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ASSESSMENT OF ECONOMIC FACTORS AFFECTING THE SATELLITE POWER SYSTEM

VOLUME 1
SYSTEM COST FACTORS

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ASSESSMENT OF ECONOMIC FACTORS AFFECTING THE SATELLITE POWER SYSTEM

VOLUME I

SYSTEM COST FACTORS

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center

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ABSTRACT

This study, conducted over the period April 1978 through November 1978, addresses four issues relevant to SPS costing and selection of preferred SPS satellite configurations:

1. Consideration of economic factors in the SPS system studies that relate to selection of SPS satellite configuration

2. Analysis of the proper rate of interest for use in SPS system definition studies

3. Study of the impacts of differential inflation on SPS system definition costing procedures

4. Utility interface and SPS baseline design.

The first three issues are discussed in this volume. The fourth issue is discussed in Volume 2 of this report.

A cost-risk comparison of the Rockwell International and Boeing Company SPS satellite configurations showed a significant difference in the levelized cost of power from them. It is concluded, from the assessment reported herein, however, that this difference is the result more of differences in the procedures for assessing costs rather than in the satellite technologies required or of any advantages of one satellite configuration over the other. On the other hand, however, a real advantage of the Boeing SPS development program does appear over the Rockwell SPS development program. This advantage is primarily due to the fact that the Boeing SPS development program contains one additional decision point prior to the commitment of the major fraction of the development funds.

Analysis of the proper rate of interest for use in SPS system definition studies leads to the conclusion that the appropriate rate of discount is 4 percent. This rate of discount is justified by examining both the real cost of capital to the federal government, that is, real interest rates on U.S. treasury bonds, and the opportunity costs of capital measured in terms of real pretax return on assets obtained by 1600 major U.S. corporations. This rate of discount is also in keeping with federal policy on energy conservation.

A procedure is presented for SPS cost estimating taking into account differential inflation that is likely to occur between now and the time that SPS would be implemented. The major item of differential inflation to be expected over this period of time is the real cost of labor. This cost is likely to double between today and the period of SPS construction.

NOTE OF TRANSMITTAL

The study reported herein was conducted for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration, under Contract No. NAS8-33002. The final report is provided in two volumes. This volume is prepared and submitted by ECON, Inc. The second volume has been prepared for ECON by Arthur D. Little, Inc. ECON study manager for this effort has been Dr. George A. Hazelrigg, Jr. Other individuals contributing to this study include Messrs. Gregg Fawkes and Keith Lietzke. The MSFC COR and Co-COR for this study were Messrs. Milton A. Page and Joseph W. Hamaker respectively.

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1. INTRODUCTION

During the period January 1975 through March 1977, ECON, Inc., teamed with Arthur D. Little, Inc., Grumman Aerospace Corporation and Raytheon Company, performed an economic study and assessment of Satellite Power Systems (SPS) for the George C. Marshall Space Flight Center. As a part of this study ECON determined the range of likely costs for electric power from SPS and, based on these results, developed an economic rationale for proceeding with an SPS development program. In the conduct of this work an economic evaluation methodology was developed appropriate to long-range energy projects such as SPS. This methodology recognizes explicitly the uncertainties inherent in research and development of long-range energy alternatives and deals with them directly. To begin with, uncertainties are quantified using a risk analysis computer model. Then the results of the risk analysis are used in a decision analytic evaluation of candidate SPS development programs. This methodology is particularly suitable as an aide to the selection of preferred SPS satellite configurations and the formulation of corresponding SPS development programs.

The above study also identified a number of key economic issues relevant to the development and selection of preferred SPS satellite configurations. In a follow-on study to this work, beginning in August 1977, ECON addressed three such related issues: the effect of an SPS development program on optimal fossil fuel consumption patterns, a study of the benefits attributable to alternative uses of SPS technologies and a study of the electric power market penetration of SPS. This study was completed in January 1978 and provided interesting new insights to a number of critical economic issues relevant to SPS.

As a result of the above studies, a number of economic factors affecting the satellite power system, its development, design and costing, were identified. Four of these issues are addressed in the study reported here. This study was conducted over the period April 1978 through November 1978. The issues covered include the following:

1. Consideration of economic factors in the SPS system studies that relate to selection of SPS satellite configuration
2. Analysis of the proper rate of interest for use in SPS system definition studies
3. Study of the impacts of differential inflation on SPS system definition costing procedures
4. Utility interface and SPS baseline design including:
   a. Receiving antenna site selection
   b. Power pooling issues
   c. Implications for SPS design.

Results of the study on issues 1 through 3 are reported in this volume. Study results on issue 4 are reported in a second volume authored by Arthur D. Little, Inc.

1.1 Economic Factors Relating to Selection of SPS Satellite Configurations

Two candidate SPS satellite configurations were examined in detail in this study. These include the 5 GW gallium aluminum arsenide solar cell SPS configuration developed by Rockwell International under contract to the George C. Marshall Space Flight Center and a 10 GW silicon solar cell SPS configuration developed by the Boeing Company under contract to the Johnson Space Center. A risk analysis model was developed for each of the two above configurations. The model made use of the data generated by the respective contractors to provide cost-risk data on both satellite configurations. The cost-risk model follows the

work breakdown structure established for the SPS by the Marshall Space Flight Center. Documentation of the cost-risk models for these two SPS satellite configurations is provided in Appendices B and C of this report.

In addition to the cost-risk modeling described above, the proposed SPS development programs for each of the two configurations were also analyzed. Parametric data on this analysis are presented, showing the economic value of the respective development programs as a function of the busbar of price of energy from competing alternatives, in Figure 1.1. Based upon the data provided by the contractors and the assumptions made in the performance of the analysis, the break-even busbar price of energy on January 1, 1999 is shown to be in the range of 20-35 mills/kWh (1977), not including taxes or insurance. The Rockwell International configuration and development program was further analyzed parametrically in terms of the learning rate on SPS system costs and the differential escalation rate in the busbar price of power from competing alternatives.

In performing the risk analysis, a number of inconsistencies between the Rockwell and Boeing works were uncovered. The area of inconsistency of most concern to this study involves the procedure and assumptions used in costing SPS system components. Cost estimates for SPS system components represent forecasts or predictions of the future and as such cannot be precise. Varying rationales by which such cost estimates are obtained lead to significantly different results. As a result, the projected costs for the Boeing and for the Rockwell SPS systems, on a levelized cost of energy basis, are significantly different. We believe that this difference is due primarily to these inconsistencies and not to any inherent differences in the satellite system itself. Thus, a major recommendation deriving from this study is that further SPS costing should be developed by a cost analysis committee consisting of representatives of both contractors and NASA and

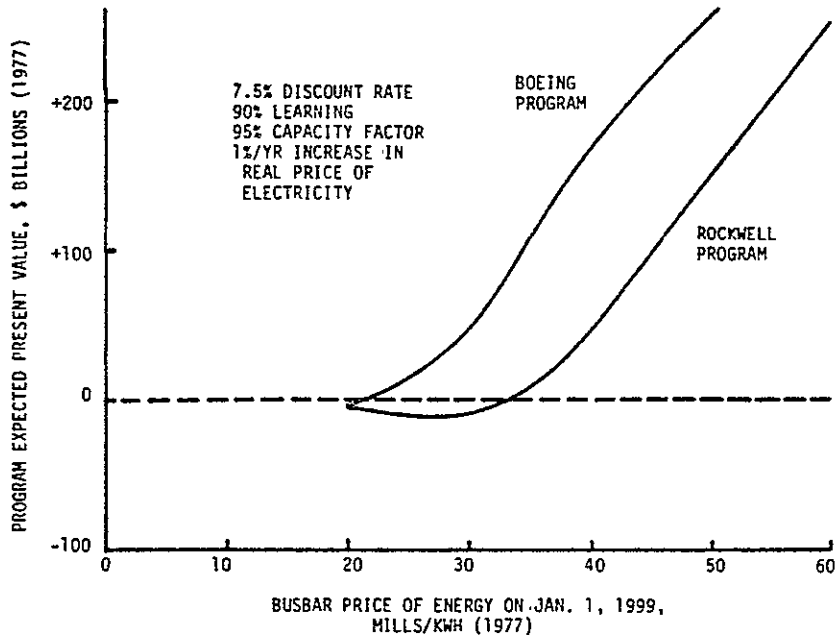

FIGURE 1.1 R&D PROGRAM VALUE AS A FUNCTION OF BUSBAR PRICE OF ENERGY

including also a qualified economist or operations research individual to assure that cost ground rules and cost estimates are internally consistent and are consistent with mathematical and economic theory.

1.2 Rate of Interest for Use in SPS System Definitions Studies

An analysis of the appropriate rate of interest for use in SPS system definition studies was conducted and the results derived from this study were used in a preliminary evaluation of the Rockwell International SPS satellite configuration to illustrate the differential impact of the recommended discount rate compared to the 7.5 percent discount rate used in SPS studies to date. The appropriate rate of discount was determined by bounding the problem from two sides. On the low side, the actual cost of capital to the government was considered. The risk-free standard for the real cost of capital to the government is measured by the interest rate on U.S. treasury bonds corrected for inflation.

While during recent periods this interest rate has occasionally been negative, over the past several years it has tended to lie in the region of 1 to 2 percent.

On the high side, the discount rate is bounded by the opportunity cost of capital. This cost is measured most appropriately by the rate of return on assets generated by industry, corrected for the effects of inflation. This rate, measured by examining the profit and loss sheets for 1600 U.S. corporations over the past 15 years, has recently tended to be in the range of 5 to 6 percent. The argument for an appropriate rate of discount for use in SPS system definition studies further draws upon the work of Von Neumann, performed in the 1930s. Von Neumann demonstrated that, in a linear economy, the maximum stable rate of discount is equal to the rate of technological innovation. Over the past 50 years or so, this has tended to be slightly above 3 percent per year. Thus, it is concluded that an appropriate rate of discount for use in SPS system definition studies would lie between 3 and 5 percent, with this range representing the approximate resolution of this study. Consequently, 4 percent, or the midpoint of this range, is the recommended rate of discount. This rate of discount is also compatible with an overall federal policy of energy conservation. Such would not be the case at a 7 to 10 percent rate of discount.

