Obtaining a sufficient number of firms of an appropriate size to provide such competition poses problems in the early stages of commercialization. The current engineering estimates suggest that the economies of scale are such that building more than one--or at least many more than one--system of mass drivers, catchers and space manufacturing facilities would be unreasonably inefficient. Thus in the early stages of commercialization, so as to guard against monopoly abuses, certain components of the overall system might best be left in government hands or at least heavily regulated. As the level of SPS production increases with time, these problems will be alleviated.

Another qualification concerns control of the space habitat. Workers may object to the idea of living in a company town, particularly if their time of residence were extensive and they had dependents. This aspect suggests that in the initial period of commercialization the habitat would continue to be controlled by the government. As time passes an increasing degree of self-government by habitat residents would seem likely. The pace and extent to which this is brought about and its implications for the interactions between space workers, space companies, and citizens on earth deserves attention, but is beyond the purview of this paper.

The major component of the overall energy-producing system under discussion which is likely to be taken over by private enterprise first are the SPS's and their rectennas. These might be bought by the utility companies to which they feed power. It should be noted that they quickly come to comprise the majority of the capital in the system. The problems associated with such a takeover appear to be relatively minor. The following are two of the more important:

1. Regulation of SPS orbits aimed at such matters as preventing collisions, minimizing eclipses of one satellite by another, and deciding upon who gets the more desirable orbits.

2. Maintenance of SPS's. It would probably be inefficient for each utility company to acquire the know-how and capabilities needed for its own maintenance. Thus some other mechanism for providing this service would seem preferable.

III. Assumptions

The calculation of benefits and costs for the model used in this analysis are for Americans who remain on earth. The real discount rate which should be employed is therefore one that is appropriate for the government. A conservatively high 10% has been chosen for this purpose. A more sophisticated analysis would take into consideration the fact that the program would eventually be taken over by private enterprise. This would be dealt with by saying that private enterprise must receive a reasonable rate of return--say, 15% real. Then the benefits and costs would be calculated for the government: the costs are those paid by the government and the benefits are what remains after allocating private enterprise a sufficient amount for its 15% profit. The benefit cost ratio for the government could then be derived by discounting at 10%.

Benefits depend to a considerable extent on the difference between what the price of electricity would be if the technology is not developed as compared to what it would be if it is developed. It is therefore crucial for accurate results to insure that prices for competing sources of electricity are calculated by assuming that the rate of return on capital invested in them is the same as the real discount rate being used in the model in question.

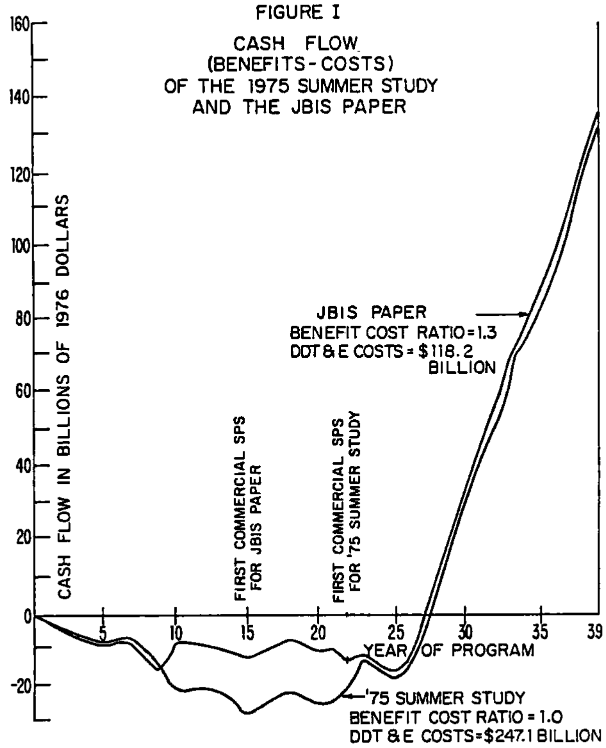
The prices of other energy sources, given at various points throughout the remainder of the paper, are then calculated using a 10% real discount rate. If the more sophisticated approach suggested above had been used, then these prices would have to be recalculated using the 15% discount rate. The more sophisticated model was not employed here for several reasons: e.g., the timing of when the program should be converted from government to private control has not been worked out; also, crude calculations indicate that the more sophisticated analysis would have only a minor effect on the results.

