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SPACE-BASED SOLAR POWER CONVERSION AND DELIVERY SYSTEMS STUDY

SECOND INTERIM REPORT
VOLUME III

ECONOMIC ANALYSIS OF SPACE-BASED SOLAR POWER SYSTEMS

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SPACE-BASED SOLAR POWER CONVERSION AND DELIVERY SYSTEMS STUDY

SECOND INTERIM REPORT

VOLUME III

ECONOMIC ANALYSIS OF SPACE-BASED SOLAR POWER SYSTEMS

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

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ABSTRACT

This study of space-based solar power systems (SSPS) addresses a variety of economic and programmatic issues relevant to the development and deployment of an SSPS fleet. Specifically, the study focuses on the costs, uncertainties and risks associated with the current photovoltaic SSPS configuration, and with issues affecting the development of an economically viable SSPS development program. In particular, the desirability of a low earth orbit (LEO) demonstration satellite and a geosynchronous (GEO) pilot satellite is examined and critical technology areas are identified. In addition, a preliminary examination of utility interface issues is reported.

The main focus of the effort reported herein has been the development of SSPS unit production (nth item), and operation and maintenance cost models suitable for incorporation into a risk assessment (Monte Carlo) model (RAM). The RAM was then used to evaluate the current SSPS configuration expected costs and cost risk associated with this configuration. By examining differential costs and cost risk as a function of postulated technology developments, the critical technologies, that is, those which drive costs and/or cost risk, have been identified. It is shown that the key technology area deals with the productivity of man in space, not, as might be expected, with some hardware component technology.

An assessment of LEO and GEO test satellites as components of the SSPS development program was performed using a decision tree approach. Three specific development program options were examined. It is shown that the most desirable program option, of those options examined, is the direct development option. That is, within the context of the assumptions made and the preliminary cost estimates for the LEO and GEO test satellite subprogram options examined, these tests have a negative net value. Based upon the results of the risk assessment, a programmatic risk assessment was conducted. This assessment indicates that the probability of successfully implementing the current configuration SSPS appears to be sufficiently high so that an economically justifiable program plan for the pursuit of the SSPS concept can be developed.

It should be cautioned that the economic analyses discussed herein are preliminary and make use of program plans and data that need further review. Thus, while the methodologies employed are sound and may lead to significant results, and the insights gained from these analyses may be valuable, decisions should be based on the results only after a thorough review of the cost model, the data used and the assumptions made for the analyses.

Finally, a few utility interface issues were identified and preliminarily examined. These include the need for and cost of installed reserve as a function of SSPS reliability/availability, the effect of power fluctuations due to clouds, precipitation and Faraday rotation, and the effect of power outage due to solar eclipse near the equinoxes.

NOTE OF TRANSMITTAL

The economic analysis of a space-based solar power system developed and reported in this volume has been prepared for NASA, George C. Marshall Space Flight Center, under Contract NAS8-31308. ECON study manager for this effort during the period 1 February to 30 June 1976, was Dr. George A. Hazelrigg, Jr. Data for the analysis have been provided by the Grumman Aerospace Corporation under subcontract to ECON. The Grumman study manager was Mr. Rudolph J. Adornato.

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1. INTRODUCTION TO COST, UNCERTAINTY AND RISK ANALYSIS OF SPACE SYSTEMS

An investment or engineering decision involves the commitment of resources with the hope of future benefits. In order to determine how best to commit resources, decision makers are forced to predict, forecast, or guess the future. The uncertainty about the exact course of future events creates risk in the form of unforeseen fluctuations in the resulting resource costs and cost-flow patterns. Since the future is not (and generally cannot be) known with certainty, the evaluation, comparison and decision making process must explicitly take into account the effect of uncertainty and risk.

The above notion is brought to light most vividly by a simple coin-toss game described by Daniel Bernoulli that has become known as the St. Petersburg paradox [1]. First, a player must pay to enter the game. Then, a fair coin is tossed until it falls heads on the nth toss at which time the player receives a prize of $\$2^n$. The question is, how much the player should be willing to pay to enter the game. Since the probability of a head first occurring on the nth toss is $(\frac{1}{2})^n$, the expected value* of the game is infinite.

$$E.V. = \sum_{n=1}^{\infty} 2^n \left(\tfrac{1}{2}\right)^n = \infty$$

Thus, a decision maker who does not consider risks should be happy to pay any sum of money to enter the game. Yet, although the possible winnings are very high, the probability of winning a significant amount is remote. For example, the player can win only $32 if a head first occurs on the fifth toss but his chance of lasting to the fifth toss without a head is only 1/32. In fact, to take the illustration one step further, it can be noted that the player should expect that the expected value of the game, infinity, will never be achieved. Thus, not only should one never count on an expected value occurring but, in addition, there exist special cases for which the expected value can never occur.

Clearly, informed decisions and proper selection of alternatives or courses of action should be based upon more than the consideration of

---

*The expected value (E.V.) or mean value of a function, $f(x)$, of a random variable, x, is the sum of all values $f(x)$ may take, each value weighted by its probability of occurrance, $p(x)$, or mathematically:

$$E.V. = \sum_{\text{range of } x_i} f(x_i)\, p(x_i)$$

the most likely or expected situations - they should consider the relative levels of risk. In order to accomplish this, risk must be quantified in the same sense that most likely or expected values are quantified. In other words, decision makers must take into account what can go right and what can go wrong and the chance of going right or wrong and this should be done quantitatively. A method is presented in the following pages which demonstrates how engineering and cost uncertainties and reliability can be taken into account in order to quantitatively assess costs and cost risks associated with space power systems.

Figure 1.1 places risk analysis in perspective with typical engineering analyses. Most engineering analyses are point estimates. A point estimate is obtained by inputting the "best guess" or estimate of the various system parameters into a model to obtain "single number" estimates of system cost or performance. Point estimating procedures seek an answer to the question, What do you think? It is often recognized that point estimates can be wrong. Thus, a next step is generally to conduct a sensitivity analysis. A sensitivity analysis considers variations around the "best guess" parameters of the point estimate and thus addresses the question, What if you are wrong? Risk analysis, on the other hand, adds a new dimension by addressing the question, What do you know? To do this, it provides a framework for adding ranges and probability distributions of system parameters for input to system models and provides, as output, ranges and probability distributions of system cost and performance rather than single number estimates of these values.

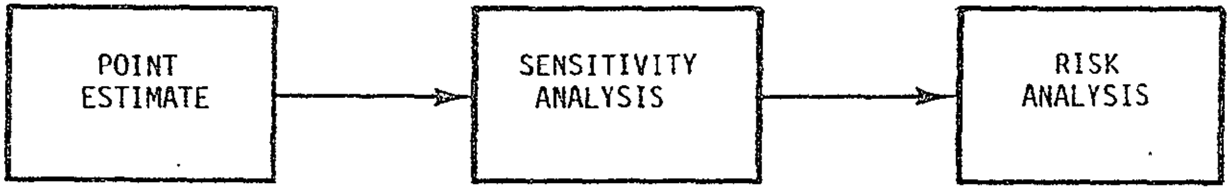
The answer to the question, What do you know?, incorporates the answer to the question, What do you think? As shown in Figure 1.2, the answer to the question, What do you think?, is typically the most likely value for a parameter to take on. That is, it is the value of the parameter for which the probability density function* obtains a maximum. In addition, however, it includes information such as the minimum and maximum values which the parameter can assume (that is, the range of the parameter outside of which there is zero probability of occurrence of the parameter) and confidence bounds which serves to establish the form of the probability density function.

As an adjunct to the above discussion, it can be observed that, in general, for continuous distribution functions such as the one shown in Figure 1.2, there is a zero probability that exactly the most likely value will occur. In other words, there is probability one that the answer to the question, What do you think?, is wrong.

---

*The probability density function, $p(x)$, gives the probability per unit of x that a random variable, x, lies between the value x_0 and $x_0+\Delta x$ for very small Δx. That is, the probability that x takes on a value between x_0 and $x+\Delta x_0$ is

$$p(x_0)\Delta x$$



"BEST GUESS" OF SYSTEM PARAMETERS

- MASSES
- EFFICIENCIES
- RELIABILITIES
- COSTS

PROVIDES "SINGLE NUMBER" ESTIMATE

WHAT DO YOU THINK?

VARIATIONS OF SYSTEM PARAMETERS AROUND THE "BEST GUESS"

- Δ MASSES
- Δ EFFICIENCIES
- Δ RELIABILITIES
- Δ COSTS

PROVIDES "SENSITIVITY" OF SINGLE NUMBER ESTIMATE TO INPUT DATA

WHAT IF YOU ARE WRONG?

RANGES AND DISTRIBUTIONS OF SYSTEM PARAMETERS

PROVIDES EXPECTED VALUE AND DISTRIBUTION OF "SINGLE NUMBER" ESTIMATE

WHAT DO YOU KNOW?

Figure 1.1 Risk Analysis

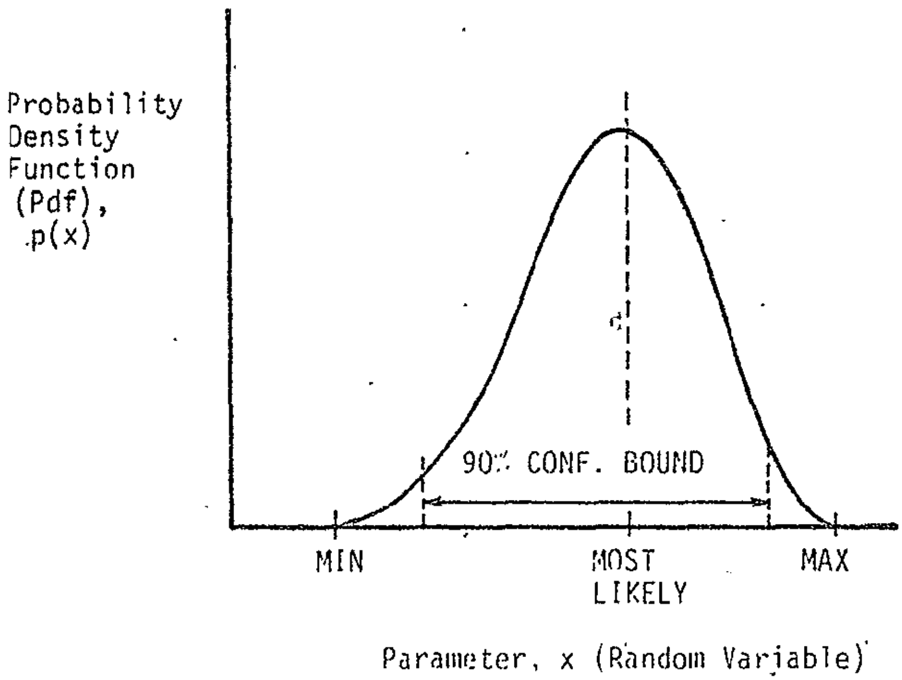


Figure 1.2 Quantifying the State-of-Knowledge Relative to a Parameter, x

One is thus led to question the validity of point cost estimates. Indeed, without performing a risk analysis, cost estimates are generally wrong and almost invariably low. The reason for this is easily explained within the context of risk analysis. System cost estimates are generally performed by dividing the system into subsystems, costing the subsystems individually and summing these costs to obtain the total system cost. However, it must be recognized that a cost estimate is a forecast of the future and thus can be expressed only as a probability distribution. Hence, single point estimates are, in fact, samples from such distributions. A characteristic of most aerospace subsystem cost probability distributions is that they are skewed such that the mean or expected value of the distribution is higher than the most likely value. But it is the most likely value that is generally obtained by soliciting point estimates. Now, when one adds the subsystem costs together to obtain the total system cost, whether it is explicitly recognized or not, one is adding probability distributions; and the mean value theorem asserts that, if one adds together a number of probability distributions, the resulting distribution tends to approach a normal (Gaussian) distribution for which the expected value and the most likely value are the same, and these are equal to the sum of the expected values of the component distributions, not the sum of the most likely values. Thus, in the summation process, the increment of cost between the most likely value and the expected value for each subsystem is left out and the resulting sum is low by the sum of these increments. Figure 1.3 illustrates this phenomenon. A, B and C are component subsystems of the total system. Solicitations of point cost estimates result in the most likely values, L_A, L_B and L_C. The sum of the cost differences between the most likely values and the expected values, E_A, E_B and E_C, namely $\Delta_A+\Delta_B+\Delta_C$, is neglected in point cost estimates. Thus, the estimate of E_{SYS} or L_{SYS}, the expected or most likely values of total system cost, is low by this amount. This explains why most cost estimates are low. Of course, in general, one does not obtain expected values anyway and the cost of any particular system may deviate from the expected value by some amount that can be estimated only by performing a risk analysis.

1.1 Uncertainty, Risk and Decision Making

Decision makers are often confronted with a wide range of alternatives from which they must select one or a few alternatives to pursue. The selection of the "best" alternative must invariably consider the risks inherent in each candidate alternative. For example, consider the investment of private savings. Clearly, a vast number of alternatives exist ranging all the way from placing the savings in a government insured bank account to placing the total sum on Crazy Horse to win in the fifth at Belmont. In between these extremes (and maybe beyond them) are all the opportunities present in the stock market. Obviously, the private investor who puts his entire savings into the investment that offers the

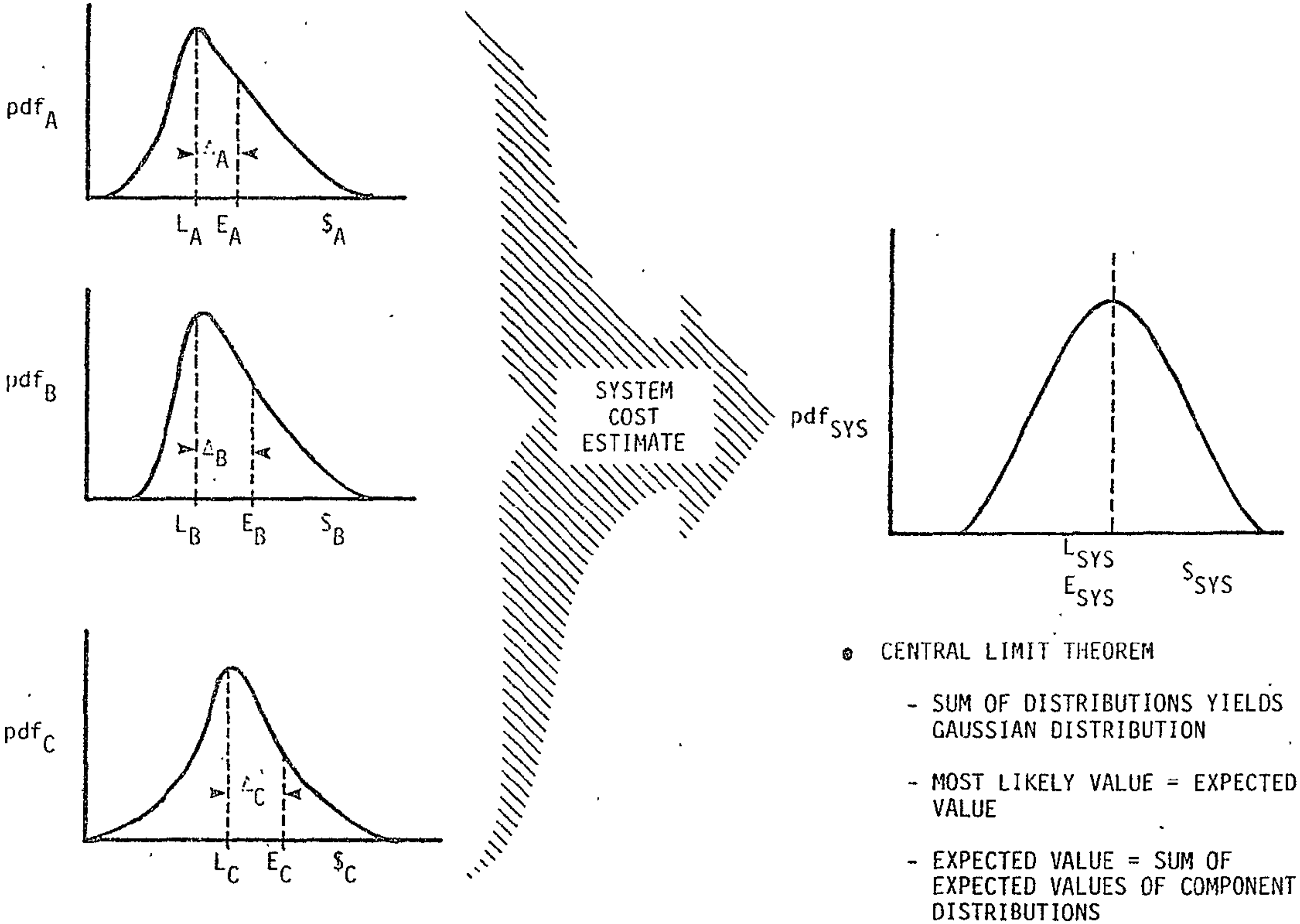


Figure 1.3 Illustration that Point Cost Estimates are Generally Low

possibility of the highest return is rare.* Most investors readily admit foregoing significant potential returns to obtain added security (reduced risk) in an investment. The same philosophy must also apply for the federal government in the selection of alternative courses of action to meet the energy needs of the nation in the year 2000 and beyond.

At this point, however, one finds oneself on the horns of a dilemma. On the one hand, the technologies that offer the opportunities for the greatest potential payoff are precisely those technologies for which there is the greatest risk; whereas, those technologies for which the risks are acceptable provide limited opportunities for energy independence and energy assurance. How then is it possible to economically justify the pursuit of advanced, high risk technologies with potentially high payoff? The answer lies in the development of technology implementation programs with controlled risks. Risk-controlled programs are programs in which the decision maker is never forced to make a decision that has a negative expected value in order to pursue a technology development, and they are programs in which the "down side" risk associated with technology development decisions is maintained at or below an acceptable limit.

A simple game serves to illustrate this principle. A player must pay $100 to enter the game. Then a thumbtack is flipped 20 times. If it lands point up 15 or more times, the player wins and his prize is $250 ($150 net). Otherwise the player loses. The key to the value of the game is, of course, the probability of the thumbtack landing point up on any particular toss, R. Unlike a fair coin, however, one can only guess about the value of R. But rather than to guess only a single number for R, the player is wise to describe his state-of knowledge about R, $P_R(R)$. For example, see Figure 1.4 which is one individual's guess at $P_R(R)$. Independent of the state-of-knowledge about R, it is possible to assess the chance of winning the game, $P_W(R)$, as a function of R.** This is shown in Figure 1.5. Then, it is straight forward to compute the player's expectation of winning the game,

$$\text{EXPECTATION OF WINNING} = \sum_R P_R(R) \times P_W(R) = .297$$

and from this computing the expected value of the game.

$$\text{EXPECTED VALUE} = \text{PRIZE} \times \text{CHANCE OF WINNING} = \$74.25$$

---

*For good reason. Few such investors exist who have non-negative savings.

**The probability of 15 or more "ups" out of 20 flips is the sum of the probabilities of 15 out of 20, 16 out of 20, 17 out of 20, 18 out of 20, 19 out of 20 and 20 out of 20. The values for each of these probabilities are derived from the binomial distribution.

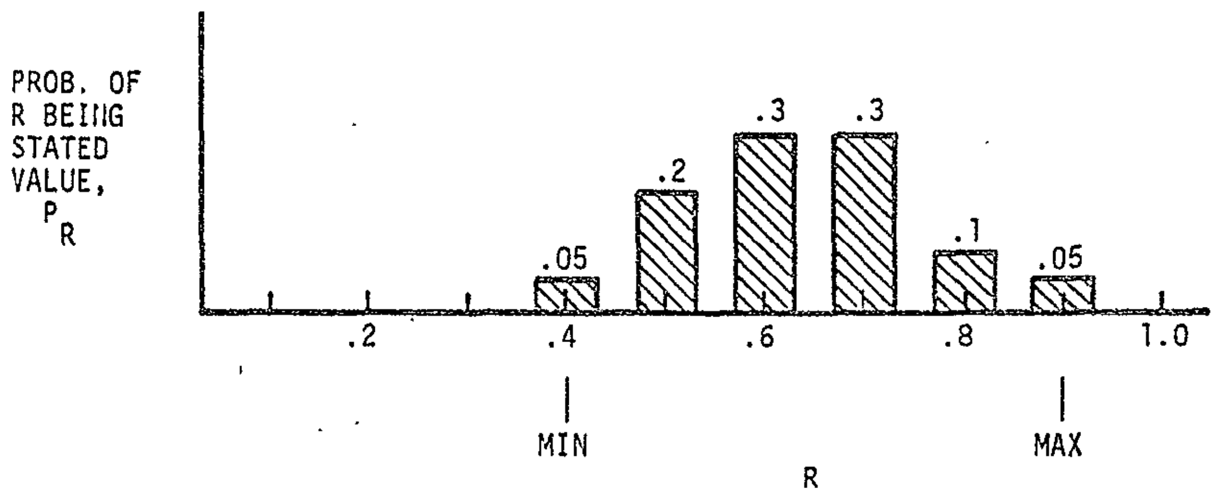


Figure 1.4 The State-of-Knowledge on R

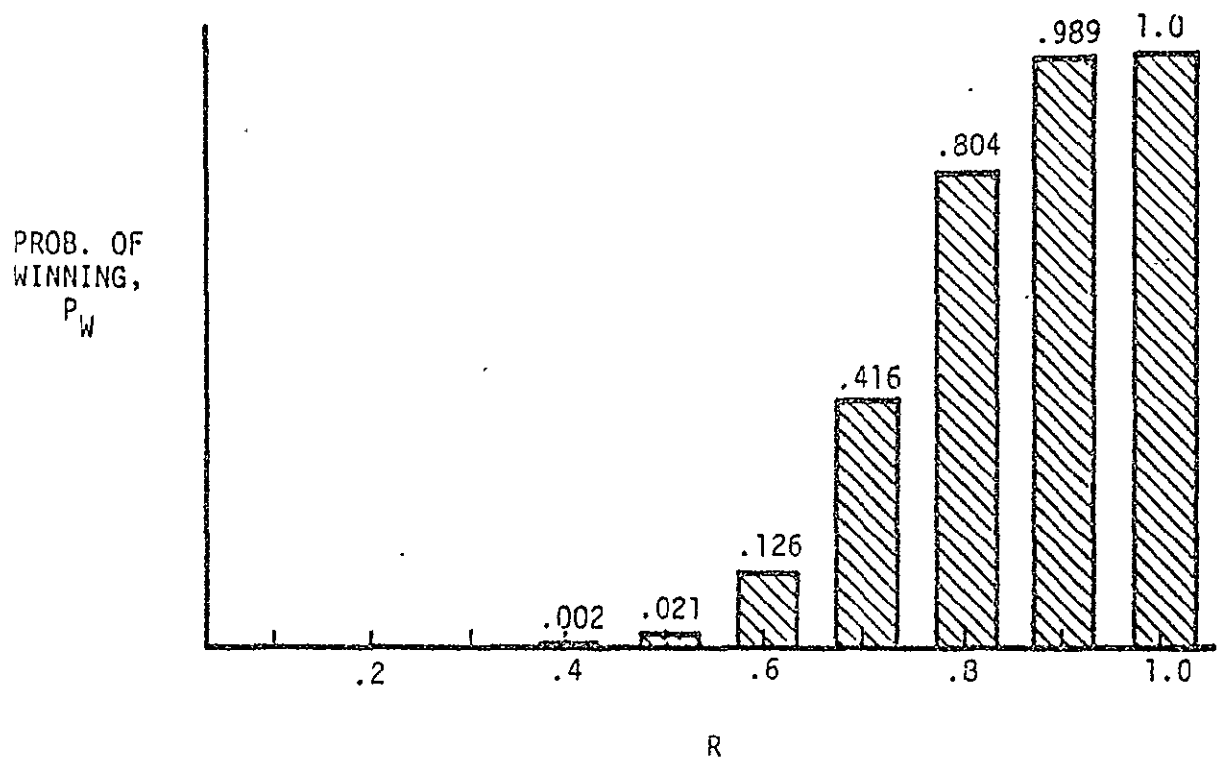


Figure 1.5 The Chance of Winning as a Function of R

Note in the example shown that the game has an expected value of $74.25 which is less than the $100 entry fee. Thus, the net expected value of the game is negative.

It is interesting here to point out the meaning of the expected value. Clearly, the game pays either $0 or $250. Thus, the expected value will never be obtained. The proper interpretation, however, is that, if the player played a large number of independent games such as this, his winnings would be approximately equal to the sum of the expected values of the individual games. Hence, if the player can play a large number of games, each with a positive net expected value, he can expect, with a high degree of confidence, to obtain a net positive payoff. If, however, some of the games have negative net expected values, the player can expect his total payoff to be reduced. A corollary to this for the federal government is that only those technology application programs with a positive expected value should be undertaken.

The thumbtack flip game presented above can be illustrated in terms of a decision tree as shown in Figure 1.6. The decision is to enter the game or not. If the answer is no, the player remains at his status quo. If the answer is yes, the player encounters a net expected loss of $25.75. Thus, it might well be expected that a prudent player would choose not to enter the game.

Can the game be changed in any way that would lead to a positive net expected payoff? Note that the key to the fact that the game has a net negative payoff is the state-of-knowledge on R, Figure 1.4. Suppose that state-of-knowledge could be improved for a small cost. For example, suppose the player could "rent" the thumbtack for $10, flip it a large number of times and, thus, determine the value of R precisely. Now the decision tree takes on the form shown in Figure 1.7. If the player decides to enter the game, he first commits only $10 to test the thumbtack. Then, and only then, if the thumbtack passes the test, that is, if R is equal to or greater than 0.8 in the decision rule shown, the player enters the game. Because the player is able to determine R at a low cost, he is able to control his risk and thus establish a positive net expected payoff for the game.

The game of technology application and the role of economic studies in this game is very similar to the thumbtack flip game. It is very much a game of information in which the objective is to establish a technology application program plan that controls risk and provides a positive net expected payoff. This is accomplished by a sequence of studies, analyses and tests that provide information necessary to move forward through the program. And like the thumbtack flip game, the ultimate mechanism for controlling risk is the option to exit (or not enter) the game. In a technology implementation program, it is the option to recognize that the program has failed and to terminate it. If a program plan that has a positive net expected payoff cannot be developed, it

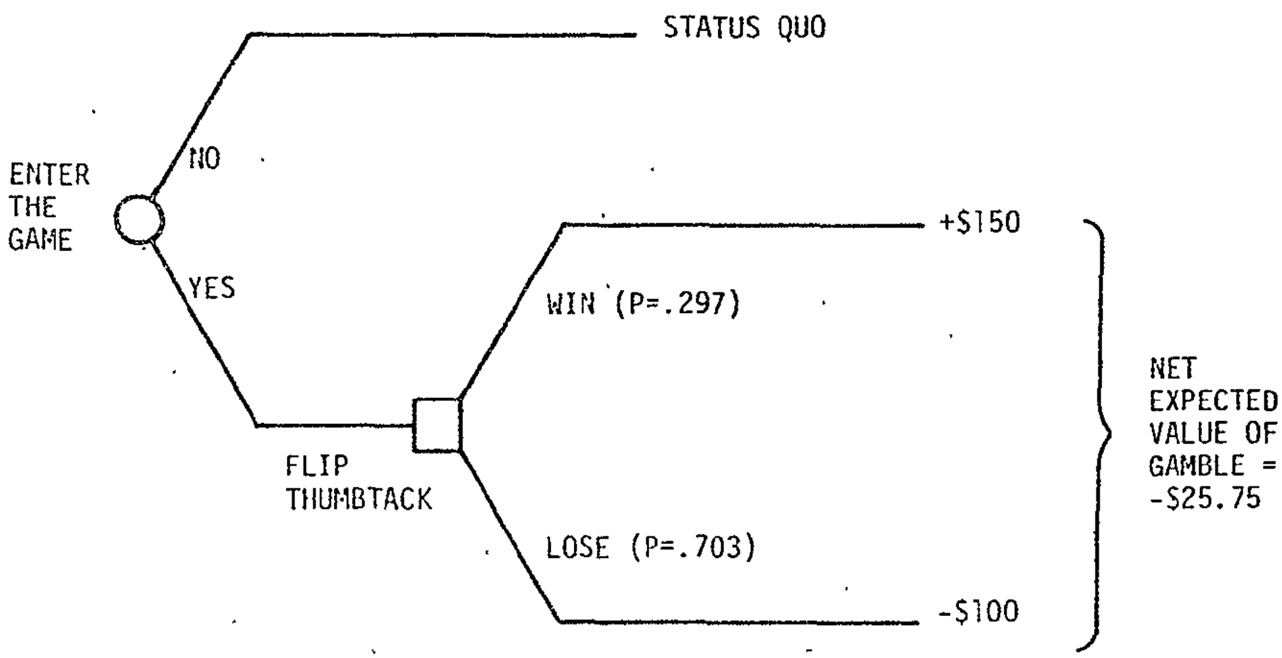


Figure 1.6 A Decision Tree Illustration of the Thumbtack Flip Game

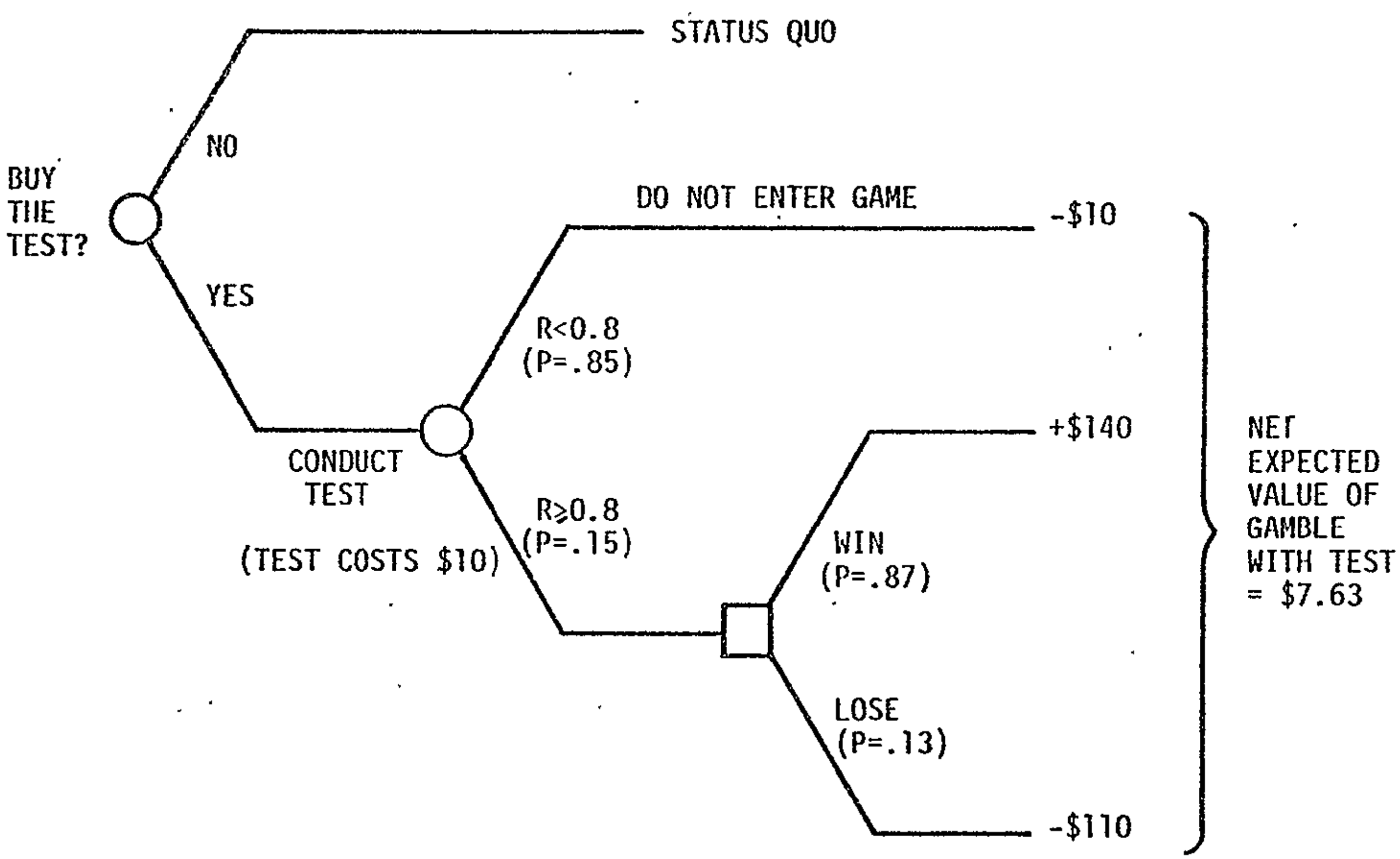


Figure 1.7 Decision Tree for the Thumbtack Flip Game with a Test

is a clear indication that the technology is not sufficiently developed to undertake an implementation program and the only thing that can be justified is a low level program of basic research. Risk analysis provides the mechanism for evaluating the probabilities necessary to establish and evaluate alternative program plans.

1.2 General Procedure

A risk analysis to evaluate the state-of-knowledge relative to space-based solar power systems (SSPS) needs to address the unit production and the operation and maintenance cost risks for SSPS units subsequent to the first unit.* The procedure for doing this is to first develop a deterministic cost model and then to incorporate this cost model in a Monte Carlo simulation computer program as shown in Figure 1.8. The data, consisting of system component costs, efficiencies, masses, reliabilities, etc., are input as probability distributions--states-of-knowledge. These variables are then sampled by the use of a sequence of random numbers. The sampled inputs are entered as deterministic numbers into the cost model and the results stored in a table. The process is then repeated several times (perhaps 250 to 1000 times) and the stored results thus generated are used to produce statistics and probability distributions that describe the risk associated with a specific alternative. In rare cases, with sufficiently simple problems, it is possible to perform a risk analysis without resorting to computer simulation techniques. The case of SSPS is far from this simple.

1.2.1 Cost Modelling

To perform a cost-risk analysis one must first produce a cost model. The cost model should provide for the interdependencies of various cost components. For example, if the mass of some system component increases, the number of launches required increases, the number of men to assemble the system increases, etc. Also, it is important that the model be constructed so as to minimize modelling error, that is, to minimize errors in the representation of system costs. To some extent, it is possible to create such models; however, the process is largely an art and it is difficult, if not impossible, to describe a procedure for the development of such models.

The cost models developed for the risk analysis of SSPS are described in Section 2 and Appendices A and B of this volume.

1.2.2 Uncertainties

Uncertainties in the value of system parameters, such as costs, masses, efficiencies, etc., are the result of an imperfect state-of-

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*In general, the first unit will not be a production satellite and, hence, its costs will not be reflective of the long-term economics of SSPS.

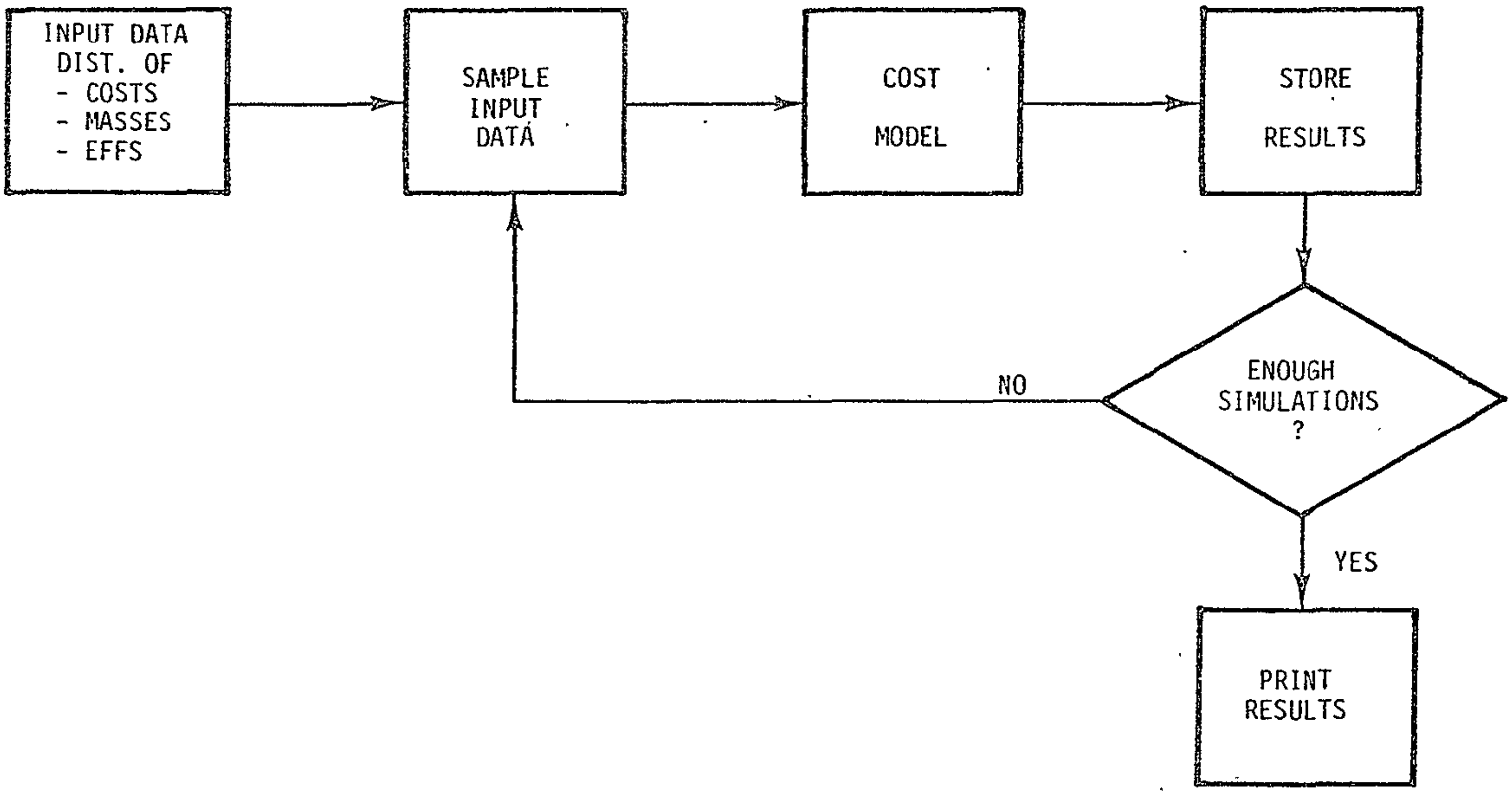

Figure 1.8 Risk Analysis Methodology for Unit Production and Operation and Maintenance Costs

knowledge relative to all components and aspects of the system. The magnitude of the uncertainties is related to the time in the system development cycle that the estimates are made and the state-of-development of the component technologies at that time. Uncertainties may, admittedly, be difficult to quantify. However, it might be inferred that the more difficult it is to quantify uncertainties, the greater the uncertainties are. The basic problem, thus, is to quantify uncertainty, that is, to define the state-of-knowledge.

The quantification of uncertainty requires that informed estimates be made of ranges of uncertainty of key variables and their probability distributions within the range. The uncertainty assessments can be made by individuals with the assistance of an experienced analyst or, for example, they can be made by an experienced group of individuals using Delphi type techniques [2,3].* Such estimates are very subjective in nature and quantitatively express the attitudes regarding the uncertainties. The estimates reflect past experience with similar efforts, problems which have been encountered in the past, insights into problem areas which might develop, etc.

Uncertainties can be quantified. In fact, most large corporations use risk analysis techniques which employ uncertainty assessments as a standard procedure in the evaluation and comparison of new business alternatives [4-10]. A methodology for establishing the shape of uncertainty profiles is described in Appendix D.

1.2.3 Effect of Reliability

The effect of reliability in various operations and components is to introduce risk into a system even if all costs, masses, efficiences, etc., are known precisely. The fact that there is a chance for failures

*The Delphi technique, initially researched at RAND, is a technique of systematically obtaining opinions from a panel of experts on a particular issue. The Delphi technique eliminates the committee approach for making estimates. It replaces direct confrontation and debate with a carefully planned program of sequential individual interrogations, usually conducted by questionnaires. The series of questionnaires is interspersed with feedback derived from the respondents. Respondents are also asked to give reasons, anonymously, for their expressed opinions, and these reasons are subjected to a critique by fellow respondents, The technique puts emphasis on informed judgement. It attempts to improve upon the panel or committee approach by subjecting the views of individual experts to each other's criticism in ways that avoid face-to-face confrontation and preserve anonymity of opinion and of arguments advanced in defense of those opinions.

to occur implies that there is a chance that costs will be incurred to remedy the failure. Since failures cannot generally be predicted (precisely), there exists an inherent variability in the cost of constructing or maintaining any system in which failures can occur.

The maintenance of an SSPS requires dealing with failures. To the extent that such failures can influence operation and maintenance costs, there is variability in these costs that must be accounted for in the risk analysis. While failures of various sorts, for example, launch vehicle failures, can occur in the production phase of an SSPS unit these have been neglected in the risk model described herein. The cost and risks associated with component failures in the operation and maintenance of an SSPS unit are included in the operation and maintenance cost-risk model. The procedure for their computation is described in Section 2.2.

1.3 Comparison of Alternatives

The ultimate purpose of any economic analysis of the sort described herein is to support a decision making process, that is, to provide guidance in the comparison and selection of alternatives. This includes choices between alternatives within a particular program, for example, between various SSPS configurations; or between alternative programs, for example, between SSPS and terrestrial alternatives. It is worth reiterating here, as proven above, that choices between alternatives cannot, in general, be made on the basis of most likely or expected values above. Rather, consideration must be given to both the expected outcome and the associated risk.