1.3 Impacts of Differential Inflation on SPS System Definition Costing Procedures

The effects of inflation on SPS system definition costing procedures was analyzed. First, it is argued that system costing can appropriately be done using constant year dollars. However, because of the fact that the time period of construction of the SPS is 20 to 50 years in the future, it is additionally desirable to account for expected trends in specific sectors of the economy which will result in differential inflation between these sectors and the economy as a whole. The

procedure advocated divides costs into three economic categories: labor, resources and capital. Costing procedures in each category are defined separately.

It has been observed that over the past 100 years the productivity of labor has increased steadily at a rate slightly over 3 percent per year. This continued increase in productivity has resulted in increasing real compensation for labor, that is, increasing real wage rates. If previous trends continue, this will result in roughly a doubling of the cost of labor between the present time and the early period during which the SPS construction would commence. Thus, the cost of labor should be differentially inflated accordingly.

The cost of capital is discussed in detail as a separate task in Section 3 of this report and reviewed above in Section 1.2. The recommended real cost of capital for SPS system definition and costing is 4 percent per year. Variations about this number, however, are likely to occur, thereby resulting in a component of uncertainty in the total SPS cost.

Finally, resources are dealt with. Many resources required for SPS construction and operation are found in abundance. The major question with respect to these resources is only how one should estimate their price for the time period of interest. It is suggested that long-term average prices are perhaps a good guess, but that the historical volatility in price should also be examined as an indication of the likely uncertainty in the present ability to forecast these prices. Other resources may be scarce or depleting. For these resources, it may be appropriate to consider the cost of alternative resource supplies or, particularly in the case of energy resources, to explicitly account for economic rents attributable to depletion of the resource in question.

In any case, considerable uncertainty exists in any estimate of resource costs for the time period of interest.

2. COST-RISK AND PROGRAMMATIC ANALYSIS OF CURRENT SPS SATELLITE CONFIGURATIONS

The purpose of the cost-risk analysis described herein is to determine the current state-of- knowledge that exists on candidate SPS system configurations: a determination which is a necessary ingredient of the comparison of alternative SPS satellite configurations. First, the risk analysis output reflects explicitly--if it is conducted properly--a measure of the effect of component technology uncertainties on system performance and cost. Second, risk analysis allows a proper identification of those technologies which are critical to the development of an economically efficient system, a process of identification which is not possible by means of a nonstatistical analysis. The proper identification of critical technologies is a vital part of the development of efficient, candidate SPS R&D programs. Third, risk analysis results are a necessary input to decision making and program evaluation. The methodology which is used to conduct cost-risk analyses and to employ the results in programmatic evaluations is reviewed below. Readers wishing more detail than is provided here are referred to Chapter 3 of "Space-Based Solar Power Conversion and Delivery Systems Study--Volume V, Economic Analysis,"* which provides a more detailed description of the theoretical basis for the techniques applied here. Following the review of the methodology, the results from the analysis of the two candidate SPS configurations developed by Rockwell International and the Boeing Co. are presented.

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*Prepared for NASA George C. Marshall Space Flight Center under Contract No. NAS8-31308 by ECON, Inc., March 31, 1977.

2.1 Methodology

2.1.1 Cost-Risk Analysis

The purpose of the risk analysis described herein is to provide a computational tool for statistical system costing. The output of the risk analysis is a probability distribution of system costs (capital investment, operation and maintenance, and total life cycle). The necessary components of the risk analysis include an engineering system model, a cost model and data which describe the current state-of- knowledge on the system. The engineering system model must, to the appropriate level of detail, reflect the interrelationships of the various system components, such that, when one of the physical parameters is varied, all of the adjustments necessary to accommodate that change are reflected in the new output describing the system and its performance. For example, if solar cell efficiency varies from a nominal value, the size (hence, total mass) of the solar array varies as well, and this change in solar array size must be calculated along with corresponding changes in total satellite mass, the requirements for space transportation (hence, transportation cost), and so on.

At the level of analysis presented here, system relationships are mostly represented by linear approximations or scaling laws which, while they work fairly well owing to the fact that many portions of the SPS system scale in a linear fashion over reasonable ranges, are, nonetheless, an approximation that must be recognized. The system masses are generally calculated as functions of area or power throughput, with areas and power throughputs being determined by the efficiencies of the power conversion and distribution elements of the system. The series of power conversion steps in the SPS system may be characterized as an efficiency chain, a generalized version of which is presented in Figure 2.1. Most of the system components of the SPS satellite and ground station are related directly

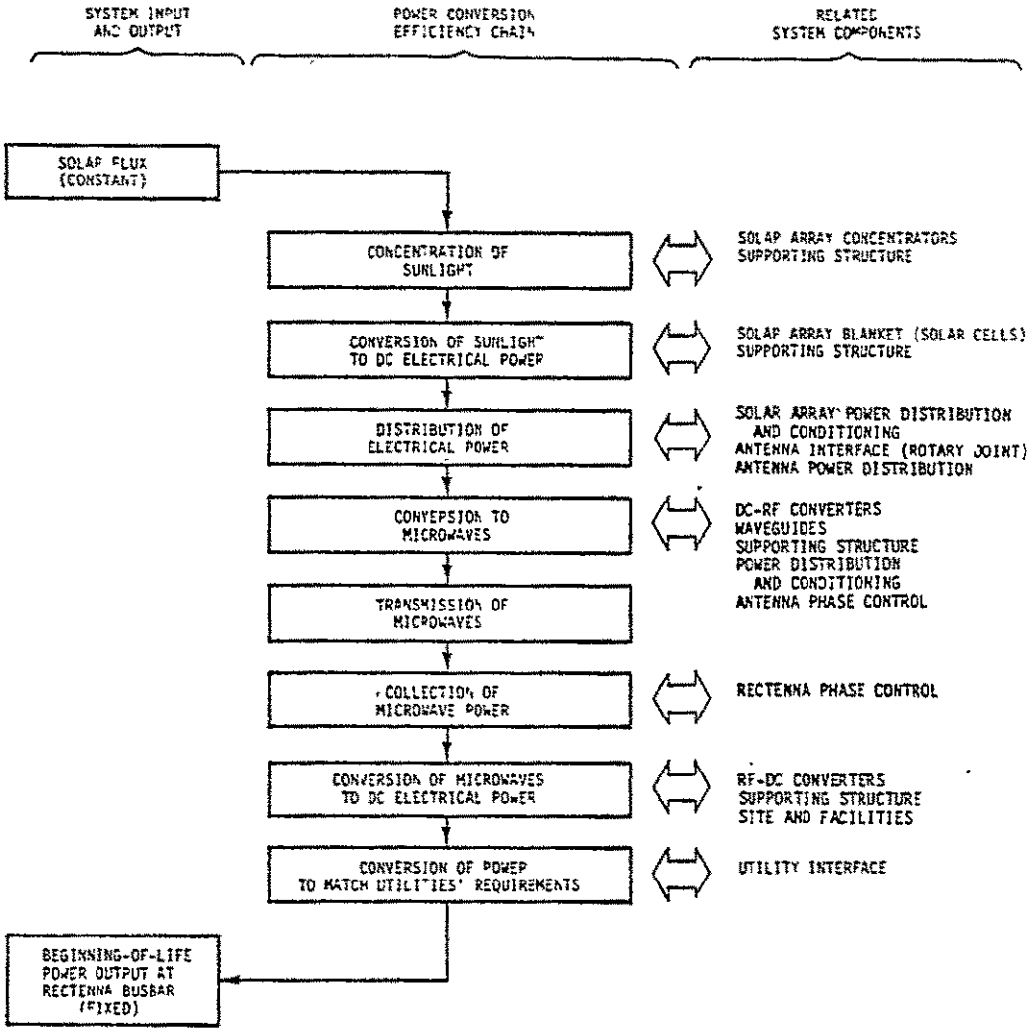


FIGURE 2.1 RELATIONSHIP OF SPS COMPONENTS TO THE SYSTEM EFFICIENCY CHAIN

to the efficiency chain. Other components are more directly correlated to total SPS satellite subsystems.

The cost model translates the output parameters of the engineering system model (such as the total mass, size or power throughput of subsystems, the total number of launch vehicle flights to LEO, etc.) into estimates of the total system cost. The general logic flow of the interaction of these two models is depicted in Figure 2.2. The cost models employed in this analysis are formulated to calculate the production and operations and maintenance (O&M) costs for a single unit, in this case the "theoretical first unit" (TFU). While the comparison of TFUs of different configurations is a convenient approach, to do this it is necessary to apportion the costs of equipment which is used for the construction of more than one satellite appropriately among the satellites constructed by such equipment. To accomplish this apportionment of costs, the cost models calculate annuities at the prescribed discount rate to repay the cost of each piece of equipment over its design life. This annuity is then divided equally among all of the satellites constructed in one year. In this manner, the cost of equipment common to the construction of more than one satellite is properly accounted for in the cost of each satellite. However, it is only direct charges such as transportation and assembly costs which are attributed to each satellite, not sunk costs such as R&D costs. Other assumptions involved in the engineering system model and the cost models used in the analyses here are described below.