The remaining assumptions (as well as the inner workings of the model) are discussed at length in the JBIS paper and therefore will be mentioned only briefly here. The U.S. market was assumed equal to the market for new plants. This market comes about partly because of the growth in the need for electricity and partly because existing plants eventually wear out. The foreign market for our exports in the case of nuclear plants has been about one-half the size of the U.S. market. It was assumed that this would likewise be the case for space colonization power. Because of the risk inherent in new technology, the demand in a given year is not initially equal to what is called the market size above. Rather the market must be penetrated over a period of time. Ten years was taken as the length of the penetration period. After this time, demand is equal to the sum of the U.S. and foreign markets. The market size was assumed to grow at 5% per year. Benefits are taken as revenue from the sale of electricity plus the benefit obtained by consumers due to lower electrical rates. All costs are in 1976 dollars.

IV. Comparison of the JBIS Paper and the 1975 Summer Study

The JBIS paper represents a revised version of the '75 summer study where some additional optimization has been done. Figure I summarizes the results of these analyses by a comparison of cash flow diagrams. Both programs build their first full-scale SPS during year 15 of the program. This is a commercial SPS for the JBIS analysis. The first commercial SPS for the '75 summer study is built in year 22. The SPS's built prior to that are not commercialized because they cannot completely pay for themselves. In both graphs the difference between benefits and costs eventually becomes explosively positive. This is because after SPS production begins, annual costs are roughly proportional to the number of new SPS's built while annual benefits are roughly proportional to the total number of SPS's which have ever been built. The main difference between the programs is that in the JBIS approach a second generation shuttle system is built earlier in the program than in the '75 summer study. DDT&E costs are defined as all costs which occur prior to the first commercial SPS minus any electricity benefits from earlier SPS's plus any additional costs incurred by the construction of the first habitat. The '75 summer study has a DDT&E cost of $247.1 billion and a benefit cost ratio of 1.0. For the JBIS paper these parameters are $118.2 billion and 1.3. A benefit cost ratio of

1.0 means that the benefits are just sufficient to cover the costs including interest. A ratio of 1.3 implies that even if the costs in every year of a program were to increase by a factor of 1.3, the program would still be worthwhile.



V. Cost Projections of Other Terrestrial Electricity Sources

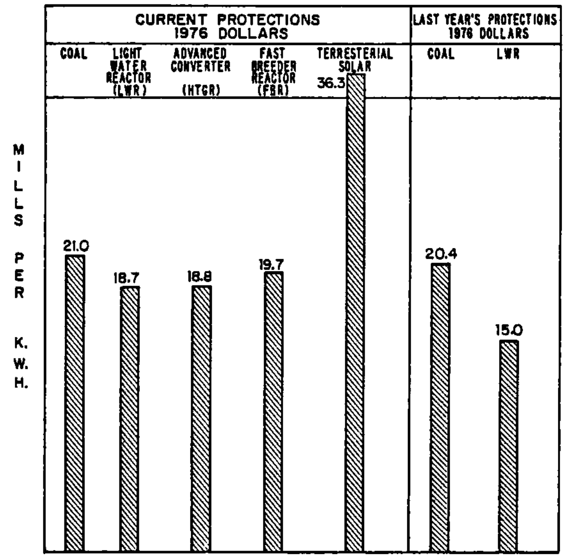
Figure II gives the projected costs at busbar for the major existing and potential terrestrial sources of electricity. The projections for existing sources were made by calculating the costs of building a new plant now under the assumption that these would remain the same in real terms over the time horizon of the model. In actuality these prices are expected to rise.