The risk profile of many alternatives approaches a normal or Gaussian distribution* to a sufficient extent that it suffices to describe these alternatives in terms of their expected value and risk (standard deviation). Now, consider the range of alternatives contained within the set of systems labeled SSPS, expressed in terms of their expected value and risk (Figure 1.9). Certainly there exist many ways of implementing a technology to produce an SSPS. Each way results in a unique expected value and risk as shown by the points plotted in Figure 1.9. It should be the objective of the program manager to determine the "best" technology implementations. These are those implementations which simultaneously maximize the expected value and minimize the risk. Given any technology base to work from, there is a limit to the extent to which these mutually competitive goals can be simultaneously met. This limit is known as the technology frontier and it represents the locus of best achievable combinations of expected value and risk commensurate with the specified technology base. The selection of the "best" alternative from the

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*A normal distribution can be fully described by two parameters, the mean or expected value and the standard deviation of the distribution. Other distributions require description by other parameters and full description of a distribution may require specification of several parameters.

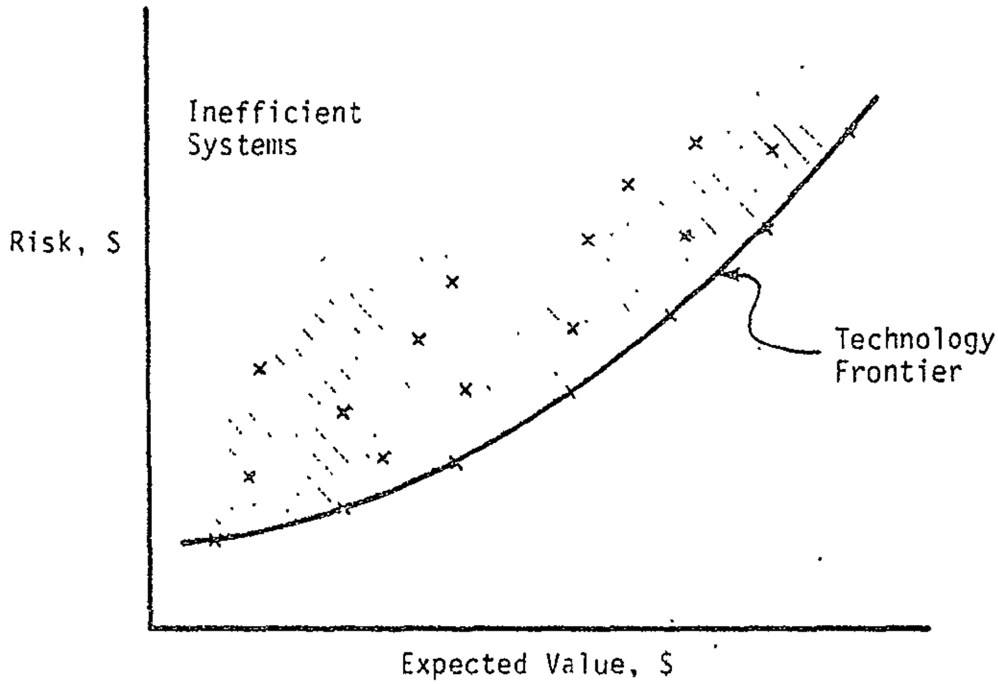

Figure 1.9 Development of the Technology Frontier

technology frontier requires a statement of the decision maker's risk preferences. It cannot be made by economic principles alone.

Thus, in terms of the selection of alternatives within a program, the purpose of a risk analysis is to define the technology frontier. The selection of alternatives between competing programs is accomplished by comparing the technology frontiers (Figure 1.10). As shown, Technology B might be SSPS, Technology C, terrestrial nuclear and Technology A, terrestrial fossil fuel--the curves are arbitrarily drawn here for illustrative purposes only. As shown, Technologies B and C always dominate A. Thus, A would never logically be chosen on economic grounds. On the other hand, the selection between Technologies B and C depends on the risk preferences of the decision maker. A highly risk-averse decision maker would forego the potential to obtain a high value in order to obtain reduced risk by choosing to implement Technology B in the region of expected value that produces low risk. A less risk-averse decision maker might choose Technology C, seeking the opportunity to capture a higher value.

In the end analysis, it is the decision maker(s) who decides what technologies to use and how to implement them based upon his personal set of preferences. The economist or analyst cannot make such decisions for him. However, the economist, analyst and engineer, working together, can provide the decision maker with information that fully describes the potential consequences of each alternative choice so that a well-considered selection can be made. The purpose of risk analysis is to provide the methodological framework for obtaining this information.

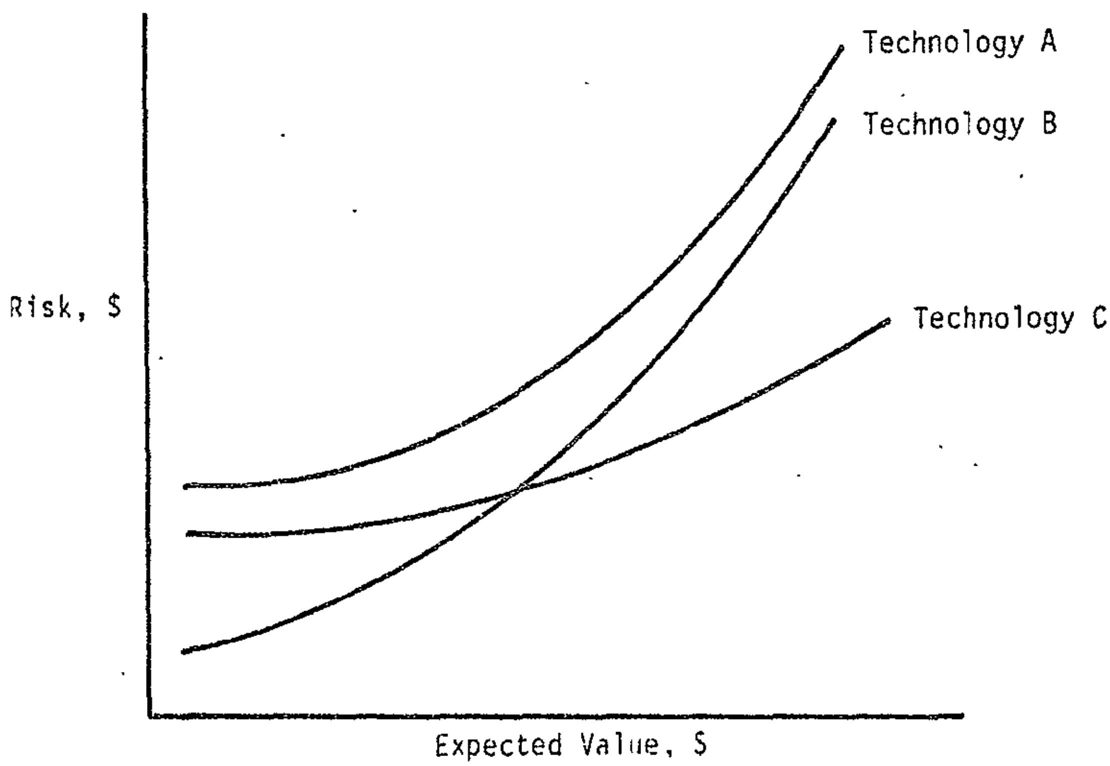

Figure 1.10 Comparison of Technology Alternatives

2. COST MODELLING OF SPACE-BASED SOLAR POWER SYSTEMS

The SSPS program is divided into three major cost categories: development, unit production and operation and maintenance as shown in Figure 2.1. The development includes all activities that occur through initial operation of the first full-scale unit and the unit production cost model includes all recurring costs for producing the "nth" (typically second) SSPS unit--satellite and ground equipment. The reason for this division of costs is the variety of methods by which the first unit could be built, for example, by growth from a 500 MW pilot satellite, whereby the costs of the first unit would not relate in any direct way to the costs of, say, the second unit.

The emphasis in this phase of study has been on the development of recurring cost models (both unit production and operation and maintenance) for an SSPS unit to serve as the basis for a risk analysis model. Descriptions of the unit production cost and the operation and maintenance cost models follow (Sections 2.1 and 2.2, respectively).

2.1 Unit Production Cost Model

The unit production cost model is based on sizing relationships provided by Grumman Aerospace Corporation [11], and the Raytheon Company [12]. A complete mathematical exposition of these relationships is found in Appendix A. The model in its present state of development identifies and represents the major cost elements for the current SSPS configuration and assembly scenario. The results of the model must still be considered to be preliminary, because, whereas the cost elements have all been addressed, many issues of scheduling and operations have not. For example, the model currently does not explicitly account for amortization of certain equipment by annuities, as sufficient information is not yet available concerning the timing of procurements or rates of utilization for this (transportation and assembly) equipment, nor does the model account explicitly for the timing of procurement of satellite and ground station components. Availability of such information in the future will allow continued refinement of the model. However, it is to be noted that these are refinements to the basic cost model and should not be interpreted as elements, the lack of which destroys the basic integrity of the model.

The central feature of an SSPS performance evaluation is a chain of power conversion and transmission efficiencies. This efficiency chain forms the backbone of the unit production cost model as seen in Figure 2.2., which shows the correspondence of system components to elements in the SSPS efficiency chain.

Most of the sizing (hence, cost estimation) of system components is done on the basis of power throughput. Since the power output

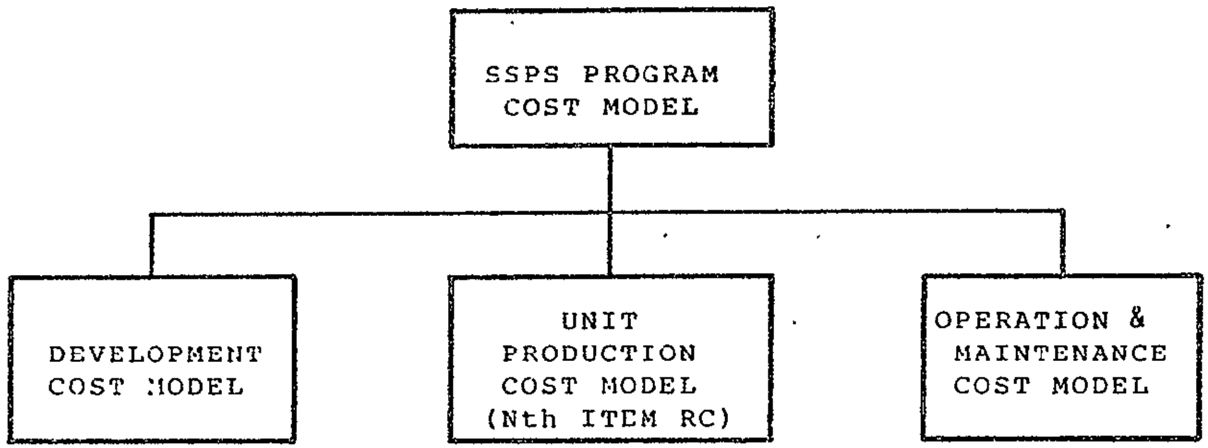

Figure 2.1 SSPS Program Cost Model

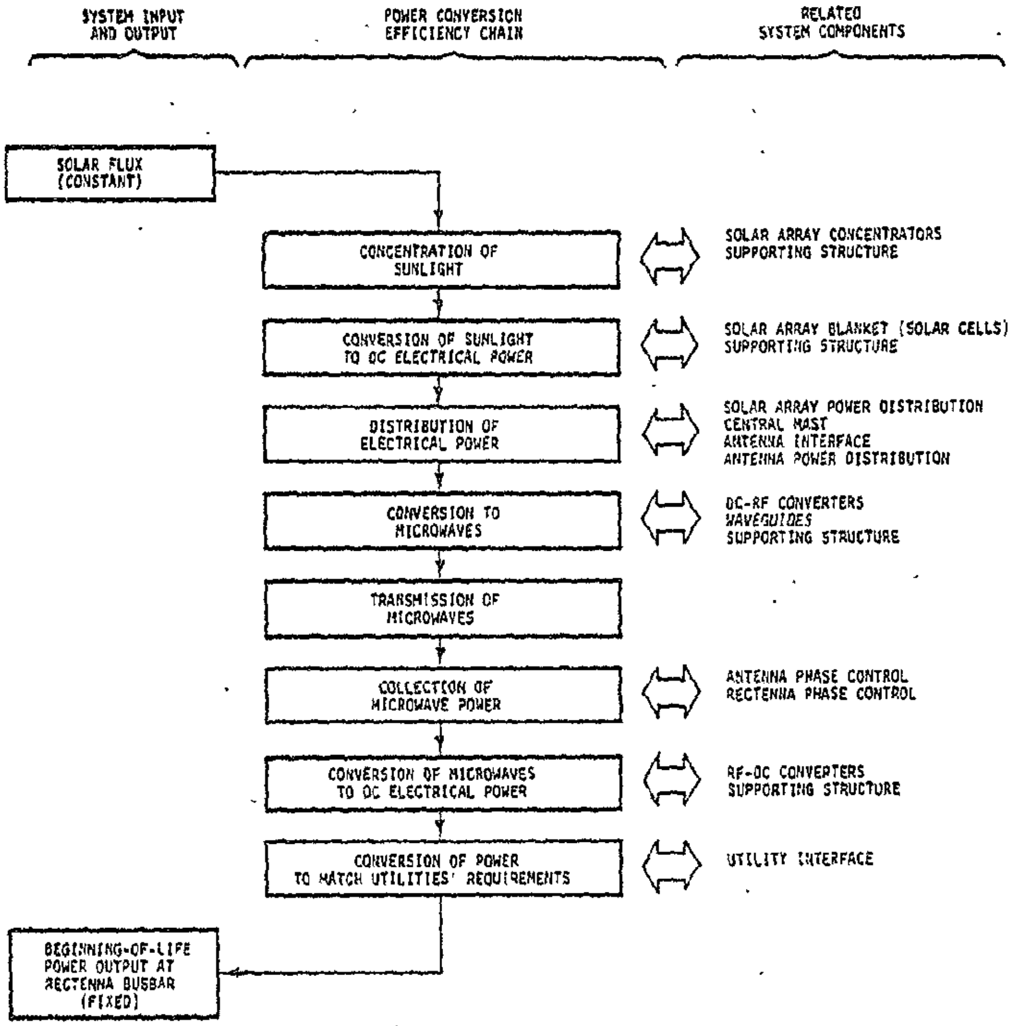

Figure 2.2 Relationship of SSPS Components to the System Efficiency Chain

is constrained as a design parameter in this study, a change in any element in the efficiency chain affects the power throughput (hence, size and cost) of all of the system components preceding it in the chain.

The unit production cost model has five Level 3 components, as shown in Figure 2.3: ground station, LEO (low earth orbit) launch, space station and assembly, LEO-GEO (geosynchronous earth orbit) transportation, and satellite procurement. Each of these cost components is dealt with in detail below; an overview of the model's structure is provided in Figure 2.4. The model has been kept as general as possible, that is, insofar as possible, design and performance parameters have been treated as variables. Certain assumptions, however, are implicit in the model, such as construction in low earth orbit as opposed to geosynchronous orbit. Wherever such limitations occur in the model, they have been called out in the discussion that follows. In future developments of the model, greater generality will be developed, allowing examination of the effects of a wider range of design tradeoffs.

2.1.1 Ground Station Cost Model

This cost model consists of the cost of land and site preparation for both the receiving antenna structure and a safety zone around the receiving antenna, rf-dc converters, phase control equipment and utility interface. The size of the rectenna was set in the Raytheon MPTS study [13], based upon 20 mW/cm^2 being an acceptable maximum power density level and 2.45 GH_Z being the optimum frequency for transmission. Hence, the model does not allow tradeoffs among receiving antenna area, cost, and power density; costs are determined on the basis of power level. However, the receiving antenna technology is one of the most developed of those underlying the SSPS concept, and it was felt that the inability to recreate the rectenna size, cost and power density tradeoffs did not pose a serious limitation to the model's effectiveness at this point in time.

More detailed consideration of rectenna design and cost characteristics should be included in future developments of the model.

2.1.2 LEO Launch Cost Model

This model includes the cost of procuring and operating fleets of heavy lift launch vehicles (HLLV's) and Space Shuttles to launch to LEO the materials and personnel necessary for the construction placement and final check-out of an SSPS satellite. The HLLV's are used to launch equipment and supplies and the shuttles are used to rotate on-orbit personnel. The model allows consideration of payload masses, load factor, unit costs, launch operations costs per flight and vehicle design life. The costs for both vehicles are determined on a "per launch" basis by dividing the unit cost over the expected life of the vehicle and adding the launch operations and refurbishment costs per flight. The number of HLLV flights is calculated by dividing the total mass of the satellite

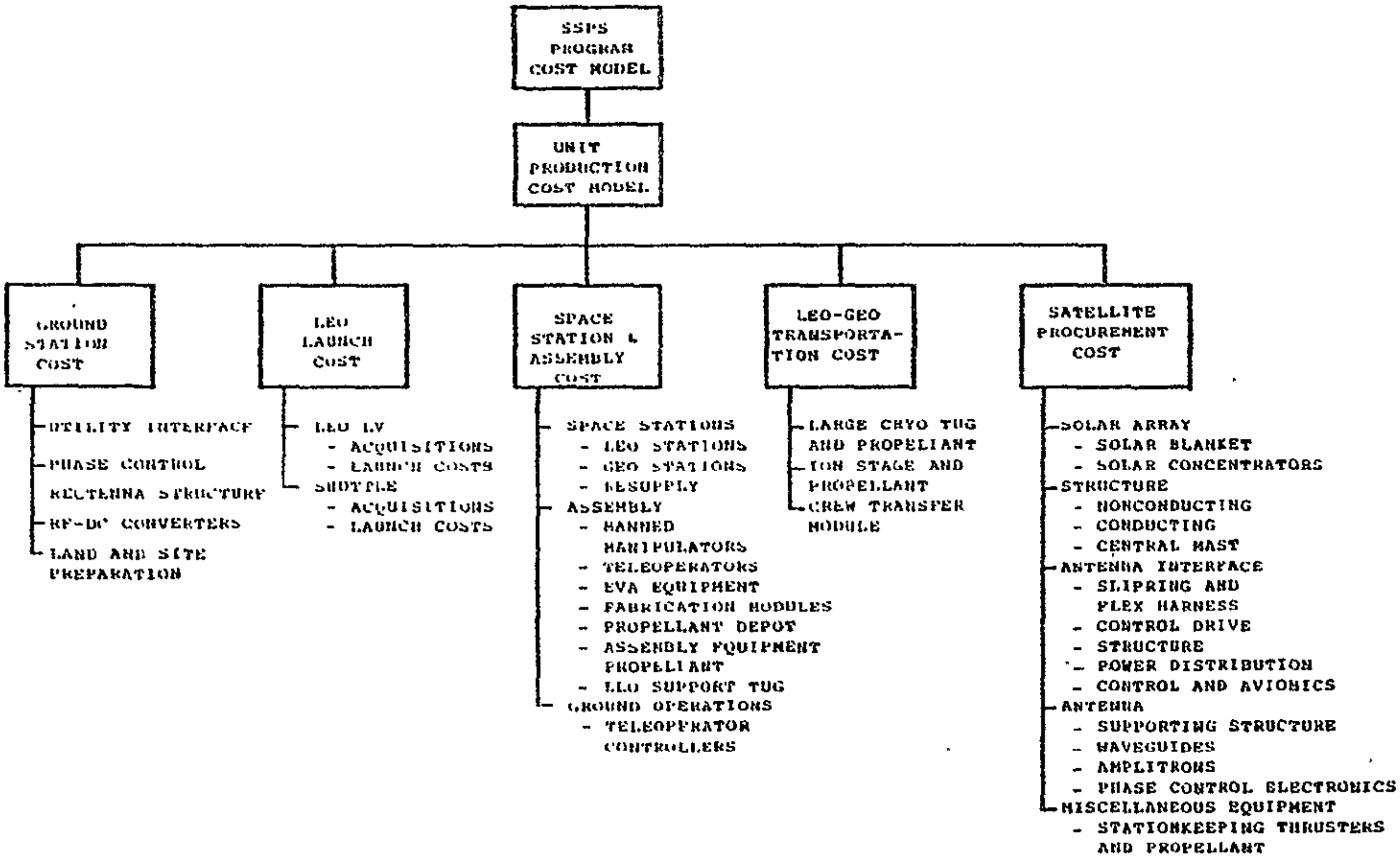

Figure 2.3 Unit Production Cost Model

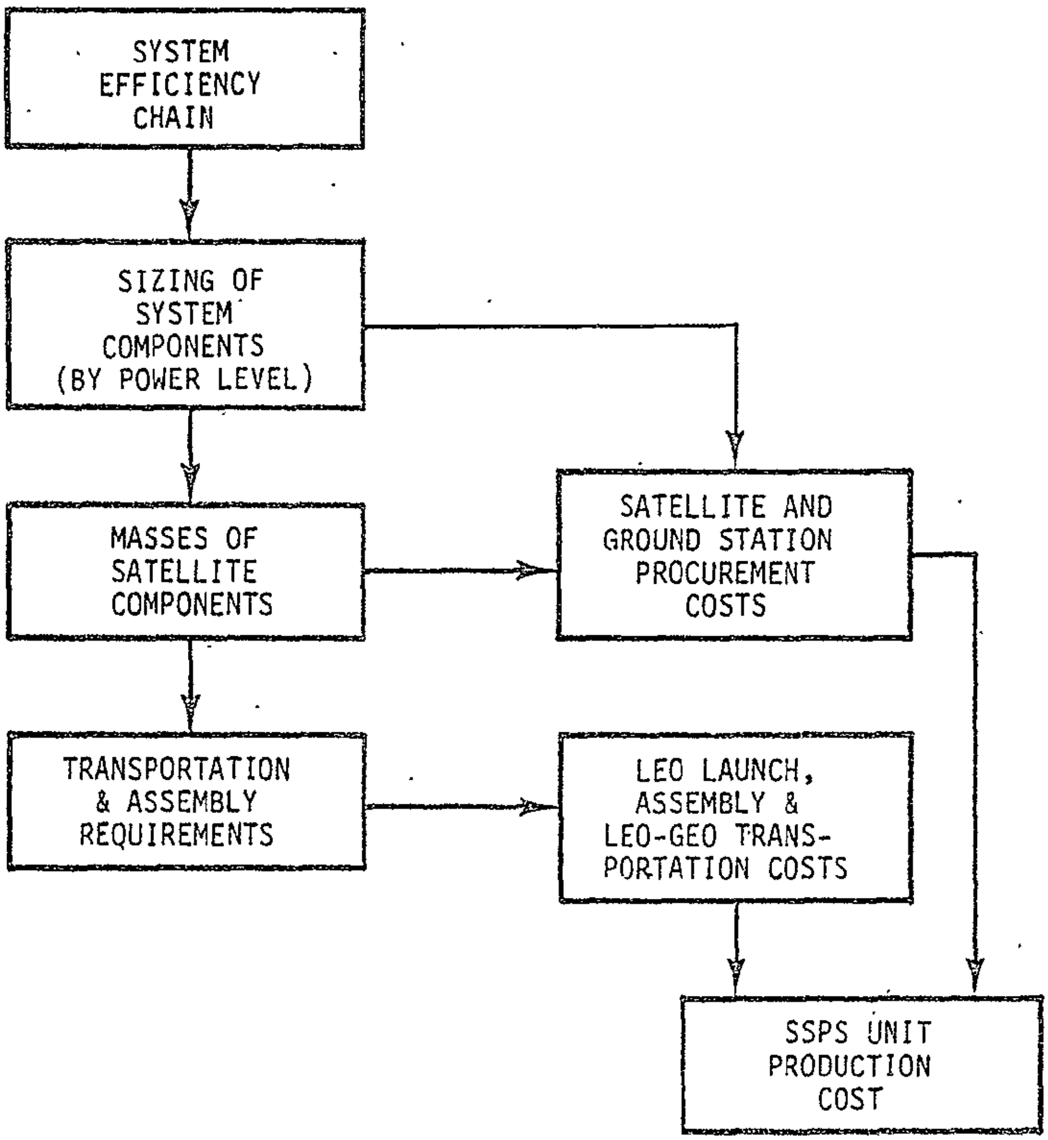

Figure 2.4 General Logic Flow of the SSPS Unit Production Cost Model

and required assembly equipment by the payload of the HLLV and its load factor. Similarily, the number of shuttle flights is determined by the number of personnel needed on orbit, the number of personnel carried per shuttle flight and the rate of personnel rotation.

One limitation of the model in its present form is that it does not consider such operations factors as vehicle refurbishment (turnaround) time. Such scheduling factors will have to be considered as the model is refined because the rate of launch may be expected to be very non-uniform for the construction of a single SSPS satellite, although the overall launch facility activity level could be expected to become more uniform (allowing more efficient use of resources) as more SSPS satellites are constructed simultaneously, given proper planning to accomplish this. In addition to more detailed consideration of launch operations, explicit consideration of launch vehicle reliability should be included in furture model development.

2.1.3 Space Station and Assembly Cost Model

This model represents the costs of: remote-controlled teleoperators and their ground controllers, space stations and station supply, EVA equipment, support tugs, manned manipulator modules and structure fabrication modules. The number of teleoperators and personnel needed on orbit is determined by the total mass of the satellite to be constructed, the different rates of fabrication for on-orbit personnel and teleoperators, the total construction time allowed and the percentages of the satellite to be constructed by on-orbit personnel as opposed to teleoperators. Factors of availability (reliability) and productivity for both man and machine can be examined separately from basic rates of fabrication. Both transportation and procurement costs of all space station and assembly equipment are amortized over the expected life of the equipment.

Little consideration could be given within the resources of this study to the extremely complicated operations research issues of scheduling of the assembly activities; these issues (and concomitant productivity) of both on-orbit personnel and equipment represent major areas of uncertainty to be explored in the future. In the near-term development of the model, different rates of assembly for different levels of complexity (for example, structural integration versus electronics checkout) should be developed as well as the capability to examine other assembly scenarios than the LEO assemply and GEO final checkout option to which the model is now constrained.

2.1.4 LEO-GEO Transportation Cost Model

This model represents the costs of transferring the satellite from its LEO assembly site to GEO for final checkout and operation. The model includes the costs of: an advanced ion stage used for propulsion, a large cryo tug and a crew module to transfer GEO personnel, a LEO depot to store both cryo and ion propellants; and the propellants themselves. The two vehicles are sized for their payloads and the number of trips, and the cost of the propellants is added to the amortized cost (unit cost divided by expected life) of the vehicles. Likewise, the propellant depot is amortized. The ion stage makes a single flight per SSPS satellite and the number of large cryo tug flights depends on the crew rotation rate.

At this point, no consideration has been given to vehicle reliability which could have a significant impact on both total transportation and component procurement costs. Furthermore, the model accounts for one GEO space station per SSPS satellite, whereas the space station might be used for final checkout of a number of satellites; as more information becomes available concerning SSPS construction rate and operation and maintenance requirements, a proper accounting of this station can be made. Also to be included, as information becomes available through further studies, is a relationship between ion stage size and cost, the cost of a cryo return stage for the ion stage and the cost of the degradation of the satellite solar arrays used to power the ion stage during the trip to GEO.

2.1.5 Satellite Procurement Cost Model

The satellite procurement model utilizes relationships which size the solar array blankets and concentrators based on solar cell efficiency, concentrator efficiency and the solar flux. The structure is sized by the area of the blanket, the antenna interface and antenna components sized by their respective power levels. All costs derive from cost relationships: cost/unit area for the array blankets and concentrators, cost/unit mass for structure and cost/unit power for the microwave transmission portions of the satellite.

The details for sizing and costing this satellite configuration are fairly well developed. The major limitations at this point include an inability to internally size the satellite for different concentration ratios (this can be done by input variables, however) and an inability to tradeoff transmitting antenna size, cost and power density against ground station size and cost.

2.2 Operation and Maintenance Cost Model

The second element of SSPS unit recurring costs which was modelled in this study phase was the cost of operation and maintenance (O&M). The model contains four Level 3 components, as shown in Figure 2.5: launch facility O&M, ground station O&M, space station and support O&M and satellite O&M; these are developed separately below.

2.2.1 Launch Facility O&M Cost Model

This component of the O&M model represents the cost of one heavy lift launch vehicle (HLLV) flight to low earth orbit and accompanying advanced ion stage (AIS) transfer to geosynchronous orbit of the material necessary (to supply the on-orbit maintenance personnel) as well as the cost of launch facility mission control personnel.

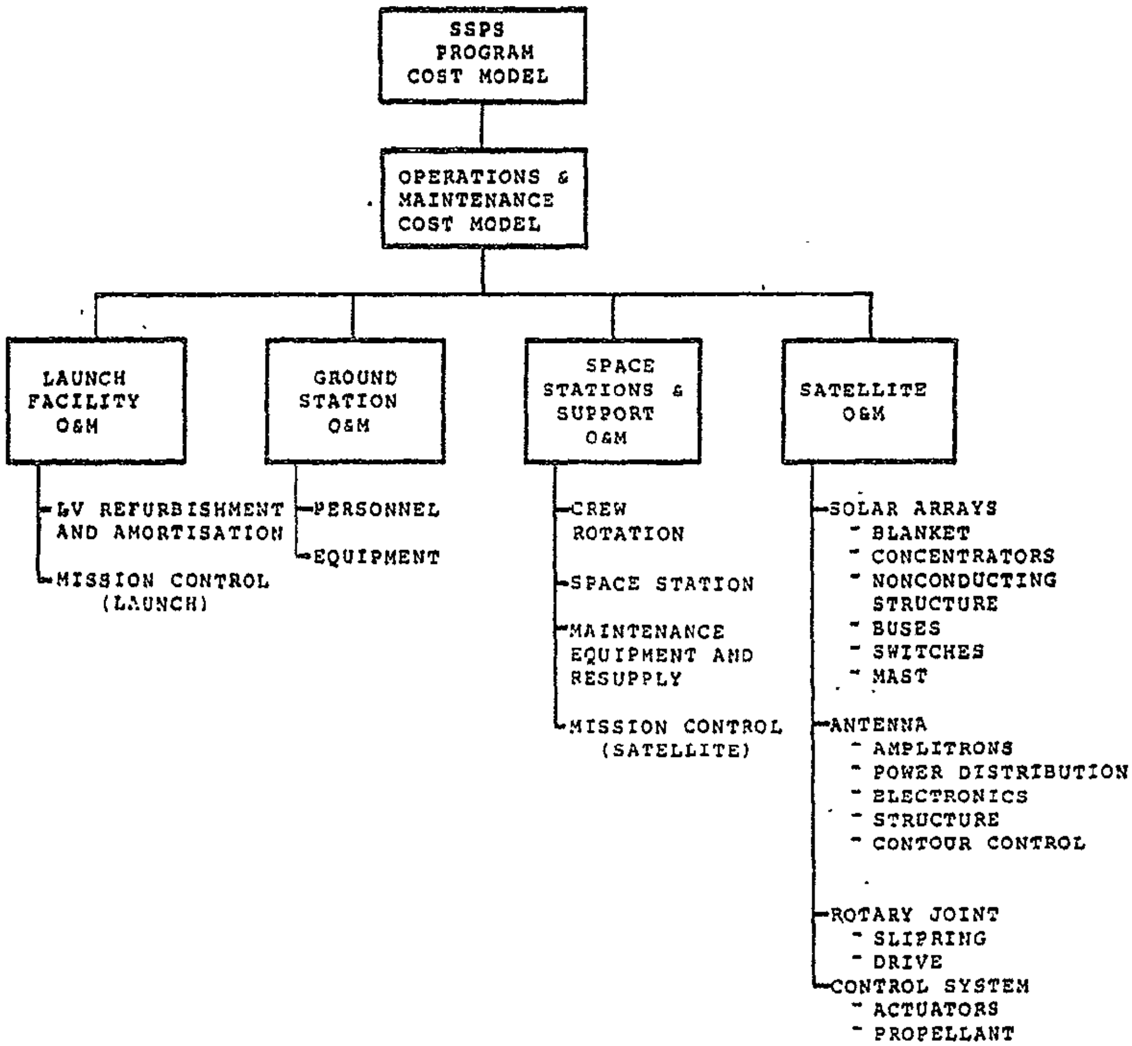

Figure 2.5 Operation & Maintenance Cost Model

2.2.2 Ground Station O&M Cost Model

The component of ground station O&M cost includes the cost of both equipment replacement (at an assumed percentage rate per year) and ground station operation and maintenance personnel.

2.2.3 Space Station and Support O&M Cost Model

The cost of crew rotation is derived from the vehicle costs and the assumed rate of annual rotation. The costs of the GEO space station and the maintenance support equipment used by on-orbit personnel includes the amortized cost of procuring and transporting the station and equipment and, finally, the cost of the mission control to support the space station and on-orbit O&M equipment is derived from an assumed cost per unit output power.

2.2.4 Satellite O&M Cost Model

The major cost associated with maintenance of an SSPS satellite is that of replacing components that fail. To serve as a guideline for the failure rates that might be expected from SSPS satellite components, the failure rates of recent equipment such as that on the Orbiting Astronomical Observatory (OAO) have been used. Whereas it might be expected that reliability rates would be considerably improved through learning connected with SSPS construction, it is also true that SSPS components will have to be mass-produced (unlike the hand-built components of the OAO, for example), possibly resulting in lower reliability. Given that these two opposite effects will be occurring in a way that cannot now be predicted, the failure rates for recent or current equipment have been used as reasonable guidelines for this phase of analysis.

The smallest components which might be replaced in each subsystem in the event of failure have been identified, as well as the costs of procurement, transportation and installation on a cost-per-unit-mass basis.

Although the structures have been included as satellite components, it is expected that they will be designed so that their probability of failure during a 30-year lifetime is zero.

The failure rates of smallest replaceable components are sampled in a Monte Carlo simulation to calculate a probability distribution for annual O&M costs. The rate of replacements of units of a given satellite component is a random variable that depends on the mean time between failure for that component. That is to say, the nature of failures is such as to produce uncertainty in the annual O&M cost despite potentially perfect knowledge of all costs. In the Monte Carlo simulation the rate of replacement is obtained as a probability distribution over integer numbers of replaced units. The computer algorithm for computing the distribtuion of component replacements is shown in Figure 2.6.

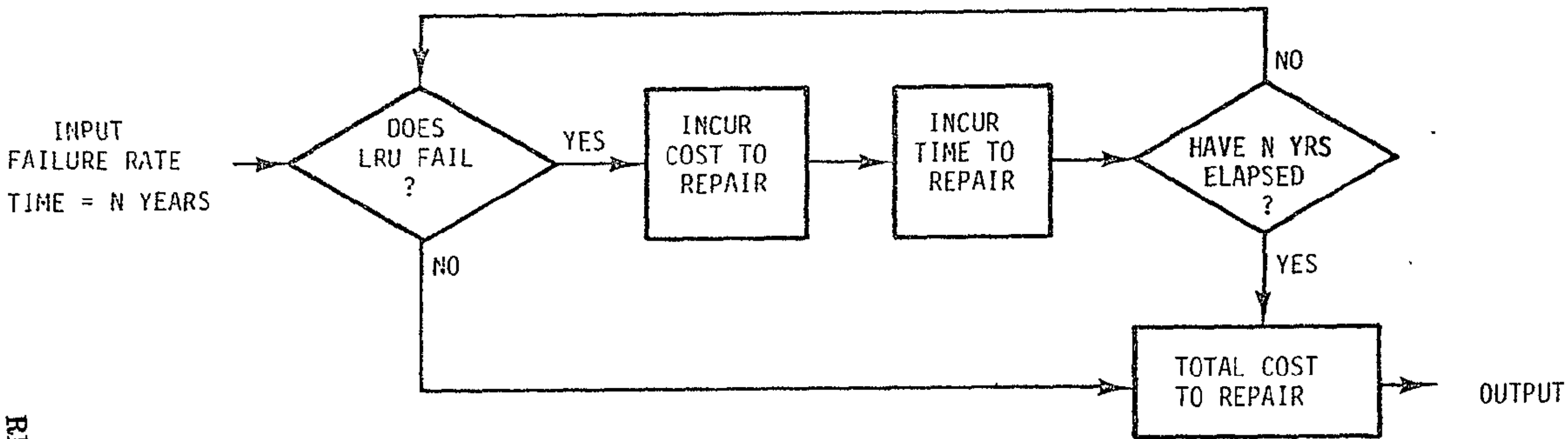

Figure 2.6 Computer Algorithm for Computing Cost of Replacing Failed Components

Each component is interrogated to determine if it fails during the period of consideration. If it does, it is replaced and the replacement part is interrogated to determine if it fails in the remaining time. The process is continued until the time period considered ends. Then, replaced units and replacement costs are accounted for.

3. ANALYSIS OF UNCERTAINTY AND RISK IN SPACE-BASED SOLAR POWER SYSTEMS PRODUCTION, OPERATION AND MAINTENANCE

3.1 Current State-of-Knowledge

The cost and risk analysis discussed in this section is based upon the current configuration SSPS, illustrated in Figure 3.1, which is sized to generate 5258 MW* of rectified power at the output bus of the receiving antenna at the beginning of life of the system. This power level was chosen to provide economies of scale while keeping the peak microwave power density in the center of the rectenna to 20 mW/cm^2, a level that is expected to meet anticipated environmental standards. The 20 mW/cm^2 value approaches the anticipated threshold level for affecting changes in the ionsphere. It is noted, however, that the effects of these anticipated changes are unknown.

The satellite's mass in orbit is deterministically estimated to be 22.776x10^{6}kg, using the most likely values described below. An operating frequency of 2.45 GHz was selected based on considerations of power transmission efficiency, low susceptability to brownouts in rain and minimal potential problems with radio frequency interference. The transmitting antenna is an active planar phased array which uses amplitrons for dc-to-rf power conversion. The photovoltaic power source nominally generates 8935 MW of power using an advanced 100-micron thick silicon blanket that has an initial nominal efficiency of 12.9 percent at a solar concentration ratio of two. The overall efficiency from solar blanket busbar to ground station busbar is nominally estimated to be 58 percent.

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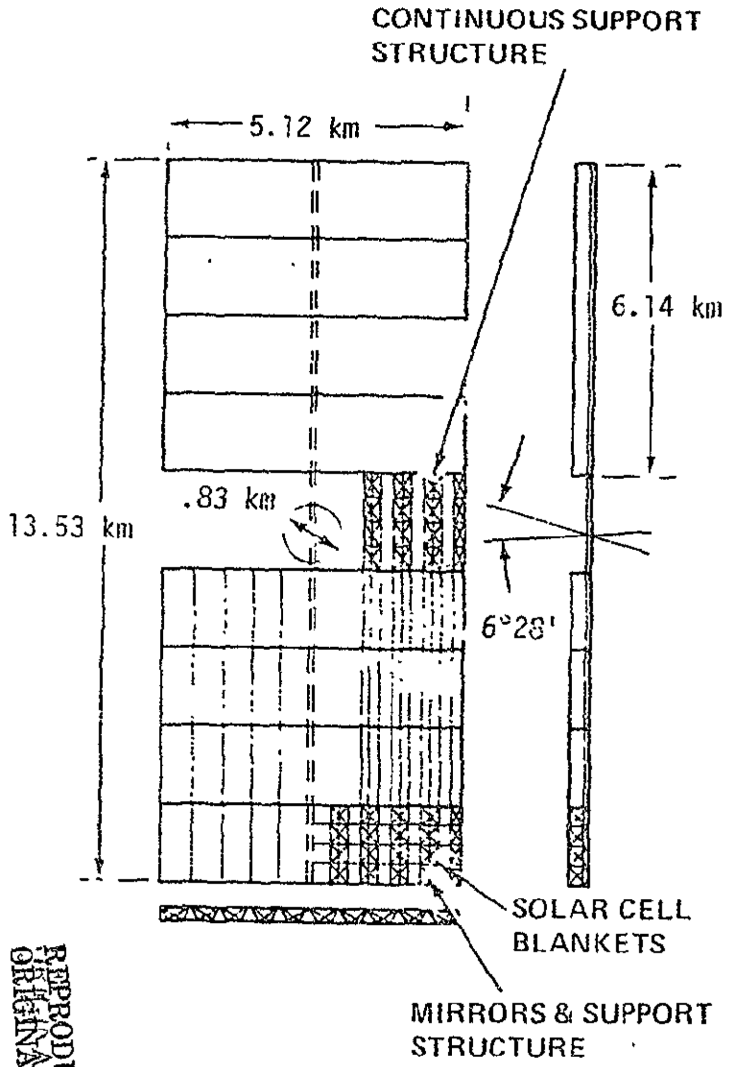
*The 5000 MW power level commonly used in earlier phases of this study refers to the power output at the beginning of the sixth year of operation, although the satellite was designed to handle the higher beginning-of-life power level. (Degradation in the power level occurs throughout the life of the satellite because of an estimated 1 percent per year degradation in system efficiency.) The five-year point for power output represents a weighted average of power output over the lifetime of the satellite for the purpose of revenue projection. Because the rate of solar cell degradation and the discount rate are treated explicitly as variables in revenue projections, the actual beginning-of-life power output level will henceforth be used to describe the SSPS power level. Note that this adjustment of designated power level does not itself affect the sizing or costing of an SSPS.



- Concept Description

  Collects solar power using photovoltaic converters and transmits power to Earth as microwave power. The microwave power is rectified to dc power at the ground receiving station.