The final component necessary to conduct a cost-risk analysis is a set of data to characterize the current state-of-knowledge about the technical and economic parameters of the system under consideration. The possible range of values for any of these parameters is typically represented as a probability distribution which is

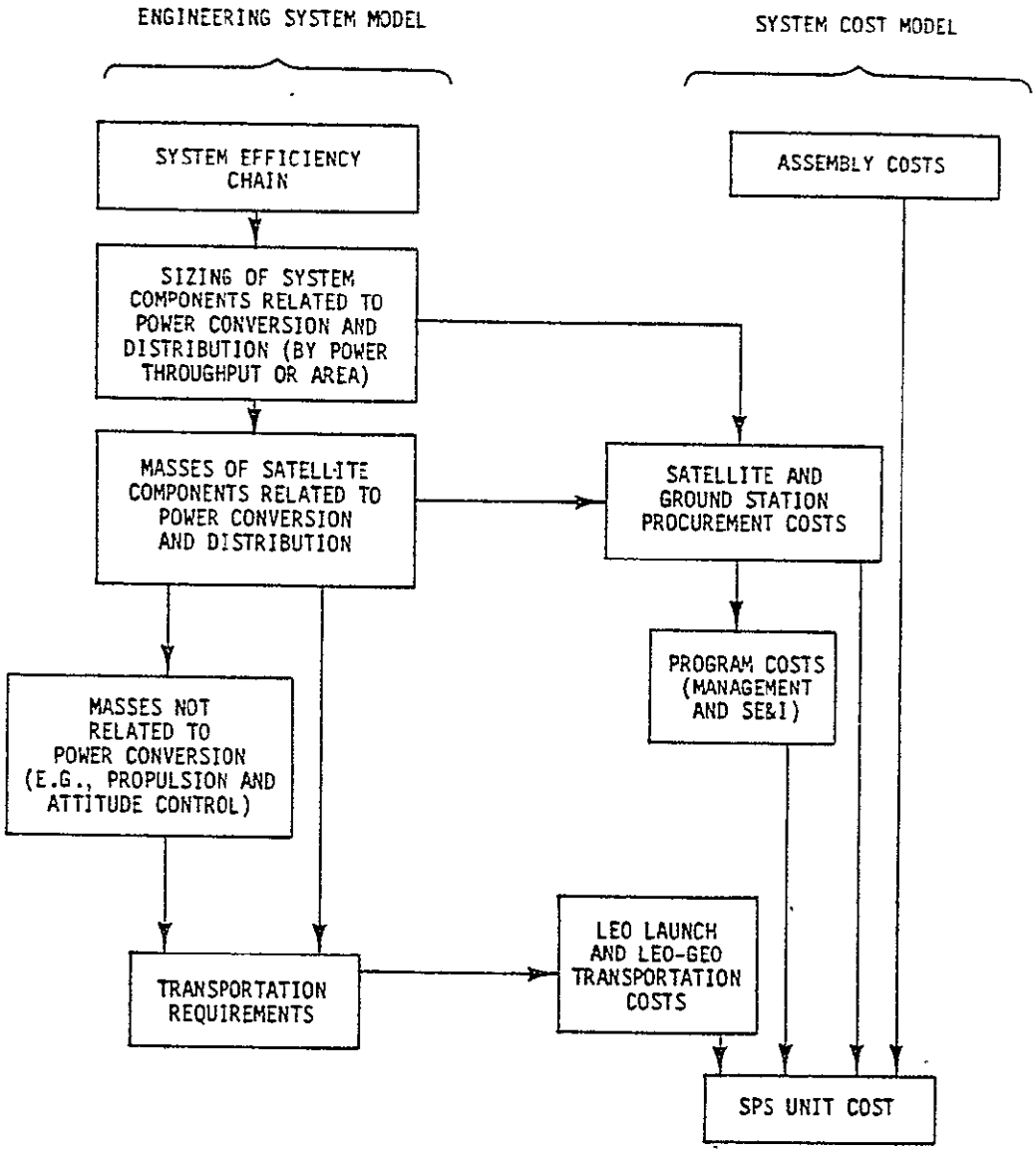


FIGURE 2.2 GENERAL LOGIC FLOW OF ENGINEERING AND COST MODELS FOR SPS COST-RISK ANALYSIS

the subjective assessment by those knowledgeable about a factor assigning probabilities to each value within the range of possible values. If a risk assessment is conducted properly, the minimum value for each parameter distribution will be set at a value for which there is "very low" probability of the actual value occurring below that minimum value in the distribution; likewise, the maximum value should be set such that there is "very low" probability that the actual value will be found to exceed that maximum value in the distribution. The maximum likelihood point in the distribution should correspond to the current "best estimate," again subjectively assessed by experts, and the shape of the distribution should reflect the current state-of-knowledge in that the more sharply peaked the distribution is, the greater the degree of confidence in the estimate of the parameter value. Conversely, a flatter distribution would reflect a lower degree of confidence in the estimate. This latter degree of sophistication in risk analysis (the shape of the input parameter distributions) could not be employed within the scope of the current effort. The actual distributions used are shown in Figure 2.3. For the purposes of this analysis the shape of the distribution depends upon the position of the most likely value within the range of values.

One method for performing a risk analysis involves a Monte Carlo simulation on the engineering system and cost models, that is, random sampling is conducted to produce a deterministic set of input data for the two models and the resulting system cost (or other output parameter) is stored. The process is repeated until it has been determined by statistical means that a significant output sample has been generated. This risk analysis procedure is depicted below in Figure 2.4. The results of a risk analysis are conveniently presented as cumulative distribution functions, showing the probability of a given output parameter, such as total unit