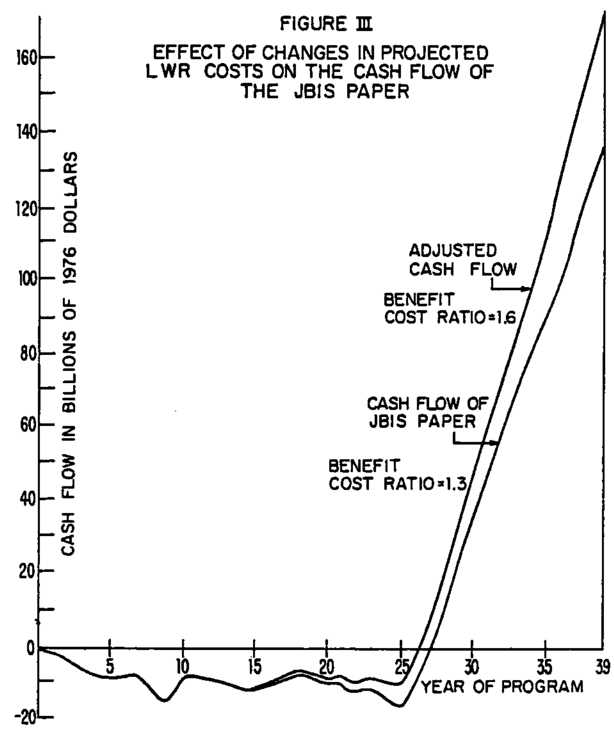
From Figure II we see that it is LWR (Light Water Reactor) power at 18.2 mills per K.W.H. which is the cost to be beat. The '75 summer study and the JBIS paper were based on data which are a year older. Their corresponding cost to be beat was 15.0 mills for LWR's. The increase in real terms from 15.0 to 18.2 mills represents a deterioration in the position of LWR power which the model had conservatively assumed would not occur.

The impact of this change on the results presented in the JBIS paper is given by the cash flow diagrams of Figure III. The benefit cost ratio rises from 1.3 to 1.6

FIGURE II

COST PROTECTIONS





VI. Major Sources of Benefit Underestimation

As has already been mentioned, the real price of electricity in the absence of the program will probably rise instead of remain constant. If this is true, then the actual benefits will be higher than those that have been calculated.

In its derivation of the benefits, the model assumes that the amount of electricity sold would not be increased due to the fall in the cost of producing energy that occurs as a consequence of the development of the new technology. To the extent that the amount sold did increase, there would be additional benefits.

All of the benefits discussed so far have been electricity benefits. There are a host of additional benefits which are ignored by the model. These are discussed in the JBIS paper and therefore will only be listed here:

- Improved environment
- Communications and other earth-sensing satellites
- Space manufacturing
- Cost reductions that can be obtained for programs that NASA would do anyhow
- Spinoffs and scientific knowledge
- Improvements in the balance of payments
- Benefits to other nations
- Long-run energy independence

The above comments suggest that the results of future evaluations of the benefits will give larger totals.

VII. Incorporation of the Results of the '76 Summer Study

At the 1976 NASA/Ames summer study of space manufacturing facilities, Driggers and Newman produced nominal, median uncertainty, and maximum uncertainty cost estimates. Three options with respect to the timing of the program were examined. Costs were assumed to be independent of the option which was chosen. All options involved a buildup to a productive capacity of five 10 gigawatt SPS's per year and were analyzed over a time period which ends with 20 SPS's producing electricity. The key difference between the options was the rate at which the program proceeded. The numbers taken from the study for use in this paper come from the median uncertainty cost estimates and the mid-length program option[1].

As is usual when dealing with two different studies, the method used by one was not completely compatable with that of the other. As an example, the buildup in the '76 summer study from an annual output of 1 full-scale SPS to an output of 5 occurred at a rate which is considerably more than that which can be justified by the demand assumptions of the author's model. However, the '76 summer study's maximum output of 5 SPS's before reaching its time horizon is well below the maximum that the author's model attains before reaching its more distant time horizon.