- Typical Characteristics (Derived From Deterministic Estimate Based on Most Likely Values)

- Power	5258 MW (b.o.l.)
- Mass	22.8×10^6 kg
- Size	13.53x5.12 km
- Orbit	Geosynchronous
- Life	30 Years
- Operating Frequency	2.45 GHz
- dc-to-dc Efficiency	58%
- Solar Array Efficiency	10.4% (12.3% blanket efficiency)
- Initial Operation Date	1990-1995

Figure 3.1 Current Configuration of an SSPS Satellite

The design concept has two large solar cell arrays, each approximately 6 km x 5 km, inter-connected by a carry-through structure of dielectric material. An 0.83 km diameter microwave antenna is located on the centerline between the two arrays and is supported by the central power transmission bus (mast) structure that extends the full length of the power station. The antenna is attached to the mast structure by a joint system which rotates 360 degrees in azimuth (east-west) and ± 8 degrees in elevation (north-south). The solar cell blankets are laid out between channel concentrators stretched over a supporting frame.

A range of uncertainty naturally occurs in trying to project the state of design parameters or cost components that will exist in the 1990-2000 time period during which an early SSPS might be built. The range of uncertainty is reduced as the state-of-knowledge improves -- generally through studies, testing or technological development. For factors about which little is known, a probability density function describing the state-of-knowledge is likely to be fairly broad and fairly flat, that is, that there is no pronounced likelihood that any particular outcome within the possible range of outcomes will occur. With development of the state-of-knowledge, however, the range of possible outcomes becomes more narrow and a peakedness in the distribution may arise around the expected (or most likely) value. The narrower the range and the more peaked the distribution (hence, the better one can predict the outcome), the more developed the state-of-knowledge is said to be.

In order to represent in the SSPS program cost model (described in Chapter 2) the state-of-knowledge that exists for the design factors relating to SSPS, ranges were established with maximum and minimum values, and a most likely value was assigned. The rule observed in setting the maximum (worst) and minimum (best) values was that there is zero probability of the outcome exceeding the assigned maximum or being less than the assigned minimum. Most likely values were estimated based on available information and engineering judgement.

It was beyond the scope of this study to develop probability density functions in the manner described in Appendix D. However, distributions were assigned as shown in Figure 3.2 that might be representative of design factors, the states-of-knowledge of which are not well developed, that is, the distributions are not sharply peaked, however, neither are they particularly broad. For each variable, the particular distribution was selected based on the location of the most likely value between the minimum and maximum values. It is expected that this process would be refined, for example, according to Appendix D, in future work.

The range of values and the most likely value for each design factor may be found in Appendix C, along with the sources for these data. It should be noted that these data are specific to the current configuration SSPS and are intended to represent the state-of-knowledge with respect to this particular configuration at this point in time.

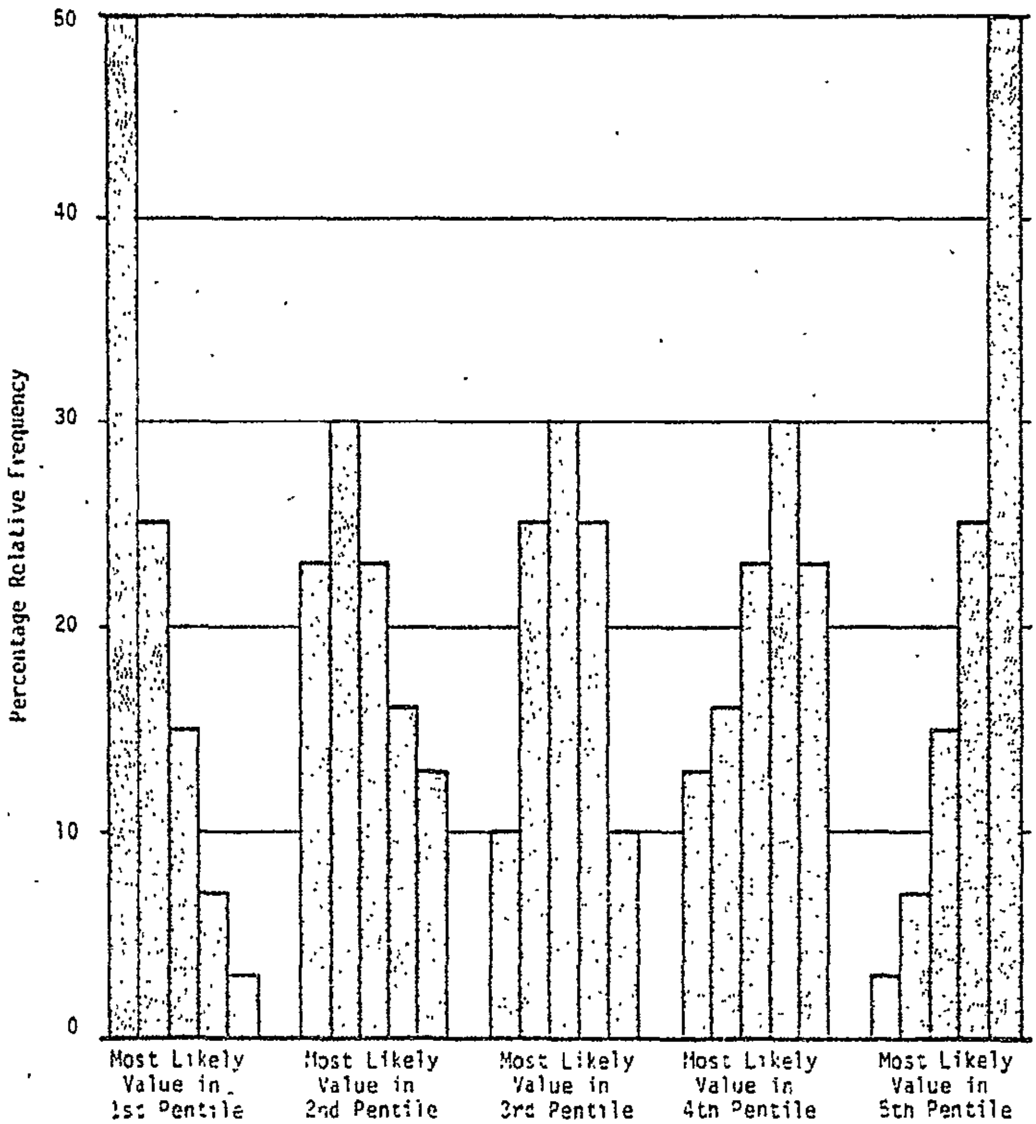


Figure 3.2 Uncertainty Profiles

Some adjustments have occurred during this phase of the study in the assignment of most likely values for a number of design factors. These adjustments have come as the result of more detailed analysis both in this study and in related studies (such as the space station studies being conducted by Grumman Aerospace Corporation). The adjustments having the greatest impact on system size and cost involve the solar array blanket: the values for specific cost, specific mass and solar cell efficiency which had previously been treated as target values, are now viewed as the most optimistic values.

3.2 Risk Assessment of the Current Configuration

Based upon the assessment of the state-of-knowledge discussed in Section 3.1 and Appendix C, a risk assessment of the current configuration SSPS was conducted. The assessment provides probability distributions of unit production costs (nth unit)* and operation and maintenance costs; see Figures 3.3 and 3.4. These figures show the cumulative distribution functions, referred to as risk profiles, for costs. The probability value shown on the ordinate represents the probability (or confidence) that the current configuration SSPS could be produced (Figure 3.3) or operated and maintained (Figure 3.4) for a value shown on the abcissa or less under the current state-of-knowledge. Thus, for example, there is a 50 percent chance that the second unit SSPS could be constructed for $14.2 billion (1974 dollars) or less. Alternatively, if one wished to commit to the construction of the second unit today and, furthermore, if one wished a 90 percent confidence of successfully completing that unit, one would have to commit about $20 billion (1974 dollars) to the project (for that unit--that is, in excess of the DDT&E program).

Of course, one could argue over the accuracy of the curves shown in Figures 3.3 and 3.4. These curves are preliminary and do not include all of the uncertainties inherent in the current configuration SSPS.**

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* Because the first unit is not a production unit and may be constructed by various alternative methods, for example, growth to full-scale from a pilot plant, the cost model does not apply to this unit. The model applies essentially to the second and subsequent units. However, after the second unit it should be expected that unit production costs will decrease from the value computed by the cost model due to learning effects.

** The analysis presented does not account for the uncertainties in the microwave system as an assessment of these uncertainties must be made by Raytheon and hence was beyond the scope of this effort.

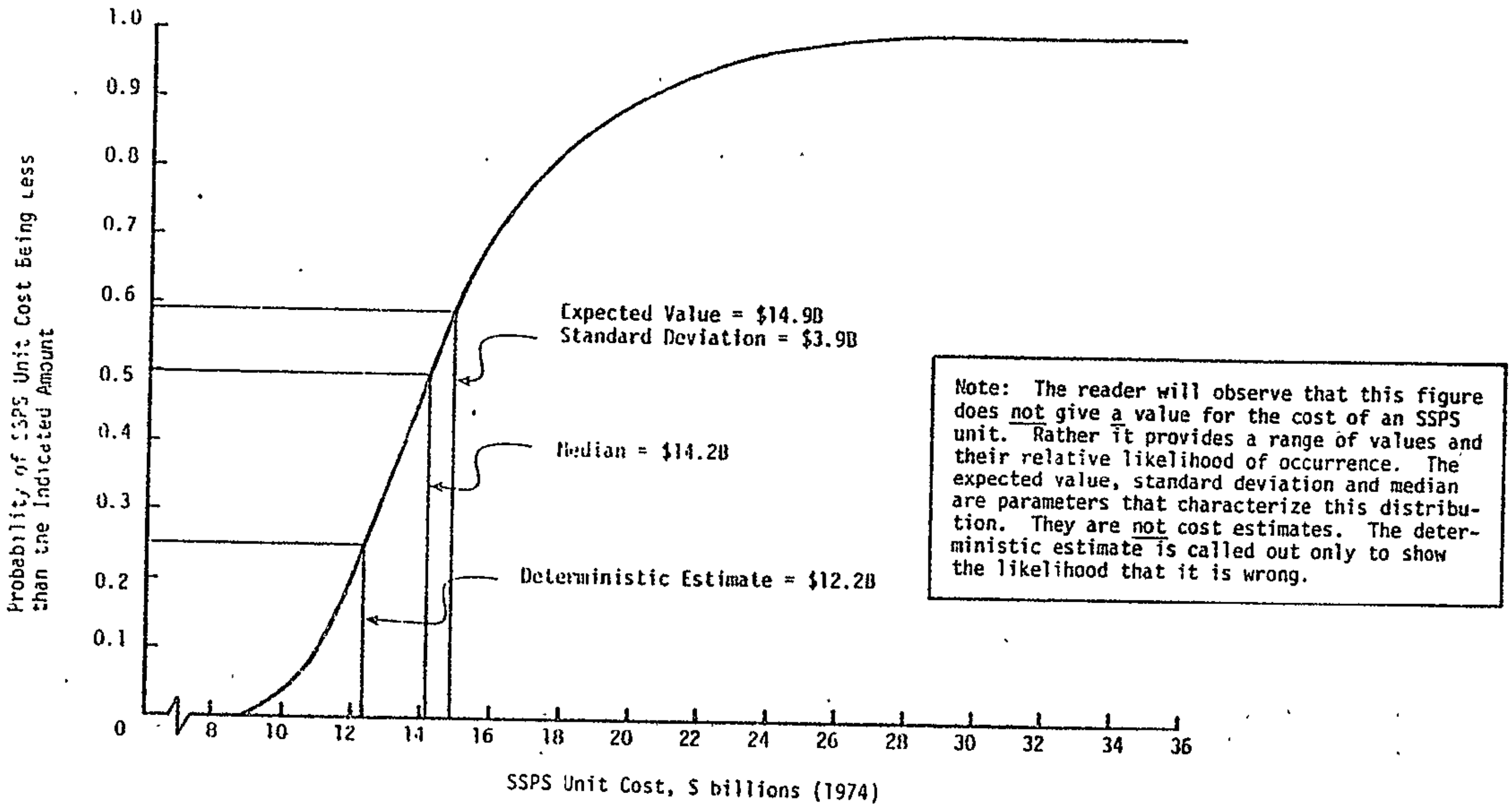

Figure 3.3 Cumulative Distribution Function of SSPS Unit Cost

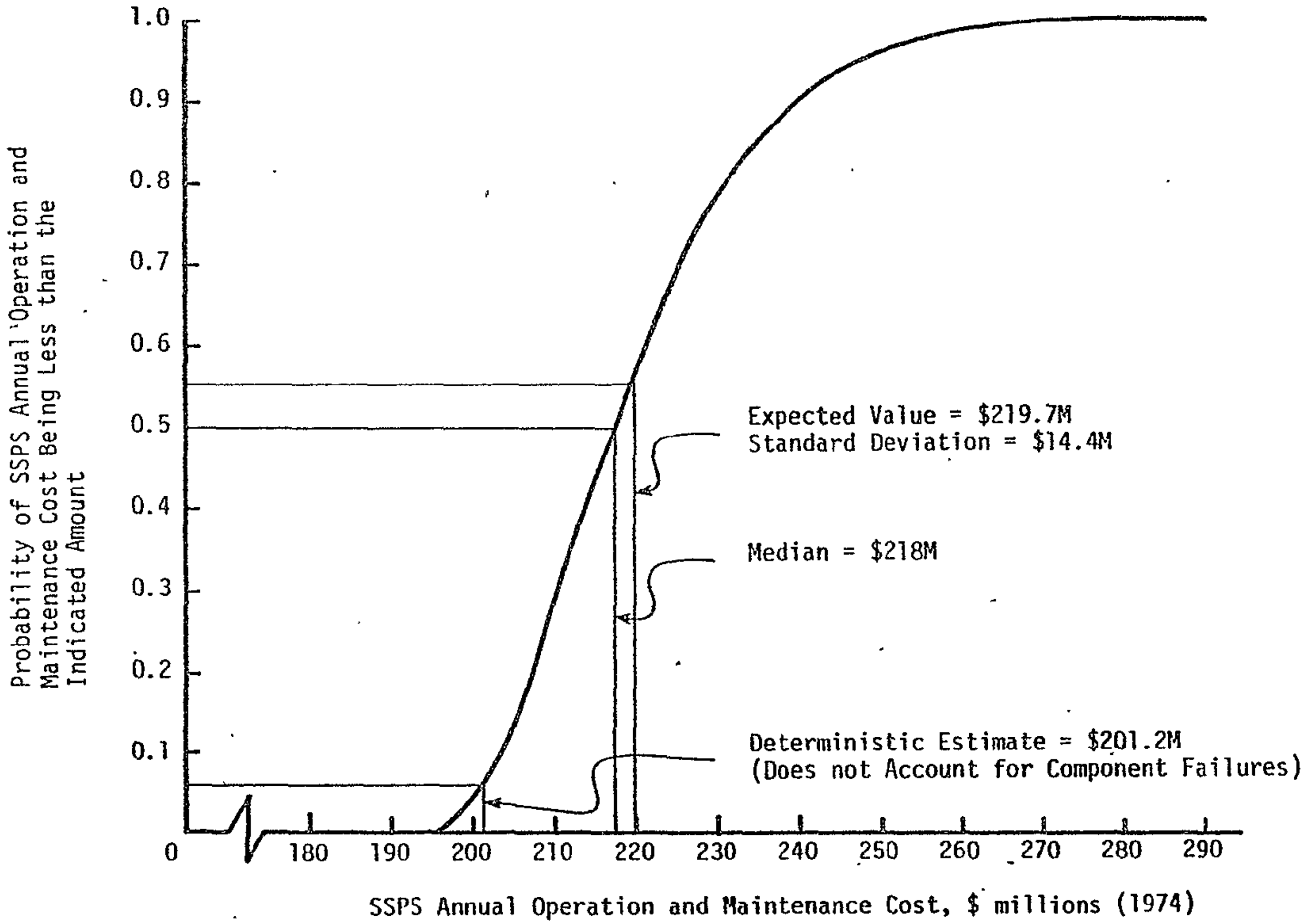

Figure 3.4 Cumulative Distribution Function of SSPS Operation and Maintenance Cost

Thus, if anything, the high end of the unit production risk profile is optimistic. However, arguments over the high end of the risk profile do not necessarily apply to the low end and, thus, have only a limited effect on the decision process. Furthermore, one would probably never choose to commit $20 billion to the production of a single SSPS unit since it is unlikely that the price that could be obtained for power at the rectenna busbar would be sufficiently high to pay back this capital cost.

What knowledge about the desirability of pursuing an SSPS development program can be legitimately gleaned from Figures 3.3 and 3.4? First, consider the process of obtaining cost estimates. Figure 3.3 shows that a cost estimate for the current configuration SSPS based upon deterministic estimates of all parameters in the cost model (most likely values) yields $12.2 billion (1974 dollars).* Note that there is only about a 25 percent chance of the unit production cost being this low and note that more appropriate estimates, the median cost, the expected cost and the 90 percent confidence costs, are substantially higher. The discrepancy between the deterministic estimate and the expected cost, some $2.7 billion or 22 percent, is strictly the result of the system costing phenomenon illustrated in Figure 1.3. To obtain any more information from these distributions, it is necessary to combine them with additional data and assumptions in order to examine the probability distribution of net present value of an SSPS unit. Accordingly, the following assumptions are made:

1. The SSPS unit availability factor is 0.95. That is, it is producing power 95 percent of the time. This includes power outages due to solar eclipses near the equinoxes.

2. The power output of the SSPS unit decreases by one percent per year due to degradation of various components.

3. The lifetime of the SSPS unit is 30 years.

4. The capital investment in the SSPS unit is made in one lump-sum payment two years prior to the initial operation data of the SSPS unit.

5. In the initial year of operation, the price of power at the rectenna busbar is 30 mills/kWh (1974 dollars).

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*This is somewhat higher than the previous estimate of $7.6 billion which was based on certain technologies achieving their most optimistic values. The cost model used can, in fact, replicate the $7.6 billion figure given the same assumptions.

6. The real price of power at the rectenna busbar (1974 dollars) increases at the rate of one percent per year.

7. No charge is made for taxes and insurance.

8. Present value computations use a discount rate of 7.5 percent.

With the above assumptions, the cumulative distribution function of net present value (revenues minus costs) of an SSPS unit referenced to the initial operation date is as shown in Figure 3.5.* The proper interpretation of this curve is that there is about a 21 percent chance that, under the conditions of the above assumptions, the second SSPS unit will be economically viable. Also, the expected value and the median of the net present value distribution occur at substantially negative values. The clear implication of this is that not enough is known at present about the technologies required for the production of an SSPS unit to commit to a program to produce such a unit at this time.

The most critical assumption inherent in Figure 3.5 is the price of power at the rectenna busbar at the initial operation date. This assumption is treated parametrically in Figure 3.6 with the remaining assumptions held unchanged. Clearly, increases in the price of power at the rectenna busbar significantly increase the probability of an SSPS unit being economically viable.

In summary, the following conclusions can be drawn from the results of the risk assessment of the current configuration SSPS:

1. There is a finite chance that the current configuration SSPS could be economically viable. The magnitude of this chance is dependent primarily on the price of power at the rectenna busbar during the period of operation of the SSPS unit. Subject to the assumptions outlined above and a price of 30 mills/kWh for power at the rectenna busbar at the initial operation date, there is about a 21 percent chance that the second SSPS unit would be economically viable.

2. The economic viability of SSPS units beyond the second unit should improve due:

*Note that Figure 3.5 cannot be derived directly from Figures 3.3 and 3.4 and the stated assumptions because there is some degree of correlation between the unit production costs and the operation and maintenance costs that must be accounted for. Thus, the curve of Figure 3.5 is computed as an independent output of the risk assessment.

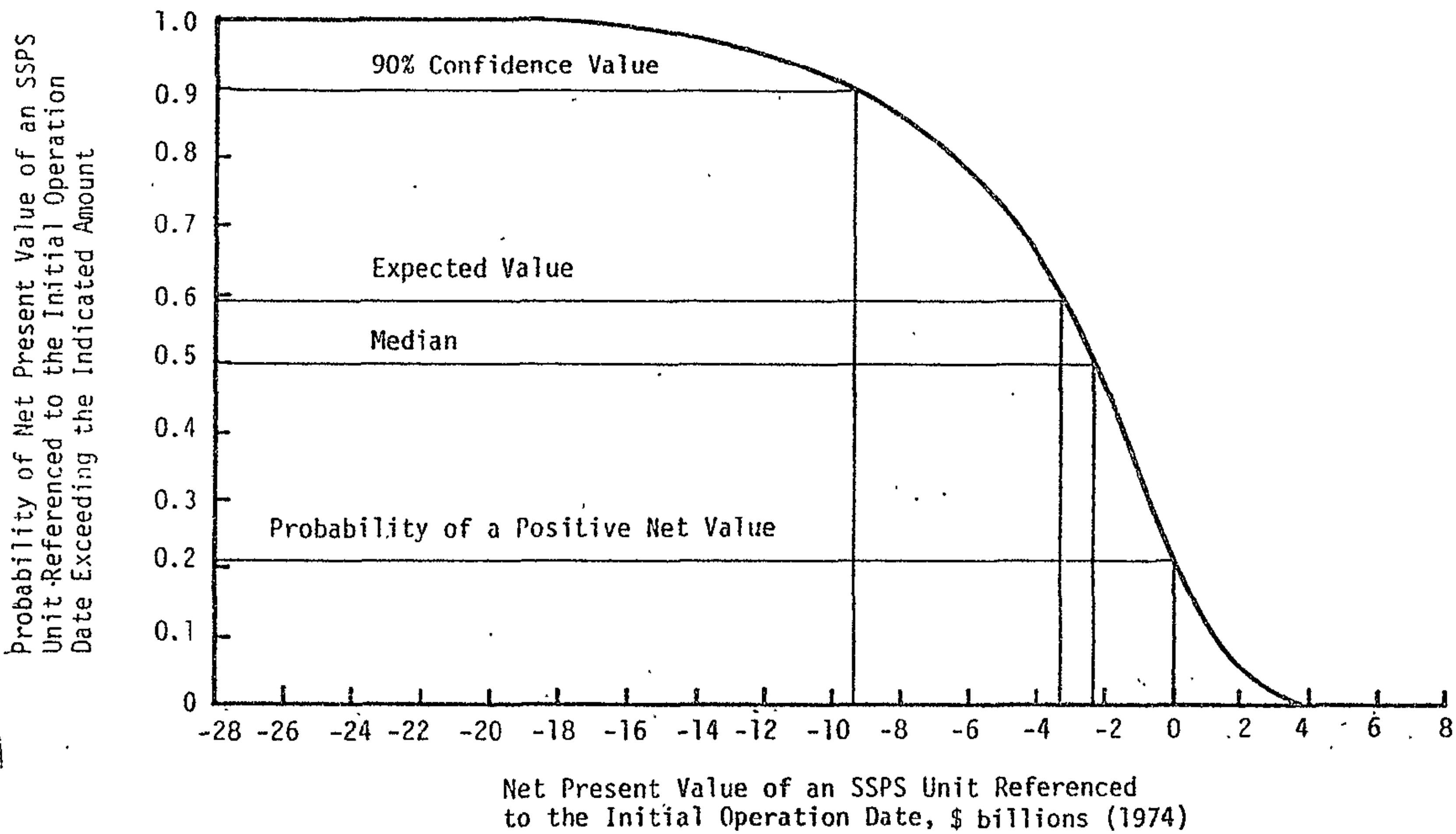

Figure 3.5 Cumulative Density Function of the Net Present Value of an SSPS Unit Referenced to the Initial Operation Date

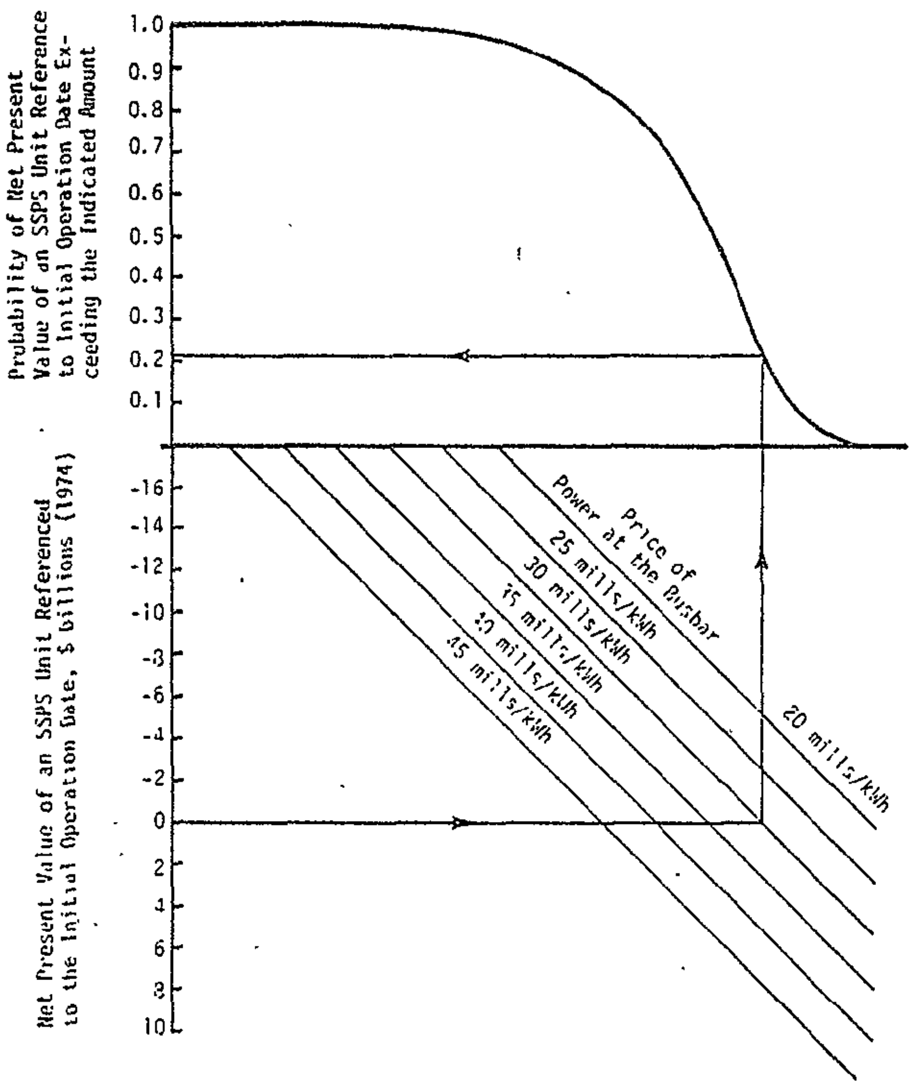

Figure 3.6 Cumulative Distribution Function of Net Present Value of an SSPS Unit at the Initial Operation Date as a Function of Price of Power at the Rectenna Busbar

a. to learning effects which should enable reduced unit production costs on subsequent units, and

b. to an expected increase in the price of power at the rectenna busbar at the initial operation date of subsequent units.

3. The technology required to produce, operate and maintain a current configuration SSPS unit is not sufficiently developed or known to commit to the production of such an SSPS unit at this time.

The above conclusions do, however, support a decision to continue "low level" SSPS system studies and analyses with the purpose of formulating an economically viable program plan, that is, a program plan with a positive expected value and controlled risks, for the development of the SSPS concept.

4. ANALYSIS OF ALTERNATIVE PROGRAM PLANS

Previous sections of this report have been directed at the development and use of a risk analysis model for the assessment of cost-risks associated with the production of an SSPS unit (satellite and ground station). This section makes use of the results of the risk analysis to assess three alternative SSPS development program plans and to gain insights necessary for improving the proposed plans. The three program plans considered are described below.

4.1 Direct Development Program

The Program I, Direct Development, schedule is shown in Figure 4.1. The program begins with a supporting research and technology (SR&T) program in 1977 and proceeds into the design, development, test and engineering (DDT&E) phase in 1984. The decision to produce the first unit is made in 1987 and the initial operation date of the first unit is December 31, 1991. The final social and environmental (FS&E) impact statement is required on December 31, 1983, the technology is set as of December 31, 1986 and the heavy lift launch vehicle (HLLV) is required on January 1, 1989.

After the initial operation date (IOD) of the first unit, it is assumed that four years elapse before the IOD of the second unit. This is because the first satellite is essentially a full-scale test and time is required for redesign of the satellite to achieve lower second unit costs. Beginning with January 1, 1996, new satellites become operational at the rate of two per year through 1999. Then, beginning on January 1, 2000, four new satellites become operational each year until a total of 109 satellites have been produced.

A more detailed description of the program plans is given in Volume II of this report.

4.2 GEO Test Satellite to Full-Scale Program

The Program II, GEO Test Satellite to Full-Scale, schedule is shown in Figure 4.2. The program begins with an SR&T phase in 1977. A preliminary social and environmental impact statement is required on December 31, 1979 and on January 1, 1980 the decision to develop a 500 MW GEO test satellite is made. The IOD of the GEO test satellite is December 31, 1985. Committment to the DDT&E of the full scale satellite is made on January 1, 1985. In reality, this decision would probably be reviewed after the IOD of the GEO test satellite, however, this degree of freedom is not considered here. A committment to produce the first satellite is made on January 1, 1987, and the satellite IOD is December 31, 1991. The decision to proceed with the implementation of subsequent units is made on January 1, 1992.

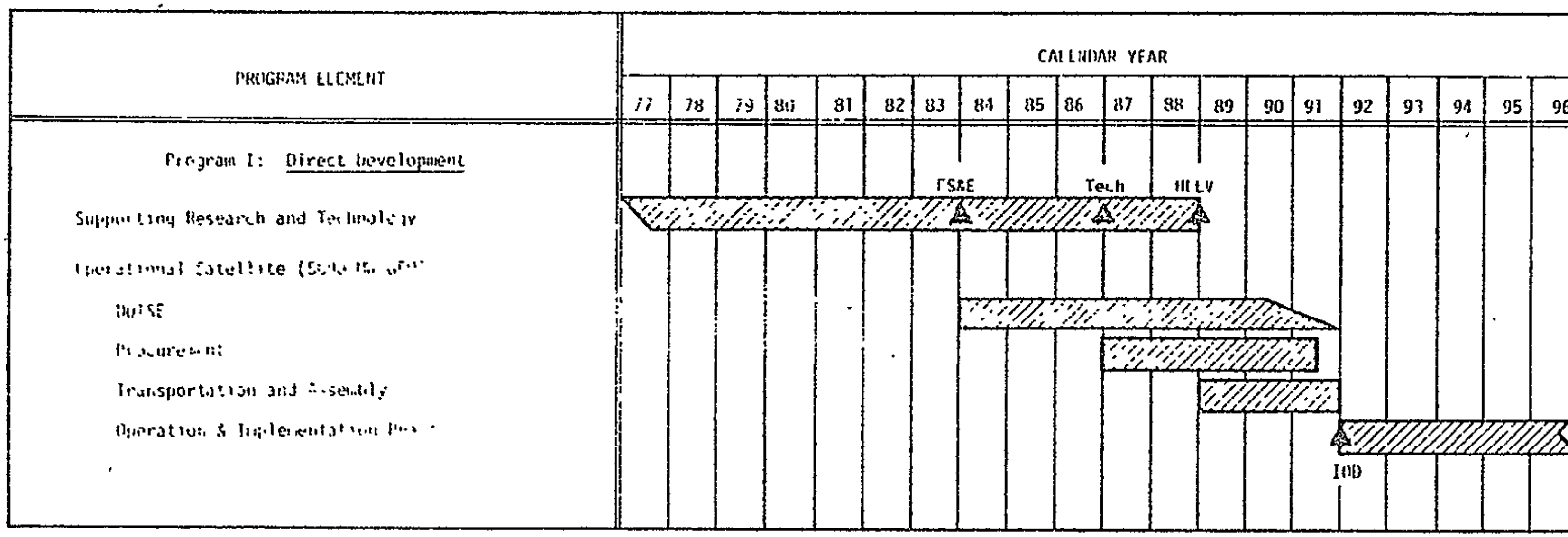

Figure 4.1 Program I Schedule

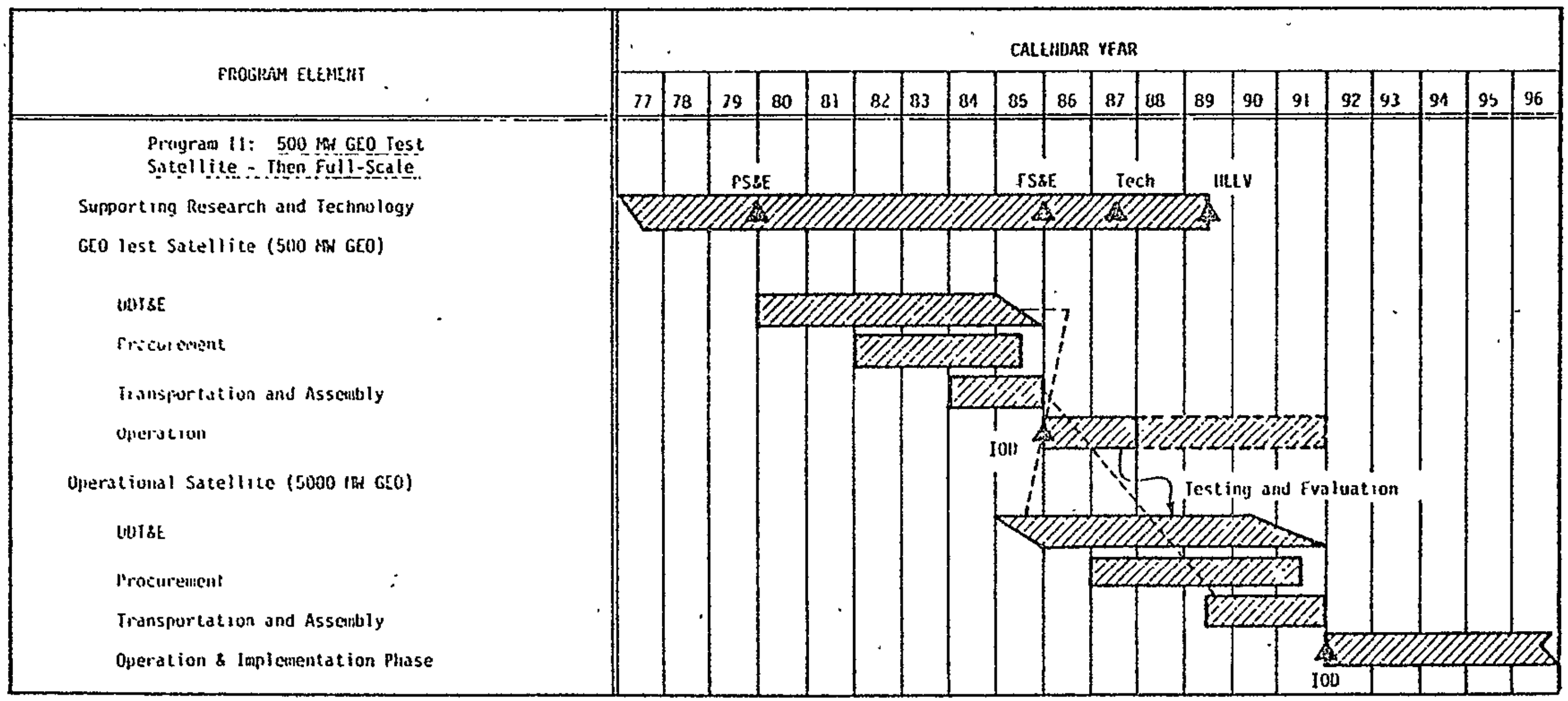

Figure 4.2 Program II Schedule

Implementation of subsequent units proceeds with the second unit IOD on January 1, 1994. Two new units become operational each year through 1999, then four new units are added each year until 109 units have been produced. In this program, only a two-year lag is provided between the IOD's of unit 1 and 2 since the additional information gained from the GEO test satellite should enable better design of the first unit, thus requiring less redesign of the second unit than in Program I.

4.3 LEO and GEO Test Satellites to Full-Scale Program

The Program III, LEO and GEO Test Satellites to Full-Scale, schedule is shown in Figure 4.3. The program begins with an SR&T phase in 1977. Committment to a LEO test satellite is made in 1980 and the IOD of the satellite is December 31, 1985. Committment to a GEO test satellite is made on Janaury 1, 1985, and the IOD of the GEO satellite is December 31, 1990. Committment to the DDT&E of the full-scale satellite is made January 1, 1992. The IOD of the first full-scale unit is December 31, 1995. The decision to implement units 2 through 109 is made on January 1, 1996.

Implementation of units 2 through 109 begins with the IOD of the second unit on January 1, 1997 and proceeds at the rate of two per year through 1999, then four per year through the 109th unit. In this program, there exists only a one-year lag between the IOD of the first and second units because, first, two test satellites are flown in this program and, second, the IOD of the first unit is four years later than in Programs I and II. Thus, the first unit should be essentially a production unit and require very little redesign.

It should be noted that these three programs are approximate and not yet well-developed. Assumptions had to be made to perform the following analysis. In future work, these assumptions should be reviewed and revised program plans developed.