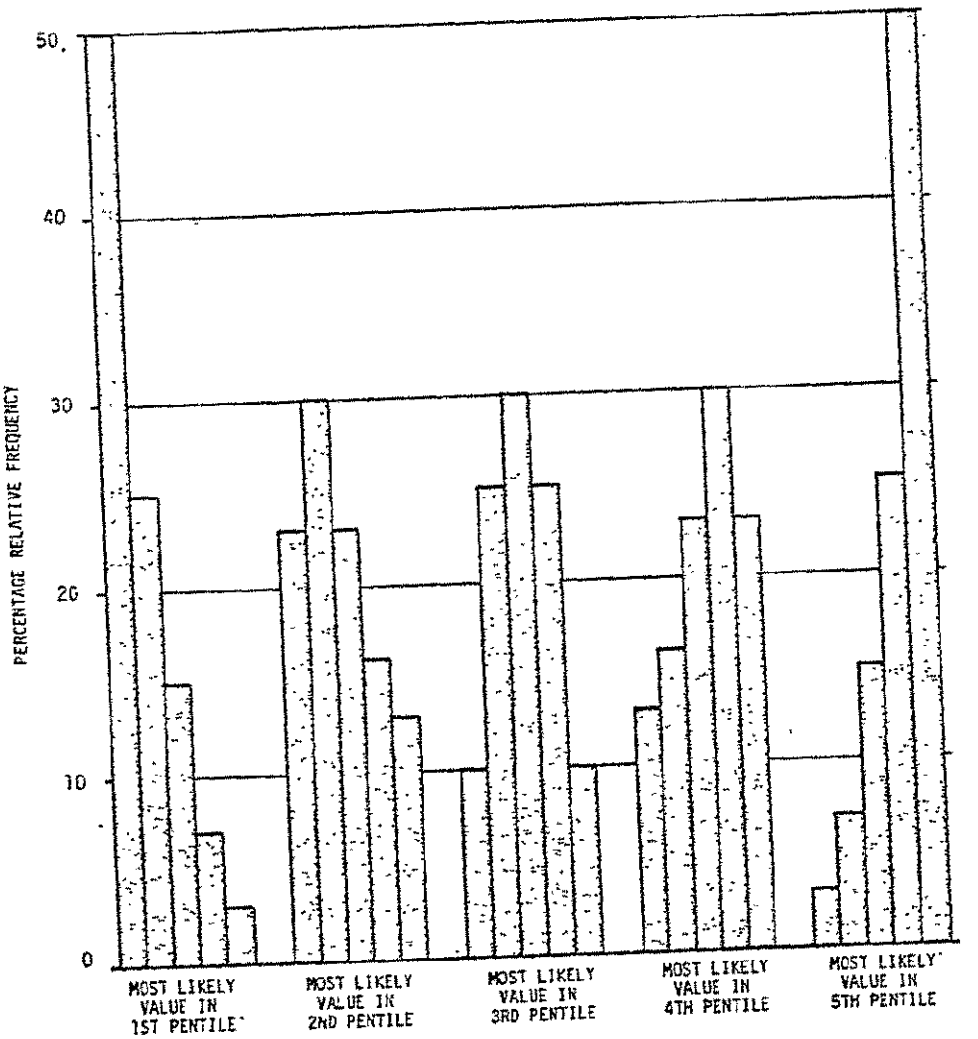


FIGURE 2.3 UNCERTAINTY PROFILES

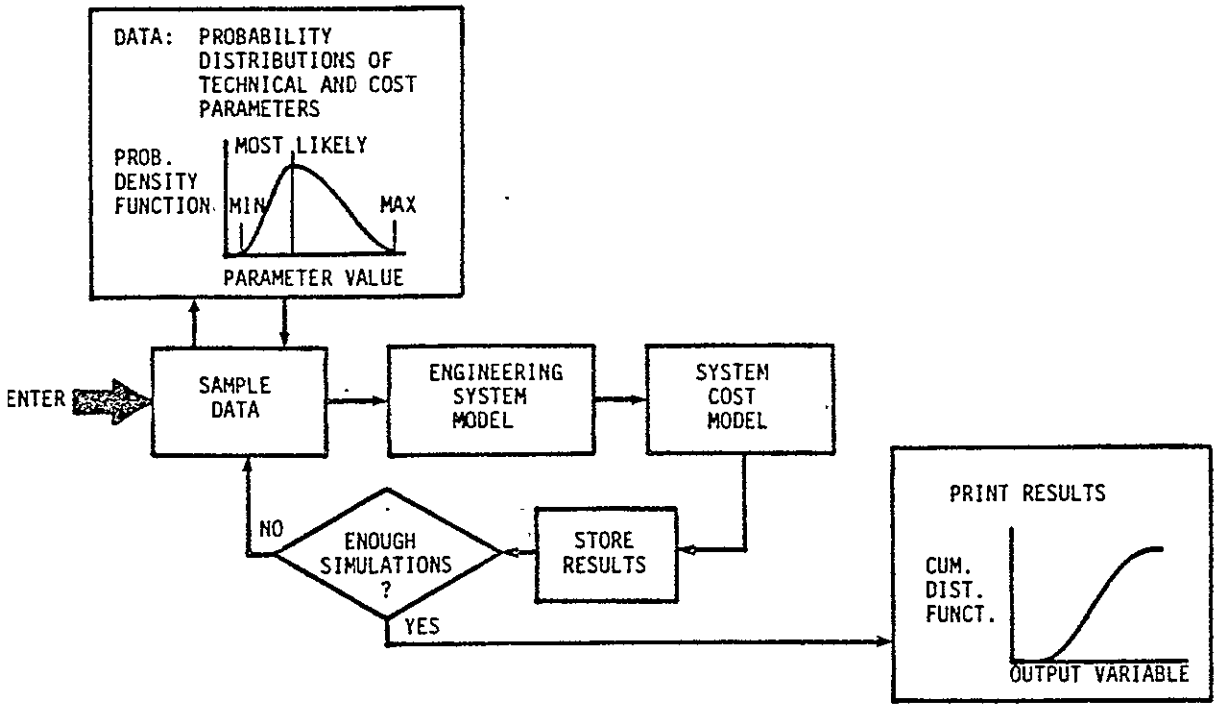


FIGURE 2.4 RISK ANALYSIS PROCEDURE

cost, being less than the indicated amount. While the output parameter distribution functions clearly result from the use of subjective probability assessments as inputs, that is, they are not derived from the sampling of actual events, they do provide an interesting, and probably the best available, basis for comparison of alternative system configurations, in that a risk comparison explicitly includes a description of the uncertainty which exists on each system configuration cost estimate. The usual alternative to risk analysis is a simple "point estimate" of cost and other parameters. Presented only with point estimates of, say, the installed cost per kilowatt of competing electrical generation technologies, a decision maker is deprived of any indication of how reliable these estimates are, that is, of what the likelihood is that each estimate will be met or exceeded. Risk analysis creates a framework in which subjective judgment may be incorporated at the most appropriate level (component by component) and accounted for in a mathematically

correct fashion. Therefore, if the risk analysis is conducted properly, the results will be an accurate reflection of what is really known about any given system and what the total effect is of what is not known on estimates of system performance and cost. And so long as risk analyses of competing systems are conducted in a consistent manner, comparison of the results will be far more enlightening from the standpoint of program decision making than the comparison of point estimates.

2.1.2 Identification of Critical Technologies

The framework for cost-risk analysis outlined above provides a mechanism for assessing the individual technology elements which comprise the present state-of-knowledge. Technology elements are critical to the current state-of-knowledge if, given perfect information on them, this information could substantially influence decisions regarding the system development and implementation. For the SPS it is assumed that programmatic decisions will be keyed, among other conditions, to the total life-cycle costs of a single SPS. Therefore, a technology element is critical if it alone can have a significant effect on the cost-risk profile (meaning both risk--the slope of the risk curve--and expected cost).

To determine the impact of a technology element on the risk profile, one assumes that perfect information on the technology element can be made available. In terms of the input variables to the risk analysis model, perfect information is expressed as a deterministic value or spike distribution for that variable. However, the value that any particular variable will ultimately assume, between the minimum and maximum limits estimated as a part of the cost-risk analysis, cannot be known in advance (that is, today). Thus, it is necessary to input deterministic values for each technology element, one at a time, over the range from the minimum to the maximum possible values for each variable to determine the range of potential outcomes from the information-gathering process. In the

work performed here, each input variable is assigned three deterministic values corresponding to the minimum, most likely and maximum values which the parameter takes on in the cost-risk analysis. All other input data remain unchanged. Critical technologies are then identified by observing the variables which had the largest effect on the expected value and standard deviation of the total life-cycle cost probability distribution.

It is interesting to compare this approach for the identification of critical technologies to the deterministic approach more often used and referred to here as a sensitivity analysis. In a sensitivity analysis one produces a deterministic cost estimate of the system by the use of a system cost model. Then, one by one, the input variables to this cost model are varied from their nominal values to pessimistic or worst-case values. The effect that this has on the total system cost is then noted and the critical technologies are identified by observing which input variables have the largest influence on the total system cost. Unfortunately, this procedure, while simpler than the risk analysis outlined, is mathematically incorrect and can lead to substantially wrong answers. This is so because of nonlinear interactions between variables in the model each of which contain some uncertainty. Consider the simple example where the cost is given as the product of two variables A and B. And consider the case when the distributions representing the current state-of-knowledge on A and B are as shown in Figure 2.5. Due to the long tail nature of the distribution on variable B the risk and cost sensitivities to variable A are greatly enhanced. Under a case of simple nonlinearities such as that illustrated here it is not uncommon for a deterministic analysis to underestimate the criticality of the state-of-knowledge on variable A by a factor of two or more.

Risk analysis thus provides a mathematically correct basis for identifying technologies critical to the development of an SPS. In general, one would expect

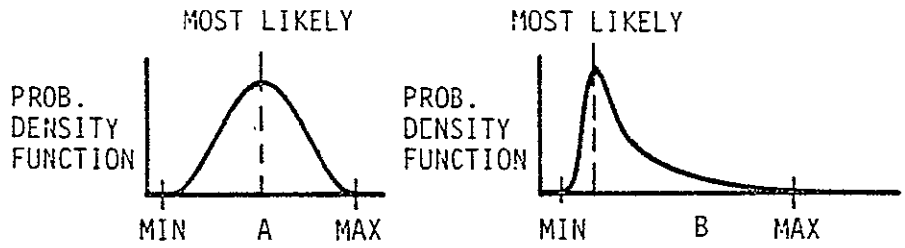


FIGURE 2.5 EXAMPLE STATES-OF-KNOWLEDGE

that these are the technology elements that should be addressed early in a research and development program so that an improved state-of-knowledge will be available for future programmatic decisions.

2.1.3 Decision Analytic Approach to Program Evaluation

A key purpose which the decision maker serves in a research and development program, such as the SPS program, is to assure that the technology is successfully developed (if that is possible within schedule and budget constraints) while simultaneously minimizing exposure to risks. This is accomplished by segmenting the overall research and development program into a number of discrete phases. During each phase of the program, research and development activities are carried on with the aim of providing information for subsequent decisions within the program. The subsquent decisions can be to continue the program as planned, to terminate the program or to alter it in some substantial way. It is precisely this process of sequential information buying that enables a program manager to control risk by not pursuing those technologies which appear to be dead-ended and instead to focus project resources on those technology areas which promise the most payback.

The information provided by a cost-risk profile of an SPS configuration can be used as a basis for the evaluation of a particular R&D program. The evaluation

uses a decision analytical procedure with the cost-risk data as an input. The procedure for such an evaluation is outlined in Figure 2.6. A particular R&D program is defined in terms of the experiments to be conducted in each phase of the program directed at "buying information," that is, the reduction of uncertainty about the technical and economic parameters of the system. Also defined are the "decision points" where the program is evaluated and either continued, redirected or terminated, based upon the information developed during the preceding phases of the program. The costs associated with each phase of the R&D program must be estimated, as well as the expected improvements in the state-of-knowledge on the system resulting from the experiments conducted. These expectations of improvements in the state-of-knowledge are expressed in this work as expected percentage reductions in the uncertainty (standard deviation, for example, of the distribution of each parameter) to be achieved as of each decision point. Furthermore, an