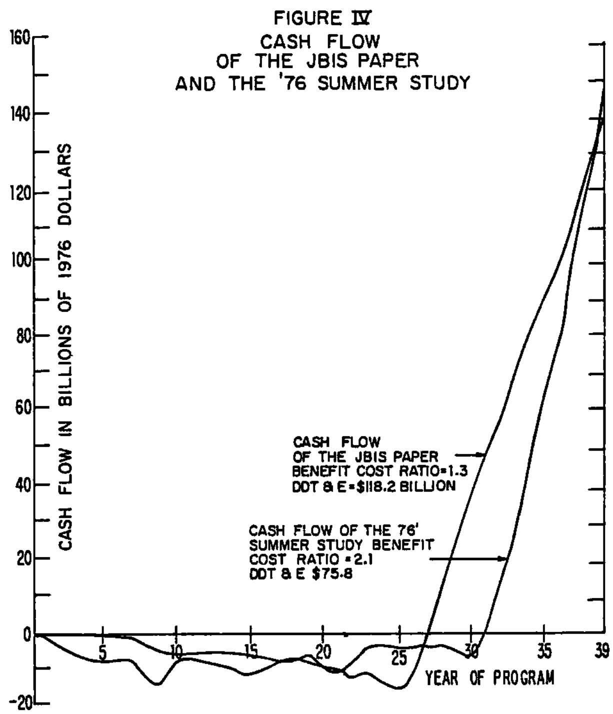
Some adjustments in program timing were therefore found to be necessary when combining the two approaches. This task was undertaken in accordance with the general philosophy that the economic assumptions should be taken from the author's previous work, while the cost assumptions should come from the '76 summer study. When in doubt as to how to proceed, the author used the more conservative possibility. As a consequence, there is considerable room for additional optimization in the resulting program.

One such adjustment was the development of a second generation shuttle system during the seven years immediately prior to the first full-scale SPS. In the JBIS article this was done considerably earlier in the program, while in the '76 summer study it was not done at all. The question as to when and whether such a transportation system should be developed depends critically on the volume of space traffic. It is clear that given the author's assumptions concerning demand, this system should be developed by some point. The point selected here is not intended to be optimal. It might be better, for instance, to postpone its development until after the first few SPS's are built and thus, among other advantages and disadvantages, reduce front end costs.

For most items the '76 summer study costs are lower than they are in the JBIS article. Of major importance are the reductions in the costs per lb. of parts bought on earth for SPS's and chemical processing and fabricating plants. The increase in labor productivity and the fall in DDT&E costs are also of considerable significance. In order to be comparable with the results in the JBIS paper, DDT&E costs are taken here to consist of (1) the $47.1 billion mentioned by Driggers and Newman[2] for the cost of establishing a prototype manufacturing facility and lunar import system; plus (2) $28.7 billion to cover the costs of: development of the second generation shuttle system; upgrading of the production capabilities of the entire system until it can produce one full-scale SPS per year; and that portion of the costs of the first habitat which are not covered by the $47.1 billion.

The total of $75.8 billion represents a large decrease from the $118.2 billion DDT&E costs of the JBIS paper. The cash flow diagrams for the two analyses are compared in Figure IV. That which is labelled as the cash flow of the '76 summer study incorporates both the changes in costs and the changes in the projected prices of competing sources of electricity which were discussed earlier.

The resulting benefit cost ratio is 2.1 which compares quite favorably with the 1.3 for the JBIS paper.



The major cost driver is the cost of parts made on earth for the SPS's and chemical processing and fabricating plants. These are interrelated because one way that the costs of imported SPS parts can be reduced is by producing more of them in space. However, this requires larger and more sophisticated chemical processing and fabricating plants and therefore increases their costs. It should also be noted that to date, it is in this area that the least amount of technical work has been done. We have a reasonable idea of how to extract metallurgical grade materials of various types from lunar materials. But at that point in the production process our knowledge becomes sparse. Very little work has been done on reoptimizing an SPS for SMF construction. What parts need to be imported from earth? What is required to fabricate the rest in space? Accurate answers to these questions would greatly reduce the economic uncertainty of the program.

At this early stage of analysis the cost estimates as a whole naturally suffer from a high level of uncertainty. Thus significant cost escalations are possible. However, it should not be forgotten that there are important reasons as to why costs may fall. The median uncertainty cost estimates of the '76 summer study--not the study's nominal (baseline) estimates--have been used above. There is considerable room for further optimization. Finally, the author is aware that O'Neill and his associates have, since the '76 summer study, found ways to significantly lower costs. Unfortunately these developments are too recent to incorporate into this paper.