4.4 Decision Tree Analysis of Alternative Program Plans

The analysis of alternative program plans begins with an assessment of the current state-of-knowledge relative to the present configuration SSPS. This is assessed in Section 3 and results in the probability distribution of second unit costs shown in Figures 4.4 and 4.5, which provide both the cumulative distribution and probability density functions respectively of the present value of the total (life cycle, that is, capital investment plus operation and maintenance) unit costs referenced to the initial operation date of that unit. Throughout the analysis which follows, this cost is the key decision variable. Note that the first unit cost is not important here insofar as the first unit is essentially a prototype and its costs do not necessarily relate to the second and subsequent unit costs. In the computation of the unit costs shown, it is assumed that the capital investment for the SSPS unit is made in a lump sum payment two years prior to the initial operation date of the unit and a discount rate of 7.5 percent is used. In addition, the following assumptions are made:

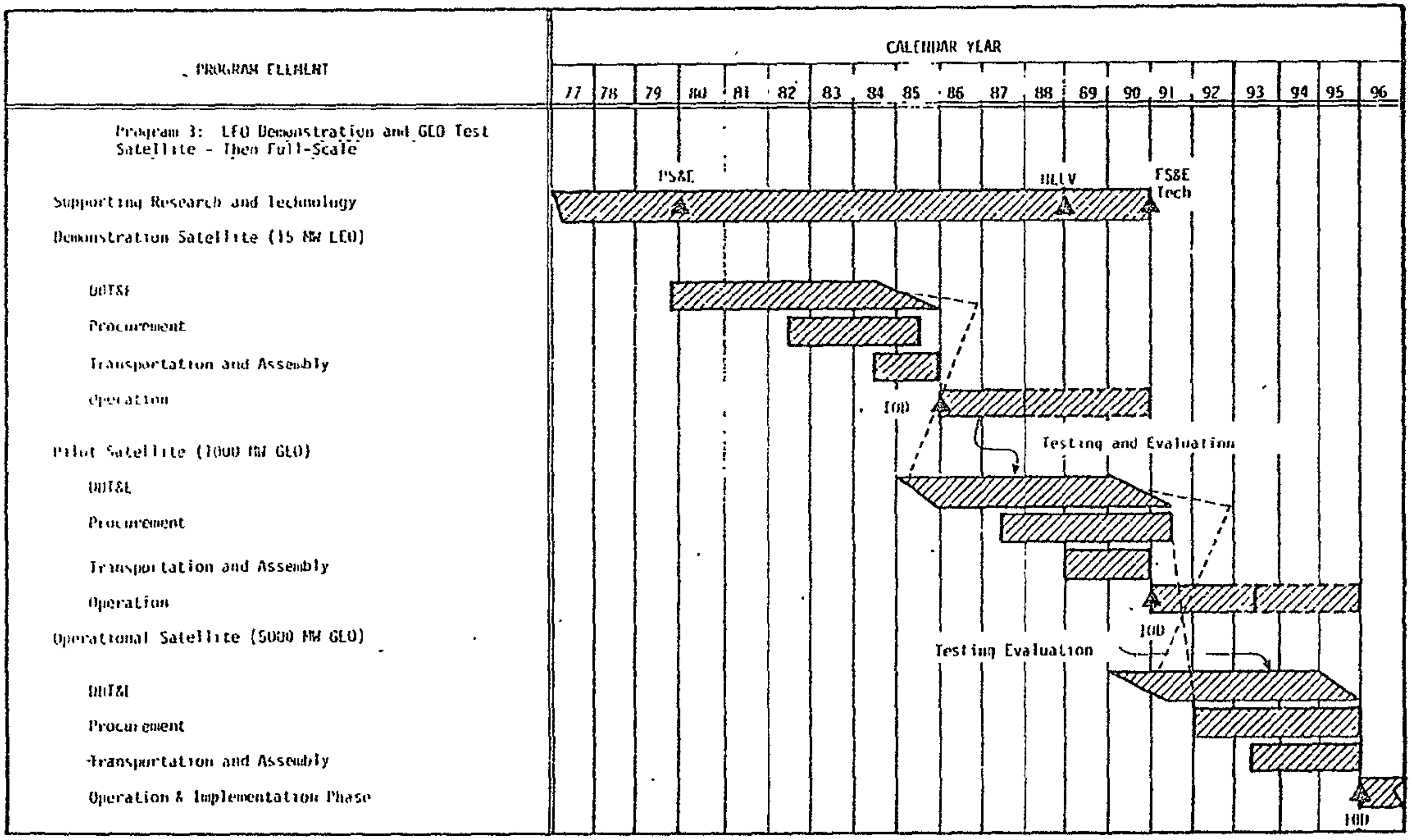

Figure 4.3 Program III Schedule

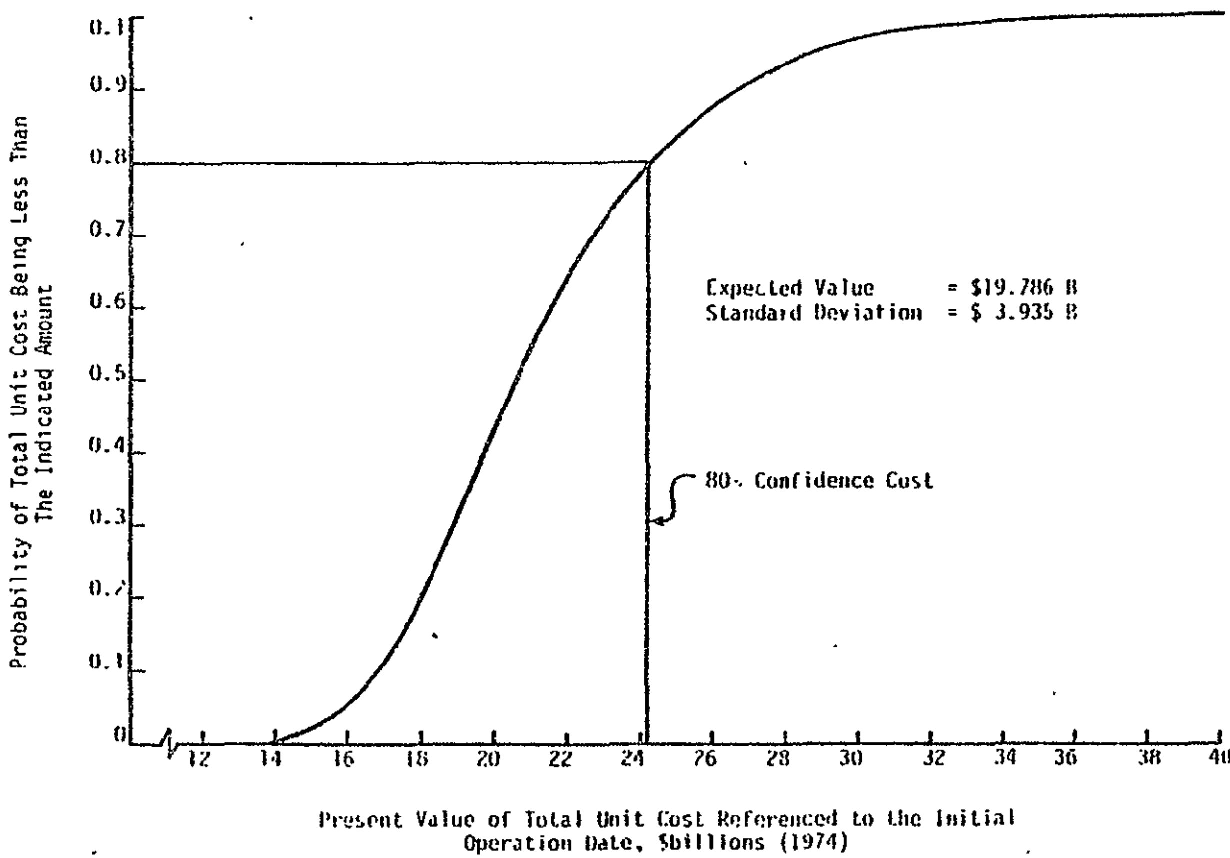

Figure 4.4 Cumulative Distribution Function Of Total (Life Cycle) Second Unit Costs

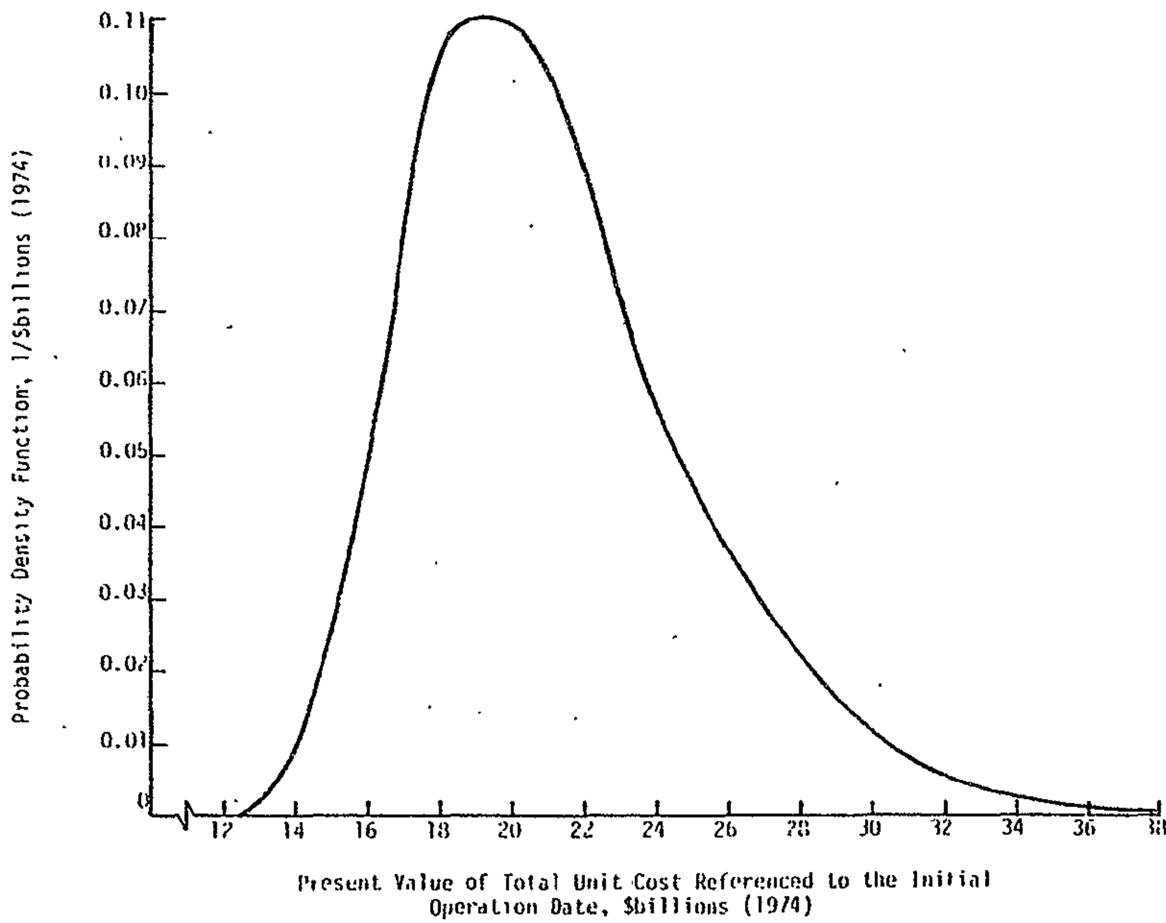

Figure 4.5 Probability Density Function Of Total (Life Cycle) Second Unit Costs

1. The beginning-of-life power of each unit is 5258 MW.

2. The SSPS power output decreases at 1 percent per year from the beginning of life throughout the unit lifetime.

3. Each SSPS unit has a lifetime of 30 years.

4. Each SSPS unit is producing power 95 percent of the time.

5. Implementation of second and subsequent satellites is described in Sections 4.1, 4.2 and 4.3. That is, the initial operation date of the second unit is as follows:

   Program I - January 1, 1996
   Program II - January 1, 1994
   Program III - January 1, 1997

   Thereafter, units come on line at the rate of two per year through 1999, then at the rate of four per year until 109 units have been produced.

6. The cost of the third and subsequent satellites is related to the cost of the second satellite according to a 90 percent learning relationship. That is, the cost of the nth unit, C_n, is given as a function of the cost of the second unit by the relation

$$C_n = C_2 \quad 0.859^{\ln (n-1)}$$

7. The price of power at the rectenna busbar is assumed given on January 1, 1992. After that date, the real price increases at the rate of 1 percent per year.

It is assumed that a decision to select one of the three alternative programs will be made on January 1, 1977, thus all following data are referenced to that date. Under the conditions of the above assumptions, the present value of gross revenues of each program is given as a function of the price of power at the rectenna busbar on January 1, 1992, in Figure 4.6. Likewise, the present values of total costs for units 2 through 109 are given as a function of the present value of the second unit total cost referenced to the initial operation date of that unit in Figure 4.7. From these figures and from the present values of costs of each program (including operation and maintenance costs on the first unit), the net present value of each program is determined as a function of the second unit cost and the price of power on January 1, 1992, as shown in Figure 4.8. The price of power in this figure does not include an allowance for taxes and insurance. Thus, if taxes and insurance are 8.6 mills/kWh as previously estimated, the curves

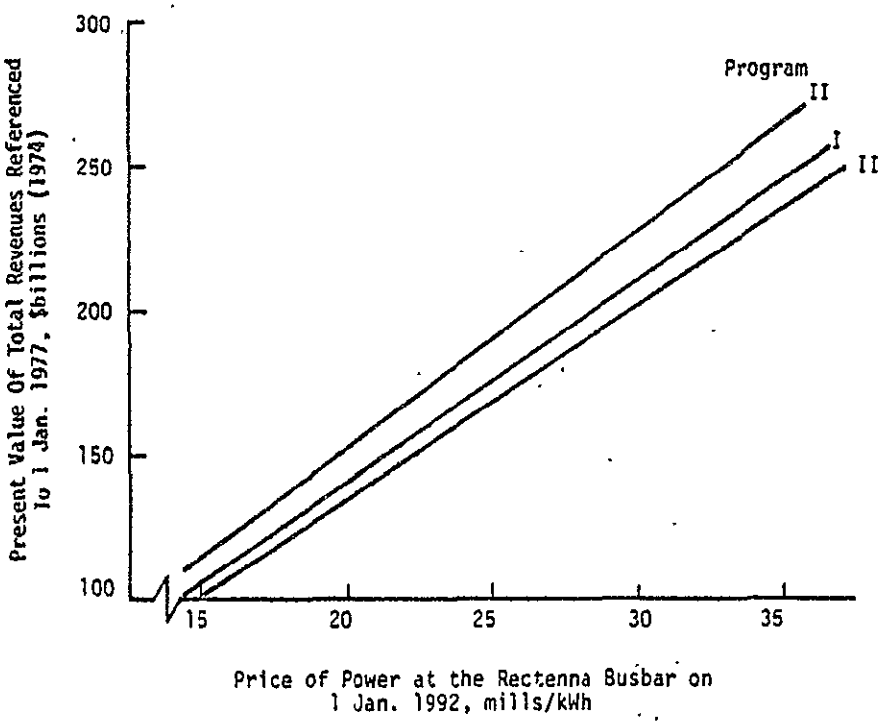

Figure 4.6 Present Value of Gross Revenues Generated by Each Program

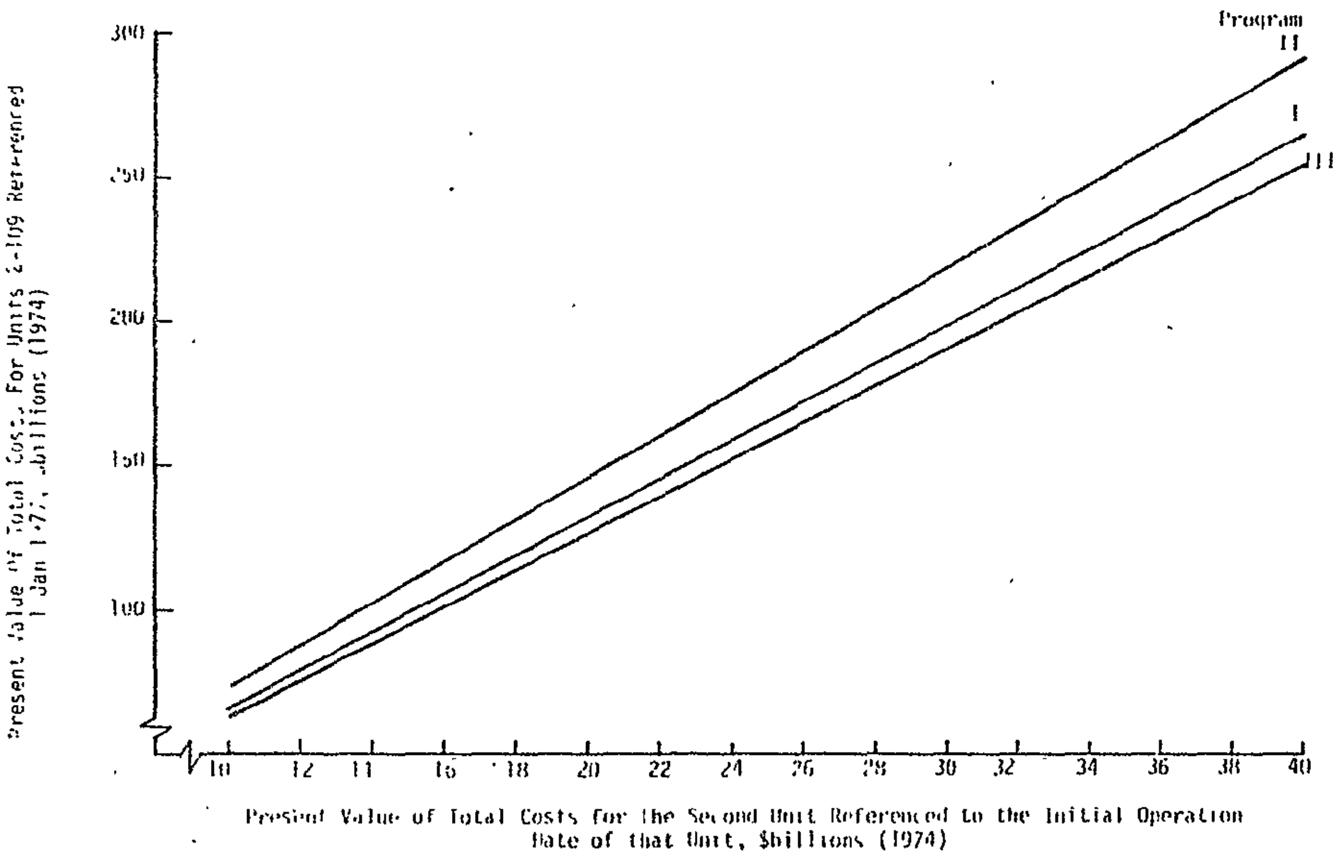

Figure 4.7 Present Value Of Total Costs For Units 2 Through 109

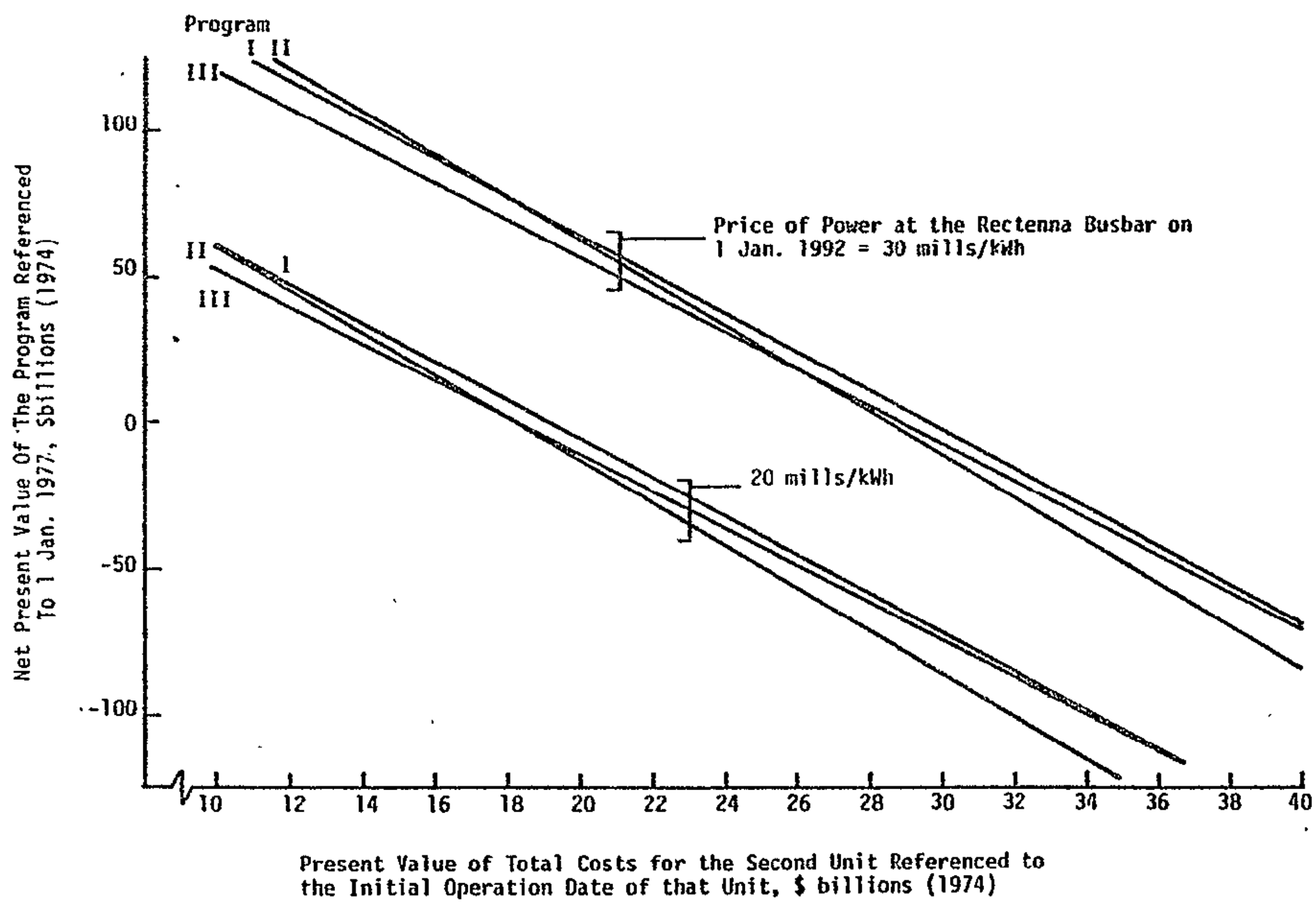

Figure 4.8 The Net Present Value of the Alternative Programs

labelled 20 mills/kWh would actually represent a total price of 28.6 mills/kWh at the rectenna busbar on January 1, 1992. In the analysis that follows, it is assumed that the price of power at the rectenna busbar on January 1, 1992, is 20 mills/kWh (or 28.6 mills/kWh including 8.6 mills/kWh allowance for taxes and insurance).

The alternative program plans are now analyzed to determine their expected values. As outlined in Section 1, a go-ahead decision on a specific program plan should be predicated on the basis that that plan has a positive expected value and that risks associated with the plan are adequately controlled. Selection of the best program plan would normally be to choose that plan that yields the highest expected value at the desired decision-making confidence level. The confidence level for decision-making chosen for this analysis is 80 percent. While this is a moderately high confidence level, it is not so high as to arouse disputes over the accuracy of the tail (high end) of the distribution shown in Figure 4.4.

To proceed with the analysis, the program plans outlined above are expressed in the form of decision trees as shown in Figures 4.9, 4.10 and 4.11. At each decision point in these decision trees, there is a specific criteria based upon which the decision will be made to continue or to terminate the program. These criteria are derived as shown in Figures 4.12, 4.13 and 4.14. First, the state-of-knowledge as of January 1, 1977, is assessed as shown in Figure 4.4. Then, the 80 percent confidence state-of-knowledge is established--with 80 percent confidence, the second SSPS unit can be produced at a cost of $24.1 billion (1974) or less. This state is plotted as a point in each of Figures 4.12, 4.13 and 4.14. Next, the "break even" cost of the second unit is computed for each program plan. This is the cost of the second unit for which there is exactly zero net present value for the entire program (present value of costs equals present value of revenues). This cost, for each program plan is taken as the technology target and is also plotted. This shows the cost that the second unit must come in at or below for a "successful" program. Thus, in Program I, a successful program is defined as one which proves that the second unit costs are equal to or less than $18.9 billion (1974) by January 1, 1992--the initial operation date of the first unit and the completion date of the development program. At that date, a decision will be made to implement the second and subsequent units or to discontinue the program with the operation of the first unit. For simplicity, the decision rule is then taken as a linear improvement in the 80 percent confidence bound of the technology during the development program. These curves are shown as the 80 percent confidence technology requirements for each program. If the technology development is such that the 80 percent confidence technology bound remains under the 80 percent confidence technology requirement throughout the development program, then the development program will be a success.

Many other decision rules could be formulated. In fact, the one discussed here is probably not the best. For example, the target

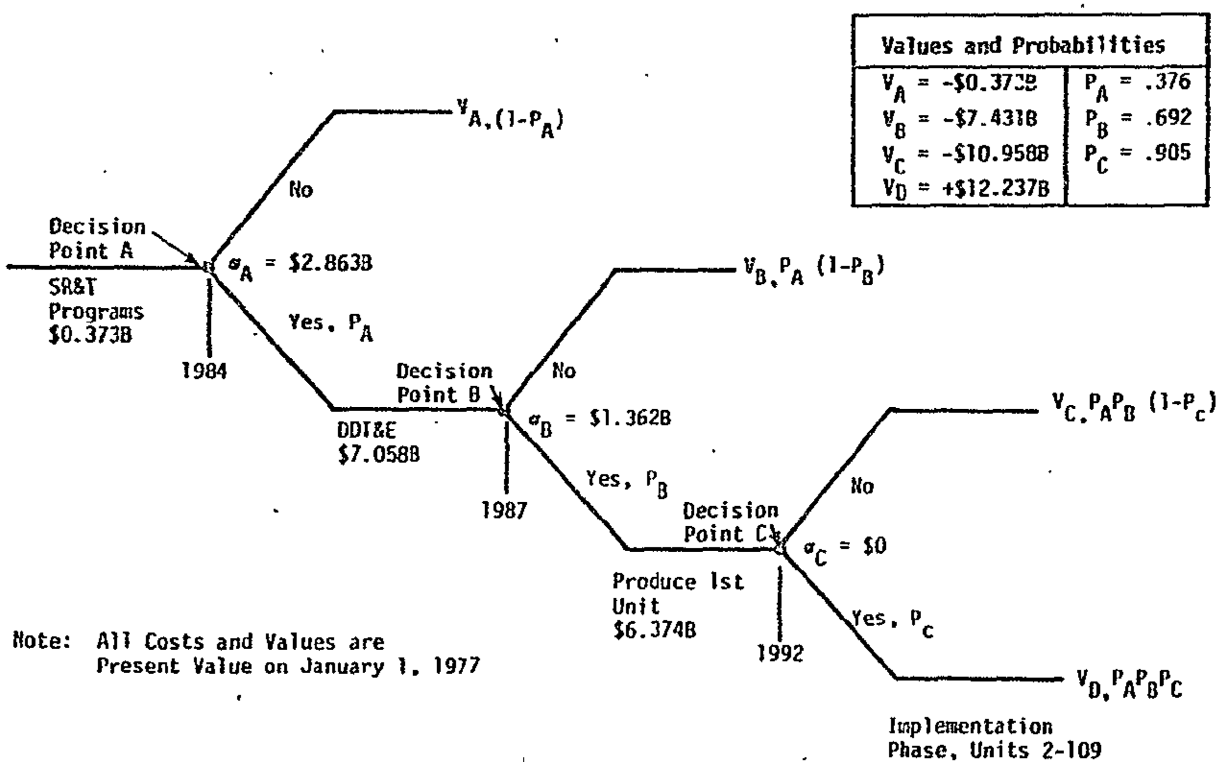

Figure 4.9 Decision Tree Representation of Program I

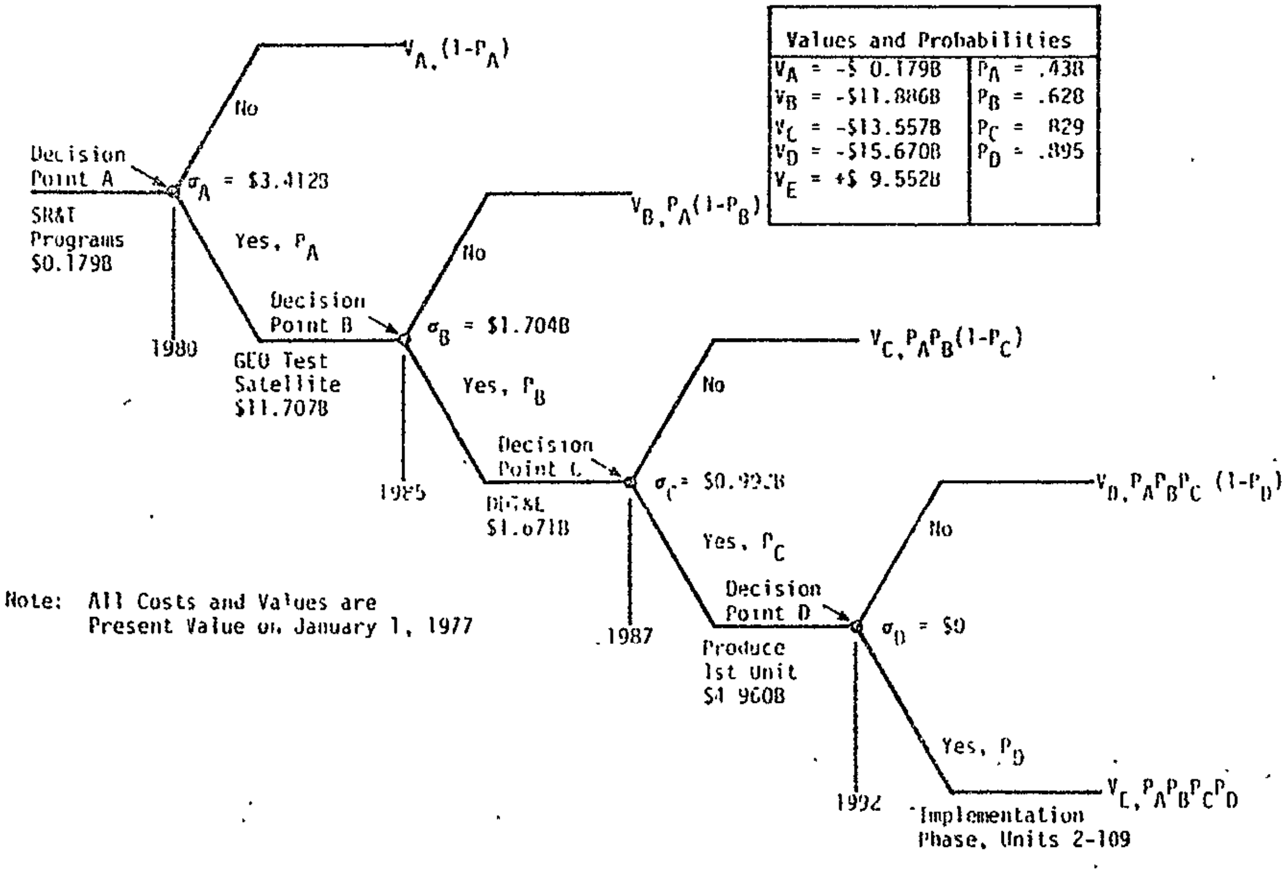

Figure 4.10 Decision Tree Representation of Program II

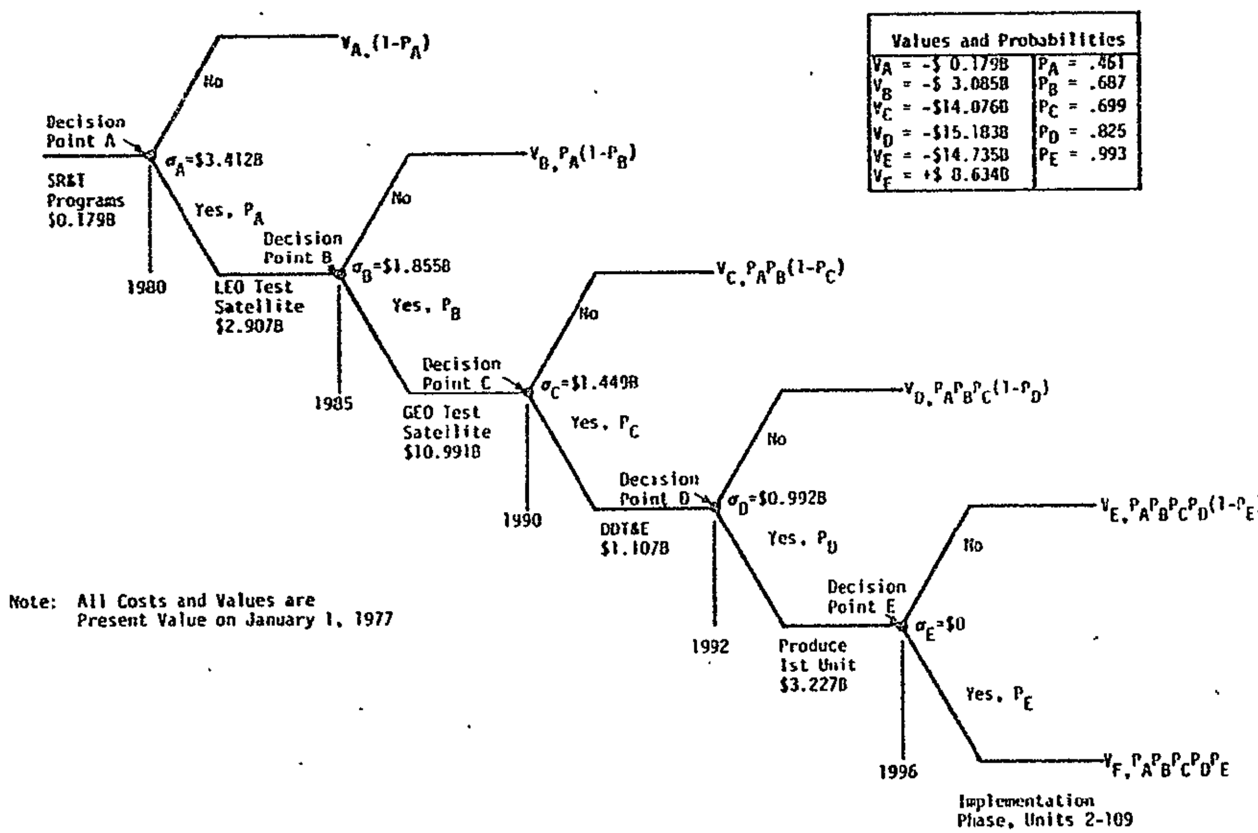

Figure 4.11 Decision Tree Representation of Program III

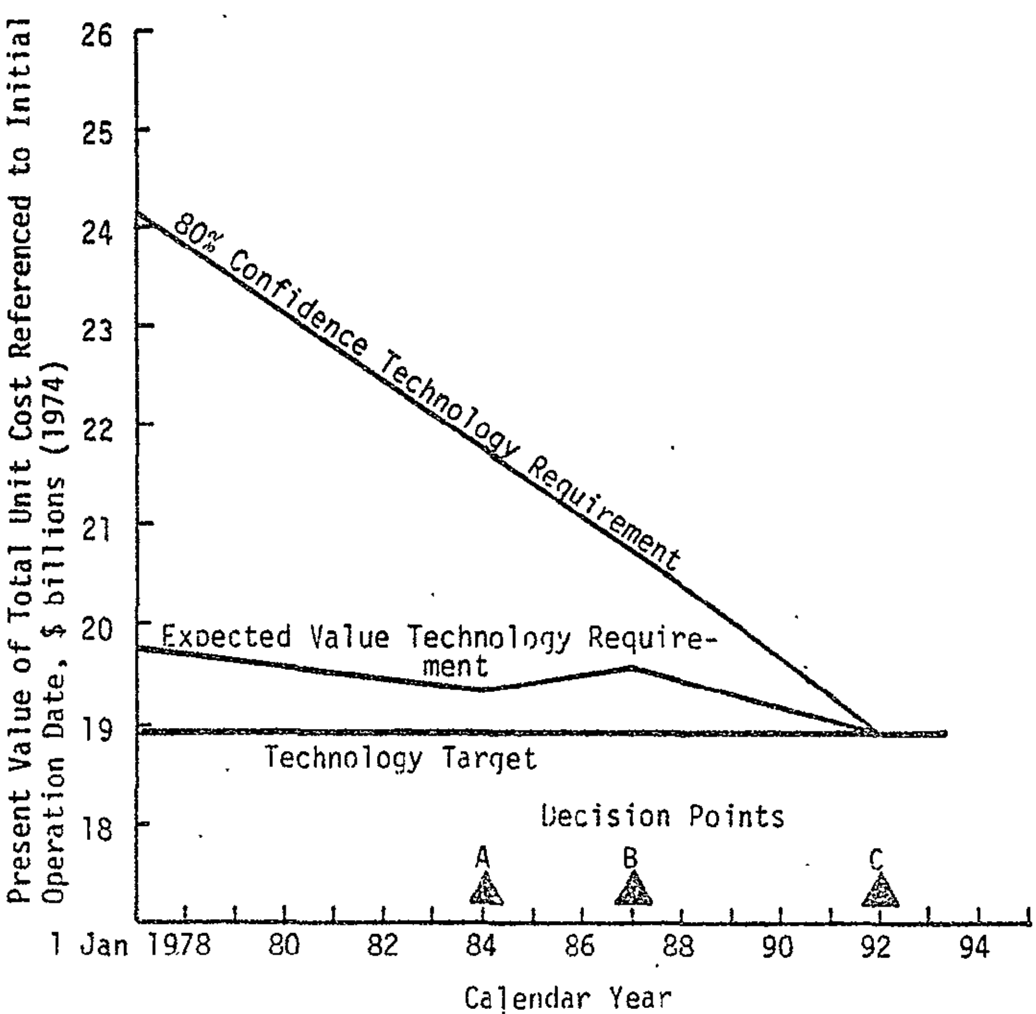

Figure 4.12 Decision Rule For Program I

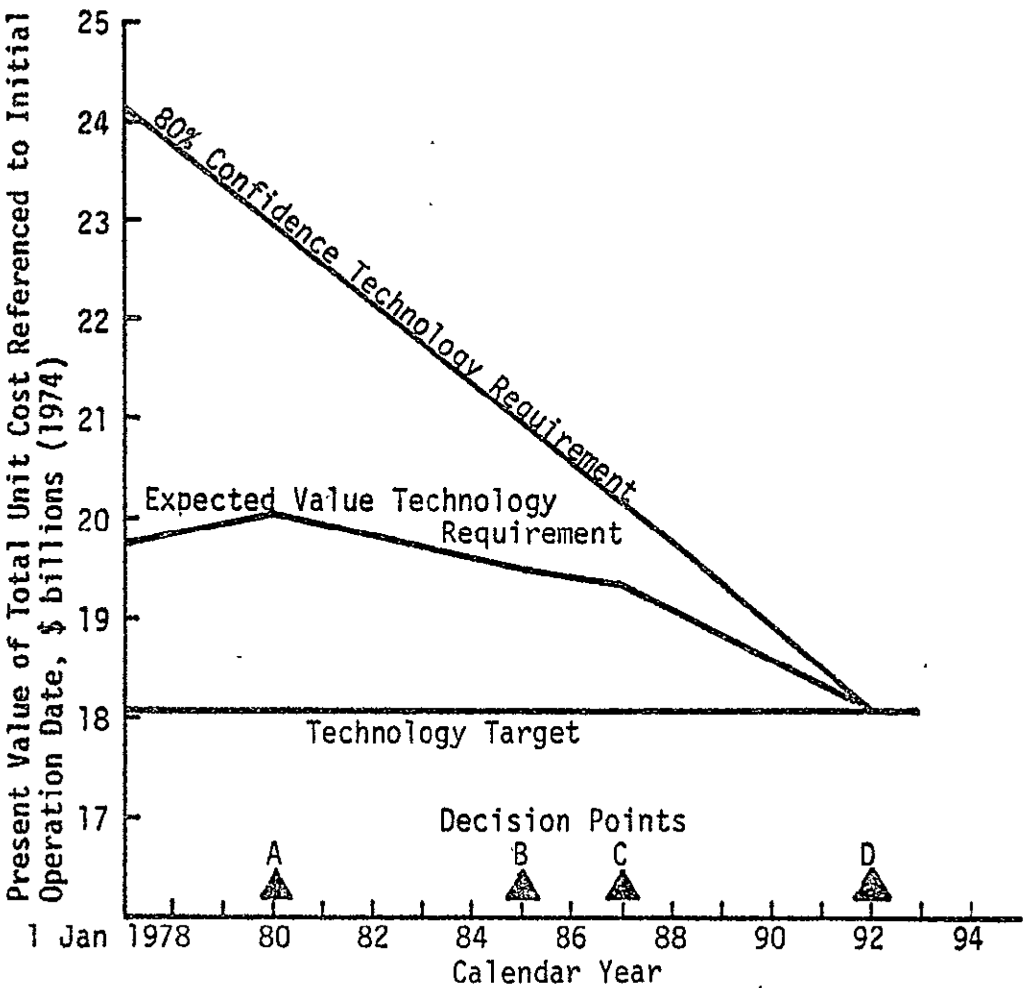

Figure 4.13 Decision Rule For Program II

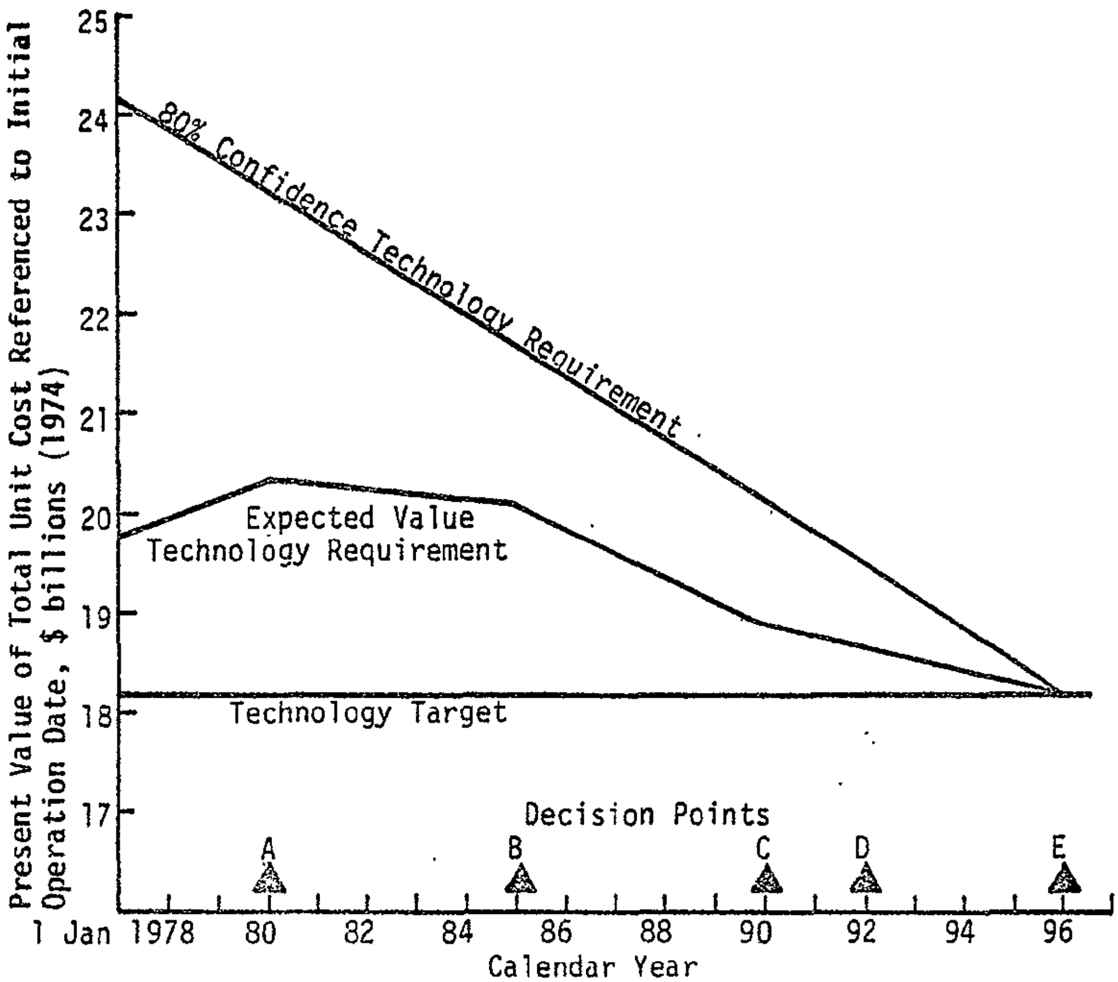

Figure 4.14 Decision Rule For Program III

technology could be based on breaking even only with respect to unsunk (that is, uncommitted) funds. This would improve the chance of success of the program, but would not assure payback of the development costs. In addition, there is no reason that the technology requirement must improve linearly with time, although this rule does seem to lead to quite logical technology requirements.

The process of program control consists of "testing" the technology at each decision point. Based on the results of this test, the program continues or is terminated. The test consists of measuring the state-of-knowledge at each decision point at the 80 confidence level.

In the computation of expected value for each program plan, it is necessary to assess the prior probabilities (that is, the probabilities based on today's state-of-knowledge, before the test takes place) that each test will be passed or failed. To do this, each branch of the decision tree is thought of as a process of buying information on the cost of the second unit. As such, the work performed on these branches does not change the cost of the second unit,* rather it determines with increasing accuracy what that cost is. Thus, a key part of this analysis is an assessment of the accuracy with which the second unit cost will be known at future points in time. To perform this assessment, the improvements in the states-of-knowledge of each variable of the cost model resulting from work performed on each branch of each decision tree have been subjectively estimated. These estimates are shown in Appendix E. Then, the risk analysis model was run to establish the magnitudes of the cost-risks associated with each decision point. The values of the resulting standard deviations of cost estimates, σ_A, σ_B, etc., at each decision point are shown in Figures 4.9, 4.10 and 4.11.