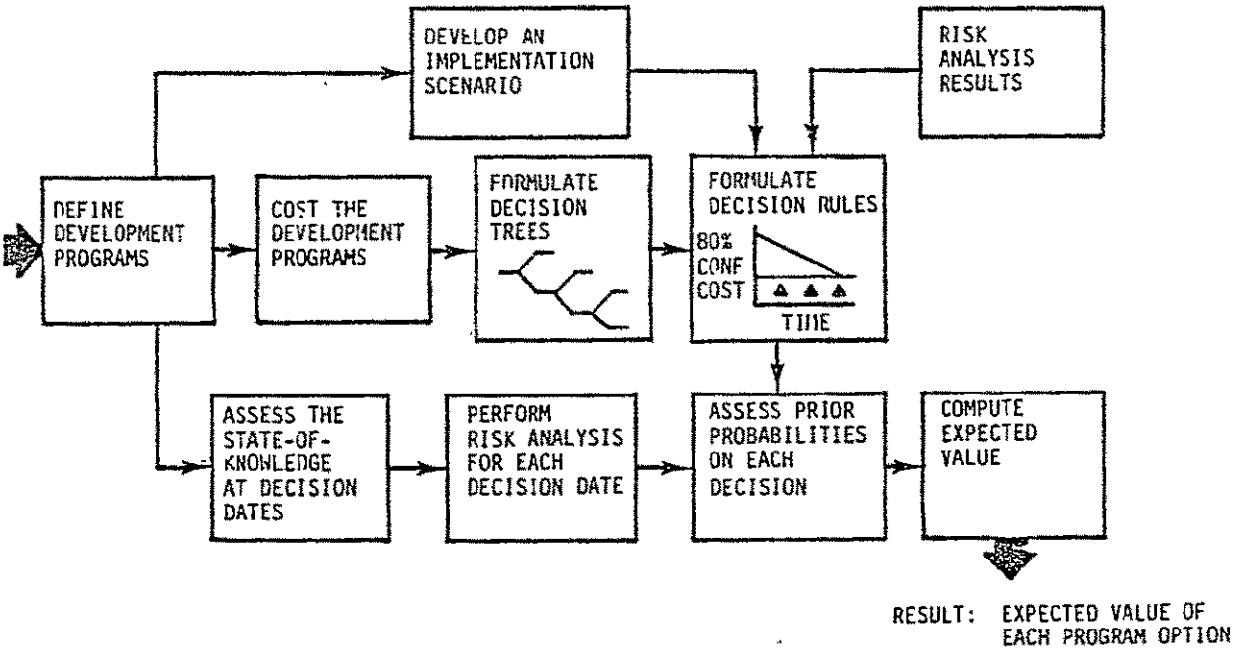


FIGURE 2.6 AN OUTLINE OF THE DECISION ANALYTIC PROCEDURE USED TO CALCULATE THE EXPECTED VALUE OF EACH PROGRAM OPTION

implementation scenario must be defined in terms of the number and scheduling of operational units to be produced. For purposes of the evaluation, the program is expressed as a decision tree with each branching point corresponding to a decision point and each branch corresponding to a potential decision. The original cost-risk profile for the system is used as a prior distribution of total life-cycle cost for the system. It represents everything that is known about the system today. Decision rules are needed to determine, at each decision point, whether to continue or terminate the program (more complicated decision trees may be formulated involving parallel technology development efforts and the like; however, the analyses here have been formulated on a simple go/no-go basis at each decision point). The decision rule applied here is that at each decision point the state-of-knowledge extant must meet a technology target which corresponds to a linear improvement in the 80 percent confidence bound for the technology from the current state-of-knowledge to the "break even" cost for the TFU. This is the cost of the TFU for which there is exactly zero net present value for the entire program (present value of costs equals present value of revenues). 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.

To calculate the expected value of a program, risk analyses are performed on the data for each decision point reflecting the expected percentage reductions in the range of uncertainty on each parameter. The resulting standard deviations of the state-of-knowledge on the total life-cycle cost are used along with the 80 percent confidence technology target described above to create cumulative distributions* which represent the decision rules. Using a process described in detail in

*These distributions are assumed to be Gaussian and therefore may be uniquely specified by a mean value (which may be derived from the 80 percent confidence value) and a standard deviation.

Appendix G of the previously cited report* the prior probabilities of each decision point are calculated. The prior probabilities represent the likelihood of proceeding successfully at each decision point. The decision tree itself is evaluated by weighting successively the value of each branch (taking costs to be negative and revenues positive) by the probability of reaching that branch and then summing the expected value of each branch to arrive at the expected value for the entire program represented by the decision tree. The results from such programmatic evaluations can be used to rank SPS program and configuration alternatives. In the "zero budget" sense, if a program has a positive expected value, then one is economically justified in undertaking the first phase of that program. If more than one program option has a positive value, the one with the highest expected value is the one that is economically preferred. Again, the reader who wishes a more detailed description of the theory and application of these techniques to SPS program evaluation is referred to the previously cited report.

When confronted with a cost-risk profile, many program planners become very concerned with the potential that such a system has to incur very large costs for its production, that is, with the long tail of the distribution ranging up to rather high costs. Such concern however, is the result of a misunderstanding of the role of the program manager. It is, in fact, the purpose of the program manager to insure that the program would be terminated in a timely manner if in fact it becomes evident that the actual system costs will lie toward the upper end of the cost range as opposed to the lower end. It is the opportunity posed by the probability that the cost could lie at the lower end of this range that the program manager should seek to capitalize upon. Thus, a properly structured research and

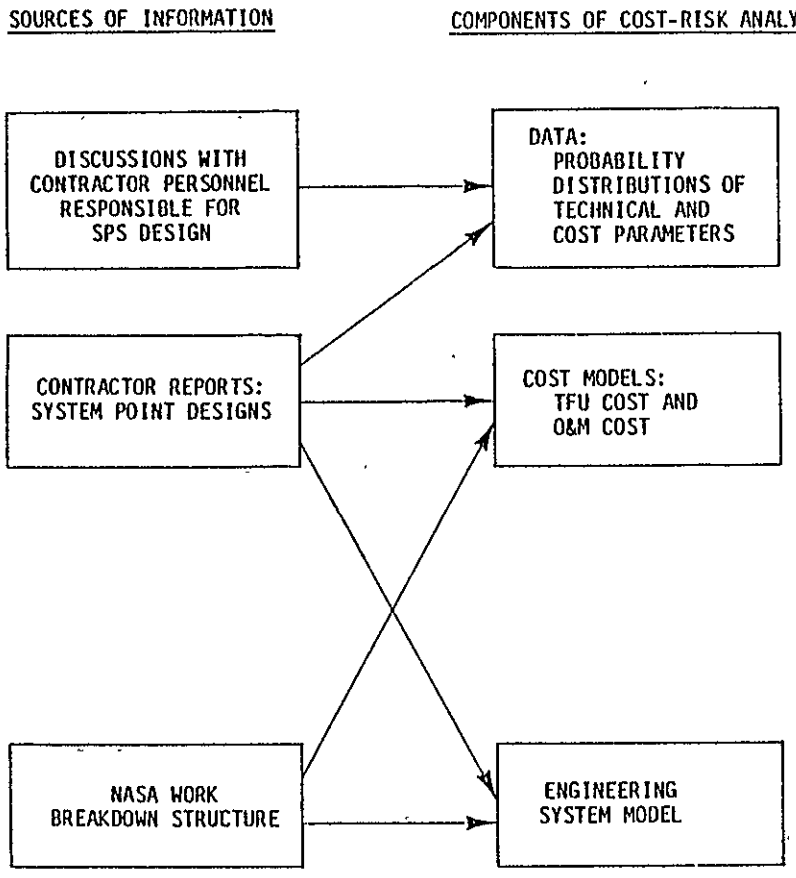
*See footnote on page 7.

development program is one which offers the opportunity to buy information to determine what the system will, in fact, cost when all research and developments are completed, to proceed with the program if, at any point, it is economic to do so, or to terminate further work on the project as soon as it becomes clear that this is the economic choice to make.

2.1.4 Assumptions and Ground Rules for a Consistent Comparison of Alternative SPS Configurations and Programs

The sources of information for the components of the cost-risk analysis and the major assumptions used in constructing the models are reviewed in Figure 2.7. Models of the two system configurations to be analyzed were derived first from contractor reports and then verified through two series of discussions with contractor personnel responsible for the design work. The NASA Work Breakdown Structure (NASA TM 78155l, January 1978) served as a guide for the organization and reporting of the engineering system and cost models. The assumptions employed in the programmatic evaluation are listed in Table 2.1, including: unit size, lifetime, availability and output power level; fleet size, implementation rate and cost reduction learning curve; discount rate; price of power and price of power escalation rate; and taxes and insurance. It should be noted that the results of the analyses in the next two subsections below 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 models, the data representing the current state-of-knowledge and the assumptions made for the analysis.

Some modifications were made to the input data obtained from the contractors, in order to assure, where possible, that the same costs and performance characteristics were being assumed for similar equipment. Therefore, adjustments were made in the efficiency chains for the two systems to reconcile



ASSUMPTIONS FOR COST-RISK ANALYSIS

DATA:

- -CURRENT STATE-OF-KNOWLEDGE
- -ALL COST ESTIMATES IN MID-1977 $
- -ALL ESTIMATES FOR "THEORETICAL FIRST UNIT" (TFU)

COST MODELS:

- -DEVELOPMENT COSTS NOT INCLUDED
- -COST OF ASSEMBLY AND TRANSPORTATION EQUIPMENT AMORTIZED OVER SATELLITES CONSTRUCTED WITH IT
- -CAPITAL COST SPREAD FOR DISCOUNTING PURPOSES BY A BETA DISTRIBUTION BEGINNING 4 YEARS BEFORE INITIAL OPERATION DATE (IOD) AND REACHING A PEAK 6 MONTHS BEFORE IOD
- -DISCOUNT RATE = 4% PER ANNUM
- -OVERALL SE&I AND PROGRAM MANAGEMENT = 2% AND 1% OF TFU COST, RESPECTIVELY
- -SATELLITE AND GROUND STATION SE&I AND PROGRAM MANAGEMENT TAKE AS FRACTIONS OF THEIR RESPECTIVE COSTS

ENGINEERING SYSTEM MODEL:

- -EOL POWER OUTPUT USED
- -SYSTEM PERFORMANCE IS THAT ANTICIPATED FOR TFU

FIGURE 2.7 SOURCES OF INFORMATION AND ASSUMPTIONS USED IN COST-RISK MODELS

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TABLE 2.1 PROGRAMMATIC EVALUATION ASSUMPTIONS

- END-OF-LIFE POWER OUTPUTS OF 5 GW FOR THE ROCKWELL CONFIGURATION AND 10 GW FOR THE BOEING CONFIGURATION ARE USED FOR REVENUE CALCULATIONS
- SATELLITE LIFETIME IS 30 YEARS
- EACH UNIT IS PRODUCING POWER 95 PERCENT OF THE TIME
- INITIAL OPERATION DATE (IOD) OF THE FIRST UNIT IS ONE YEAR LATER THAN THE IOD OF THE PROTOTYPE IN EACH PROGRAM; THE IMPLEMENTATION RATE FOR THE ROCKWELL CONFIGURATION IS FOUR SATELLITES CONSTRUCTED PER YEAR, AND THE IMPLEMENTATION RATE FOR THE BOEING CONFIGURATION IS TWO SATELLITES PER YEAR
- THE TOTAL FLEET SIZE FOR THE ROCKWELL CONFIGURATION IS 120 SATELLITES (INCLUDING THE PROTOTYPE) AND FOR THE BOEING CONFIGURATION IS 60 SATELLITE (INCLUDING THE PROTOTYPE)
- THE COST OF THE SUBSEQUENT UNITS IS RELATED TO THE COST OF THE TFU BY A 90 PERCENT LEARNING RELATIONSHIP
- DISCOUNT RATE IS 4.0 PERCENT
- REAL PRICE OF ELECTRICITY AT THE BUSBAR INCREASES 1 PERCENT PER YEAR, BEGINNING WITH A PRICE OF 30 MILLS/kWH AT THE IOD OF THE FIRST UNIT
- NO CHARGES WERE COMPUTED FOR TAXES OR INSURANCE

differences so that both configurations were analyzed with the same efficiency chain. For similar types of equipment, the same proportional ranges were used to express the uncertainty on related input parameters; however, no adjustments were made in the "most likely" estimates for these parameters. The only other adjustments which were made were to set the design lives of the space construction bases to 30 years for both configurations. These changes represent only those necessary to eliminate the most obvious inconsistencies in design estimates for the two systems. It did not fall within the scope of this effort, nor would there have been sufficient definition of engineering assumptions for the two configurations to rectify all of the differences which exist between the two configurations in analysis, design and cost estimation of similar equipment.