VIII. Comparisons with the ECON Study of Earth-Launched SPS's

At the writing of this paper, ECON, Inc., was engaged in an economic study of the version of an SPS which Peter Glazer's pioneering work has made famous. The key difference between it and the version of most concern here is that all of its components would be manufactured on earth and launched from there. The information taken from ECON's study which is used in this paper comes from their second interim report[2]. While some of ECON's assumptions will probably be modified before their final report, it is unlikely that these will qualitatively change the nature of the arguments which follow.

The author's analysis of the '76 summer study was redone using ECON's economic assumptions, the purpose being to get an indication of the degree of conservativism of the author's model. There were two changes of particular significance. One was the use of a 7.5% instead of a 10% real discount rate. The other was the assumption that the price of electricity would rise until, by 1992, it was 20 mills in 1974 dollars after which its price in constant dollars would increase at the rate of 1% per year. Recall that the author's model effectively assumes that this price will remain at its present level in terms of constant dollars.

The results were that the benefit cost ratio rose from the 2.1 value of the '76 summer study to 5.2. This means (given ECON's assumptions) that even if the costs in every year of the SMF program increased by a factor of 5.2, the program would still be worthwhile.

IX. Risk

The previous remarks have neglected risk. Initially one is likely to consider the risk to be higher for SMF-made than for earth-launched SPS's.

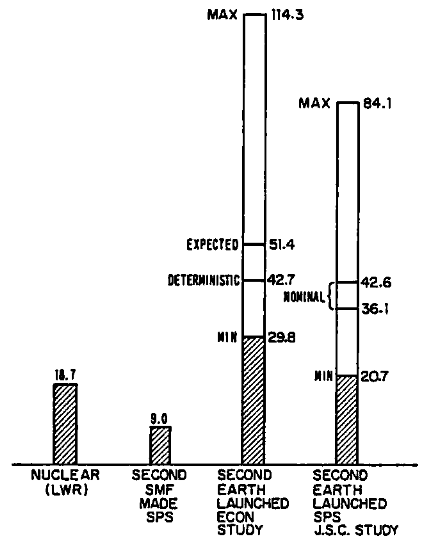
There are several reasons for this view. The analysis of earth-launched SPS's is at a more advanced stage and thus is likely to be more accurate. The earth-launch approach has fewer systems elements which suggests a lower possibility of a major unforeseen technological problem. Greater experience with earth- as opposed to space-based production also favors the reliability of the estimates for earth-launched SPS's. One advantage of the SMF approach is that it requires fewer technical advances in certain key SPS technologies. This is because the SPS's which would be built by SMF's have a mass per 10 gigawatt satellite which is larger by a factor of 2.9 than the SPS's built in the earth-launched approach. Even so, if these were the only major considerations most people would conclude that the SMF option is riskier.

The plausibly dominant factor which is often initially overlooked is the importance of the fact that the expected cost of electricity is substantially lower for SMF-made SPS's.

Consider the nightmarish possibility that after spending tens of billions of dollars it is discovered that SPS's will not be able to compete. This discovery would not only kill the program but probably most of its administrators and a sizeable fraction of the rest of NASA as well. Minimizing the probability of such a catastrophe is almost synonymous with minimizing risk. This probability not only depends on the usual considerations of the variance about one's cost estimates but also upon the difference between the best estimates of the cost of SPS electricity and of the costs of the competition.

Relevant cost comparisons are made in Figure V. The costs shown there for a recent study by the Johnson Space Center (J.S.C.) are for an SPS of the type under investigation by ECON[3]. The J.S.C. study calculated the costs under the assumption of a 15% real rate of return on capital. The costs given in Figure V have been recalculated for a 10% real rate of return so as to be comparable with the other cost figures in this paper. The J.S.C costs range from 20.7 to 84.1 mills per K.W.H. and a nominal value between 42.6 and 36.1. The usual procedures for calculating the max, min, etc., were used.