Now, given the 80 percent technology requirement and given the states-of-knowledge at each decision point, it is possible to compute the prior probabilities that each branch of each decision tree will result. It is first necessary to establish the expected value technologies at each decision point. This is done by assuming that the form of the probability distribution of second unit cost is Gaussian (or normal) and that the 80 percent cumulative probability point occurs, for each decision point, on the 80 percent confidence technology requirement line. Thus, the required state-of-knowledge at Decision Point A of Program I is expressed as a Gaussian distribution with a standard deviation of $2.863 billion (1974) and an 80 percent cumulative distribution point of about $21.7 billion (1974). The expected value technology requirement can be derived as the mean of this distribution. Thus, the expected value technology requirement lines shown on Figures 4.12, 4.13 and 4.14 represent the required expected values of cost estimates made at the time of the

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*This is because throughout the analysis, the cost of the second unit is taken to be the estimated cost that will occur, as a result of the planned technology programs, at the time that the second unit is produced.

corresponding decision points. The methodology for computing the prior probabilities of taking each branch on a decision tree is given in Appendix F.

The resulting values are shown in Figures 4.9, 4.10 and 4.11. Finally, the expected value of each program is computed as the sum of the outcomes for each path through the corresponding decision tree weighted by the probability of occurrance of the path. The expected values for the three program plans considered are as follows:

Program I: +$1.15 billion (1974)
Program II: -$1.10 billion (1974)
Program III: -$0.92 billion (1974)

Under the specific set of assumptions chosen for this analysis, only Program I has a net positive expected value. Thus, of the three specific program options examined, one could only economically justify undertaking Program I. However, recall that this analysis is subject to many assumptions and preliminary cost estimates. For example, decision making is conducted at the 80 percent confidence level. At a lower confidence level, or at a higher price for power at the busbar, Program II or III or a variant of these programs may become the desired alternative. The appropriate confidence level for decision making might not be 80 percent: this needs to be examined in further studies and the uncertainty relative to the price of power at the busbar should be incorporated into future analyses. Changes in other parameters could also alter the above result.

The reason that the test satellites proposed have negative net value, becomes apparent from an examination of the program decision trees. The proposed test satellite subprograms cost more than the economic value they provide. Thus, they add negative value to the overall program. However, this conclusion pertains only to the test satellite subprograms proposed in Programs II and III. It remains possible that other test satellite subprograms might be developed with a net positive value. These programs would probably make use of smaller test satellites to "buy" essentially the same information at a substantially reduced cost. Thus, it is recommended that the costs and informational gains associated with smaller test satellites be examined.

As a final warning, the results of the above analysis depend upon the assumptions made. Changes in the assumptions may change the conclusions. Thus, while the insights gained may be valuable, decisions should be based on this analysis only after a thorough review of the cost model, the cost model (state-of-knowledge) data and the assumptions made for the analsis. If the results of this analysis stand up under thorough review, then one is justified in recommending a go-ahead decision on Program I since the expected value of this program is positive. However, it should be observed that the expected value of Program I is only a small fraction of the total monies to be expended on the program. Thus, before one makes a recommendation to proceed with this program, it is probably wise to try to refine the program plan so as to increase its expected value.

5. IDENTIFICATION OF CRITICAL TECHNOLOGIES AND ISSUES

A variety of technical, social and environmental issues exist with respect to the development and production of an SSPS. The purpose of this section is to identify and, to a limited extent, quantify these issues. Some of the issues, particularly the social and environmental issues, might support differences in the price of power at the rectenna busbar versus the busbar of a conventional power plant. Others, particularly the critical technologies, affect the cost and risk of an SSPS unit. The work documented below is a "first cut" at identifying critical technologies and issues as they drive the economics of an SSPS unit and should not be construed as final and definitive results based upon which actions should be initiated. Rather, the results are presented here for review and to provide guidance for continuing technical and economic studies of SSPS. These results represent an interim status only and should be viewed in that context.

5.1 Critical Issues

Associated with SSPS are numerous social and environmental impacts which need to be understood prior to implementation. Decisions concerning the appropriate level of all such "impacts" (that is, interactions between an SSPS and the environment) are guided by an expression of social preferences--whether through the economic system or through government regulation. For example, regulations concerning noise levels from launch vehicles or down-range launch safety will affect the location of the launch complex. Implicit in the expression of social preferences is a weighing of the benefits of one method or use against the benefits of others. For instance, a decision on where to locate the receiving antenna involves a comparison of the benefits of SSPS-delivered electricity against the benefits of other uses for the same piece of land; in this example, in addition to the economic evaluation of relative benefits (as reflected in the price of the land), social preferences would be expressed concerning less tangible values such as aesthetics through regulatory processes such as land zoning. In any event, the expressions of social preferences become design considerations affecting both the technical and economic characteristics of the system.

Even where there exists a clear social value for imposing design conditions or constraints (for example, safety from radiation that is detrimental to human health), it might not be clear what effect a given SSPS design could have because sufficient scientific data do not presently exist (for example, it is not known precisely at what level of microwave radiation a health hazard exists). These areas of uncertainty may require testing--in this example, to establish the effects on health due to various levels of long-term exposure to microwave radiation. As this uncertainty is reduced by testing, an SSPS can be designed that assures compliance with the perceived safety needs, yet more nearly approaches the economic potential of the concept.

All of the areas of social and environmental impact associated with an SSPS that have been identified to date [14,15] are summarized in Table 5.1. This table lists the major areas of impact by the three main system elements: launch complex and operations, orbital system, and rectenna and power interface systems. These impacts were then organized in the manner suggested by Figure 5.1: first, according to those impacts which are critical, that is, those which might have substantial detrimental local or even global impacts (for example, interaction of the microwave beam with the ionosphere) which would render an SSPS socially unacceptable or which cause substantial economic uncertainty (for example, acceptable microwave densities affecting rectenna size) and those impacts which clearly could not; next, according to those impacts which could be tested (such as effects of exposure to microwave energy) and those which could not (such as shifts in demographic patterns resulting from the location of terrestrial facilities). At this time, there appear to be no impacts with which there are associated large uncertainties and that are thought to be critical, but which are not amenable to testing to reduce uncertainty or simply to a logical decision process. The impacts considered to be both testable and critical represent the areas of social and environmental risk associated with an SSPS which must be dealt with in the development of a test/validation/documentation program. These risks are summarized in Table 5.2. More complete descriptions of each impact that has been identified to date follow.

5.1.1 Launch Complex and Operations

Land Management: The decision on where to locate the facilities to handle SSPS-related launch activities must balance such issues as proximity to sources of materials to be launched and propellants, down-range safety, launch advantage provided by southerly location, and climate and weather patterns. In addition to these considerations, the issue of possible alternative land uses arises for whatever sites are being examined. This impact is a decision variable (nontestable, noncritical).

Waste Heat: The waste heat from the launch vehicles is one of two sources of terrestrial waste heat associated with SSPS (the other being the rectenna). While the exact effect in the atmosphere of such heat is not known, it is thought to be negligible, even with a high level of traffic; hence, this impact is a decision variable (possibly testable, but noncritical).

Safety and Control: If there are populated areas down-range of the launch facility, adequate safeguards must exist to insure that they are not endangered by either routine launchings or in the event of a launch failure; this risk is considered in the launch site decision (nontestable, but criticality controlled by location--that is, by decision).

Environmental Modification: Two major environmental impacts that have been identified with the launch complex are the noise from the launch vehicles and the pollutants injected into the atmosphere by propellant combustion. Noise levels must be taken into account in

Table 5.1 SSPS-Related Social and Environmental Impacts Identified to Date

SYSTEM ELEMENT \ TYPE OF IMPACT	LAND MANAGEMENT	RADIANT ENERGY DENSITIES	WASTE HEAT	SAFETY & CONTROL	ENVIRONMENTAL MODIFICATION	RESOURCE EXTRACTION & MANUFACTURING	AESTHETICS	SOCIAL EFFECTS
LAUNCH COMPLEX & OPERATIONS	COMPETING DEMANDS		LAUNCH VEHICLES	LAUNCH SYSTEM SAFETY	NOISE POLLUTION LAUNCH FAILURE	LAUNCH FACILITIES LAUNCH VEHICLES PROPELLANTS	APPEARANCE & DESPOILMENT	DEMOGRAPHIC SHIFTS
ORBITAL SYSTEM		INTERACTION WITH IONOSPHERE EFFECTS ON ON-ORBIT PERSONNEL		BEAM CONTROL ASSEMBLY SAFETY	RADIO FREQUENCY INTERFERENCE	COMPONENT MATERIALS	NIGHTTIME REFLECTIONS	RELIANCE ON SPACE TECHNOLOGY
RECTENNA & POWER INTERFACE SYSTEMS	COMPETING DEMANDS MULTIPLE USE CHANGES IN LAND-USE PATTERNS	EFFECTS OF LONG-TERM EXPOSURE	10-15% OF TOTAL TRANSMITTED ENERGY	BEAM CONTROL POWER INTERFACE CONTROL	LOCAL EFFECTS OF WASTE HEAT	RECTENNA FACILITY COMPONENTS	APPEARANCE & DESPOILMENT	CHANGE IN DEMOGRAPHIC PATTERNS

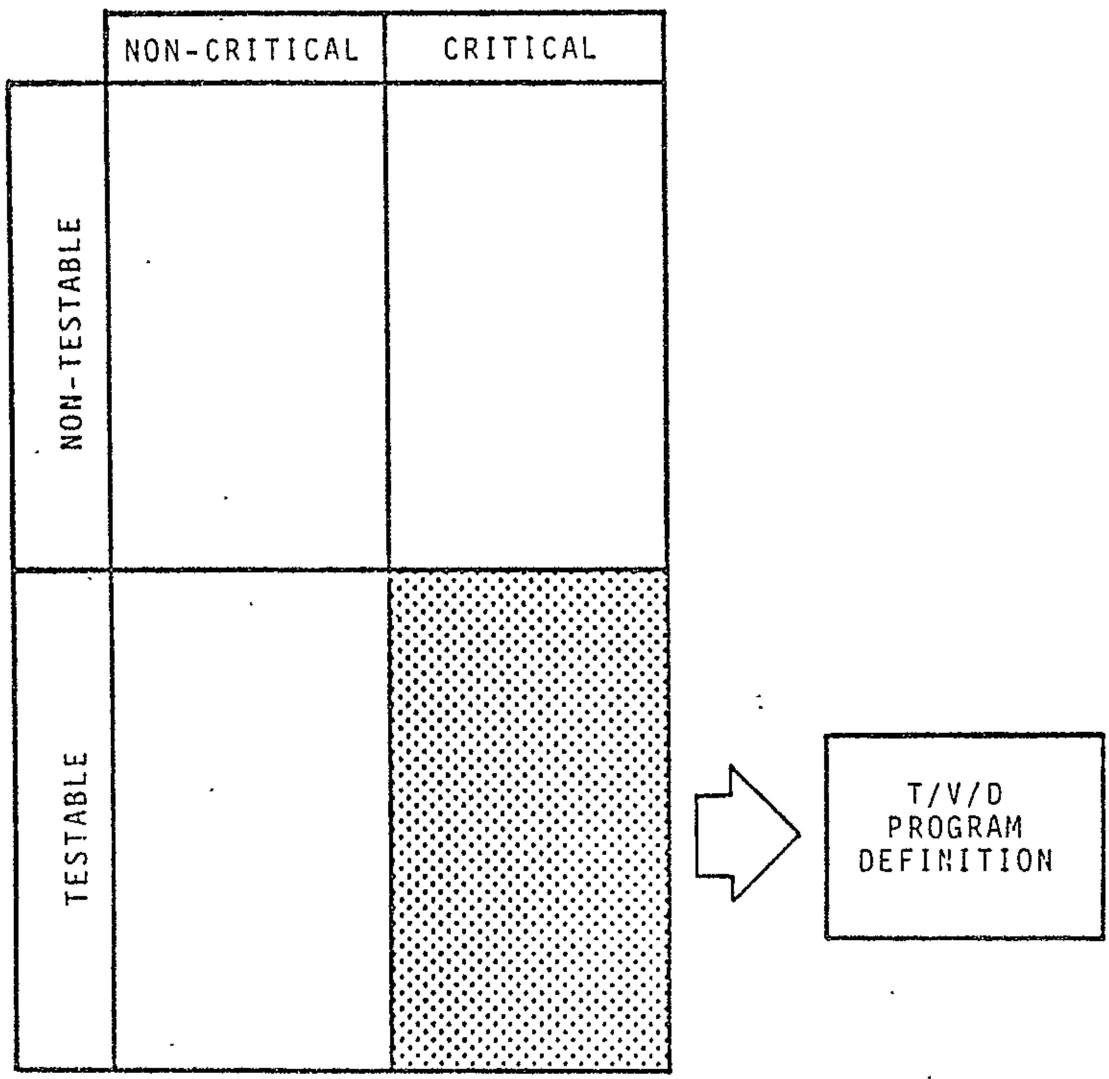

Figure 5.1 Social and Environmental Impact Matrix

Table 5.2 Critical and Testable SSPS Social and Environmental Risks

RADIANT ENERGY DENSITIES	SAFETY AND CONTROL	ENVIRONMENTAL MODIFICATION
INTERACTION OF BEAM WITH IONOSPHERE	BEAM CONTROL	EFFECT OF PROPELLANT POLLUTANTS ON ATMOSPHERE
EFFECTS OF LONG-TERM MICROWAVE EXPOSURE ON HUMANS, PLANTS AND ANIMALS	ASSEMBLY SAFETY	RADIO FREQUENCY INTERFERENCE
		LOCAL WASTE HEAT EFFECTS AT RECEIVING ANTENNA

siting and designing the launch facilities (testable, noncritical) and the effect of different propellant combustion products in the atmosphere must be carefully considered (testable, critical). Constraints placed on propellant types and launch site location could affect transportation costs. Another area of environmental concern deals with the possible nature of the materials being taken into orbit, for example, gallium-arsenide solar cells, which could cause a threat due to potential catastrophic failure of the launch vehicle. These considerations could force the use of less efficient materials. Whether or not the risks are to be taken is a matter of decision (nontestable, critical).

Resource Extraction and Manufacturing: The type and amounts of the materials necessary for launch site construction must be considered, but this is not expected to pose any difficulties as no critical material types or amounts are involved. The use of these materials to support the SSPS project is a social decision justified, through prices for these materials, if SSPS is economically viable (nontestable, noncritical).

Aesthetics: The effect of the launch facilities on the appearance of the surroundings will be considered in the siting decision (nontestable, noncritical).

Social Effects: Location of the launch site will undoubtedly result in local demographic shifts; this is, of course, a necessary adjustment to provide labor support for launch operations (nontestable, noncritical).

5.1.2 Orbital System

Radiant Energy Densities: It will be necessary to determine in advance the extent and type of interactions of the microwave beam with the atmosphere, particularly in the ionosphere where such interactions may affect the F-layer or may attenuate the beam itself, reducing transmission efficiency (testable, critical). Also of concern is the effect of microwave energy densities on on-orbit maintenance personnel (testable, critical) which could affect the cost of on-orbit maintenance.

Safety and Control: This represents a major area of concern, particularly in beam control. Safety systems will have to insure that there is no chance of a focused beam wandering from the rectenna area in the event that pointing control is lost. Whereas it is expected that the beam will become de-focused should the pointing system fail, testing is necessary to assure that the safety systems are "fail-safe" (testable, critical). This is a technology item that could affect the social acceptability of an SSPS. Its economic effect is uncertain but probably small. Safety of on-orbit personnel is also a concern during the construction phase (testable, critical) and can affect the orbital assembly rate.

Environmental Modification: The effects of such large power transmissions via microwaves is not known and will have to be tested. Problems with sidelobes and reradiated energy causing radio frequency interference must be dealt with in a careful test program. The results of this program will be necessary for final frequency allocation and filter design which can affect system efficiency and transmission losses (testable, critical).

Resource Extraction and Manufacturing: Resource considerations will be important design variables; however, it is not expected that SSPS requirements (even in such critical materials as platinum, samarium, or cesium) will be more than a small fraction of current consumption (nontestable, noncritical).

Aesthetics: Structures as large as an SSPS satellite will create noticeable nighttime reflections. To accept these reflections is a social decision (nontestable, noncritical).

Social Effects: Power from space could represent man's first reliance on space technology for basic needs. The exact effects of the perception of this is hard to predict. Also, there will be new political and security considerations connected with reliance on large power sources that might be vulnerable to sabotage (nontestable, noncritical).

5.1.3 Rectenna and Power Interface Systems

Land Management: Land-use considerations with respect to the receiving antenna include competing demands, the possibility of multiple-use, and projected changes in land-use patterns, such as the location of energy-intensive industries near rectenna sites or the moving of population areas away for the purposes of safety. These factors will be reflected in land prices and zoning as a reflection of social preferences (nontestable, noncritical).

Radiant Energy Densities: An important area of uncertainty exists concerning the effects of long-term, low-level exposure to microwave energy. An extensive testing program is necessary to determine the effects of such exposure on human, animal and plant life in the rectenna area and surroundings (testable, critical). Constraints imposed by maximum allowable microwave densities can affect the rectenna site location, design and areal extent.

Waste Heat: Rectification losses at the receiving antenna will result in the generation of waste heat equivalent to 10 to 15 percent of the total transmitted energy. It is expected that by controlling the albedo of the antenna surface the average heat value for the area can be maintained. However, because the rectenna waste heat release will be continuous, the daily temperature cycle will be changed. The effect that this change will have on plant and animal life as well as local weather patterns is not expected to be large (possibly testable, noncritical).

Safety and Control: As mentioned in Orbital System Safety and Control, maintenance of beam control is crucial (testable, critical). In addition, the safety and reliability of the utility power interface must be assured (testable, noncritical).

Environmental Modification: (see Rectenna and Power Interface Waste Heat).

Resource Extraction and Manufacturing: An analysis of material requirements similar to that for other parts of the system must be conducted for this segment of the system. It is expected that there will be no problems, as most of the material used is aluminum, for the antenna structure (nontestable, noncritical).

Aesthetics: So large a structure as the receiving antenna will certainly have an effect on the appearance of the surroundings. This must be considered in the siting analysis (nontestable, noncritical).

Social Effects: Changes in demographic patterns may well result from the location of the receiving antenna. These are the result of social choices (nontestable, noncritical).

The above identified issues could each affect the production and the operation and maintenance costs of an SSPS unit. While they are identified above, no assessment has yet been made of their specific impact on costs. This work remains to be performed in continuing studies.

5.2 Critical Technologies

In this section, the technologies critical to the economically successful production of a current configuration SSPS are identified. These technologies are identified in terms of their contribution to the cost and risk of SSPS unit production as follows. First, the risk profile of the current configuration SSPS was established as is described in Section 3. Then from the list of inputs to the risk analysis model, 56 potentially significant technology items were identified. As identified in Section 3, each of these variables has associated with it a state-of-knowledge that is described by a probability density function ranging from a minimum value to a maximum value. (Based on today's knowledge, there is probability zero that a parameter will lie outside the range so described. Furthermore, the probability density function has its maximum value at the most likely value of a parameter.) The assessment of critical technologies focuses on the minimum, maximum and most likely values of each significant input variable. The effect of removing uncertainty in each of these variables is then investigated by setting the range over which each variable may vary to zero, one-by-one, first to the minimum value, then the most likely value and then the maximum value. That is, the effect of removing uncertainty in each variable is investigated over the full range of values which, by today's state-of-knowledge, each variable may take on. For example, to determine the contribution to cost and risk of the cost of the solar array blanket per unit area, that cost is input to the risk model as a deterministic value, first at its minimum value, then at its most likely value and, last, at its maximum value, holding all other inputs as they are described in Section 3. The results of this exercise are given in Table 5.3 with the variables listed in three groups. The top group in the table presents the results for the critical technology areas. These are the technologies that drive the cost and risk. They include:

- solar cell efficiency
- specific mass of the solar blanket
- fraction of satellite assembled by man
- rate of manned assembly
- rate of remote assembly
- LEO space station unit cost
- solar array blanket specific cost.

It is interesting to note that these critical technologies encompass only two general areas, uncertainties associated with the solar arrays, that is, solar array costs, mass and performance, and uncertainties associated with the assembly of large systems in space. These seven elements of risk are plotted in Figure 5.2 which visually shows the potential for control of cost and risk by technology development in each area.* This figure clearly shows the driving technology to be the rate of manned assembly--that is, the productivity of man in space is the major cost and risk driver for the current configuration SSPS. Since this conclusion could substantially affect future SSPS development programs, it is recommended that it be subjected to a careful review before being fully accepted. It must be emphasized again that these results derive from subjective assessments of the state-of-knowledge relative to the current configuration SSPS and are subject to variability upon review. However, there is little doubt that this is an area of uncertainty that needs to be dealt with sooner rather than later.

The second group of variables in Table 5.3 are variables that are only moderately important cost and risk drivers. These are variables which should probably receive attention as components of major study areas but, at this time, do not deserve specific studies for their resolution.

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*Note that control of risk obtains not only due to removal of uncertainty in the variable under consideration but also due to the fact that uncertainty in other system components may be reduced due to such removal of uncertainty. For example, removing uncertainty in the rate of manned assembly also removes uncertainty in the number of LEO space stations required, the number of shuttle flights, the number of EVA units, etc. On the other hand, solar array blanket specific cost affects only the cost of the solar array, hence, removal of this area of uncertainty has little effect on total risk.

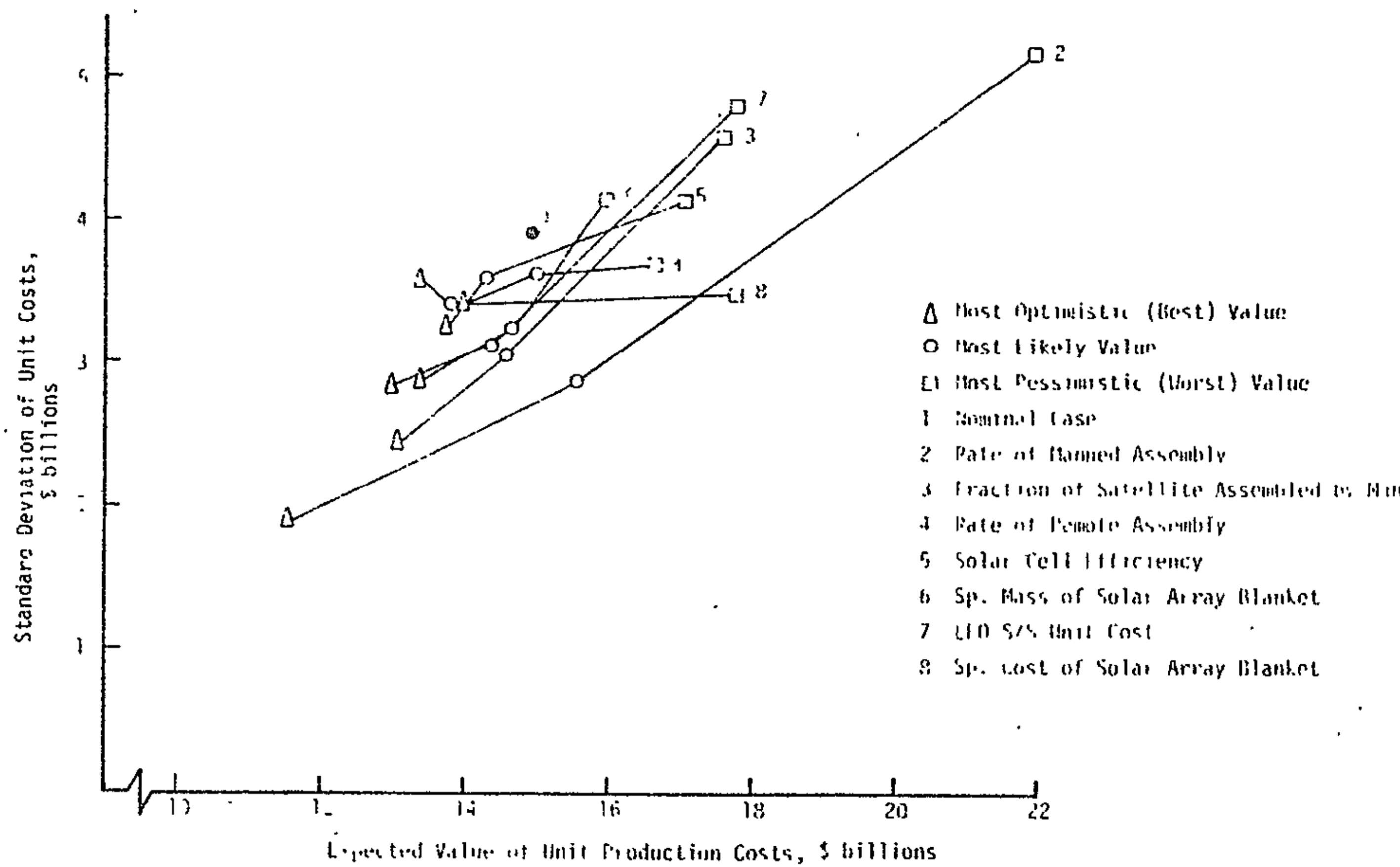

Figure 5.2 Effect of Removing Uncertainty on Cost Components--
Major Cost- and Risk-Driving Factors

Table 5.3 The Effect on Cost and Cost Risk*
of Changes in the State-of-Knowledge

	Item	Range of Values ($Billions, 1974)					
		Best		Most Likely		Worst	
		Mean Cost	Cost Risk	Mean Cost	Cost Risk	Mean Cost	Cost Risk
	Nominal**	3.76	--	14.92	3.86-	144.83	--
Major Cost- and Risk-Driving Factors	Rate of Manned Assembly	11.56	1.90	15.57	2.87	21.91	5.16
	Fraction of Satellite Assembled by Man	13.05	2.43	14.53	3.05	17.56	4.56
	Rate of Remote Assembly	13.93	3.42	14.96	3.61	16.65	3.67
	Solar Cell Efficiency	13.74	3.26	14.27	3.59	17.04	4.13
	Specific Mass of the Solar Blanket	13.34	2.87	14.67	3.24	15.92	4.13
	LEO Space Station Unit Cost	12.99	2.83	14.34	3:07	17.74	4.77
	Solar Array Blanket Specific Cost	13.33	3.49	13.84	3.42	17.27	3.48
Factors Having Noticeable Cost- and Risk-Driving Effects	EVA Equipment Unit Cost	14.49	3.17	14.56	3.59	15.16	3.88
	DC-RF Converter Specific Cost	14.45	3.21	14.95	3.82	15.00	3.49
	Nonconducting Structure Specific Cost	14.57	3.49	14.82	4.09	15.22	3.67
	Central Mast Specific Cost	14.57	3.52	14.71	3.69	15.14	3.68
	Rectenna Structure Specific Cost	14.66	3.65	14.75	3.79	15.13	3.85
	Crew Rotation Period	14.00	3.13	14.99	3.84	15.77	3.95
	HLLV Average Load Factor	14.40	3.61	14.83	4.06	15.61	3.57
	Number of Personnel per Shuttle Flight	14.34	3.34	14.70	3.60	15.90	4.08
	Launch Cost per Shuttle Flight	14.22	3.73	14.15	3.27	16.85	3.85
	HLLV Unit Cost	14.52	3.60	14.87	3.63	15.18	3.93
	Launch Cost per Shuttle Flight	14.59	3.52	14.70	3.65	15.28	4.14
	Teleoperator Unit Cost	14.49	3.48	14.46	3.61	15.51	3.65
	DC-RF Converter Efficiency	14.27	3.61	14.79	3.58	15.25	4.07
	RF-DC Converter Efficiency	14.17	3.26	14.62	3.17	15.00	3.54
	Specific Mass of the Solar Concentrators	14.24	3.15	14.97	3.82	15:17	3.59
	Specific Mass of Waveguides	14.40	3.48	14.55	3.63	15.74	3.91
	Miscellaneous Mass	14.73	3.64	14.80	3.77	14.92	3.88
	Personnel Productivity Factor	14.04	3.30	14.56	3.56	15.64	3.66
	Fabrication Rate of Modules	14.61	3.69	14.73	3.57	14.89	3.96

Table 5.3 The Effect on Cost and Cost Risk* of Changes in the State-of-Knowledge (continued)

	Item	Range of Values ($Billions, 1974)					
		Best		Most Likely		Worst	
		Mean Cost	Cost Risk	Mean Cost	Cost Risk	Mean Cost	Cost Risk
Factors Having No Noticeable Cost- and Risk-Driving Effects	Beam Collection Efficiency	14.61	3.69	15.17	3.72	14.89	3.22
	Ratio: Conducting Structure Mass to Array Area	15.00	3.66	14.60	3.67	14.94	3.56
	Ratio: Nonconducting Structure Mass to Array Area	14.71	3.41	14.69	3.64	14.97	3.54
	Specific Mass of Central Mast	14.76	3.45	14.84	3.78	14.55	3.55
	Specific Mass of DC-RF Converters	14.68	3.40	14.86	4.08	15.30	3.82
	Specific Mass of Antenna Interface	14.89	3.84	14.60	3.41	15.06	3.74
	Specific Mass of Phase Control Electronics	14.65	3.58	14.89	3.64	14.85	3.91
	Teleoperator Availability Factor	14.53	3.42	14.95	3.74	14.85	3.89
	Teleoperator Work Factor	14.75	3.82	14.61	3.30	15.18	3.93
	Fabrication Module Availability Factor	14.98	3.90	14.56	3.78	14.85	3.70
	Manipulator Availability Factor	14.89	3.77	15.18	3.72	14.63	3.18
	Fabrication Module Unit Mass	14.54	3.41	14.62	3.15	14.59	3.37
	Manipulator Unit Mass	14.55	3.73	14.75	3.37	14.70	3.37
	LEO Space Station Unit Mass	14.47	3.21	14.98	3.83	14.93	3.50
	Crew Module Unit Mass	15.02	3.66	14.60	3.60	14.93	3.56
	GEO Space Station Unit Mass	14.84	3.50	14.69	3.64	14.83	3.45
	Fabrication Module Unit Cost	14.74	3.60	14.72	3.60	14.57	3.54
	Shuttle Unit Cost	14.74	3.50	14.78	3.51	14.67	3.58
	Manipulator Unit Cost	14.73	3.85	14.92	3.72	14.75	3.49
	GEO Space Station Unit Cost	14.79	3.70	14.56	3.78	15.03	3.90
	AIS Unit Cost	14.83	3.96	14.69	3.57	14.75	3.69
	Antenna Power Distribution Specific Cost	14.52	3.15	15.16	3.72	15.03	3.80
	Phase Control Specific Cost	14.50	3.41	14.60	3.15	14.69	3.37
	Waveguide Specific Cost	14.68	3.37	14.73	3.37	14.60	3.73
	Solar Array Concentrator Specific Cost	14.79	3.45	14.68	3.64	14.97	3.50

Table 5.3 The Effect on Cost and Cost Risk* of Changes in the State-of-Knowledge (continued)

	Item	Range of Values ($Billions, 1974)					
		Best		Most Likely		Worst	
		Mean Cost	Cost Risk	Mean Cost	Cost Risk	Mean Cost	Cost Risk
Factors Having No Noticeable Cost- and Risk-Driving Effects	Conducting Structure Specific Cost	14.57	3.49	14.82	4.09	15.22	3.67
	Miscellaneous Equipment Specific Cost	14.87	3.84	14.61	3.41	15.05	3.73
	Rectenna Site Specific Cost	14.63	3.59	14.88	3.65	14.89	3.90
	RF-DC Converter Specific Cost	14.98	3.68	14.90	3.57	15.17	3.44
	Power Interface Specific Cost	14.68	3.60	14.68	3.60	14.74	3.53
	Phase Control Specific Cost	14.78	3.56	14.67	3.65	14.76	3.53

*"Cost Risk" is the standard deviation of the cost estimate.

**The nominal case includes: for best value, a deterministic-cost estimate using the best values for each design factor; for most likely value, a Monte Carlo simulation using the full range for each design factor; for worst value, a deterministic cost estimate using the worst values for each design factor.

Finally, the third group of variables includes those variables that are weak cost and risk drivers. In general, the effect of technology development in these areas is not of sufficient magnitude to be resolved by the risk analysis model.

As a note of caution in the interpretation of values in Table 5.3, it should be recognized that these values derive from a Monte Carlo simulation, that is, they are obtained by sampling probability distributions. They are not the result of precise computation. Thus, these data contain some amount of noise. For example, determination of expected costs is accurate to about \$200 million one sigma or about ±1 percent. Determination of risk is also accurate to about the same absolute amount or about ±5 percent. This amount of noise accounts for the apparent inconsistencies in some of the results presented in Table 5.3, particularly with respect to the Group 3 variables.

In summary, the risk analysis model has been used to identify the technology areas that are the major drivers of cost and risk--the critical technologies. It is concluded that there are two major areas of critical technology:

1. the ability to construct large systems in space, and

2. solar cell blanket mass, cost and efficiency.

Of these technology areas, the productivity of man in space is key. It is recommended that:

1. these conclusions be reviewed by a "panel of experts," and

2. assuming that their validity is confirmed, these technology areas should be addressed by detailed study early in the continuing program.

6. PROGRAMMATIC RISK ANALYSIS

Given the results of Section 4, a brief programmatic risk assessment is possible. This discussion will focus on Program I as that is the only program, of the specific alternatives analyzed, that has a positive expected value. The development program consists of three major subprograms: an SR&T subprogram, a DDT&E subprogram and a first unit production subprogram. Success in each of these subprograms can be defined as achieving a state from which a decision to continue the program can be justified. Then, from Figure 4.9, it is seen that the probability of a successful SR&T subprogram is .376, the probability of a successful DDT&E subprogram is .692 given that the SR&T subprogram is successful and the probability of a successful first unit production subprogram is .905 given that the DDT&E subprogram is successful.

The probability of success of the program is the product of the probabilities of success of each branch. Thus, there is a probability of .235 that Program I will be successfully completed. This compares with a probability of about .32 (from Figure 4.4) that the current configuration could be economically viable given Program I. Thus, the program as presently planned yields about a 27 percent chance of rejecting a viable outcome. That is, given that the current configuration is economically viable, there is about a 27 percent chance that it will be classified as not viable, resulting in a program failure. This is the result of inaccuracies in the measurements of projected second unit costs at Decision Points A and B. This loss could be reduced if more accurate measurements could be obtained at about the same cost.

A more detailed programmatic risk analysis is not possible under the resources of the present effort, however, it should be performed and the framework necessary to do it resides partly within the existing risk analysis model. The procedure for a more detailed risk analysis derives from the notion that the goal of the SSPS development is to provide a state-of-knowledge based upon which a decision can be made to proceed with the implementation of the second and subsequent units and that the efforts expended in the development program are, in fact, directed at <u>measuring</u> the total unit cost of the second unit. Thus, the output of each development subprogram is a <u>measurement</u> of a system parameter or parameters vis a vis the current configuration. The goals for the measurement accuracy of each parameter at each decision point can be derived from the tables in Appendices C and E. The next step in the programmatic risk assessment will be to assess the expected level of success in achieving each of the measurement accuracy goals thus set.

It is almost a certainty that the reader is confused at this point about the interpretation placed upon the activities undertaken in a development program. Thus, the above points are explained again.

First, from the economic point of view, the justification for proceding with a development program lies in the belief that an economically viable technology implementation can be achieved. Such a belief is valid only if it finds a basis in a postulated system configuration. Then, all economic measures must be made against this system configuration. It is not possible to compute economic measures against abstract ideas, just as it is not possible to compute engineering measures against abstract ideas. For example, an engineer cannot answer the question, what are the stresses in a beam? He must be told the design of the beam and the loadings placed upon it. So must the economist be given such "design" information to perform his analyses. And just as the engineering answers change as the design changes, so also do the economic answers.

Now, the current SSPS configuration is not an existing piece of hardware. It is, in fact, a concept that might be realized at some future date. Insofar as that concept remains unchanged, all the technology development programs and analyses performed on it are only exercises of measuring parameters that describe it. Thus, until the configuration is changed, the development program is, strictly speaking, a measurement program. As such, it should be treated as a measurement program and the goals of each subprogram should be expressed in terms of measurement accuracies.

Everyone knows that design changes occur throughout a program. Design changes are made for basically two reasons: first, because the postulated configuration, when adequately measured, is found to fall outside of allowable system bounds and, second, because targets of opportunity arise to improve upon the existing postulated configuration. In either case, after the design change is made, both the engineer and the economist are dealing with a new system and must adjust their analyses accordingly. Such changes cannot be anticipated in advance. If they could, the system would be configured in the changed configuration in the first place. Thus, analyses are confined to deal with the current configuration and to base measures of system performance against this configuration.

After each design change, the program reverts back to a measurement program and remains such until the next design change. Thus, a development program can be thought of as series of measurement programs separated by discontinuties which represent design changes. To view a development program in this context offers the possibility of achieving a new dimension in the control of technology development and programmatic risk.

7. UTILITY INTERFACE ANALYSIS

An effort was made during this phase of the study to identify issues which might be important concerning the compatibility of the characteristics of the current configuration SSPS with the demands of electric utilities in the 1990 time period. How an SSPS conforms to the needs of utilities has not been analyzed and might have a significant impact on system economics. If some utility interface requirement were found to be critical, such a requirement would have to be weighed in the design process of SSPS components related to that requirement.

Potential issues were selected by reviewing the present structure and requirements of utilities and the trends that are projected for the next 15 to 20 years. Then, the salient performance characteristics of SSPS were determined in order to examine the effects of variations in these characteristics on utility design and costs. The most important SSPS features were found to be output power level, reliability and power level fluctuations (both predictable fluctuations like eclipses and random ones due, for example, to atmospheric attenuation).

The approach used for analyzing the effect and criticality of these characteristics is described below. It should be emphasized that much more detailed analysis is required--the modelling effort to do so was beyond the scope of this study. This analysis was intended only to delineate whether any of the above factors are likely to represent significant economic issues.

7.1 Effects of Reliability

Electric utilities design their generating and transmission systems to assure a standard level of reliability (usually a loss-of-load probability of one day in ten years*). This requires the utilities among other things to install greater generating capacity than necessary to meet the expected peak demand, so that if the peak loads deviate from the projections or generating capacity is lost through unscheduled outages, the load will not exceed the capacity. This installed capacity reserve margin represents a major cost component for utilities, and great care is taken in system design and scheduling to minimize the reserve margin required to maintain the design level of reliability. There are several different approaches used by utilities to calculate what the appropriate reserve margin should be. The approach generally used now is to model the sizes and reliabilities of the units in a projected system, determining all of the possible combinations of outages among the units,

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*This means that, given the sizes and reliabilities of the units in this system and the projected annual peak loads, the probability of the load exceeding the generating capacity is one day (cumulative) in ten years.

the resulting level of generation for each combination, and the probability of this level of generation occurring. These probabilities of generation level are combined with a projected probability distribution of daily peak demands for a given year to calculate the total probability of some loss of load occurring. If the resulting reliability is not adequate, more generating capacity has to be added to the planned system.

There are a number of factors which affect utility system reliability which ought to be included in such a model. The size of a new unit will create a disproportionate increase in the reserve requirement if it is very large with respect to the other units in the system or large with respect to the total system capacity. This effect will decrease as other large units are added and/or as the total system capacity increases. An example of the trend toward larger unit sizes is provided in Figure 7.1, which shows the distribution of sizes of units to be added this decade and next decade in the Eastern Central Area (ECAR), shown in Figure 7.2. The total capacity in this area is expected to increase from 55 GW in 1970, to 116 GW in 1990. The effect of SSPS unit size will be discussed later.

Another key factor in utility system reliability is the forced outage rates for the individual units which are determined historically. A forced outage is caused by the failure of a component which causes the immediate or nearly immediate* shutdown of the unit. The experience of the utility industry is that the larger the unit the higher the forced outage rate and also that new units have higher outage rates during the initial break-in period (usually the first two years, but sometimes as long as six years). There are other terms used in the industry that relate to reliability, such as "availability", which is the fraction of a time period during which a generating unit is available for operation whether or not it is in operation. The difference between the amount of time that a unit has not been forced out and the amount of time it is available includes the time for scheduled maintenance and the time it is not used. Since these outages can be scheduled to occur during off-peak periods when sufficient alternate capacity exists to compensate for the outage, whereas forced outages are as likely to occur during peak demand periods as during off-peak periods, it is the forced outage rate that is usually used to calculate the reserve requirements.

Increasing the number of generating units in a system and increasing the number of interconnections with other systems through power pooling both have the effect of reducing required reserve margins. The seasonal distribution of peak loads can also have an effect on reserve

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*A shutdown immediately or up to the very next weekend is defined as a forced outage on the basis of which the reserve margin is determined. If the shutdown can be postponed until the weekend, it is treated as a planned outage which does not require reserve capacity.