2.2 An Evaluation of Rockwell SPS Configuration and Program Plan

The Rockwell International SPS configuration and program plan which were subjected to cost-risk and programmatic evaluations are described in "Satellite Power Systems (SPS) Concept Definition Study," Final Report, April 1978, prepared for the George C. Marshall Space Flight Center under contract NAS8-32475. The basic features of this system are reviewed in Table 2.2. The models which were developed to represent the Rockwell configuration in the risk analyses conducted here are listed in Appendix B. The data corresponding to the input variables of these models are found in Appendix D. For simplicity in review and comparison, the engineering and cost equations are presented in a unified format using the NASA Work Breakdown Structure (NASA TM 78155, January 1978) as a guideline. The relationship between the accounts listed in the Work Breakdown Structure and the models used to analyze the two SPS configurations is depicted in Figure 2.8. Once again, it is noted that the research and development costs are not amortized over the satellites constructed, as this approach would not represent the actual timing

TABLE 2.2 ROCKWELL SPS CONFIGURATION AND CONSTRUCTION SCENARIO
• ALUMINUM STRUCTURE
• GALLIUM-ALUMINUM ARSENIDE SOLAR CELLS
• CONCENTRATION RATIO = 2.0
• END-OF-LIFE POWER OUTPUT AT THE BUSBAR = 5 GW
• GEO FABRICATION AND ASSEMBLY
• ELECTRIC CARGO ORBIT TRANSFER VEHICLE (INDEPENDENT)
• HORIZONTAL TAKE-OFF, SINGLE-STAGE-TO-ORBIT WINGED HEAVY LIFT LAUNCH VEHICLE

of the decisions and the incurring of costs. Rather development costs are taken into account in the programmatic evaluations. The Initial Capital Investment Account in the NASA WBS corresponds directly to the TFU Cost Models reported in the Appendices. The distinction in the NASA WBS between the Replacement Capital Investment and Operations and Maintenance accounts is useful for the purposes of computation of taxes and insurance. However, as neither taxes nor insurance are considered in this analysis, the two accounts have been combined into a single O&M model for each configuration.

A cost-risk analysis was conducted on the Rockwell configuration using the methodology described above, employing the models listed in Appendix B. The current state-of-knowledge for each input parameter (in terms of minimum, maximum and most likely values) is listed in Appendix D. The resulting cost-risk profile is shown in Figure 2.9. The nominal case shows an expected value TFU cost of about $33 billion (1977 dollars) and a minimum value of about $19 billion. This

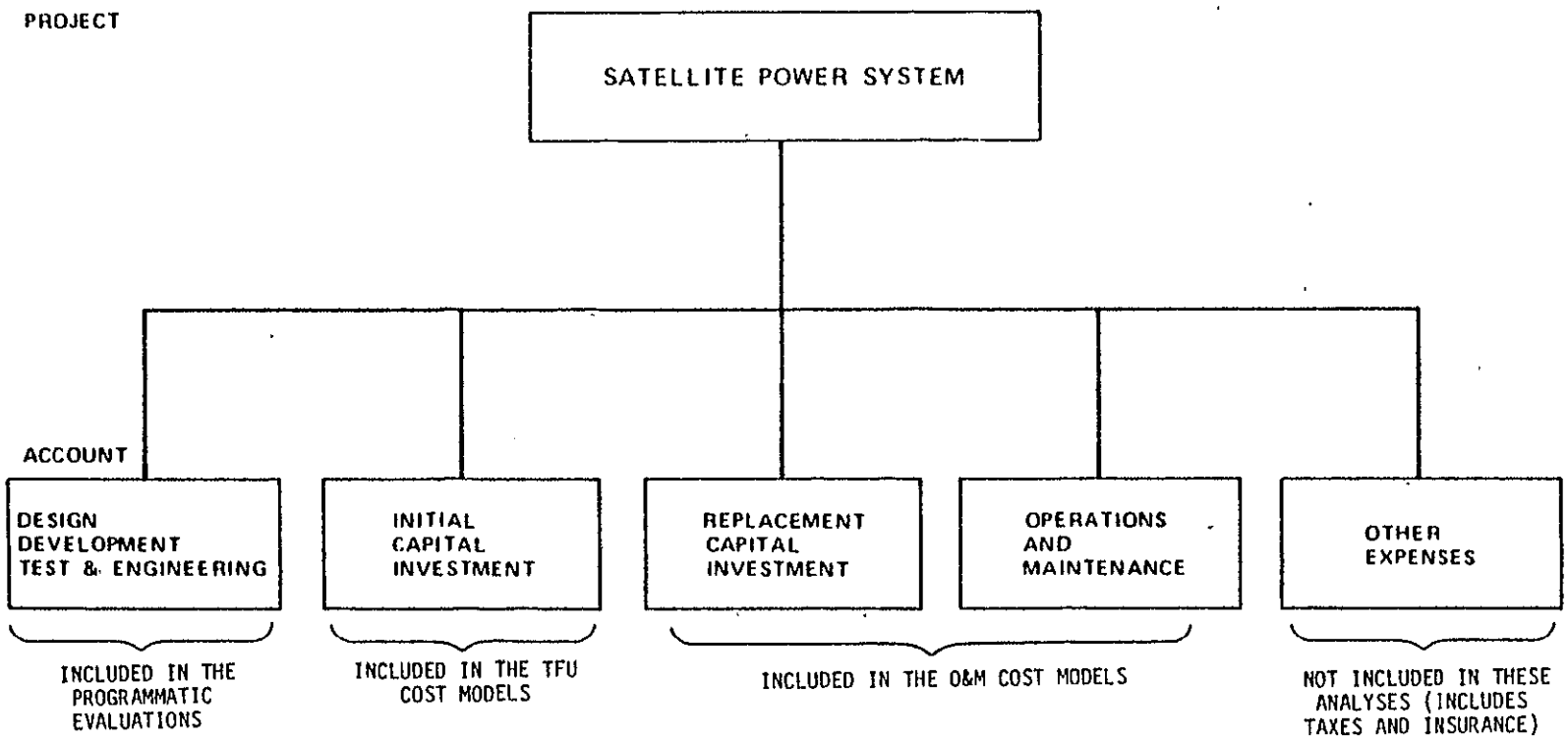

FIGURE 2.8 RELATIONSHIP BETWEEN THE NASA WORK BREAKDOWN STRUCTURE AND THE COST MODELS USED IN THE ECON COST-RISK ANALYSES OF THE ROCKWELL AND BOEING CONFIGURATIONS

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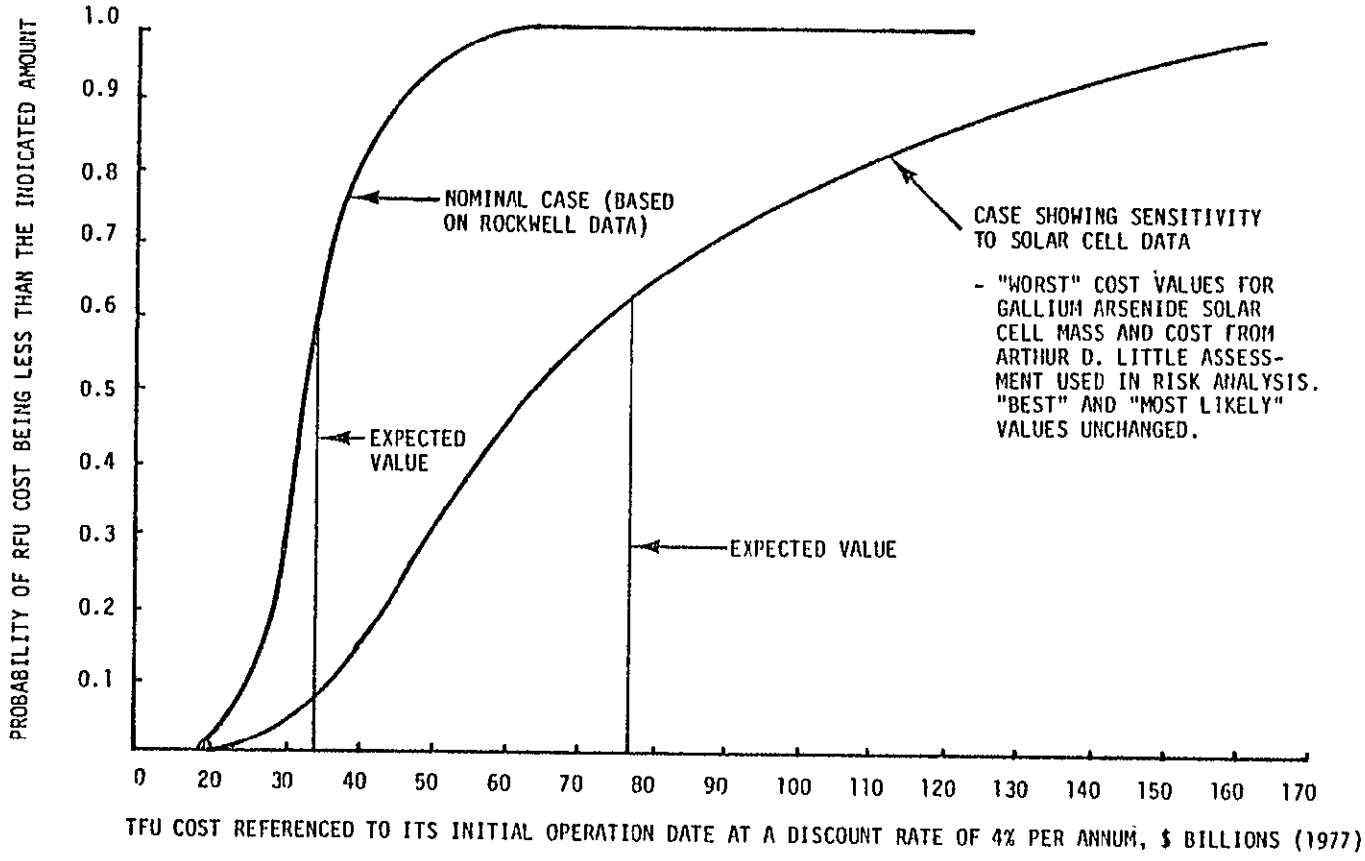