FIGURE V
COST COMPARISONS
MILLS PER K.W.H.
(1976 DOLLARS)



The ECON study employed an innovative approach in obtaining its (29.8 - 114.3) range of estimates[2]. A probablistic cost distribution with a max and a min value was estimated for each of the major components of their SPS. From this information, a probablistic cost distribution for the entire SPS was calculated. The expected value of this distribution is 51.4 mills per K.W.H. Its deterministic value--defined as the cost estimate of the SPS if the costs of all components are taken to be equal to their most likely values--is 42.7 mills.

The 18.7 mills for LWR power, given in Figure V, represents (as was mentioned earlier) the cost which the author's model assumes must be bettered in order for SPS power to be competitive. Note that even the minimum cost estimates of the earth-launched SPS calculated by ECON and J.S.C. fail to meet this criterion. Of course the use of 18.7 mills for this purpose is a conservative point on a probablistic distribution of the costs of competing energy sources, a distribution which will hopefully be estimated with tolerable accuracy in the future.

At present it is clear that there is some overlap between this distribution and the range of cost estimates for earth-launched SPS's. There is, therefore, some possibility of earth-launched SPS's becoming competitive, but this is not large.

The ECON study with its more liberal economic assumptions (some of which were mentioned previously) estimates that this probability is only 23.5%.

In contrast, an SMF-made SPS would be able to produce electricity at a cost of 9.0 mills--less than half of the 18.7 mill current cost.

Earth-launched SPS electricity requires good luck to be competitive. SMF electricity requires only the absence of bad luck. The significantly lower cost of SMF electricity suggests that the SMF program may have lower risks.

The above comments should not be interpreted as saying that the present funding of earth-launched SPS's should be discontinued. There are a number of energy projects currently being studied which show less promise. Low level funding for such projects is justified on the grounds that it reduces the risk now faced by society of not being able to find any reasonable solution to the energy crisis. It is less clear as to whether the level of funding for earth-launched SPS's should be substantially increased. Of course more funds can be justified for work which is also of use to the SMF approach than for work which is not.

X. Conclusion

The economics of SMF's are very promising. Additional study at a higher level of funding is warranted. The evidence suggests that NASA should consider undertaking a wide-ranging systems analysis to determine whether its baseline SPS program should be shifted from the earth-launched to the SMF option.

Bibliography

[1]Driggers, Gerald W. and Newman, John, "Establishment of a Space Manufacturing Facility," forthcoming.

[2]ECON, Inc., "Space-Based Solar Power Conversion and Delivery Systems Study, Second Interim Report, Volume I, Executive Summary," Prepared for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, under Contract No. NAS8-31308, June 30, 1976.

[3]Johnson Space Center, Initial Technical, Environmental and Economic Evaluation of Space Solar Power Concepts: Volume II--Detailed Report (JSC11568), August 31, 1976, Houston, Texas.

[4]Heppenheimer, T.A. and Hopkins, Mark Myron, "Initial Space Colonization: Concepts and R&D Aims," Astronautics & Aeronautics, March 1976.

[5]Hopkins, Mark Myron, "A Preliminary Cost Benefit Analysis of Space Colonization: Abstract," in Criswell, David R. (ed.), Lunar Utilization: Abstracts of Papers Presented at a Special Session of the Seventh Annual Lunar Science Conference, 16 March, 1976, Sponsored by NASA through The Lunar Science Institute and The Johnson Space Center, Houston, Texas.

[6]Hopkins, Mark Myron, "A Preliminary Cost Benefit Analysis of Space Colonization," Journal of the British Interplanetary Society, forthcoming.

[7]NASA Ames/Stanford University 1975 Summer Study of Space Settlements.

[8]NASA Ames/OAST 1976 Summer Study of Space Manufacturing Facilities.

[9]O'Neill, Gerard K., "Engineering a Space Manufacturing Center," Astronautics & Aeronautics, October 1976.

DISCUSSION

Q. What are the characteristics of the launch vehicles proposed for use, and at what point in the program do you propose their introduction?

A. The launch system that I used is based on the Apollo launch vehicle engine, the Fl. It is the same one that was used in the 1975 summer study.

Q. In dealing with the fly-back Fl, how did you characterize it in terms of cost per pound in low orbit?

A. The costs per pound in LEO and HEO are assumed to be $25 and $75 respectively. The development cost is taken to be 9½ billion.