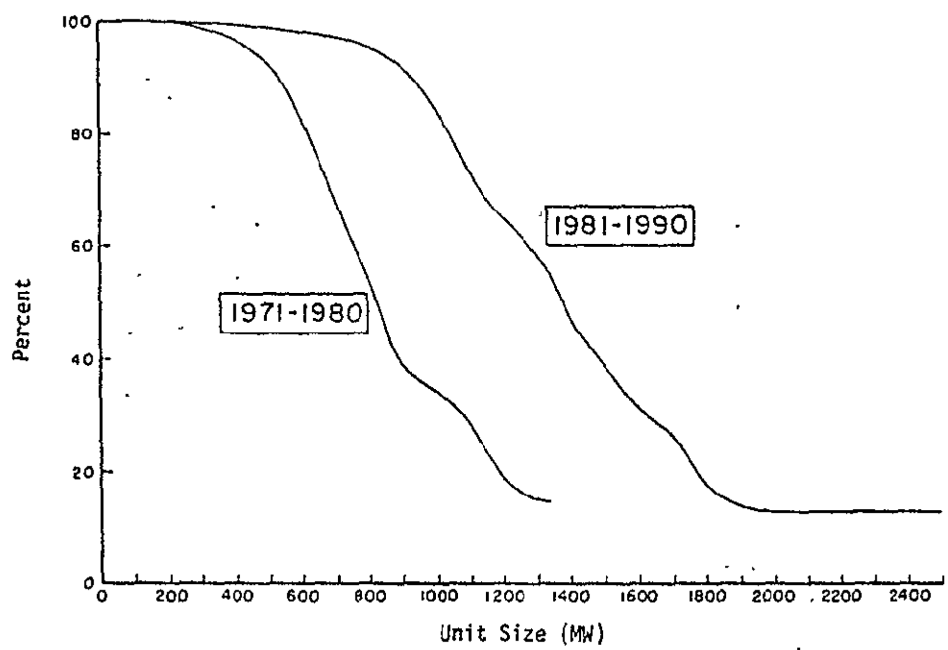

Figure 7.1 Cumulative Distribution of Steam Generating Units Added Between Years (Percent of Installed on Generating Units Sizes Equal or Greater Than Abscissa) For the East Central Region (Source: Federal Power Commission, The 1970 National Power Survey - Part II)

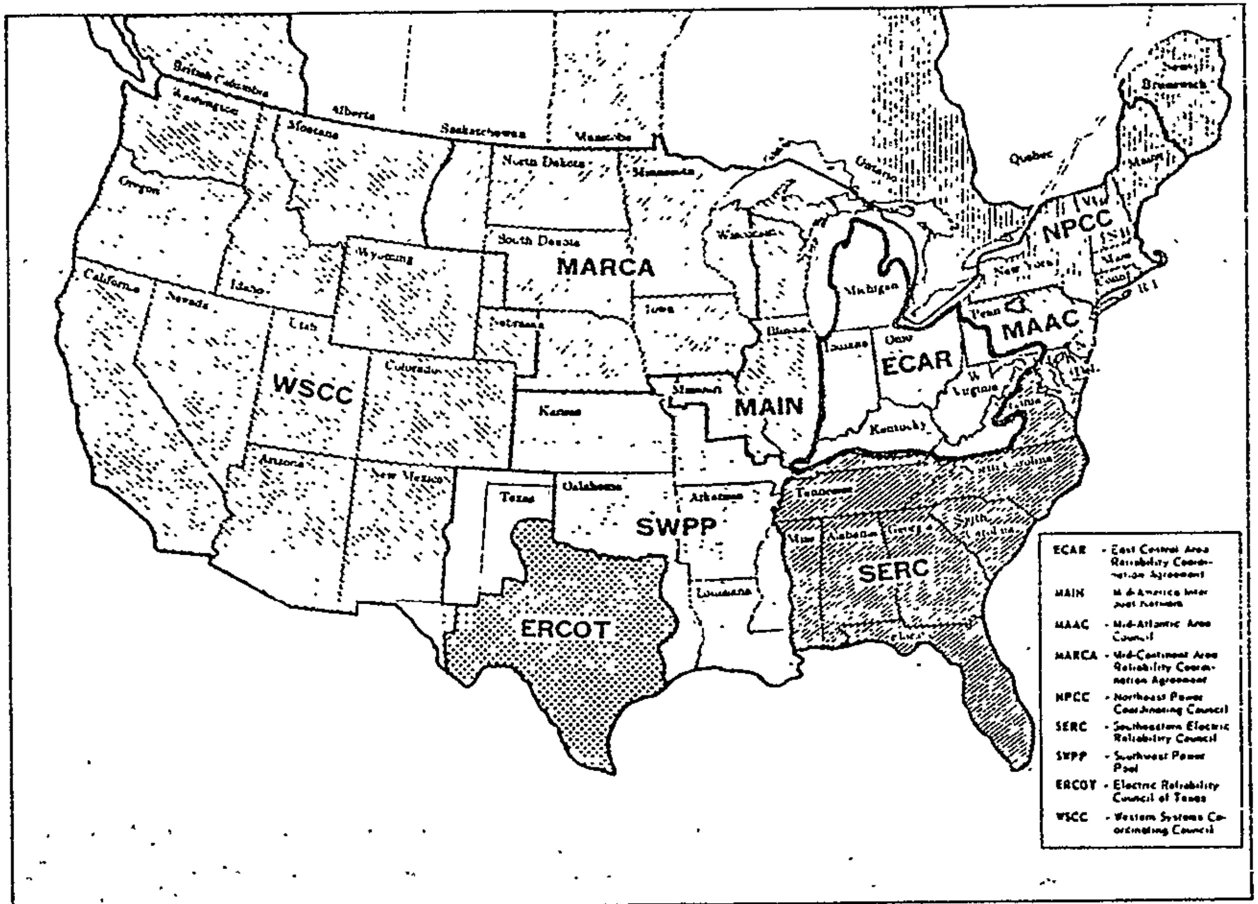

Figure 7.2 Geographic Area of the Eastern Central Area Reliability Coordination Agreement (Source: Federal Power Commission, Annual Report 1973)

margin; if there is wide variation between seasonal peaks, then planned outages can be scheduled for lower demand seasons without requiring reserve capacity. If, however, the load is fairly balanced from season to season, then it may be necessary to install reserve capacity to allow planned outages, such as those necessary for maintenance.

In recent years the utility industry has been experiencing a need for increasing reserves, primarily because of the introduction of large (800-1000 MW and larger) new units to systems composed of much smaller (100-300 MW) units. In addition, the reliabilities of the new units have, in many cases, been substantially below their expected levels. With unit size levelling off in the future and with power pool interconnections increasing, the reserve margin might be expected to decline, so long as load levelling (the balancing of seasonal peak demands) does not force the installation of reserve capacity to allow for scheduled outages.

SSPS reliability is expected to be high because it is a largely passive, de-centralized system, which does not involve high temperatures or pressures in the generation of power. These are factors which contribute to the high forced outage rates of new, large units.

Availability rates are used in calculating the cost of power from baseload generation plants, because availability rates account for the time that a plant is not able to produce power due to maintenance or other scheduled outages. The effect of availability on the cost of power can be significant, especially for capital-intensive generation methods such as nuclear reactors or SSPS. Based on cost data provided by Arthur D. Little, Inc.,* the total busbar energy cost has been calculated as a function of unit availability,** for three different generation systems: light water reactor, liquid metal fast breeder reactor and direct coal-fired plant. These relationships between energy costs and generating unit availability are displayed in Figure 7.3. Given that SSPS availability is expected to be about 95 percent, it is clear from Figure 7.3 that SSPS could tolerate a somewhat higher life cycle cost per kilowatt and still produce power at the same energy cost. Light water reactors currently are designed for 80 percent availability; an SSPS operating at 95 percent availability (Case A) could cost approximately $70/kW more than the light water reactor and produce power at the

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*These cost data were provided for use in the "Space-Based Solar Power Conversion and Delivery Systems Study--Interim Summary Report," March 13, 1976.

**A single value for installed cost for each system was given. This installed cost was factored up by the availability rate in calculating the cost of the capital component of the total busbar energy cost. A uniform increment appropriate to each system was added to cover fuel, operation and maintenance, taxes and insurance; hence, the only factor that was varied was the cost of capital, as affected by availability.

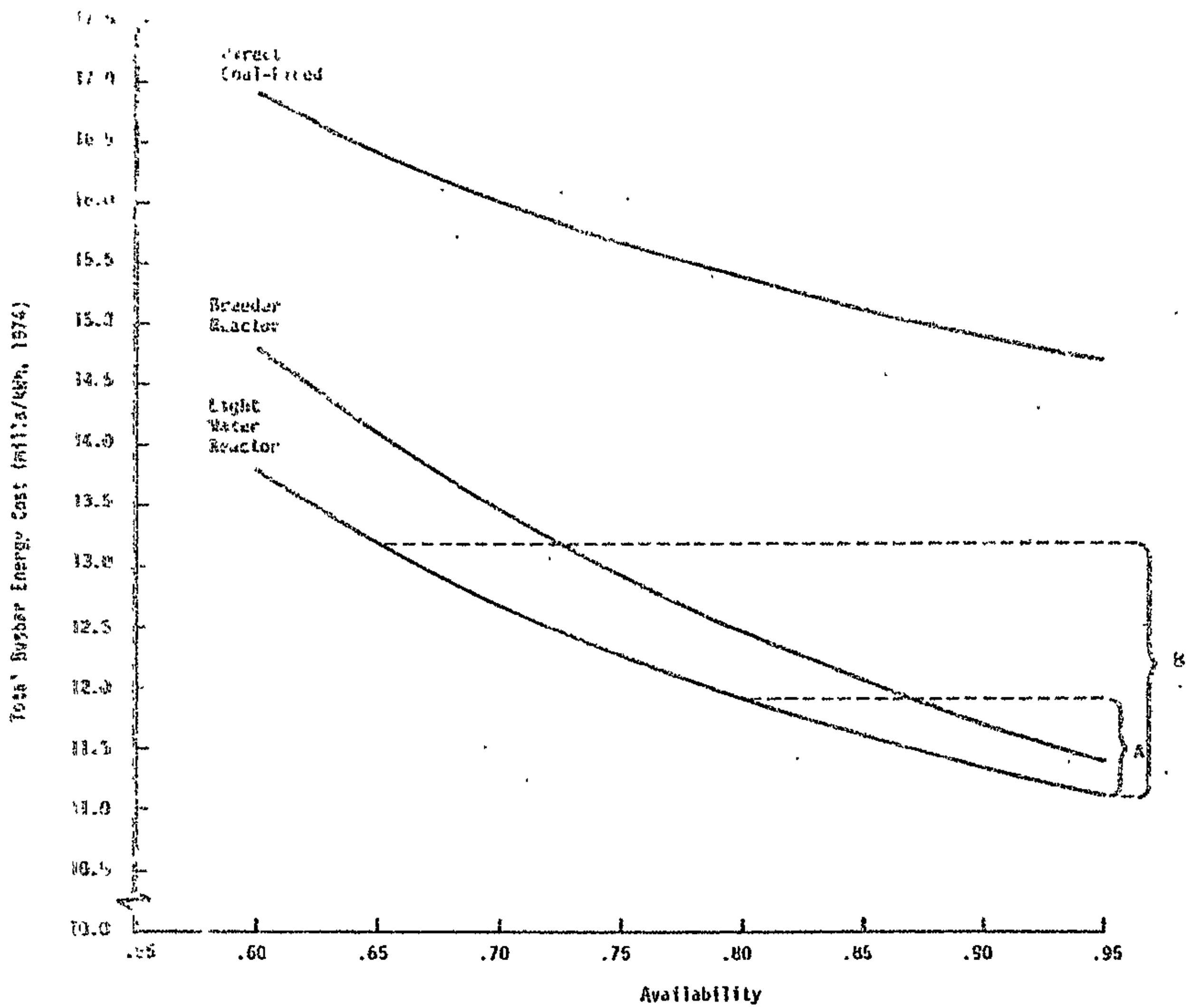

Figure 7.3 Relationship of Generating Unit Availability to Total Energy Cost

same cost. The industry-wide experience for light water reactors at the moment is closer to 65 percent*; if this value remains unchanged, an SSPS costing $200/kW more than the nuclear plant (Case B) could produce power at the same cost. Thus, the level of reliability projected for SSPS could be an important economic factor.

In addition to reliability, SSPS size in both absolute and relative terms is an important consideration in calculating the system reserve requirements and accompanying costs resulting from the introduction of an SSPS. A simulation which would estimate the cost effect of the addition of SSPS's to realistic representations of utility systems projected for 1995 could not be conducted within the scope of this study. However, an examination was made of the effect on reserve margin requirements of adding an SSPS to several systems, each containing units of uniform size and reliability, over a range of system sizes that might be typical in the future (30-50 GW). The results are presented in Figure 7.4. The unit sizes used were 1 GW and 2.5 GW, and the forced outage rates used were 8.7 percent** and 15 percent*** for the 1 GW plants and 22 percent**** for the 2.5 GW plants.

The approach used in this analysis was to determine for each of the system configurations (1 GW units at an 8.7 percent outage rate, 1 GW units at a 15 percent outage rate and 2.5 GW units at a 22 percent outage rate) the necessary installed capacity reserve margin needed to insure the one-day-in-ten-years loss-of-load probability used by most utilities as a reliability standard. These reserve calculations were conducted both for a given configuration system without an SSPS, and for the same type of system with an SSPS accounting for 5 GW of the total capacity. These calculations were conducted for three different levels of SSPS forced outage rates.

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*This lower availability is the result of a number of factors including rapidly increasing unit size, non-standardized construction, safety shutdowns and the fact that a large number of units are relatively new and still in their break-in period.

**This value is an average between the future mature fossil plant and the future mature nuclear plant forced outage rates projected by the Northeast Regional Advisory Committee to the Federal Power Commission. These values are optimistic compared with present experience.

***This value represents a typical system forced outage rate for present power pools.

****This value corresponds to current experience with new large generating units. Whereas improvement upon this level is expected in the future, it has been used here as a pessimistic value.

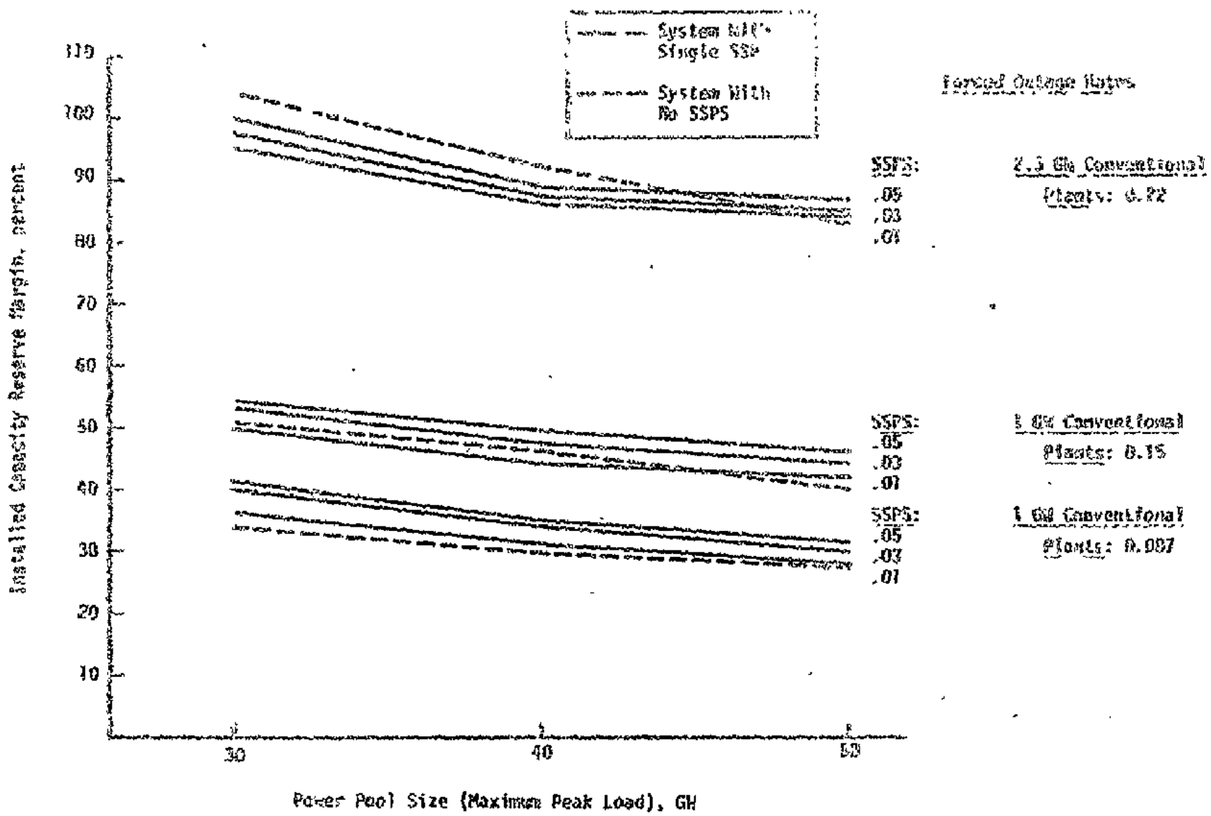


Figure 7.4 Installed Capacity Reserve Requirements as a Function of Utility System Size and SSPS Reliability Level

It can be noted from Figure 7.4 that the inclusion of an SSPS is sometimes advantageous (that is, it reduces the required reserve margin) and sometimes disadvantageous, depending upon the system size and the reliability of the constituent units. Whether or not the SSPS is advantageous also depends on the reliability of the SSPS.

The purpose of this examination was to determine whether or not the installed reserve requirement posed by SSPS might be critical. From this analysis, reserve requirements do not appear to represent a critical economic issue. In fact, under certain circumstances, an SSPS may reduce the necessary reserve margin. The maximum effect noted here is about 4 percent of the installed capacity which would constitute approximately a 0.5 to 2.0 mills/kWh difference in busbar energy cost due to cost of capital (excluding operation, maintenance and fuel), depending upon the assumed installed cost ($100/kW to $300/kW).

Further study is needed both to determine what the likely reliability level will be for SSPS and what the affect of an SSPS of such a reliability would be on a realistic representation of utility systems with the unit size and reliability characteristics that might be expected in the 1995 time period. Such analysis should also include the affects on system reliability of system interconnections and pooling.

7.2 Effects of Solar Eclipses

An SSPS satellite in geosynchroneous orbit will experience eclipses around midnight of varying durations in the periods surrounding the two equinoxes, as shown in Figure 7.5. These eclipse periods occur during times that are daily and seasonal "valleys" in demand for nearly all utilities. Representative daily and seasonal load cycles are shown in Figures 7.6 and 7.7, respectively.

Given that the eclipses occur during off-peak periods and that they are predictable, so long as sufficient alternate generating capacity is available, an SSPS eclipse may be treated as a planned outage not requiring installed reserve capacity. The costs then associated with an eclipse are the marginal costs of whatever alternate capacity is used to generate power during the eclipse period. The costs of alternate generation means have been assessed parametrically, and the results are presented in Table 7.1. The costs associated with an eclipse do not appear to be critical because in the worst case examined here (having to use peaking capacity during the duration of the eclipses) the average annual generating cost of power produced by an SSPS baseload system would only be increased by 0.5 mills/kWh.

The scope of this study did not allow examination of the assumption of alternate capacity being available, as power during an SSPS eclipse would probably be provided by power pooling or other interconnections between utility systems. The size of power pools and the number of interconnections is growing. (An example of this expansion is provided in Figure 7.8.) It was noted in the example in Section 7.1, that the Eastern Central Area Reliability Coordination Agreement will oversee an installed

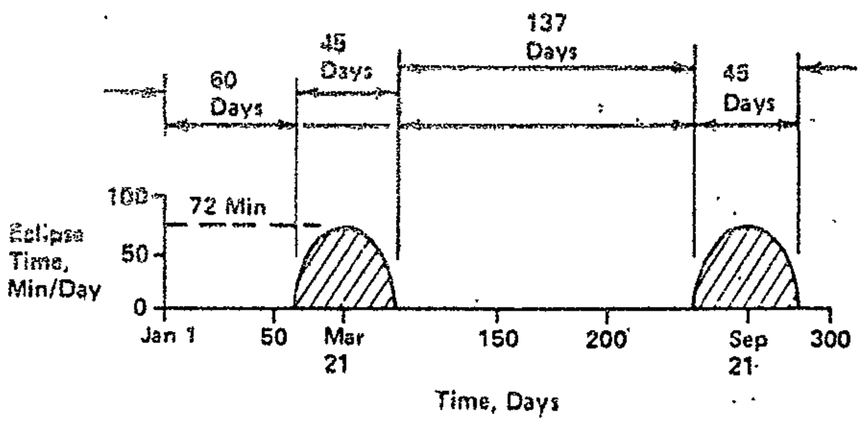


Figure 7.5 Duration of SSPS Eclipses at Synchronous Equatorial Orbit

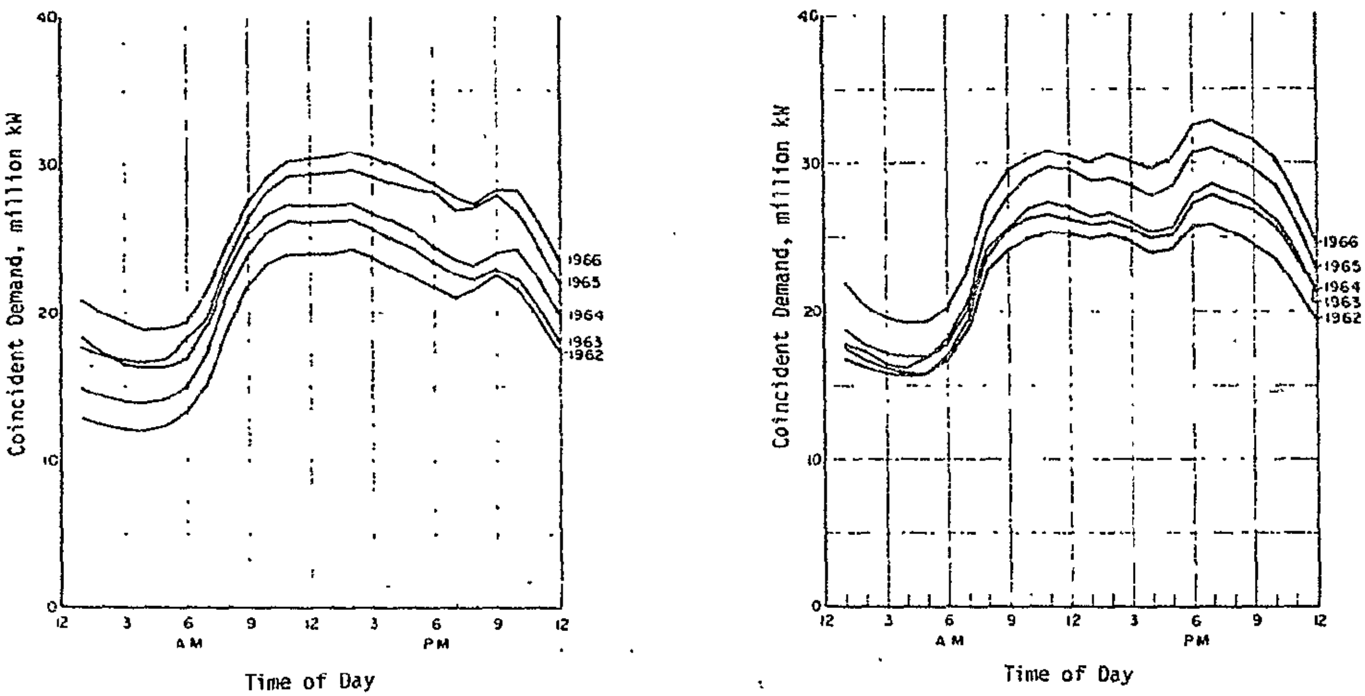


Figure 7.6 Daily Load Cycles for Summer Peak (Left) and Winter Peak (Right) Days Among ECAR Systems for 1962-66. (Source: Federal Power Commission. The 1970 National Power Survey - Part II.)

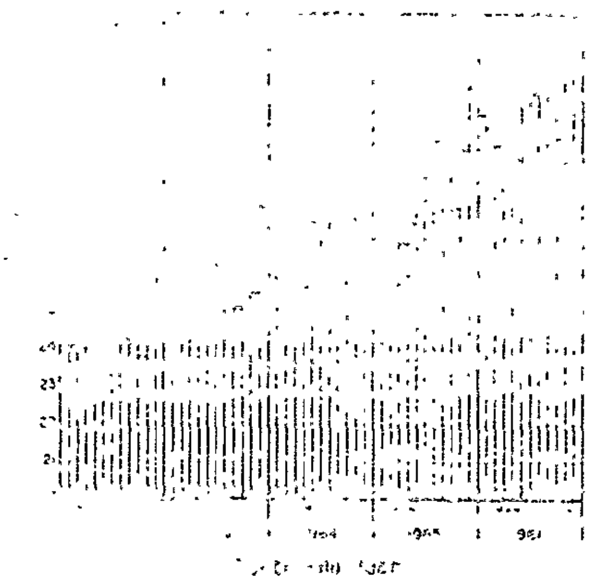
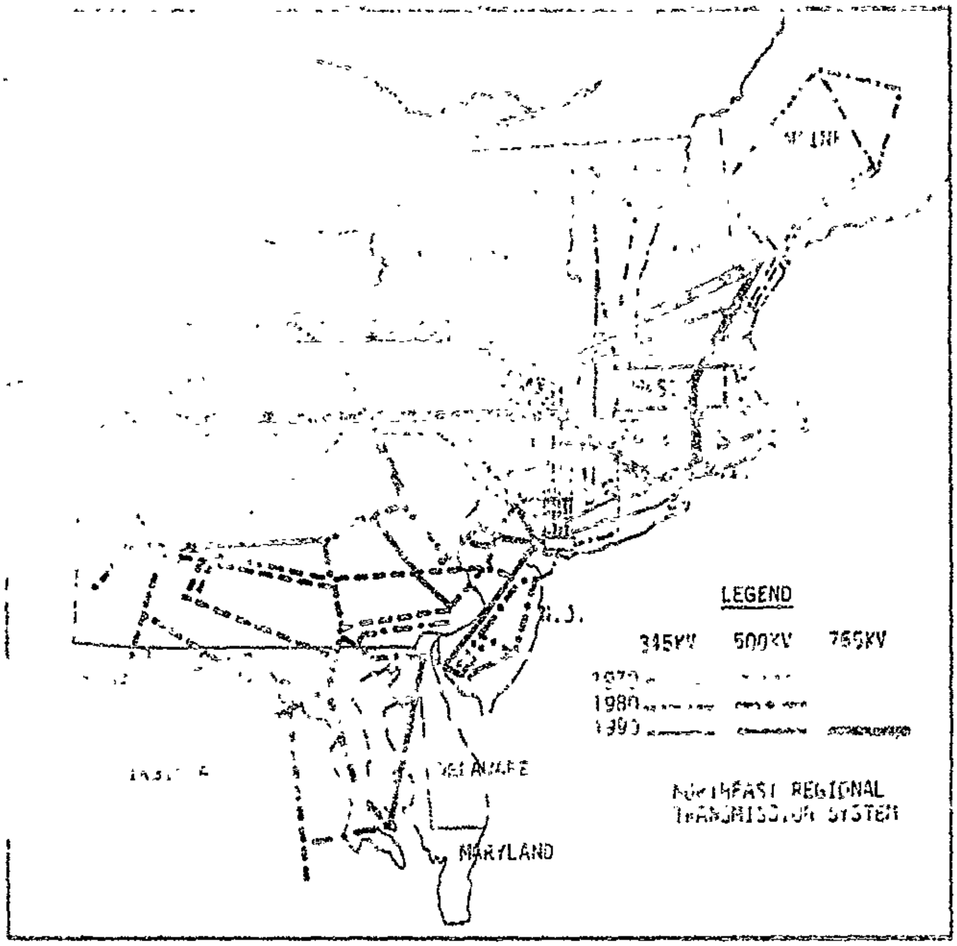


Figure 7.7 Seasonal Variation of Monthly Peak Loads Among ECAR Systems (Source: The 1970 Power Survey - Part II.)

Table 7.1 Annual Generation Costs of Alternate Sources to Cover SSPS Unit Eclipse Time

Source of Alternate Generation	Capital Cost ($/kW, 1974)	Fuel Cost (mills/kWh, 1974)	Operation Time* (hrs)	Annual Cost ($, 1974)
Baseload Plants	--	6.0	135	4.05×10^6
Intermediate Load Plants	--	14.0	135	9.45×10^6
Peakload Plants	150	30.0	135	22.01×10^6

*Operation time assumes one and one-half hours of operation per eclipse period to account for start-up time.



[illegible] Transmission
[illegible] 1970 through 1990 (Source: Federal Power
Commission, The 1970 National Power Survey [illegible])

capacity of over 100 GW in 1990. The effect of this pooling would be to reduce the cost of providing power during an SSPS eclipse. However, with SSPS satellites displaced by 2400 km in synchronous orbit, during maximum eclipse periods, seven satellites would be occulted at any point in time; hence, a given power pool area might be faced with replacing the capacity of several SSPS's during an eclipse period. The interaction of the effects of pooling and multiple occultations is a complicated one requiring further study. An additional concern for further study should be the extent and effect of occultations of one satellite by another.

7.3 Effect of Power Fluctuations

The transmission frequency (2.45 GHz) of the current configuration SSPS was selected, in part, because of its relative insensitity to attenuation by atmospheric constituents. According to the Microwave Power Transmission System Study [13] the greatest fluctuation in power level that might be expected from attenuation due to atmospheric effects such as heavy rain (50 mm/hr) is $\pm$ 1 percent. Electric utilities are not able to sustain substantial fluctuations of power for significant periods of time without equipment damage. The daily operating reserve of utilities is composed of standby capacity that can be brought on-line within ten to twenty minutes as well as loads that can be interrupted on short notice (typically one minute).

If the fluctuations in SSPS transmitted power are sufficiently rapid, then the effect will be a derating (reduction in the rated capacity) of SSPS. The effect on the cost of power produced by SSPS of various levels of power fluctuation is presented in Figure 7.9, with the effect of the expected variation of 1 percent to be an increase of about 0.2 mills/kWh in SSPS cost of capital,* hence, an equivalent increase in the user charge of SSPS-produced power.

This analysis represents a "worst case" approach in that it assumes that fluctuations in transmitted power would render a certain percentage of SSPS power unusable, whereas in fact, there are a number of economic uses to which fluctuating or interruptible power can be put, including electrolysis or other automated processes. However, even in the worst case of power being lost, it does not appear that power fluctuations within the range currently anticipated for SSPS pose a significant economic issue.

*This estimate represents a lower bound in that it does not include the component of O&M cost that is directly related to installed capacity regardless of operation time.

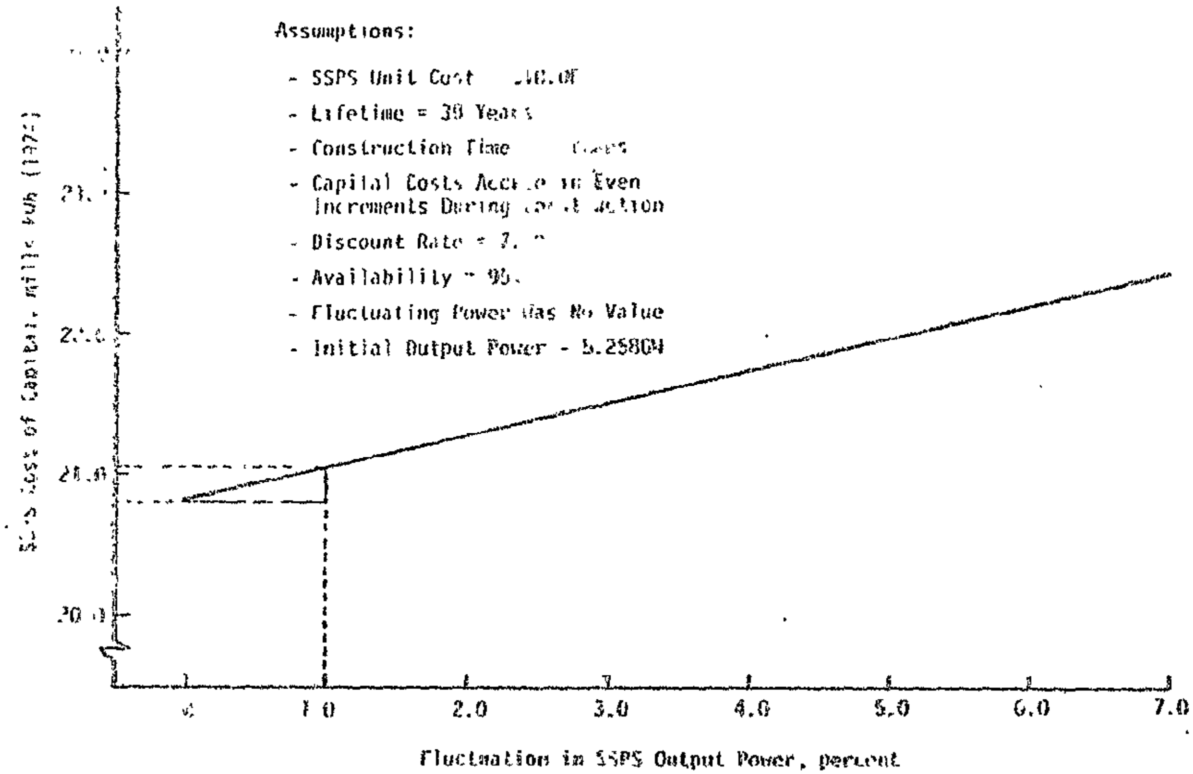


Figure 7.9 Effect on the Cost of SSPS-Produced Power of Fluctuations in Power Transmission

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APPENDIX A

UNIT PRODUCTION COST MODEL

The following is a listing of the equations incorporated in the Unit Production Cost Model. (A description of the cost model is found in Section 2.1.) The definitions of the variables used in these equations have been gathered together at the end of this appendix in order to avoid repetition.

Satellite Mass

$$A_B = \frac{P_{IN}}{P_F \; F \; \eta_{eff}}$$

$$M_{SAB} = m_{SAB} \; A_B$$

$$A_C = \frac{(\eta_{eff} - 1) \; A_B}{\eta_{CONC}}$$

$$M_{SAC} = m_{SAC} \; A_C$$

$$M_{STC} = m_{STC} \; (A_C + A_B)$$

$$M_{STNC} = m_{STNC} \; (A_B + A_C)$$

$$M_{STCM} = m_{STCM} \; (\sqrt{2r_A \; (A_C + A_B)} \; + \; r_L \; D_{ANT})$$

$$M_{ANTS} = m_{ANTS} \; P_{ANT}$$

$$M_{DC-RF} = m_{DC-RF} \; P_{DC-RF}$$

$$M_{WG} = m_{WG} \; P_{DC-RF}$$

$M_{ANT-INT}$ = [illegible] $_{ANT-INT}$

$M_{[illegible]}$ = [illegible]

[illegible] = [illegible] M_{EC-RF} + M_{WG} + $M_{ANT-INT}$ + M_{PCE}

[illegible] = [illegible] + M_{SAC} + M_{STC} + M_{STNC} + M_{STCM} + M_{ANT} + M_{MISC}

A[illegible]

[illegible] = [illegible] $_{TOT\ SAT}$

[illegible] = [illegible] $M_{TOT\ SAT}$

[illegible] = $\frac{M_{MANNED}}{R_{MANNED}}$

[illegible] = $\frac{M_{REMOTE}}{R_{REMOTE}}$

[illegible] = $\frac{T_{MANNED}\ f_S}{T_{CONST\ LEO}\ \gamma_M}$

$$N_{TELE} = \frac{T_{REMOTE}}{T_{CONST\ LEO}\ f_{TELE\ AV}\ f_T}$$

N_{FAB} = $\frac{M_{STC} + M_{STNC} + M_{WG} + M_{STCM}}{f_{FAB}\ R_{FAB}\ T_{CONST\ LEO}}$

N_{MANIP} = $\frac{\gamma\ N_{[illegible]}}{f_S\ T_{MANIP}}$

$$N_{LEO\ S/C} = \frac{N_{LEO}}{f_{LEO\ S/C}}$$

M_{FAB} = [illegible]

$$M_{TELE} = m_{TELE} N_{TELE} a_{TELE}$$

$$M_{TUG} = m_{TUG} N_{TUG} a_{TUG}$$

$$M_{EVA} = m_{EVA} f_{EVA} (N_{LEO} + N_{GEO})$$

$$M_{MANIP} = m_{MANIP} N_{MANIP} a_{MANIP}$$

$$M_{LEO\ S/S} = m_{LEO\ S/S} N_{LEO\ S/S} a_{LEO\ S/S}$$

$$M_{AE\ PROP} = f_{AE\ PROP} M_{TOT\ SAT}$$

$$M_{S/S\ RES} = f_{S/S\ RES} (N_{LEO} T_{CONST\ LEO} + N_{GEO} T_{CONST\ GEO})$$

$$M_{CREW} = m_{CREW} a_{CREW}$$

$$M_{GEO\ S/S} = m_{GEO\ S/S} a_{GEO\ S/S}$$

Masses Related to Interorbit Transportation

$$\alpha_{LCT} = e^{\Delta V_{LCT}/V_{J_{LCT}}}$$

$$m_{LCT\ PROP} = \frac{\lambda_{LCT} (\alpha_{LCT} - 1)}{\lambda_{LCT} - (\alpha_{LCT} - 1)(1 - \lambda_{LCT})} M_{CREW}$$

$$M_{LCT} = \frac{m_{LCT\ PROP} (1 - \lambda_{LCT})}{\lambda_{LCT}}$$

$$M_{LCT\ PROP} = m_{LCT\ PROP} \frac{T_{CONST\ GEO}}{T_{ROT}}$$

$$\alpha_{AIS} = e^{\Delta V_{AIS}/V_{J_{AIS}}}$$

$$M_{AIS\ PROP} = (M_{GEO\ S/S} + M_{TOT\ SAT}) \frac{\lambda_{AIS}(\sqrt{\alpha_{AIS}} - 1)}{\lambda_{AIS} - (\alpha_{AIS} - 1)(1 - \lambda_{AIS})}$$

$$M_{AIS} = \frac{M_{AIS\ PROP}(1 - \lambda_{AIS})}{\lambda_{AIS}}$$

$$M_{PROP\ DEPOT} = m_{LHT} \frac{M_{LH}}{f_{LHT}} + m_{LOXT} \frac{M_{LOX}}{f_{LOXT}} + m_{IT} \frac{M_{AIS\ PROP}}{f_{IT}}$$

Total Mass to LEO

$$M_{UMAE} = M_{FAB} + M_{TELE} + M_{AE\ PROP} + M_{TUG}$$

$$M_{MAE} = M_{EVA} + M_{MANIP} + M_{LEO\ S/S} + M_{GEO\ S/S} + M_{S/S\ RES}$$

$$M_{IOVP} = M_{LCT} + M_{AIS} + M_{LCT\ PROP} + M_{AIS\ PROP} + M_{CREW} + M_{PROP\ DEPOT}$$

$$M_{LEO} = M_{UMAE} + M_{MAE} + M_{IOVP} + M_{TOT\ SAT}$$

LEO Launch Cost

$$N_{HLLV} = \frac{M_{LEO}}{M_{P/L}\ f_{LOAD}}$$

$$N_{H\ UNITS} = \frac{N_{HLLV}}{f_{H\ LIFE}}$$

$$N_{SHUTTLE} = \frac{N_{LEO} \frac{T_{CONST\ LEO}}{T_{ROT}}}{f_{SHUTTLE}} + \frac{N_{GEO} \frac{T_{CONST\ GEO}}{T_{ROT}}}{f_{SHUTTLE}}$$

$$N_{S\ UNITS} = \frac{N_{SHUTTLE}}{f_{S\ LIFE}}$$

$$C_{HLLV} = c_{HLLV} N_{HLLV} + c_{H\ UNIT} N_{H\ UNIT}$$

$$C_{SHUTTLE} = c_{SHUTTLE}\, N_{SHUTTLE} + c_{S\ UNIT}\, N_{S\ UNIT}$$

$$C_{LLC} = C_{SHUTTLE} + C_{HLLV}$$

Space Station and Assembly Cost

$$C_{UMAE} = c_{FAB}\, N_{FAB}\, a_{FAB} + c_{TELE}\, N_{TELE}\, a_{TELE} + c_{AE\ PROP}\, M_{AE\ PROP} + c_{TUG}\, N_{TUG}\, a_{TUG} + c_{GRD\ OP}\, N_{TELE}\, f_{GRD}\, T_{CONST\ LEO}$$

$$C_{MAE} = c_{EVA}\,(N_{LEO} + N_{GEO})\, f_{EVA} + c_{MANIP}\, N_{MANIP}\, a_{MANIP} + c_{LEO\ S/S}\, N_{LEO\ S/S}\, a_{LEO\ S/S} + c_{GEO\ S/S}\, N_{GEO\ S/S}\, a_{GEO\ S/S} + c_{S/S\ RES}\, M_{S/S\ RES} + (N_{LEO}\, T_{CONST\ LEO} + N_{GEO}\, T_{CONST\ GEO})\, c_{ORBP}$$

$$C_{S/S\&A} = C_{UMAE} + C_{MAE}$$

LEO-GEO Transportation Cost

$$C_{LEO\text{-}GEO} = C_{LCT}\, a_{LCT} + C_{AIS}\, a_{AIS} + c_{LCT\ PROP}\, M_{LCT\ PROP} + c_{AIS\ PROP}\, M_{AIS\ PROP} + C_{CREW}\, a_{CREW} + c_{LHT}\, \frac{M_{LH}}{f_{LHT}}\, a_{LHT} + c_{LOXT}\, \frac{M_{LOX}}{f_{LOXT}}\, a_{LOXT} + \frac{c_{IT}\, M_{AIS\ PROP}}{f_{IT}}\, a_{IT}$$

NOTE: The ratios M_{LH}/f_{LHT}, M_{LOX}/f_{LOXT} and $M_{AIS\ PROP}/f_{IT}$ are integers rounded up.