FIGURE 2.9 ROCKWELL SPS CONFIGURATION COST-RISK PROFILE

cost-risk profile reflects far less risk (variability)than one might expect for a technology in the state of development of SPS with the leadtime that is necessarily involved (at least 20 years before commercial implementation). The sensitivity of this estimate of the current state-of-knowledge to an alternative view of the current state-of-knowledge is reflected in the curve, also shown in Figure 2.9, depicting an assessment of higher risk on only two variables. If one adjusts merely the high-side risk for solar cell specific cost and mass, that is, merely changes the worst case values for these two parameters to those reported in an Arthur D. Little, Inc. analysis,* leaving the best and most likely values unchanged, the cost profile is radically altered. Indeed, the expected value in the case acknowledging higher risk on two input values is more than twice that of the nominal comparison case.

The critical technologies for the Rockwell configuration were analyzed in the manner described above in Section 2.1.2. Each of the parameters which is thought to have a potentially significant effect on total system cost is set deterministically first to its maximum value, then to its most likely value, and finally to its minimum value, allowing all other parameters to vary freely (according to their defined probability distributions) in the simulation. This analytical approach simulates the effect of perfect information on the variables being examined, so that the effect on total system cost variability resulting from the variability of each parameter may be measured. Thirty-four parameters were examined for their effect on system cost and risk. Those parameters having the greatest effect on system cost and risk, that is, the major cost and risk driving factors for this configuration are listed in Table 2.3. Three basic areas of concern are indicated by

*Space Based Solar Power Conversion and Delivery Systems Study, Final Report, Volume IV, Energy Conversion Systems Studies, prepared for ECON, Inc. by Arthur D. Little, Inc. under Contract No. NAS8-31308, March 29, 1977.

TABLE 2.3 THE EFFECT OF COST AND COST RISK* OF CHANGES IN THE STATE-OF-KNOWLEDGE OF THE ROCKWELL CONFIGURATION

MAJOR COST AND RISK DRIVING FACTORS	RANGE OF VALUES, $ BILLIONS (1977)					
	BEST		MOST LIKELY		WORST	
	MEAN COST	COST RISK	MEAN COST	COST RISK	MEAN COST	COST RISK
NOMINAL CASE			33.29	6.34		
SPECIFIC COST OF THE SOLAR BLANKET	28.99	4.36	30.37	4.58	45.54	7.60
SOLAR CELL EFFICIENCY	28.55	4.26	33.99	5.86	40.21	8.18
DC-RF CONVERTER EFFICIENCY	31.28	5.47	32.72	5.74	40.32	7.28
RATIO: COST OF MICROWAVE ANTENNA ELEMENTS TO DC-RF POWER THROUGHPUT	29.68	5.91	33.19	6.20	38.09	6.65
PHASE CONTROL EFFICIENCY	31.50	5.74	32.29	6.65	35.44	7.92
ANTENNA POWER DISTRIBUTION EFFICIENCY	31.22	5.38	32.13	6.04	36.82	7.54
BEAM COLLECTION EFFICIENCY	31.70	5.90	33.19	6.12	36.89	7.08
UNIT COST OF CABLE ATTACHING MACHINES	33.36	5.94	34.30	6.56	37.98	6.38

*"COST RISK" IS THE STANDARD DEVIATION OF THE COST ESTIMATE.

this listing of cost and risk drivers. First, uncertainty about the cost and efficiency of the gallium-aluminum arsenide solar cells has the greatest effect of all the parameters examined. Second, uncertainty about a number of characteristics of the microwave transmission system, including conversion efficiencies and klystron costs, has a significant effect on system cost and risk. Third, the cable attaching machine, a fairly numerous and moderately expensive piece of assembly equipment, is found to be the element of the construction scenario whose uncertainty contributes most significantly to overall cost and risk.

A programmatic evaluation was conducted following the decision analysis techniques described above. A decision tree representation of the Rockwell development plan described in Volume VII and the Appendices of the aforementioned Rockwell report is shown in Figure 2.10. This program calls for a variety of ground- and space-based technology verification experiments to be conducted during the first phase. Flight tests, where necessary, will utilize the Shuttle. During the second phase a 1 GW prototype is constructed and, after a demonstration period, is expanded to a full-scale 5 GW plant. The final phase entails commercial implementation. The scope of this study did not allow a more detailed representation for the purposes of this programmatic evaluation because, while a more detailed program plan is described in the Rockwell report, it is necessary to subjectively estimate the improvements in state-of-knowledge on each parameter that is likely to occur as of each decision point. A means did not exist at this level of analysis to discern with greater resolution than is represented in Figure 2.10 the stages of the program with their accompanying improvements in states-of-knowledge. Based upon the previously stated assumptions underlying this analysis, the Rockwell program shows a substantial positive expected value, on the order of $324 billion (1977 dollars) present value as of January 1, 1980. The sensitivity of

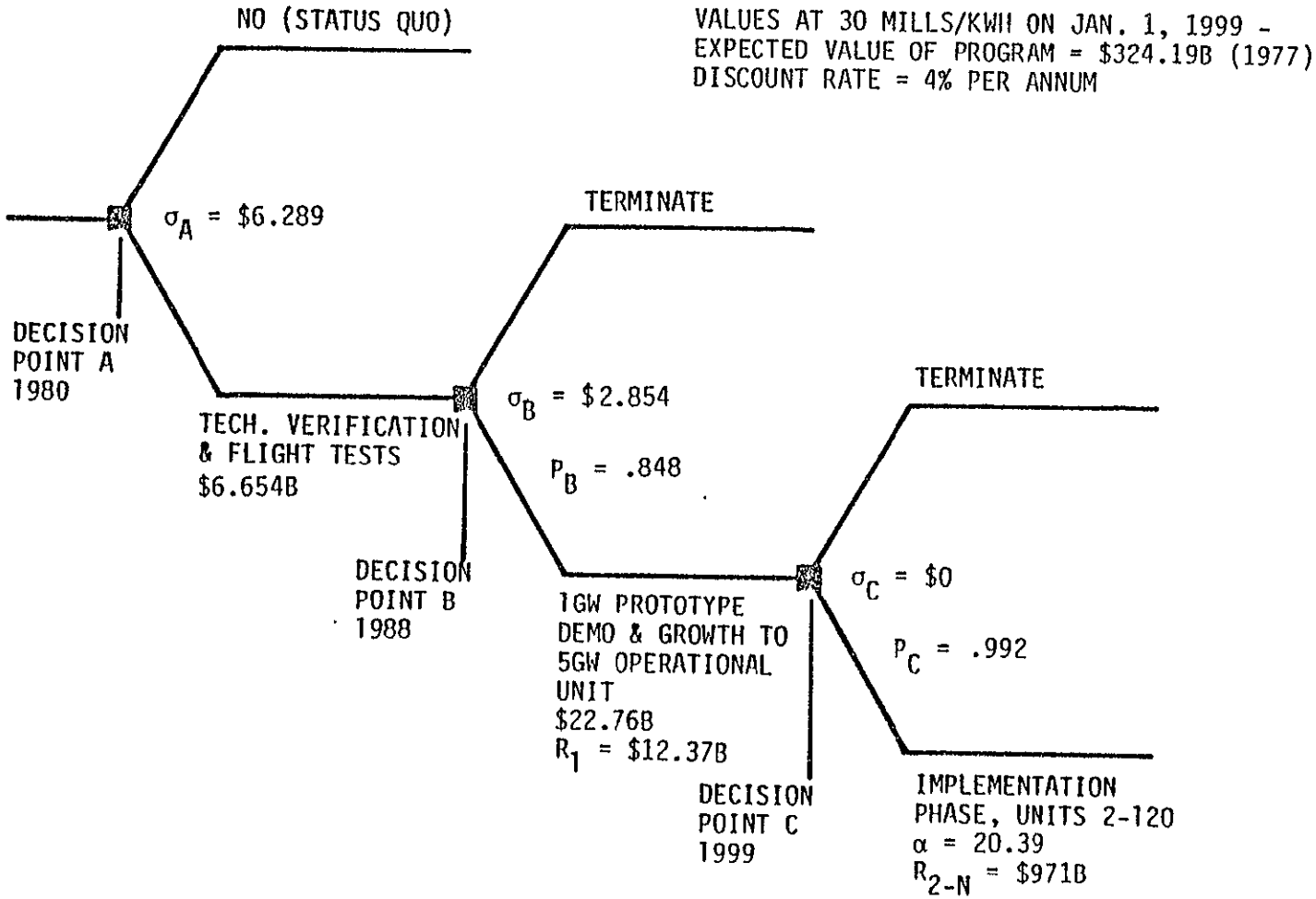

FIGURE 2.10 DECISION TREE FOR THE ROCKWELL SPS DEVELOPMENT PROGRAM

this result to the underlying assumptions is discussed below. For the moment, it should be noted that probabilities associated with decision points B and C are quite high. These high probabilities of success at each decision point are the result of several factors. First, the relatively modest risk reflected in the cost-risk profile shown above for this configuration results in a series of technology targets which are not very demanding relative to the current state-of-knowledge. Second, the relatively low discount rate (which is only appropriate if a valid risk assessment has been conducted, as noted in Section 3) allows for a greater proportion of the value of the fleet revenues to be counted in defraying the cost of building the fleet. The correspondingly higher "break-even" cost further reduces the rigor of the technology targets for the program, thus increasing the probability of success at each decision point. Third, the lower discount rate used here shifts the "prior distribution" of unit costs down by reducing the cost of capital applied to each unit over the period of its construction. Such a reduction in the prior distribution of unit cost improves the chance of success at each decision point. These latter two effects relating to discount rate are described in more detail in Section 3.