Satellite Procurement Cost

$$C_{ANT} = c_{PD}\, P_{ANT} + c_{PCE}\, P_{PCE} + c_{WG}\, P_{DC\text{-}RF} + c_{DC\text{-}RF}\, P_{DC\text{-}RF} + c_{ST}\, P_{ANT}$$

$$C_{SAT} = c_{SAB} A_B + c_{SAC} A_C + c_{STC} M_{STC} + c_{STNC} M_{STNC} + c_{STCM} M_{STCM} + C_{ANT} + c_{MISC} M_{MISC}$$

Ground Station Cost

$$C_{GRD\ STAT} = c_{RE} P_{RF-DC} + c_{STRUCT} P_{RF-DC} + c_{INTERF} P_{INTERF} + c_{PC} P_{RF-DC}$$

Total Unit Production Cost

$$C_{UPC} = C_{LLC} + C_{LEO-GEO} + C_{S/S\&A} + C_{SAT} + C_{GRD\ STAT}$$

Definitions of Unit Production Cost Model Variables

Following is a listing of the definitions of the variables used in the unit production cost model, in the order of their initial appearance in the model.

A_B = area of solar blanket (km^2)

P_{IN} = power input to the solar array (kW);

$$P_{IN} = \frac{P_{OUT}}{\Pi}$$

where P_{OUT} = power output at the rectenna busbar (kW; beginning of life, b.o.l.)

Π = system efficiency chain (i.e. the products of the efficiencies of all of the system components);

$$\Pi = \eta_{SC}\, \eta_{SAPD}\, \eta_{ANT-INT}\, \eta_{ANT\ PD}\, \eta_{DC-RF}\, \eta_{PC}\, \eta_{ION\ PROP}\, \eta_{ATM\ PROP}\, \eta_{BC}\, \eta_{RF-DC}\, \eta_{RECT\ PD}$$

where:

η_{SC} = solar cell efficiency (at given concentration ratio, b.o.l.)

η_{SAPD} = solar array power distribution efficiency

$\eta_{ANT-INT}$ = antenna interface efficiency

$\eta_{ANT\ PD}$ = antenna power distribution efficiency

η_{DC-RF} = dc-rf converter efficiency

η_{PC} = phase control efficiency

$\eta_{ION\ PROP}$ = ionospheric propagation efficiency

$\eta_{ATM\ PROP}$ = atmospheric propagation efficiency

η_{BC} = beam collection efficiency

η_{RF-DC} = rf-dc converter efficiency

$\eta_{RECT\ PD}$ = rectenna power distribution efficiency (including utility interface)

P_F = ratio of area of solar cells to area of blanket of the current configuration solar blanket (i.e., decimal fraction of total blanket area that is solar cells).

F = solar flux constant (1353 x 10^3kW/km^2)

η_{eff} = effective concentration ratio

M_{SAB} = total mass of the solar blanket (kg)

m_{SAB} = specific mass of the solar blanket (kg/km^2)

A_C = area of solar concentrator as seen by the sun (km^2)

η_{CONC} = efficiency of the concentrator

M_{SAC} = total mass of the solar concentrator (kg)

m_{SAC} = specific mass of the solar concentrator (kg/km^2)

M_{STC} = total mass of the conducting structure (kg)

m_{STC} = ratio of conducting structure mass to solar array area as seen by the sun (kg/km^2)

M_{STNC} = total mass of nonconducting structure (kg)

m_{STNC} = ratio of nonconducting structure mass to solar array area as seen by the sun (kg/km^2)

M_{STCM} = total mass of the central mast (kg)

m_{STCM} = specific mass of the central mast (kg/km)

r_A = the aspect ratio of a solar array (length/width)

r_L = factor (>1) to allow for antenna clearance (distance between solar arrays divided by the diameter of the antenna)

D_{ANT} = diameter of the transmitting antenna (km)

M_{ANTS} = total mass of the antenna structure (kg)

m_{ANTS} = specific mass of the antenna structure (kg/kW)

P_{ANT} = power input to the antenna (kW);

$$P_{ANT} = \frac{P_{OUT}}{\eta_{RECT\ PD}\ \eta_{RF-DC}\ \eta_{BC}\ \eta_{ATM\ PROP}\ \eta_{ION\ PROP}\ \eta_{PC}\ \eta_{DC-RF}\ \eta_{ANT\ PD}}$$

M_{DC-RF} = total mass of the dc-rf converters (kg)

m_{DC-RF} = specific mass of the dc-rf converters (kg/kW)

P_{DC-RF} = power input to the dc-rf converters (kW);

$$P_{DC-RF} = \frac{P_{OUT}}{\eta_{RECT\ PD}\ \eta_{RF-DC}\ \eta_{BC}\ \eta_{ATM\ PROP}\ \eta_{ION\ PROP}\ \eta_{PC}\ \eta_{DC-RF}}$$

M_{WG} = total mass of the waveguides (kg)

m_{WG} = specific mass of the waveguides (kg/kW)

$M_{ANT-INT}$ = total mass of the antenna interface (kg)

$m_{ANT-INT}$ = specific mass of the antenna interface (kg/kW)

$P_{ANT-INT}$ = power input to the antenna interface (kW);

$$P_{ANT-INT} = \frac{P_{OUT}}{\eta_{RECT\ PD}\ \eta_{RF-DC}\ \eta_{BC}\ \eta_{ATM\ PROP}\ \eta_{ION\ PROP}\ \eta_{PC}\ \eta_{DC-RF}\ \eta_{ANT\ PD}\ \eta_{ANT-INT}}$$

M_{PCE} = total mass of the phase control electronics (kg)

m_{PCE} = specific mass of the phase control electronics (kg/kW)

P_{PCE} = power input to the phase control electronics (kW);

$$P_{PCE} = \frac{P_{OUT}}{\eta_{RECT\ PD}\ \eta_{RF-DC}\ \eta_{BC}\ \eta_{ATM\ PROP}\ \eta_{ION\ PROP}\ \eta_{PC}}$$

M_{ANT} = total mass of the antenna (kg)

$M_{TOT\ SAT}$ = total mass of an operational satellite

M_{MISC} = total mass of miscellaneous equipment (kg)

β = percentage of total satellite mass to be assembled by man (input)

M_{MANNED} = total mass of satellite to be constructed by on-orbit personnel (kg)

M_{REMOTE} = total mass of satellite to be constructed by remote control (kg)

T_{MANNED} = total man-days of construction time

R_{MANNED} = rate of manned assembly (kg/man-day)

T_{REMOTE} = total machine-days of construction time

R_{REMOTE} = rate of remote-controlled assembly (kg/machine-day)

N_{LEO} = number on-orbit personnel*

$f_{TELE\ AV}$ = factor to account for downtime of teleoperators (i.e., the percentage of the time they are available)

f_T = factor to account for percentage of time that teleoperators can be doing useful work

$T_{CONST\ LEO}$ = total construction time in low earth orbit (days)

f_M = factor of productivity account for operations in space (productive time/total work time)

f_S = number of shifts per day

N_{TELE} = number of on-orbit teleoperators

N_{FAB} = total number of fabrication modules

*Throughout this cost model numbers of items which must be integers are taken as integer values rounded high (e.g., 2.3 becomes 3)

R_{FAB} = rate of fabrication of modules (kg/days)

f_{FAB} = factor to account for fabrication module downtime (i.e., the percentage of the time the units are available)

M_{FAB} = total mass of the fabrication units (kg)

m_{FAB} = mass of a single fabrication module (kg)

a_{FAB} = amortization factor for fabrication module (Note: All amoritzation factors = $T_{CONST\ LEO}$/design life of unit.)

M_{TELE} = total mass of the teleoperator units (kg)

m_{TELE} = mass of a single teleoperator (kg)

a_{TELE} = amortization factor for teleoperators

M_{TUG} = total mass of the LEO support tugs (kg)

m_{TUG} = mass of a single LEO support tug (kg)

a_{TUG} = amortization factor for LEO support tugs

M_{EVA} = total mass of extra-vehicular activity (EVA) units (kg)

m_{EVA} = mass of single EVA unit (kg)

N_{GEO} = total number of geosynchronous personnel (input)

f_{EVA} = factor to account for whether or not EVA units must be tailored to individuals or can be used repetitively and for how long

M_{MANIP} = total mass of the manned manipulator units (kg)

m_{MANIP} = mass of single manned manipulator unit (kg)

a_{MANIP} = amortization factor for manned manipulators

$M_{LEO\ S/S}$ = total mass of the low earth orbit space stations (kg)

$m_{LEO\ S/S}$ = mass of a single LEO station (kg)

$a_{LEO\ S/S}$ = amortization factor for LEO space stations

$M_{AE\ PROP}$ = total mass of the assembly equipment propellant (kg)

$f_{AE\ PROP}$ = factor used to estimate propellant requirements

$M_{S/S\ RES}$ = total mass of the space station resupply (kg)

$f_{S/S\ RES}$ = factor used to estimate space station resupply requirements (kg/man/day)

$T_{CONST\ GEO}$ = total construction time at geosynchronous orbit (days)

M_{CREW} = total mass of crew modules (kg)

m_{CREW} = mass of a single crew module (kg)

a_{CREW} = amortization factor of crew module

$M_{GEO\ S/S}$ = total mass of geosynchronous space stations (kg)

$m_{GEO\ S/S}$ = mass of a single geosynchronous space station (kg)

$a_{GEO\ S/S}$ = amortization factor for GEO space stations

α_{LCT} = ratio of total initial-to-final mass of the large cryo tug plus crew module

ΔV_{LCT} = total LEO-GEO mission ΔV (m/sec) (Note: Accounts for a two-way trip as well as maneuvering and rendezvous.)

$V_{J_{LCT}}$ = rocket exhaust jet velocity (m/sec)

$m_{LCT\ PROP}$ = mass of cryo propellants required for one round-trip to GEO (kg)

λ_{LCT} = propellant mass-fraction of the cryo tug

α_{LCT} = ratio of total initial-to-final mass of the cryo tug and crew module

M_{LCT} = mass of the large cryo tug (dry)(kg)

$m_{LCT\ PROP}$ = mass of propellant for one large cryo tug trip to geosynchronous orbit (kg)

$M_{LCT\ PROP}$ = total mass of cryo propellants used during the construction of one SSPS (kg)

T_{ROT} = time period between crew rotations (days)

α_{AIS} = ratio of total initial-to-final mass of the advanced ion stage and payload

ΔV_{AIS} = total LEO-GEO mission ΔV of the ion stage (m/sec) (Note: Accounts for a two-way trip as well as maneuvering.)

$V_{J_{AIS}}$ = exhaust jet velocity of the ion stage (m/sec)

$M_{AIS\ PROP}$ = total mass of ion propellant (kg)

λ_{AIS} = propellant mass-fraction of the ion stage

M_{AIS} = total mass of the ion stage (dry)(kg)

$M_{PROP\ DEPOT}$ = total mass of the tanks used as a propellant depot in low earth orbit (kg)

m_{HT} = mass of a single liquid hydrogen tank (kg)

M_{LH} = total mass of liquid hydrogen to be stored (M_{LH} = [1/7] $M_{LCT\ PROP}$)

f_{HT} = capacity of a liquid hydrogen storage tank (kg)

m_{LOXT} = mass of a single liquid oxygen storage tank (kg)

M_{LOX} = total mass of liquid oxygen to be stored (M_{LOX} = [6/7] $M_{LCT\ PROP}$)

f_{LOXT} = capacity of a liquid oxygen storage tank (kg) (Note: The estimate of storage for cryo propellants is based on the total amount needed for the construction of one SSPS being stored at one time; this need not be true.)

m_{IT} = mass of a single ion propellant storage tank (kg)

f_{IT} = capacity of a single ion propellant storage tank (kg)

M_{UMAE} = total mass of unmanned assembly equipment (kg)

M_{MAE} = total mass of the manned assembly equipment (kg)

M_{IOVP} = total mass of the inter-orbit vehicles and propellants (kg)

M_{LEO} = total mass launched to low earth orbit for the construction of one SSPS (kg)

N_{HLLV} = total number of heavy lift launch vehicle flights

$M_{P/L}$ = the payload to LEO of an HLLV (kg)

f_{LOAD} = average load factor for an HLLV (what percentage of payload is used)

$N_{H\ UNITS}$ = number of HLLV units acquired for the construction of one SSPS*

$f_{H\ LIFE}$ = number of flights for which HLLV designed

$N_{SHUTTLE}$ = total number of shuttle flights

$f_{S\ LIFE}$ = number of flights for which shuttle designed

$f_{SHUTTLE}$ = number of personnel that can be carried per shuttle flight

$N_{S\ UNITS}$ = total number of shuttles acquired**

C_{HLLV} = total cost of HLLV activity ($)

c_{HLLV} = cost per HLLV flight (operations) ($)

$c_{H\ UNIT}$ = cost per HLLV unit ($)

$C_{SHUTTLE}$ = total cost of shuttle activity ($)

$c_{SHUTTLE}$ = cost per shuttle flight (operations) ($)

$c_{S\ UNIT}$ = cost per shuttle unit ($)

C_{LLC} = total low earth orbit launch cost ($)

*This value is not taken to be an integer as one HLLV may service several payloads.

**This value is not taken to be an integer as one shuttle may service several payloads.

C_{UMAE} = total cost of unmanned assembly equipment ($)

c_{FAB} = unit cost of fabrication module ($)

c_{TELE} = unit cost of teleoperator ($)

$c_{AE\ PROP}$ = specific cost of assembly equipment propellant ($/kg)

c_{TUG} = unit cost of LEO support tug ($)

$c_{GRD\ OP}$ = cost per ground operator (for teleoperators) ($)

f_{GRD} = number of shifts of ground operators

C_{MAE} = total cost of manned assembly equipment ($)

c_{EVA} = unit cost of EVA equipment ($)

c_{MANIP} = unit cost of manned manipulator ($)

$c_{LEO\ S/S}$ = unit cost of LEO space station ($)

$c_{GEO\ S/S}$ = unit cost of GEO space stations ($)

$c_{S/S\ RES}$ = specific cost of space station resupply ($/kg)

C_{ORBP} = individual cost of on-orbit personnel ($/day/person)

$C_{S/S\&A}$ = total cost of space stations and assembly for one SSPS ($)

$C_{LEO-GEO}$ = total cost of LEO-GEO transportation ($)

C_{LCT} = unit cost of large cryo tug ($)

a_{LCT} = amortization factor of cryo tug

c_{AIS} = unit cost of advanced ion stage ($)
(Note: In this model there is no connection between the sizing used for mass estimation purposes [of the cryo tug and the ion stage] and the unit cost.)

a_{AIS} = amortization factor of the ion stage

$c_{LCT\ PROP}$ = specific cost of cryo tug propellant ($/kg)

$c_{AIS\ PROP}$ = specific cost of ion propellants ($/kg)

c_{CREW} = unit cost of crew module ($)

c_{LHT} = unit cost of liquid hydrogen storage tank ($)

a_{LHT} = amortization factor for liquid hydrogen storage tank

c_{LOXT} = unit cost of liquid oxygen storage tank ($)

a_{LOXT} = amortization factor of liquid oxygen storage tank

c_{IT} = unit cost of ion propellant storage tank ($)

a_{IT} = amortization factor of ion propellant storage tank

C_{ANT} = total procurement cost of the transmitting antenna ($)

c_{PD} = specific cost of antenna power distribution ($/kW)

c_{PCE} = specific cost of phase control ($/kW)

c_{WG} = specific cost of waveguide ($/kW)

c_{DC-RF} = specific cost of dc-rf converters (\$/kW)

c_{ST} = specific cost of antenna structure (\$/kW)

C_{SAT} = total procurement cost of an operational satellite (\$)

c_{SAB} = specific cost of solar array blanket (\$/km^2)

c_{SAC} = specific cost of solar concentrator (\$/km^2)

c_{STC} = specific cost of conducting structure (\$/kg)

c_{STNC} = specific cost of nonconducting structure (\$/kg)

c_{STCM} = specific cost of central mass (\$/kg)

c_{MISC} = specific cost of miscellaneous equipment (\$/kg)

$C_{GRD\ STAT}$ = total procurement cost of the ground station (\$)

c_{RE} = specific cost of real estate and site preparation (\$/kW)

c_{STRUCT} = specific cost of rectenna structure (\$/kW)

c_{RF-DC} = specific cost of rf-dc converters (\$/kW)

c_{INTERF} = specific cost of the power interface (\$/kW)

c_{PC} = specific cost of phase front control (\$/kW)

P_{RF-DC} = power input into the rf-dc converters (kW);

$$P_{RF-DC} = \frac{P_{OUT}}{\eta_{RECT\ PD}\ \eta_{RF-DC}}$$

P_{INTERF} = power input into utility interface (kW);

$$P_{INTERF} = \frac{P_{OUT}}{\eta_{RECT\ PD}}$$

APPENDIX B

OPERATION AND MAINTENANCE COST MODEL

The following is a listing of the equations incorporated in the Operation and Maintenance Cost Model. (A description of the cost model is found in Section 2.2).

Launch Facility O&M

$$C_{LVF\ O\&M} = N_{O\&M\ FLTS} \left(c_{HLLV} + a_{HLLV}\ c_{H\ UNIT} + c_{AIS\ FLT} + c_{AIS2}a_{AIS} \right) + N_{LFP}\ f_{LFP}$$

Ground Station O&M

$$C_{GST\ O\&M} = f_{GRD\ EQUIP}\ C_{GRD\ STAT} + N_{GST\ P}\ c_{GST\ P}$$

Space Station and Support O&M

$$C_{CROT} = f_{CROT} \left(c_{SHUTTLE} + a_{SHUTTLE}\ c_{S\ UNIT} + C_{TUG\ OPS} + c_{TUG}\ a_{TUG} + C_{CREW\ REF} + C_{CREW}\ a_{CREW} \right)$$

$$C_{S/S\ O\&M} = a_{S/S\ O\&M} \left(c_{GEO\ S/S} + M_{GEO\ S/S}\ c_{GEO\ TRANSP} \right)$$

$$C_{S/S\ EQUIP} = a_{S/S\ EQUIP} \left(N_{O\&M\ MANIP}\ m_{O\&M\ MANIP}\ c_{GEO\ TRANSP} + N_{O\&M\ MANIP}\ c_{O\&M\ MANIP} \right)$$

$$C_{S/S\ MC} = f_{S/S\ MC}\ P$$

Satellite O&M

$$C_{SAT\ O\&M} = \sum_{i=i}^{n} c_{SAT\ COMP_i}$$

<u>Definitions of O&M Cost Model Variables</u>

Following is a listing of the definitions of the variables used in the Operation and Maintenance Cost Model, in the order of their appearance in the model.

$C_{LVF\ O\&M}$	=	total annual cost of launch facility O&M ($/yr)
$N_{O\&M\ FLTS}$	=	total number of flights per year to resupply the maintenance space station & the manned manipulators (input) (1/yr)
c_{HLLV}	=	cost per HLLV flight (operations) ($)
a_{HLLV}	=	amortization factor for the HLLV (a_{HLLV} = 1/total number of design life flights per vehicle)
$c_{H\ UNIT}$	=	unit cost of HLLV ($)
$c_{AIS\ FLT}$	=	cost per AIS flight (operations) ($)
C_{AIS2}	=	unit cost of AIS for O&M flights ($)
a_{AIS}	=	amortization factor for the AIS
N_{LFP}	=	total number of launch facility mission control personnel (input)
f_{LFP}	=	cost per person for launch facility mission control personnel ($/yr)
$C_{GST\ O\&M}$	=	total annual cost of ground station O&M ($/yr)
$f_{GRD\ EQUIP}$	=	assumed annual (fractional) rate of ground equipment replacement

$C_{GRD\ STAT}$	=	total procurement cost of the ground station (output value of unit production cost model) ($)
$N_{GST\ P}$	=	total number of ground station O&M personnel (input)
$c_{GST\ P}$	=	cost per person for ground station O&M personnel ($/yr)
C_{CROT}	=	total annual cost of crew rotation (on-orbit O&M personnel) ($/yr)
f_{CROT}	=	number of crew rotation flights per year (no./yr)
$c_{SHUTTLE}$	=	cost per shuttle flight (operations) ($)
$a_{SHUTTLE}$	=	amortization factor for shuttle
$c_{S\ UNIT}$	=	unit cost of shuttle ($)
$C_{TUG\ OPS}$	=	cost per tug flight (operations) ($)
c_{TUG}	=	unit cost of tug ($)
a_{TUG}	=	amortization factor for tug
$C_{CREW\ REF}$	=	cost of crew module refurbishment per flight ($)
C_{CREW}	=	unit cost of crew module
a_{CREW}	=	amortization factor of crew module
$C_{S/S\ O\&M}$	=	total annual cost of space station & support O&M ($/yr)
$a_{S/S\ O\&M}$	=	amortization factor of O&M space station (fraction reflecting number of stations used per year (1/design life of space station)

$c_{GEO\ S/S}$ = unit cost of GEO space station ($)

$M_{GEO\ S/S}$ = mass of a single GEO space station (kg)

$c_{GEO\ TRANSP}$ = specific cost of transportation to GEO ($/kg)

$C_{S/S\ EQUIP}$ = total annual cost of maintenance support equipment ($/yr)

$a_{S/S\ EQUIP}$ = amortization factor for manipulators

$N_{O\&M\ MANIP}$ = total number of O&M manipulators

$m_{O\&M\ MANIP}$ = mass of a single O&M manipulator (kg)

$c_{O\&M\ MANIP}$ = cost of a single O&M manipulator ($)

$C_{S/S\ MC}$ = total annual cost of the space station mission control ($/yr)

$f_{S/S\ MC}$ = specific cost of the mission control facility ($/kW/yr)

P = power output at the rectenna busbar (beginning of life) (kW)

$C_{SAT\ O\&M}$ = total annual cost of satellite O&M ($/yr)

$c_{SAT\ COMP_i}$ = total annual cost of replacing the failed units of the i^{th} satellite component (see Table C.3) ($/yr)

$$c_{SAT\ COMP_i} = f_{SAT\ COMP_i}\ \mu_{SAT\ COMP_i}\ (c_{COMP\ PROC_i} + c_{GEO\ TRANSP} + c_{O\&M\ ASSY_i});$$

$SAT\ COMP_i$	=	the rate of replacement of units of satellite component i (1/yr)
$\mu_{SAT\ COMP_i}$	=	the mass of the lowest replaceable unit of satellite component i (kg)
$c_{COMP\ PROC_i}$	=	the procurement cost of the lowest replaceable unit of satellite component i ($/kg)
$c_{GEO\ TRANSP}$	=	specific cost of transportation to geosynchronous orbit ($/kg)
$c_{O\&M\ ASSY_i}$	=	specific cost of assembly for a unit of satellite component i ($/kg)

APPENDIX C

THE CURRENT STATE-OF-KNOWLEDGE

The current state-of-knowledge relative to the current configuration SSPS is reflected by the ranges of input variables to the risk analysis model. These ranges have been subjectively assessed and are given in Table C.1 for the unit production costs and in Tables C.2 and C.3 for the operation and maintenance costs.

The sources for these input data include one report prepared by Grumman Aerospace Corp. (A. Nathan, "Space-Based Solar Power Conversion and Delivery Systems [Study]--Engineering Data Compliation," October 13, 1975) and two reports prepared by Raytheon Co. ("Space-Based Solar Power Conversion and Delivery System Study--Microwave Power Generation, Transmission and Reception," October 31, 1975, and "Microwave Power Transmission System Studies," Volumes II and IV, December 1975).

In addition, several meetings with Rudy Adornato and C. Allan Nathan of Grumman Aerospace were conducted to review and update these data, and Owen Maynard of Raytheon Co. was consulted on several occasions concerning the microwave portions of the system.

TABLE C.1 UNIT PRODUCTION COST MODEL INPUT VALUES

INPUT ELEMENT	UNITS	VARIABLE NAME	RANGE OF VALUES		
			BEST	MOST LIKELY	WORST
Power Output at the Busbar (bol)	kW	P	*	5.258×10^6	*
Packing Factor of the Solar Blanket	Fraction	P_F	0.99	0.95	0.91
Effective Concentration Ratio	Fraction	η_{eff}	2.0	2.0	2.0
Solar Cell Efficiency (bol)	Fraction	η_{SC}	0.1440	0.1293	0.1019
Solar Array Power Distribution Efficiency	Fraction	η_{SAPD}	0.95	0.93	0.92
Antenna Interface Efficiency	Fraction	$\eta_{ANT-INT}$	0.99	0.98	0.97
Antenna Power Distribution Efficiency	Fraction	$\eta_{ANT\ PD}$	0.97	0.96	0.96
DC-RF Converter Efficiency	Fraction	η_{DC-RF}	0.90	0.87	0.85
Phase Control Efficiency	Fraction	η_{PC}	0.97	0.96	0.95
Ionospheric Propagation Efficiency	Fraction	$\eta_{ION\ PROP}$	1.00	1.00	1.00
Atmospheric Propagation Efficiency	Fraction	$\eta_{ATM\ PROP}$	0.99	0.99	0.99
Beam Collection Efficiency	Fraction	η_{BC}	0.95	0.925	0.90
RF-DC Converter Efficiency	Fraction	η_{RF-DC}	0.90	0.87	0.84
Rectenna Power Distribution Efficiency	Fraction	$\eta_{RECT\ PD}$	0.95	0.94	0.93
Specific Mass of the Solar Blanket	kg/km^2	m_{SAB}	262×10^3	400×10^3	525×10^3
Efficiency of the Solar Concentrator	Fraction	η_{CONC}	0.90	0.85	0.80
Specific Mass of the Solar Concentrator	kg/km^2	m_{SAC}	39820	59340	79120
Ratio, Conducting Struct. Mass to Array Area	kg/km^2	m_{STC}	4140	4600	5060
Ratio: Noncond. Struct. Mass to Array Area	kg/km^2	m_{STNC}	34200	38000	41800
Specific Mass of Central Mast	kg/km	m_{STCM}	43970	48850	53740
Aspect Ratio of Solar Array	Fraction	r_A	*	1.2	*
Antenna Clearance	Fraction	r_c	*	1.5	*
Diameter of Transmitting Antenna	km	D_{ANT}	*	0.83	*
Specific Mass of Antenna Structure	kg/kW	m_{ANTS}	.0802	0.0891	0.0980
Specific Mass of DC-RF Converters	kg/kW	m_{DC-RF}	0.2495	0.2772	0.4544
Specific Mass of Waveguides	kg/kW	m_{WG}	0.2473	0.2748	0.5496
Specific Mass of Antenna Interface	kg/kW	$m_{ANT-INT}$	0.0171	0.0190	0.0380
Specific Mass of Phase Control Electronics	kg/kW	m_{PCE}	0.0160	0.0178	0.0356
Miscellaneous Mass	kg	m_{MISC}	70×10^3	100×10^3	360×10^3
Percentage of Satellite Assembled by Man	Fraction	ϵ	0.20	0.30	0.50
Rate of Manned Assembly	kg/Day	R_{MANNED}	264	100	50
Rate of Remote Assembly	kg/Day	R_{REMOTE}	300	100	48
Total Construction Time	Days	t_{CONST}	*	730	*
Shift Factor	#/Day	f_S	*	3.0	*
Personnel Productivity Factor	Fraction	f_H	0.70	0.60	0.50
Teleoperator Availability Factor	Fraction	$f_{TELE\ AV}$	0.95	0.90	0.85
Teleoperator Work Factor	Fraction	f_T	0.50	0.30	0.20
Fabrication Rate of Modules	kg/Day	R_{FAB}	4560	3000	2250
Fabrication Module Availability Factor	Fraction	f_{FAB}	0.30	0.20	0.10
Percentage of Personnel Using Manipulators	Fraction	.	*	0.10	*
Manipulator Availability Factor	Fraction	f_{MANIP}	0.50	0.35	0.20

TABLE C.1 UNIT PRODUCTION COST MODEL INPUT VALUES, CONT'D.

INPUT ELEMENT	UNITS	VARIABLE NAME	RANGE OF VALUES		
			BEST	MOST LIKELY	WORST
Number of Personnel Per LEO Space Station	Number	$f_{LEO\ S/S}$	*	12	*
Fabrication Module Unit Mass	kg	m_{FAB}	1500	4540	9000
Teleoperator Unit Mass	kg	m_{TELE}	50	180	250
LEO Support Tug Unit Mass	kg	m_{TUG}	500	1364	3000
EVA Equipment Unit Mass	kg	m_{EVA}	68	90	135
EVA Unit Use Factor	Fraction	f_{EVA}	0.40	0.30	0.20
Manipulator Unit Mass	kg	m_{MANIP}	900	1940	3600
LEO Space Station Unit Mass	kg	$m_{LEO\ S/S}$	80×10^3	102×10^3	150×10^3
Assembly Equip Propellant Estimation Factor	Fraction	$f_{AE\ PROP}$	0.01	0.02	0.05
Space Station Resupply Estimation Factor	kg/man/day	$f_{S/S\ RES}$	*	10	*
Crew Module Unit Mass	kg	m_{CREW}	12×10^3	13×10^3	15×10^3
GEO Space Station Unit Mass	kg	$m_{GEO\ S/S}$	40×10^3	50×10^3	76×10^3
LCT Total LEO-GEO Mission ΔV	m/sec	ΔV_{LCT}	*	8534	*
LCT Rocket Exhaust Jet Velocity	m/sec	$V_{J_{LCT}}$	*	4564	*
LCT Propellant Mass-Fraction	Fraction	λ_{LCT}	*	0.90	*
Crew Rotation Period	Days	t_{ROT}	180	90	60
AIS Total LEO-GEO Mission ΔV	m/sec	ΔV_{AIS}	*	9754	*
AIS Exhaust Jet Velocity	m/sec	$V_{J_{AIS}}$	*	47316	*
AIS Propellant Mass-Fraction	Fraction	λ_{AIS}	*	0.835	*
Liquid Hydrogen Storage Tank Unit Mass	kg	m_{HT}	*	39105	*
Liquid Hydrogen Storage Tank Capacity	kg	C_{HT}	*	720900	*
Liquid Oxygen Storage Tank Unit Mass	kg	m_{LOXT}	*	39105	*
Liquid Oxygen Storage Tank Capacity	kg	C_{LOXT}	*	720900	*
Ion Propellant Storage Tank Mass	kg	m_{IT}	*	39105	*
Ion Propellant Storage Tank Capacity	kg	C_{IT}	*	720900	*
HLLV Payload to LEO	kg	$M_{P/L}$	*	181×10^3	*
HLLV Average Load Factor	Fraction	f_{LOAD}	1.00	0.90	0.70
HLLV Turnaround Time	Days	$T_{H\ TURN}$	*	14	*
Number of Personnel Per Shuttle Flight	Number	$f_{SHUTTLE}$	30	40	20
Shuttle Turnaround Time	Days	$T_{S\ TURN}$	*	14	*
Launch Cost Per HLLV Flight	$	C_{HLLV}	8×10^6	9×10^5	20×10^6
HLLV Unit Cost	$	$C_{H\ UNIT}$	350×10^6	400×10^6	600×10^6
Launch Cost Per Shuttle Flight	$	$C_{SHUTTLE}$	11×10^6	12×10^5	20×10^6
Shuttle Unit Cost	$	$C_{S\ UNIT}$	190×10^6	200×10^6	250×10^6
Fabrication Module Unit Cost	$	C_{FAB}	10×10^6	12×10^6	20×10^6
Fabrication Module Amortisation Factor	Fraction	A_{FAB}	*	0.2	*
Teleoperator Unit Cost	$	C_{TELE}	2.0×10^6	2.5×10^6	10.0×10^6
Teleoperator Amortisation Factor	Fraction	A_{TELE}	*	0.2	*
Assembly Equipment Propellant Specific Cost	$/kg	$C_{AE\ PROP}$	*	0.33	*
LEO Support Tug Unit Cost	$	C_{TUG}	2.0×10^3	2.5×10^6	10.0×10^5
LEO Support Tug Amortisation Factor	Fraction	A_{TUG}	*	0.2	*

TABLE C.1 UNIT PRODUCTION COST MODEL INPUT VALUES, CONT'D.

INPUT ELEMENT	UNITS	VARIABLE NAME	RANGE OF VALUES		
			BEST	MOST LIKELY	WORST
Number of Shifts for Ground Operators	Number	f_{GRD}	*	4	*
EVA Equipment Unit Cost	$	c_{EVA}	1.5×10^6	2.0×10^6	5.0×10^6
Manipulator Unit Cost	$	c_{MANIP}	8.0×10^6	11.0×10^6	30.0×10^6
Manipulator Amortisation Factor	Fraction	a_{MANIP}	*	0.2	*
LEO Space Station Unit Cost	$	$c_{LEO\ S/S}$	190×10^6	360×10^6	720×10^6
LEO Space Station Amortisation Factor	Fraction	$a_{LEO\ S/S}$	*	0.2	*
GEO Space Station Unit Cost	$	$c_{GEO\ S/S}$	95×10^6	190×10^6	360×10^6
GEO Space Station Amortisation Factor	Fraction	$a_{GEO\ S/S}$	*	0.2	*
Space Station Resupply Specific Cost	$	$c_{S/S\ RES}$	5.0	10.0	20.0
LCT Unit Cost	$	c_{LCT}	12×10^6	15×10^6	25×10^6
LCT Amortisation Factor	Fraction	a_{LCT}	*	0.2	*
AIS Unit Cost	$	c_{AIS}	150×10^6	190×10^6	1000×10^6
AIS Amortisation Factor	Fraction	a_{AIS}	*	0.2	*
Cryo Tug Propellant Specific Cost	$/kg	$c_{LCT\ PROP}$	*	0.55	*
Ion Propellant Specific Cost	$/kg	$c_{AIS\ PROP}$	*	0.33	*
Crew Module Unit Cost	$	c_{CREW}	15×10^6	23×10^6	40×10^6
Crew Module Amortization Factor	Fraction	a_{CREW}	*	0.04	*
Liquid Hydrogen Storage Tank Unit Cost	$	c_{LHT}	12×10^6	16×10^6	20×10^6
Liquid Oxygen Storage Tank Unit Cost	$	c_{LOXT}	12×10^6	16×10^6	20×10^6
Ion Propellant Storage Tank Unit Cost	$	c_{IT}	12×10^6	16×10^6	20×10^6
Liquid Hydrogen Tank Amortisation Factor	Fraction	a_{LHT}	0.67	1.0	1.5
Liquid Oxygen Tank Amortisation Factor	Fraction	a_{LOXT}	0.67	1.0	1.5
Ion Propellant Tank Amortisation Factor	Fraction	a_{IT}	0.67	1.0	1.5
Antenna Power Distribution Specific Cost	$/kW	c_{PD}	9.72	10.80	21.60
Phase Control Specific Cost	$/kW	c_{PC}	16.83	18.70	37.40
Waveguide Specific Cost	$/kW	c_{WG}	7.92	8.80	17.60
DC-RF Converter Specific Cost	$/kW	c_{DC-RF}	14.67	16.30	32.60
Antenna Structure Specific Cost	$/kW	c_{SA}	3.60	4.00	18.00
Solar Array Blanket Specific Cost	$/km²	c_{SAB}	27.5×10^6	55.0×10^6	165.0×10^6
Solar Array Concentrator Specific Cost	$/km²	c_{SAC}	1.04×10^6	2.07×10^6	6.22×10^6
Conducting Structure Specific Cost	$/kg	c_{STC}	20.0	31.0	300.0
Non-Conducting Structure Specific Cost	$/kg	c_{STNC}	20.0	31.0	300.0
Central Mast Specific Cost	$/kg	c_{STCM}	20.0	31.0	300.0
Miscellaneous Equipment Specific Cost	$/kg	c_{MISC}	219	437	750
Rectenna Site Specific Cost	$/kW	c_{RE}	10.39	22.10	44.20
Rectenna Structure Specific Cost	$/kW	c_{STRUCT}	31.69	93.20	186.40
RF-DC Convertor Specific Cost	$/kW	c_{RF-DC}	56.00	62.20	124.40
Power Interface Specific Cost	$/kW	c_{INTERF}	39.80	44.20	88.40
Phase Control Specific Cost	$/kW	c_{PC}	3.33	3.70	7.40
Solar Flux Constant	k_W	F	*	1353×10^3	*

TABLE C.2 LAUNCH FACILITY GROUND STATION, AND SPACE STATION O&M INPUT VALUES

INPUT ELEMENT	UNITS	VARIABLE NAME	RANGE OF VALUES		
			MINIMUM	MOST LIKELY	MAXIMUM
Number of O&M Resupply Flights Per Year	Number	$N_{O\&M\ FLTS}$	1	1	1
Cost Per HLLV Flight	$	c_{HLLV}	8×10^6	9×10^6	20×10^6
Amortisation Factor for the HLLV	Fraction	a_{HLLV}	.01	.01	.01
Unit Cost of HLLV	$	$c_{H\ UNIT}$	350×10^6	400×10^6	600×10^6
Cost Per AIS Flight	$	$c_{AIS\ FLT}$	1×10^5	1×10^6	1×10^6
Unit Cost of AIS for O&M flights	$	C_{AIS2}	23×10^6	23×10^6	23×10^6
Amortisation Factor for the AIS	Fraction	a_{AIS}	0.20	0.20	0.20
Total Number of Launch Mission Control Personnel	Number	N_{LFP}	320	320	320
Cost Per Person - Launch Mission Control	$/yr	f_{LFP}	43,750	43,750	43,750
Percentage Rate of Ground Equipment Replacement	Fraction	$f_{GRD\ EQUIP}$	.01	.01	.01
Procurement Cost of Ground Station	$	$C_{GRD\ STAT}$	[Input From Unit Production Cost Model]		
Total Number of Ground Station O&M Personnel	Number	$N_{GST\ P}$	60	60	60
Cost Per Person - Ground Station O&M	$/yr	$c_{GST\ P}$	60×10^3	60×10^3	60×10^3
Crew Rotation Rate	#/Year	f_{CROT}	4	4	4
Cost Per Shuttle Flight	$	$c_{SHUTTLE}$	11×10^6	12×10^6	20×10^6
Amortisation Factor for Shuttle	Fraction	$a_{SHUTTLE}$	0.01	0.01	0.01
Unit Cost of Shuttle	$	$c_{S\ UNIT}$	190×10^6	190×10^6	190×10^6
Cost Per Tug Flight	$	$c_{TUG\ OPS}$	1×10^6	1×10^6	1×10^6
Unit Cost of Tug	$	c_{TUG}	12×10^6	15×10^6	25×10^6
Amortisation Factor for Tug	Fraction	a_{TUG}	0.05	0.05	0.05
Cost of Crew Module Refurbishment	$	$c_{CREW\ REF}$	1×10^6	1×10^6	1×10^5
Unit Cost of Crew Module	$	C_{CREW}	18×10^6	23×10^6	40×10^6
Amortisation Factor of Crew Module	Fraction	a_{CREW}	0.01	0.01	0.01
Amortisation Factor of O&M Space Station	Fraction	$a_{S/S\ O\&M}$	0.10	0.10	0.10
Mass of GEO Space Station	kg	$M_{GEO\ S/S}$	76×10^3	76×10^3	75×10^3
Specific Cost of Transportation to GEO	$/kg	$c_{GEO\ TRANSP}$	106	106	106
Amortisation Factor for Manipulators	Fraction	$a_{S/S\ EQUIP}$	0.10	0.10	0.10
Total Number of O&M Manipulators	Number	$N_{O\&M\ MANIP}$	50	50	50
Mass of O&M Manipulator	kg	m_{MANIP}	182	182	182
Unit Cost of O&M Manipulator	$	$c_{O\&M\ MANIP}$	8×10^6	9×10^6	8×10^6
Specific Cost of Mission Control Facility	$/kW	$f_{S/S\ MC}$	4	4	4
Power Output at Rectenna Busbar (B.O.L)	kW	P	*	[illegible]	*

Table C.3 Satellite O&M Input Values

MAINTENANCE ELEMENT	FAILURE RATE, λ (1/MTBF, yr^{-1})	LRU * MASS (kg)	LRU PRO-CUREMENT COST ($/kg)	GEO TRANSP SPECIFIC COST ($/kg)	ASSEMBLY SPECIFIC COST ($/kg)
Solar Blanket	2.6×10^{-4}	97,900	190	106	132
Solar Concentrator	$<2.6 \times 10^{-4}$	7,687	55	106	132
Nonconducting Structure	-	-	-	-	-
Busses	10^{-9}	26,000	81	106	191
Switches	10^{-7}	97,484	190	106	132
Mast	3×10^{-2}	85,000	81	106	191
Microwave Tube	1.14×10^{-6}	3,017	236	106	132
Power Distribution	3×10^{-2}	3,017	236	106	132
Command Electronics	[0.1%/Year]	467	43,788	106	132
Antenna (Excluding Tubes)	3×10^{-2}	3,107	236	106	132
Antenna Structure	-	-	-	-	-
Contour Control	1.25×10^{-6}	22	11	106	132
Rotary Joint Slip Ring:					
- Brush	10^{-1}	10	96	106	132
- Slip Ring	10^{-1}	63	106	106	132
Rotary Joint Drive:					
- Motor/Gears	10^{-1}	1,367	98	106	132
- Limb	-	1,086	-	-	-
Control System:					
- Actuators	3.8×10^{-3}	203	7,500	106	132
- Propellant (Annual Consumption)	-	24,000	0.33	106	-

* LRU = Lowest Replaceable Unit

APPENDIX D

ESTABLISHING UNCERTAINTY PROFILES

The purpose of this Appendix is to describe a methodology for establishing uncertainty profiles. The methodology is illustrated in Figure D.1.

The first step is to establish the range of uncertainty.* The range is based upon knowledgeable persons assessing what can go right and what can go wrong. The range is then divided into five equal intervals (it has been found that it is difficult to "think" in terms of more than five or six intervals). The second step is to perform a relative ranking of the likelihood of the variable falling into each of the intervals. Once this has been accomplished, the general shape (skewed left, skewed right, central, etc.) of the uncertainty profile has been established. The third step is to establish relative values of the chance of falling into each of the intervals. For example, in the illustration, the chance of falling into the first interval is estimated to be half as likely as falling into the second interval. This is repeated for each interval relative to the previously considered interval. The last step is to solve the illustrated equation for the quantitative values by substituting the data from the previous step.

It can be helpful to have a few individuals independently perform the above procedure. Then they can compare their results and make changes accordingly.

*The proper interpretation of the range is that there is zero probability that the variable can lie outside the range. Hence, it can be inferred that there is zero probability that the minimum or maximum values will ever occur or be exceeded.

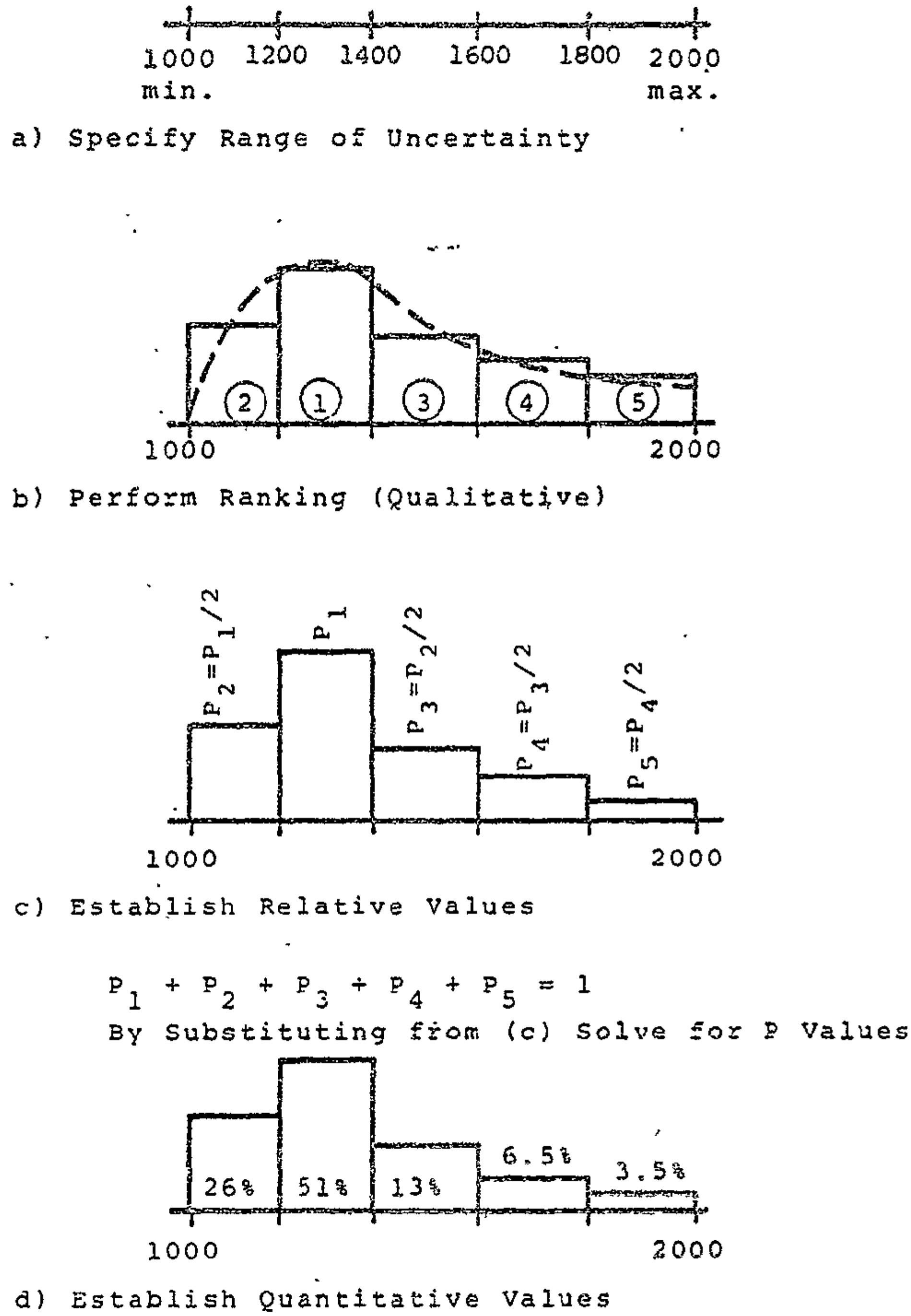

Figure D.1 Methodology for Establishing Shape of Cost Uncertainty Profile (pdf)

APPENDIX E

STATES-OF-KNOWLEDGE AT DECISION POINTS

The states-of-knowledge at the decision points of each alternative program plan have been subjectively assessed and are shown here in Tables E.1, E.2 and E.3. The numbers shown represent the percent reduction in uncertainty (that is, the range) in each variable over the state-of-knowledge today (that is, January 1, 1977). These improvements in the states-of-knowledge derive from work that is scheduled during each branch of the respective decision trees. The variables for which a dash is indicated have been treated as deterministic in the analysis conducted to date. It has also been assumed in this analysis that the state-of-knowledge relative to operation and maintenance costs does not change from the present state-of-knowledge until the IOD of the first unit at which time all uncertainty disappears.

TABLE E.1. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM I

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE-OF-KNOWLEDGE OVER TODAY, %	
			D.P. A	D.P. B
Power Output at the Busbar	kW	P	--	--
Packing Factor of the Solar Blanket	Fraction	P_F	50	100
Effective Concentration Ratio	Fraction	η_{eff}	--	--
Solar Cell Efficiency	Fraction	η_{SC}	75	100
Solar Array Power Distribution Efficiency	Fraction	η_{SAPD}	75	100
Antenna Interface Efficiency	Fraction	$\eta_{ANT-INT}$	75	100
Antenna Power Distribution Efficiency	Fraction	$\eta_{ANT\ PD}$	75	100
DC-RF Converter Efficiency	Fraction	η_{DC-RF}	75	100
Phase Control Efficiency	Fraction	η_{PC}	75	100
Ionospheric Propagation Efficiency	Fraction	$\eta_{ION\ PROP}$	--	--
Atmospheric Propagation Efficiency	Fraction	$\eta_{ATM\ PROP}$	0	100
Beam Collection Efficiency	Fraction	η_{BC}	0	100
RF-DC Converter Efficiency	Fraction	η_{RF-DC}	0	100
Rectenna Power Distribution Efficiency	Fraction	$\eta_{RECT\ PD}$	75	100
Specific Mass of the Solar Blanket	kg/km^2	m_{SAB}	30	100
Efficiency of the Solar Concentrator	Fraction	η_{CONC}	30	100
Specific Mass of the Solar Concentrator	kg/km^2	m_{SAC}	0	100
Ratio, Non-Cond. Struct. Mass to Array Area	kg/km^2	m_{STCN}	20	100
Specific Mass of Central Mast	kg/km	m_{STCM}	20	100
Aspect Ratio of Solar Array	Fraction	r_A	--	--
Antenna Clearance	Fraction	r_L	--	--
Diameter of Transmitting Antenna	km	D_{ANT}	--	--
Specific Mass of Antenna Structure	kg/kW	m_{ANTS}	30	100
Specific Mass of DC-RF Converters	kg/kW	m_{DC-RF}	30	100
Specific Mass of Waveguides	kg/kW	m_{WG}	30	100
Specific Mass of Antenna Interface	kg/kW	$m_{ANT-INT}$	30	100
Specific Mass of Phase Control Electronics	kg/kW	m_{PCE}	30	100
Miscellaneous Mass	kg	M_{MISC}	30	100
Percentage of Satellite Assembled by Man	Fraction	β	0	103
Rate of Manned Assembly	kg/Day	R_{MANNED}	25	70
Rate of Remote Assembly	kg/Day	R_{REMOTE}	25	70
Total Construction Time	Days	T_{CONST}	--	--
Shift Factor	#/Day	f_S	--	--
Personnel Productivity Factor	Fraction	f_M	25	30
Teleoperator Availability Factor	Fraction	$f_{TELE\ AV}$	0	100
Teleoperator Work Factor	Fraction	f_T	0	100
Fabrication Rate of Modulas	kg/Day	R_{FAB}	0	100
Fabrication Module Availability Factor	Fraction	f_{FAB}	0	100
Percentage of Personnel Using Manipulators	Fraction	γ	--	--
Manipulator Availability Factor	Fraction	f_{MANIP}	0	100

TABLE E.1. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM I (CONTINUED)

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE-OF-KNOWLEDGE OVER TODAY, %	
			D.P. A	D.P. B
Number of Personnel Per LEO Space Station	Number	$f_{LEO\ S/S}$	--	--
Fabrication Module Unit Mass	kg	m_{FAB}	25	100
Teleoperator Unit Mass	kg	m_{TELE}	25	100
LEO Support Tug Unit Mass	kg	m_{TUG}	0	100
EVA Equipment Unit Mass	kg	m_{EVA}	90	100
EVA-Unit Use Factor	Fraction	f_{EVA}	0	100
Manipulator Unit Mass	kg	m_{MANIP}	25	100
LEO Space Station Unit Mass	kg	$m_{LEO\ S/S}$	25	100
Assembly Equip. Propellant Estimation Factor	Fraction	$f_{AE\ PROP}$	0	100
Space Station Resupply Estimation Factor	Fraction	$f_{S/S\ RES}$	--	--
Crew Module Unit Mass	kg	m_{CREW}	25	100
GEO Space Station Unit Mass	kg	$m_{GEO\ S/S}$	25	100
LCT Total LEO-GEO Mission ΔV	m/sec	ΔV_{LCT}	--	--
LCT Rocket Exhaust Jet Velocity	m/sec	$V_{J_{LCT}}$	--	--
LCT Propellant Mass-Fraction	Fraction	λ_{LCT}	--	--
Crew Rotation Period	Days	T_{ROT}	0	100
AIS Total LEO-GEO Mission ΔV	m/sec	ΔV_{AIS}	--	--
AIS Exhaust Jet Velocity	m/sec	$V_{J_{AIS}}$	--	--
AIS Propellant Mass-Fraction	Fraction	λ_{AIS}	--	--
Liquid Hydrogen Storage Tank Unit Mass	kg	m_{HT}	--	--
Liquid Hydrogen Storage Tank Capacity	kg	C_{HT}	--	--
Liquid Oxygen Storage Tank Unit Mass	kg	m_{LOXT}	--	--
Liquid Oxygen Storage Tank Capacity	kg	C_{LOXT}	--	--
Ion Propellant Storage Tank Mass	kg	m_{IT}	--	--
Ion Propellant Storage Tank Capacity	kg	C_{IT}	--	--
HLLV Payload to LEO	kg	$M_{P/L}$	--	--
HLLV Average Load Factor	Fraction	f_{LOAD}	0	100
HLLV Turnaround Time	Days	$T_{H\ TURN}$	--	--
Number of Personnel Per Shuttle Flight	Number	$f_{SHUTTLE}$	0	100
Shuttle Turnaround Time	Days	$T_{S\ TURN}$	--	--
Launch Cost Per HLLV Flight	$	c_{HLLV}	0	100
HLLV Unit Cost	$	$c_{H\ UNIT}$	0	100
Launch Cost Per Shuttle Flight	$	$c_{SHUTTLE}$	100	100
Shuttle Unit Cost	$	$c_{S\ UNIT}$	100	100
Fabrication Module Unit Cost	$	c_{FAB}	0	100
Fabrication Module Amortisation Factor	Fraction	a_{FAB}	--	--
Teleoperator Unit Cost	$	c_{TELE}	0	100
Teleoperator Amortisation Factor	Fraction	a_{TELE}	--	--
Assembly Equipment Propellant Specific Cost	$	$c_{AE\ PROP}$	--	--
LEO Support Tug Unit Cost	$	c_{TUG}	0	100
LEO Support Tug Amortisation Factor	Fraction	a_{TUG}	--	--

TABLE E.1. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM I (CONTINUED)

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE-OF-KNOWLEDGE OVER TODAY, %	
			D.P. A	D.P. B
Number of Shifts for Ground Operators	Number	f_{GRO}	--	--
EVA Equipment Unit Cost	$	c_{EVA}	0	100
Manipulator Unit Cost	$	c_{MANIP}	0	100
Manipulator Amortisation Factor	Fraction	a_{MANIP}	--	--
LEO Space Station Unit Cost	$	$c_{LEO\ S/S}$	0	100
LEO Space Station Amortisation Factor	Fraction	$a_{LEO\ S/S}$	--	--
GEO Space Station Unit Cost	$	$c_{GEO\ S/S}$	0	90
GEO Space Station Amortisation Factor	Fraction	$a_{GEO\ S/S}$	--	--
Space Station Resupply Specific Cost	$	$c_{S/S\ RES}$	0	100
LCT Unit Cost	$	c_{LCT}	0	90
LCT Amortisation Factor	Fraction	a_{LCT}	--	--
AIS Unit Cost	$	c_{AIS}	0	90
AIS Amortisation Factor	Fraction	a_{AIS}	--	--
Cryo Tug Propellant Specific Cost	$/kg	$c_{LCT\ PROP}$	--	--
Ion Propellant Specific Cost	$/kg	$c_{AIS\ PROP}$	--	--
Crew Module Amortisation Factor	Fraction	a_{CREW}	--	--
Liquid Hydrogen Storage Tank Unit Cost	$	c_{LHT}	0	100
Liquid Hydrogen Storage Tank Unit Cost	$	c_{LHT}	0	100
Liquid Oxygen Storage Tank Unit Cost	$	c_{LOXT}	0	100
Ion Propellant Storage Tank Unit Cost	$	c_{IT}	0	100
Liquid Hydrogen Tank Amortisation Factor	Fraction	a_{LHT}	0	100
Liquid Oxygen Tank Amortisation Factor	Fraction	a_{LOXT}	0	100
Ion Propellant Tank Amortisation Factor	Fraction	a_{IT}	0	100
Antenna Power Distribution Specific Cost	$/kW	c_{PD}	25	70
Phase Control Specific Cost	$/kW	c_{PC}	25	70
Waveguide Specific Cost	$/kW	c_{WG}	25	70
DC-RF Converter Specific Cost	$/kW	c_{DC-RF}	25	70
Antenna Structure Specific Cost	$/kg	c_{AS}	25	90
Solar Array Blanket Specific Cost	$/km^2	c_{SAB}	25	90
Solar Array Concentrator Specific Cost	$/km^2	c_{SAC}	25	90
Conducting Structure Specific Cost	$/kg	c_{STC}	0	90
Non-Conducting Structure Specific Cost	$/kg	c_{SNC}	0	90
Central Mast Specific Cost	$/kg	c_{MAST}	0	90
Miscellaneous Equipment Specific Cost	$/kg	c_{MISC}	25	90
Rectenna Site Specific Cost	$/kW	c_{RE}	25	100
Rectenna Structure Specific Cost	$/kW	c_{STRUCT}	25	100
RF-DC Convertor Specific Cost	$/kW	c_{RF-DC}	25	100
Power Interface Specific Cost	$/kW	c_{PI}	25	100
Phase Control Specific Cost	$/kW	c_{PC}	25	100
Solar Flux Constant	[illegible]	F	--	--

TABLE E.2. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM II

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE - OF - KNOWLEDGE OVER TODAY, %		
			D.P.A	D.P.B	D.P.C
Power Output at the Busbar	kW	P	-	-	-
Packing Factor of the Solar Blanket	Fraction	P_F	20	90	100
Effective Concentration Ratio	Fraction	η_{eff}	-	-	-
Solar Cell Efficiency	Fraction	η_{SC}	40	90	100
Solar Array Power Distribution Efficiency	Fraction	η_{SAPD}	40	100	100
Antenna Interface Efficiency	Fraction	$\eta_{ANT-INT}$	20	100	100
Antenna Power Distribution Efficiency	Fraction	$\eta_{ANT\ PD}$	40	100	100
DC-RF Converter Efficiency	Fraction	η_{DC-RF}	40	100	100
Phase Control Efficiency	Fraction	η_{PC}	50	100	100
Ionospheric Propagation Efficiency	Fraction	$\eta_{ION\ PROP}$	-	-	-
Atmospheric Propagation Efficiency	Fraction	$\eta_{ATM\ PROP}$	0	100	100
Beam Collection Efficiency	Fraction	η_{BC}	0	100	100
RF-DC Converter Efficiency	Fraction	η_{RF-DC}	0	100	100
Rectenna Power Distribution Efficiency	Fraction	$\eta_{RECT\ PD}$	50	100	100
Specific Mass of the Solar Blanket	kg/km^2	m_{SAB}	20	90	100
Efficiency of the Solar Concentrator	Fraction	η_{CONC}	20	90	100
Specific Mass of the Solar Concentrator	kg/km^2	m_{SAC}	0	90	100
Ratio: Conducting Struct. Mass to Array Area	kg/km^2	m_{STC}	20	90	100
Ratio: Non-Cond. Struct. Mass to Array Area	kg/km^2	m_{STNC}	20	90	100
Specific Mass of Central Mass	kg/km^2	m_{STCM}	20	90	100
Aspect Ratio of Solar Array	Fraction	r_A	-	-	-
Antenna Clearance	Fraction	r_L	-	-	-
Diameter of Transmitting Antenna	km	D_{ANT}	-	-	-
Specific Mass of Antenna Structure	kg/kW	m_{ANTS}	30	30	100
Specific Mass of DC-RF Converters	kg/kW	m_{DC-RF}	30	90	100
Specific Mass of Waveguides	kg/kW	m_{WG}	30	90	100
Specific Mass of Antenna Interface	kg/kW	$m_{ANT-INT}$	30	90	100
Specific Mass of Phase Control Electronics	kg/kW	m_{PCE}	30	90	100
Miscellaneous Mass	kg	M_{MISC}	30	90	100
Percentage of Satellite Assembled by Man	Fraction	β	0	80	100
Rate of Manned Assembly	kg/Day	R_{MANNED}	0	80	90
Rate of Remote Assembly	kg/Day	R_{REMOTE}	0	30	90
Total Construction Time	Days	T_{CONST}	-	-	-
Shift Factor	#/Day	f_S	-	-	-
Personnel Productivity Factor	Fraction	f_H	0	90	90
Teleoperator Availability Factor	Fraction	$f_{TELE\ AV}$	0	100	100
Teleoperator Work Factor	Fraction	f_T	0	100	100
Fabrication Rate of Modules	kg/Day	R_{FAB}	0	90	100
Fabrication Module Availability Factor	Fraction	f_{FAB}	0	100	100
Percentage of Personnel Using Manipulators	Fraction	γ	-	-	-
Manipulator Availability Factor	Fraction	f_{MANIP}	0	100	100

TABLE E.2. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM II (Cont'd)

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE-OF KNOWLEDGE OVER TODAY, %		
			D.P.A	D.P.B	D.P.C
Number of Personnel Per LEO Space Station	Number	$f_{LEO\ S/S}$	-	-	-
Fabrication Module Unit Mass	kg	m_{FAB}	0	100	100
Teleoperator Unit Mass	kg	m_{TELE}	0	100	100
LEO Support Tug Unit Mass	kg	m_{TUG}	0	100	100
EVA Equipment Unit Mass	kg	m_{EVA}	0	100	100
EVA Unit Use Factor	Fraction	f_{EVA}	0	100	100
Manipulator Unit Mass	kg	m_{MANIP}	0	90	100
LEO Space Station Unit Mass	kg	$m_{LEO\ S/S}$	10	100	100
Assembly Equip. Propellant Estimation Factor	Fraction	$f_{AE\ PROP}$	0	100	100
Space Station Resupply Estimation Factor	Fraction	$f_{S/S\ RES}$	-	-	-
Crew Module Unit Mass	kg	m_{CREW}	0	100	100
GEO Space Station Unit Mass	kg	$m_{GEO\ S/S}$	0	100	100
LCT Total LEO-GEO Mission ΔV	m/sec	ΔV_{LCT}	-	-	-
LCT Rocket Exhaust Jet Velocity	m/sec	$V_{J_{LCT}}$	-	-	-
LCT Propellant Mass-Fraction	Fraction	λ_{LCT}	-	-	-
Crew Rotation Period	Days	T_{ROT}	0	100	100
AIS Total LEO-GEO Mission ΔV	m/sec	ΔV_{AIS}	-	-	-
AIS Exhaust Jet Velocity	m/sec	$V_{J_{AIS}}$	-	-	-
AIS Propellant Mass-Fraction	Fraction	λ_{AIS}	-	-	-
Liquid Hydrogen Storage Tank Unit Mass	kg	m_{HT}	-	-	-
Liquid Hydrogen Storage Tank Capacity	kg	C_{HT}	-	-	-
Liquid Oxygen Storage Tank Unit Mass	kg	m_{LOXT}	-	-	-
Liquid Oxygen Storage Tank Capacity	kg	C_{LOXT}	-	-	-
Ion Propellant Storage Tank Mass	kg	m_{IT}	-	-	-
Ion Propellant Storage Tank Capacity	kg	C_{IT}	-	-	-
HLLV Payload to LEO	kg	$M_{P/L}$	-	-	-
HLLV Average Load Factor	Fraction	f_{LOAD}	0	90	100
HLLV Turnaround Time	Days	$T_{H\ TURN}$	-	-	-
Number of Personnel Per Shuttle Flight	Number	$f_{SHUTTLE}$	0	100	100
Shuttle Turnaround Time	Days	$T_{S\ TURN}$	-	-	-
Launch Cost Per HLLV Flight	$	C_{HLLV}	0	50	100
HLLV Unit Cost	$	$C_{H\ UNIT}$	0	50	100
Launch Cost Per Shuttle Flight	$	$C_{SHUTTLE}$	90	100	100
Shuttle Unit Cost	$	$C_{S\ UNIT}$	90	100	100
Fabrication Module Unit Cost	$	C_{FAB}	0	90	100
Fabrication Module Amortization Factor	Fraction	A_{FAB}	-	-	-
Teleoperator Unit Cost	$	C_{TELE}	0	90	100
Teleoperator Amortization Factor	Fraction	A_{TELE}	-	-	-
Assembly Equipment Propellant Specific Cost	$	$C_{AE\ PROP}$	-	-	-
LEO Support Tug Unit Cost	$	C_{TUG}	0	100	100
LEO Support Tug Amortization Factor	Fraction	A_{TUG}	-	-	-

Table E.2. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM II (Cont'd)

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE - OF KNOWLEDGE OVER TODAY, %		
			D.P.A	D.P.B	D.P.C
Number of Shifts for Ground Operators	Number	f_{GRD}	-	-	-
EVA Equipment Unit Cost	$	c_{EVA}	0	100	100
Manipulator Unit Cost	$	c_{MANIP}	0	90	100
Manipulator Amortization Factor	Fraction	a_{MANIP}	-	-	-
LEO Space Station Unit Cost	$	$c_{LEO\ S/S}$	0	100	100
LEO Space Station Amortization Factor	Fraction	$a_{LEO\ S/S}$	-	-	-
GEO Space Station Unit Cost	$	$c_{GEO\ S/S}$	0	100	100
GEO Space Station Amortization Factor	Fraction	$a_{GEO\ S/S}$	-	-	-
Space Station Resupply Specific Cost	$	$c_{S/S\ RES}$	0	100	100
LCT Unit Cost	$	c_{LCT}	0	100	100
LCT Amortization Factor	Fraction	a_{LCT}	-	-	-
AIS Unit Cost	$	c_{AIS}	0	0	90
AIS Amortization Factor	Fraction	a_{AIS}	-	-	-
Cryo Tug Propellant Specific Cost	$/kg	$c_{LCT\ PROP}$	-	-	-
Ion Propellant Specific Cost	$/kg	$c_{AIS\ PROP}$	-	-	-
Crew Module Unit Cost	$	c_{CREW}	0	100	100
Crew Module Amortization Factor	Fraction	a_{CREW}	-	-	-
Liquid Hydrogen Storage Tank Unit Cost	$	c_{LHT}	0	100	100
Liquid Oxygen Storage Tank Unit Cost	$	c_{LOXT}	0	100	100
Ion Propellant Storage Tank Unit Cost	$	c_{IT}	0	0	100
Liquid Hydrogen Tank Amortization Factor	Fraction	a_{LHT}	0	100	100
Liquid Oxygen Tank Amortization Factor	Fraction	a_{LOXT}	0	100	100
Ion Propellant Tank Amortization Factor	Fraction	a_{IT}	0	0	100
Antenna Power Distribution Specific Cost	$/kW	c_{PD}	10	90	100
Phase Control Specific Cost	$/kW	c_{PC}	10	90	100
Waveguide Specific Cost	$/kW	c_{WG}	10	90	100
DC-RF Converter Specific Cost	$/kW	c_{DC-RF}	10	90	100
Antenna Structure Specific Cost	$/kW	c_{ST}	10	90	100
Solar Array Blanket Specific Cost	$/km^2	c_{SAB}	10	70	100
Solar Array Concentrator Specific Cost	$/km^2	c_{SAC}	10	90	100
Conducting Structure Specific Cost	$/kg	c_{STC}	0	90	100
Non-Conducting Structure Specific Cost	$/kg	c_{STNC}	0	90	100
Central Mast Specific Cost	$/kg	c_{STCM}	0	90	100
Miscellaneous Equipment Specific Cost	$/kg	c_{MISC}	10	90	100
Rectenna Site Specific Cost	$/kW	c_{RE}	10	100	100
Rectenna Structure Specific Cost	$/kW	c_{STRUCT}	10	100	100
RF-DC Convertor Specific Cost	$/kW	c_{RF-DC}	10	100	100
Power Interface Specific Cost	$/kW	c_{INTERF}	10	100	100
Phase Control Specific Cost	$/kW	c_{PC}	10	100	100
Solar Flux Constant	k_d	F	-	-	-

Table E.3. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM III

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE - OF - KNOWLEDGE OVER TODAY, %		
			D.P.B	D.P.C	A & O
Power Output at the Busbar	kW	P	-	-	
Packing Factor of the Solar Blanket	Fraction	P_F	75	90	
Effective Concentration Ratio	Fraction	η_{eff}	-	-	
Solar Cell Efficiency	Fraction	η_{SC}	60	90	
Solar Array Power Distribution Efficiency	Fraction	η_{SAPD}	60	100	
Antenna Interface Efficiency	Fraction	$\eta_{ANT-INT}$	50	100	
Antenna Power Distribution Efficiency	Fraction	$\eta_{ANT\ PD}$	50	100	
DC-RF Converter Efficiency	Fraction	η_{DC-RF}	50	100	
Phase Control Efficiency	Fraction	η_{PC}	75	100	
Ionospheric Propagation Efficiency	Fraction	$\eta_{ION\ PROP}$	-	-	
Atmospheric Propagation Efficiency	Fraction	$\eta_{ATM\ PROP}$	0	100	
Beam Collection Efficiency	Fraction	η_{BC}	0	100	
RF-DC Converter Efficiency	Fraction	η_{RF-DC}	0	100	
Rectenna Power Distribution Efficiency	Fraction	$\eta_{RECT\ PD}$	70	100	
Specific Mass of the Solar Blanket	kg/km^2	m_{SAB}	50	90	SAME AS PROGRAM II, D.P.A&C
Efficiency of the Solar Concentrator	Fraction	η_{CONC}	50	90	
Specific Mass of the Solar Concentrator	kg/km^2	m_{SAC}	50	90	
Ratio: Conducting Struct. Mass to Array Area	kg/km^2	m_{STR}	50	90	
Ratio: Non-Cond. Struct. Mass to Array Area	kg/km^2	m_{STNC}	50	90	
Specific Mass of Central Mast	kg/km	m_{STCM}	50	90	
Aspect Ratio of Solar Array	Fraction	r_A	-	-	
Antenna Clearance	Fraction	r_L	-	-	
Diameter of Transmitting Antenna	km	D_{ANT}	-	-	
Specific Mass of Antenna Structure	kg/kW	m_{ANTS}	60	90	
Specific Mass of DC-RF Converters	kg/kW	m_{DC-RF}	60	90	
Specific Mass of Waveguides	kg/kW	m_{WG}	60	90	
Specific Mass of Antenna Interface	kg/kW	$m_{ANT-INT}$	60	90	
Specific Mass of Phase Control Electronics	kg/kW	m_{PCE}	60	90	
Miscellaneous Mass	kg	m_{MISC}	50	90	
Percentage of Satellite Assembled by Man	Fraction	β	20	80	
Rate of Manned Assembly	kg/Day	R_{MANNED}	20	90	
Rate of Remote Assembly	kg/Day	R_{REMOTE}	20	90	
Total Construction Time	Days	T_{CONST}	-	-	
Shift Factor	#/Day	f_S	-	-	
Personnel Productivity Factor	Fraction	f_H	20	90	
Teleoperator Availability Factor	Fraction	$f_{TELE\ AV}$	20	100	
Teleoperator Work Factor	Fraction	f_T	20	100	
Fabrication Rate of Modules	kg/Day	R_{FAB}	20	90	
Fabrication Module Availability Factor	Fraction	f_{FAB}	20	100	
Percentage of Personnel Using Manipulators	Fraction	γ	-	-	
Manipulator Availability Factor	Fraction	f_{MANIP}	50	100	

Table E.3. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM III (Cont'd)

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE - OF KNOWLEDGE OVER TODAY, %		
			D.P.B	D.P.C	A & D
Number of Personnel Per LEO Space Station	Number	$f_{LEO\ S/S}$	-	-	
Fabrication Module Unit Mass	kg	m_{FAB}	50	100	
Teleoperator Unit Mass	kg	m_{TELE}	50	100	
LEO Support Tug Unit Mass	kg	m_{TUG}	50	100	
EVA Equipment Unit Mass	kg	m_{EVA}	100	100	
EVA Unit Use Factor	Fraction	f_{EVA}	100	100	
Manipulator Unit Mass	kg	m_{MANIP}	50	90	
LEO Space Station Unit Mass	kg	$m_{LEO\ S/S}$	100	100	
Assembly Equip. Propellant Estimation Factor	Fraction	$f_{AE\ PROP}$	50	100	
Space Station Resupply Estimation Factor	Fraction	$f_{S/S\ RES}$	-	-	
Crew Module Unit Mass	kg	m_{CREW}	100	100	
GEO Space Station Unit Mass	kg	$m_{GEO\ S/S}$	75	100	
LCT Total LEO-GEO Mission ΔV	m/sec	ΔV_{LCT}	-	-	
LCT Rocket Exhaust Jet Velocity	m/sec	$V_{J_{LCT}}$	-	-	
LCT Propellant Mass-Fraction	Fraction	λ_{LCT}	-	-	SAME AS PROGRAM II, D.P.A&C
Crew Rotation Period	Days	T_{ROT}	0	100	
AIS Total LEO-GEO Mission ΔV	m/sec	ΔV_{AIS}	-	-	
AIS Exhaust Jet Velocity	m/sec	$V_{J_{AIS}}$	-	-	
AIS Propellant Mass-Fraction	Fraction	λ_{AIS}	-	-	
Liquid Hydrogen Storage Tank Unit Mass	kg	m_{HT}	-	-	
Liquid Hydrogen Storage Tank Capacity	kg	C_{HT}	-	-	
Liquid Oxygen Storage Tank Unit Mass	kg	m_{LOXT}	-	-	
Liquid Oxygen Storage Tank Capacity	kg	C_{LOXT}	-	-	
Ion Propellant Storage Tank Mass	kg	m_{IT}	-	-	
Ion Propellant Storage Tank Capacity	kg	C_{IT}	-	-	
HLLV Payload to LEO	kg	$M_{P/L}$	-	-	
HLLV Average Load Factor	Fraction	f_{LOAD}	70	90	
HLLV Turnaround Time	Days	$T_{H\ TURN}$	-	-	
Number of Personnel Per Shuttle Flight	Number	$f_{SHUTTLE}$	100	100	
Shuttle Turnaround Time	Days	$T_{S\ TURN}$	-	-	
Launch Cost Per HLLV Flight	$	C_{HLLV}	50	100	
HLLV Unit Cost	$	$C_{H\ UNIT}$	50	100	
Launch Cost Per Shuttle Flight	$	$C_{SHUTTLE}$	100	100	
Shuttle Unit Cost	$	$C_{S\ UNIT}$	100	100	
Fabrication Module Unit Cost	$	C_{FAB}	100	90	
Fabrication Module Amortisation Factor	Fraction	a_{FAB}	-	-	
Teleoperator Unit Cost	$	C_{TELE}	90	90	
Teleoperator Amortisation Factor	Fraction	a_{TELE}	-	-	
Assembly Equipment Propellant Specific Cost	$	$C_{AE\ PROP}$	-	-	
LEO Support Tug Unit Cost	$	C_{TUG}	100	100	
LEO Support Tug Amortisation Factor	Fraction	a_{TUG}	-	-	

Table E.3. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM III (Cont'd)

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE - OF KNOWLEDGE OVER TODAY, %		
			D.P.B	D.P.C	A & D
Number of Shifts for Ground Operators	Number	f_{GRD}	-	-	
EVA Equipment Unit Cost	$	c_{EVA}	100	100	
Manipulator Unit Cost	$	c_{MANIP}	90	90	
Manipulator Amortisation Factor	Fraction	a_{MANIP}	-	-	
LEO Space Station Unit Cost	$	$c_{LEO\ S/S}$	100	100	
LEO Space Station Amortisation Factor	Fraction	$a_{LEO\ S/S}$	-	-	
GEO Space Station Unit Cost	$	$c_{GEO\ S/S}$	75	100	
GEO Space Station Amortisation Factor	Fraction	$a_{GEO\ S/S}$	-	-	
Space Station Resupply Specific Cost	$	$c_{S/S\ RES}$	100	100	
LCT Unit Cost	$	c_{LCT}	75	100	
LCT Amortisation Factor	Fraction	a_{LCT}	-	-	
AIS Unit Cost	$	c_{AIS}	0	0	
AIS Amortisation Factor	Fraction	a_{AIS}	-	-	SAME AS PROGRAM II, D.P. A&C
Cryo Tug Propellant Specific Cost	$/kg	$c_{LCT\ PROP}$	-	-	
Ion Propellant Specific Cost	$/kg	$c_{AIS\ PROP}$	-	-	
Crew Module Unit Cost	$	c_{CREW}	100	100	
Crew Module Amortisation Factor	Fraction	a_{CREW}	-	-	
Liquid Hydrogen Storage Tank Unit Cost	$	c_{LHT}	0	100	
Liquid Oxygen Storage Tank Unit Cost	$	c_{LOXT}	0	100	
Ion Propellant Storage Tank Unit Cost	$	c_{IT}	0	0	
Liquid Hydrogen Tank Amortisation Factor	Fraction	a_{LHT}	0	100	
Liquid Oxygen Tank Amortisation Factor	Fraction	a_{LOXT}	0	100	
Ion Propellant Tank Amortisation Factor	Fraction	a_{IT}	0	0	
Antenna Power Distribution Specific Cost	$/kW	c_{PD}	50	30	
Phase Control Specific Cost	$/kW	c_{PC}	50	90	
Waveguide Specific Cost	$/kW	c_{WG}	50	90	
DC-RF Converter Specific Cost	$/kW	c_{DC-RF}	50	90	
Antenna Structure Specific Cost	$/kW	c_{ST}	50	90	
Solar Array Blanket Specific Cost	$/km^2$	c_{SAB}	50	70	
Solar Array Concentrator Specific Cost	$/km^2$	c_{SAC}	50	90	
Conducting Structure Specific Cost	$/kg	c_{STC}	50	90	
Non-Conducting Structure Specific Cost	$/kg	c_{STNC}	30	90	
Central Mast Specific Cost	$/kg	c_{STCM}	50	90	
Miscellaneous Equipment Specific Cost	$/kg	c_{MISC}	50	30	
Rectenna Site Specific Cost	$/kW	c_{RE}	30	100	
Rectenna Structure Specific Cost	$/kW	c_{STRUCT}	50	100	
RF-DC Convertor Specific Cost	$/kW	c_{RF-DC}	50	100	
Power Interface Specific Cost	$/kW	c_{INTERF}	50	100	
Phase Control Specific Cost	$/kW	c_{PC}	50	100	
Solar Flux Constant	W/m^2	F	-	-	

APPENDIX F

COMPUTATION OF CONDITIONAL PROBABILITIES

This appendix details the computational procedure for determining the probabilities necessary for analyzing the decision trees presented in Section 4. It is to be noted that the probabilities are conditioned upon getting to the decision node in question. Figure F.1 shows the effects of the decision rules acting on the probability density function of the current state-of-knowledge for Program I. The population or density function after Decision Point A is obtained by taking the product of the initial probability density function with one minus the cumulative distribution representing decision rule A. Thus:

$$f_A \text{ (cost)} = f_0 \text{ (cost)} \; [1-C(M_A, \sigma_A)]$$

where $C(M_A, \sigma_A)$ is the cumulative distribution function for a Gaussian distribution of mean M_A and standard deviation σ_A. Likewise:

$$f_B \text{ (cost)} = f_A \text{ (cost)} \; [1-C(M_B, \sigma_B)]$$

and

$$f_C \text{ (cost)} = f_B \text{ (cost)} \; [1-C(M_C, \sigma_C)]$$

Then, noting that the area under curve f_0 is unity, P_A is the area under curve f_A, and:

$$P_B = \frac{\text{Area under curve } f_B}{P_A}$$

and

$$P_C = \frac{\text{Area under curve } f_C}{P_B}$$

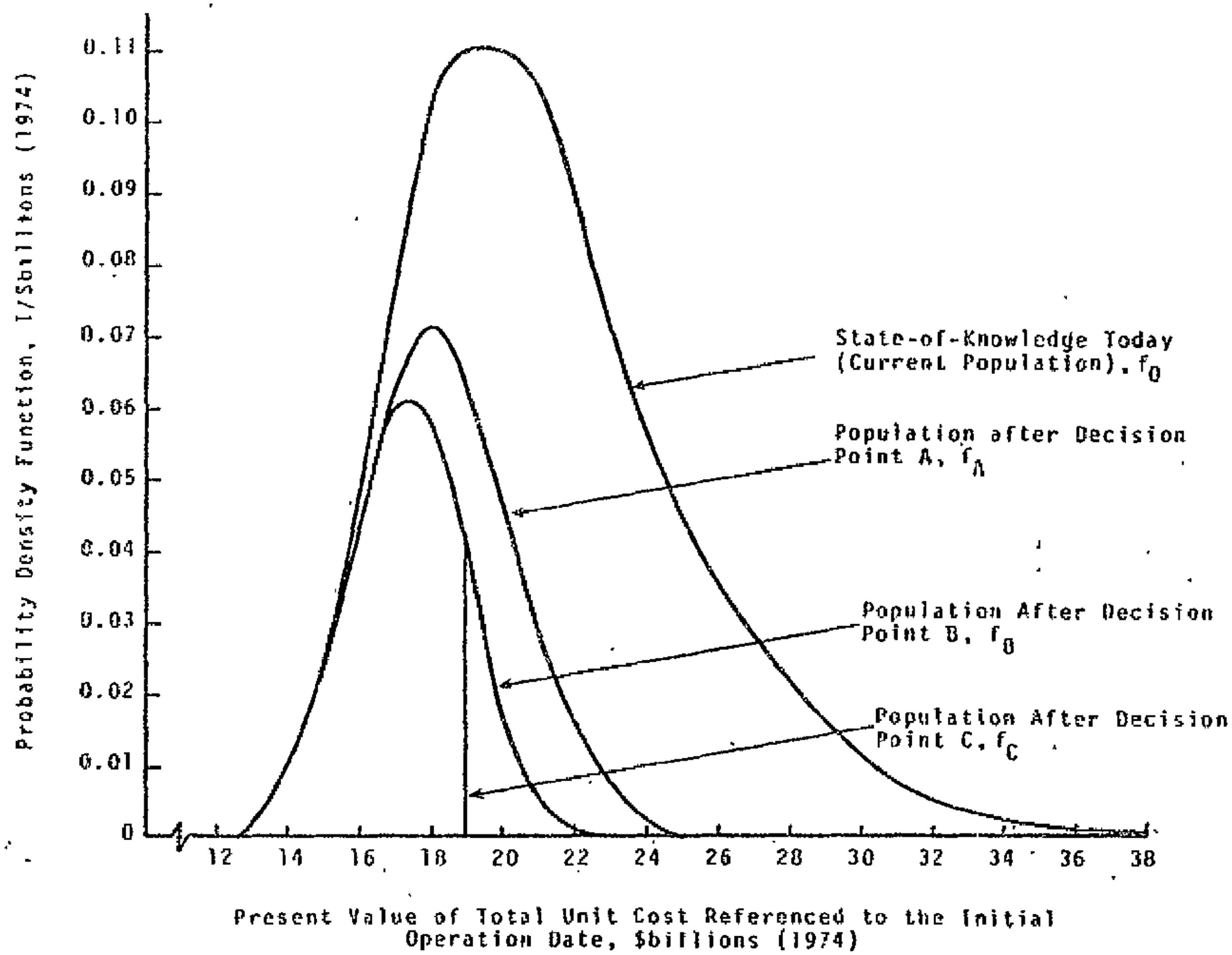

Figure F.1 Analysis of Conditional Branching Probabilities

GLOSSARY OF TECHNICAL UNITS AND ABBREVIATIONS

cm	centimeter (10^{-2} meters)
g	gram (10^{-3} kilograms)
GHz	gigahertz (10^{9} cycles per second)
GW	gigawatt (10^{9} watts)
η	efficiency (decimal fraction)
kg	kilogram (2.2046 pounds mass)
km	kilometer (10^{3} meters)
kV	kilovolt (10^{3} volts)
kW	kilowatt (10^{3} watts)
kWh	kilowatt-hours
m	meter (3.2808 feet)
micron, (μm)	millionth (10^{-6}) of a meter
MW	megawatt (10^{6} watts)
mW	milliwatt (10^{-3} watt)
RFI	radio frequency interference
solar flux	1353 megawatts per square kilometer
σ	standard deviation

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