2.3 An Evaluation of the Boeing SPS Configuration and Program Plan

The Boeing Co. SPS configuration and program plan which were subjected to cost-risk and programmatic evaluations are described in "Solar Power Satellite System Definition Study--Part III," March 1978, prepared for the Lyndon B. Johnson Space Center under contract NAS9-15196. The basic features of this system are reviewed in Table 2.4. The models which were developed to represent the Boeing configuration in the risk analyses conducted here are listed in Appendix C. The data corresponding to the input variables of these models are found in Appendix E. As with the Rockwell models described above, the engineering and cost equations are presented in a unified format using the NASA WBS as a guideline.

TABLE 2.4 BOEING SPS CONFIGURATION AND CONSTRUCTION SCENARIO
• COMPOSITE STRUCTURE
• SILICON SOLAR CELLS
• CONCENTRATION RATIO = 1.0
• END-OF-LIFE POWER OUTPUT AT THE BUSBAR = 10 GW
• LEO FABRICATION AND PREASSEMBLY; FINAL ASSEMBLY AT GEO
• ELECTRIC CARGO ORBIT TRANSFER VEHICLE (SPS-POWERED)
• VERTICAL TAKE-OFF, TWO-STAGE WINGED HEAVY LIFE LAUNCH VEHICLE

The results of the cost-risk analysis of the Boeing configuration are shown in Figure 2.11. The Boeing cost-risk profile exhibits both the same modest assessment of risk and the extreme sensitivity to changes in input variable distributions that the Rockwell cost-risk profile does. The expected value for the Boeing configuration TFU is about $40 billion (1977 dollars) with a minimum value of about $25 billion. However, if the high-side risk for the solar cell parameters (specific cost, mass and efficiency) is changed to reflect the previously cited Arthur D. Little, Inc. analysis of worst values for space-qualified, mass-produced silicon solar cells, leaving the best and most likely values unchanged, the expected value for TFU cost increases by more than a factor of two. The implications of this extreme sensitivity to alternative assessments of the current state-of-knowledge is discussed below.

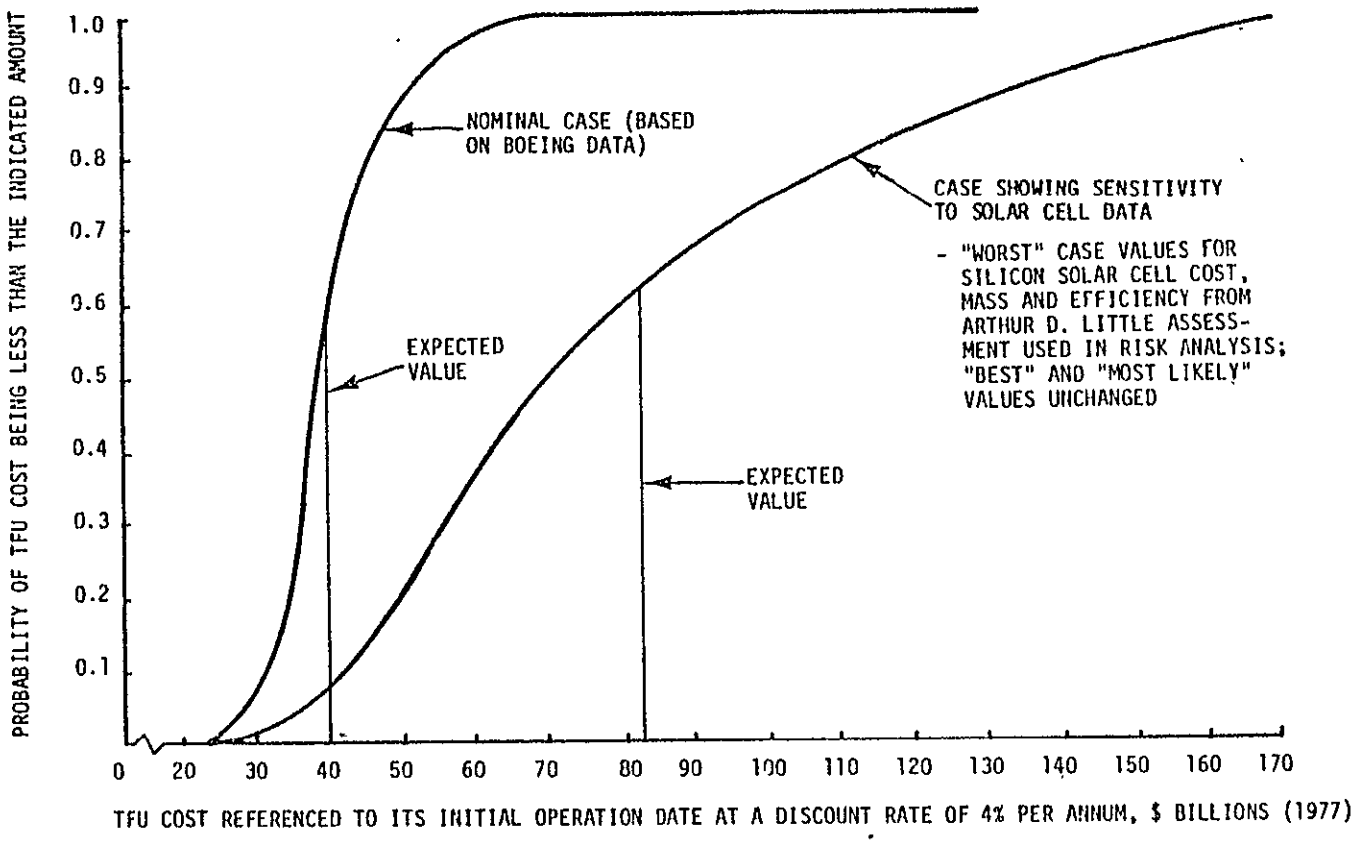

FIGURE 2.11 BOEING SPS CONFIGURATION COST-RISK PROFILE

A critical technology assessment was conducted on the Boeing configuration in the manner described above (see the methodological description and review of the results of the corresponding analysis on the Rockwell configuration). Forty-nine parameters were identified as having potentially significant effects on system cost and risk. Thirteen of these parameters were determined to be major cost and risk drivers as a result of the critical technology assessment. These major cost and risk drivers are listed in Table 2.5. In addition to the solar blanket and microwave transmission system characteristics which were identified as major cost and risk drivers of the Rockwell system, the payload mass and the operations cost of the HLLV and the cost of electric thrusters for self-powered orbit transfer were identified for the Boeing configuration. Except for these latter factors, there is a complete overlap of the critical technologies identified for both systems.

Data were gathered to conduct two programmatic evaluations. The first program included a first phase of ground-based technology development, a second phase of flight testing using the Shuttle, a third phase consisting of the construction of a minimum cost commercial prototype using a Shuttle derivative instead of the HLLV and without tooling for full-scale commercial implementation until after the success of the commerical prototype. The second program differed in that the commercial prototype was built using the HLLV and the space bases that would then be used to build the entire fleet of SPS satellites, that is, in the second program, development of the HLLV and the space construction facilities occurs before the building of the commercial prototype satellite. When these two programs were analyzed, there was found to be no significant difference between them. This result is probably due to the fact that the cost savings of not developing an HLLV earlier was largely offset by the higher transportation costs incumbent with the use of a Shuttle derivative instead. Similar offsetting costs

TABLE 2.5 THE EFFECT OF COST AND COST RISK* OF CHANGES IN THE STATE-OF-KNOWLEDGE OF THE BOEING CONFIGURATION

MAJOR COST AND RISK DRIVING FACTORS	RANGE OF VALUES, $ BILLIONS (1977)					
	BEST		MOST LIKELY		WORST	
	MEAN COST	COST RISK	MEAN COST	COST RISK	MEAN COST	COST RISK
NOMINAL CASE			40.06	7.02		
SPECIFIC COST OF SOLAR BLANKETS	34.44	5.35	36.65	5.51	54.32	7.57
DC-RF CONVERTER EFFICIENCY	37.65	6.76	39.31	7.29	47.52	9.04
OPS. COST PER FLT. OF HLLV	36.18	6.19	39.23	7.42	44.46	7.54
RATIO: COST OF RECTENNA PRIMARY STRUCTURE TO POWER THROUGHPUT	36.60	7.48	38.13	6.91	44.41	7.32
ANTENNA POWER DISTRIBUTION EFFICIENCY	36.76	6.08	38.18	6.96	44.13	8.34
BEAM COLLECTION EFFICIENCY	37.74	6.68	38.91	7.78	43.46	7.86
RECTENNA POWER DISTRIBUTED EFFICIENCY	37.69	6.98	39.83	7.30	43.26	8.34
MASS OF HLLV PAYLOAD TO LEO	37.10	6.48	39.98	7.35	42.31	7.95
RATIO: COST OF SELF-ORBIT TRANSFER THRUSTERS TO SATELLITE MASS	38.17	7.29	39.50	7.42	43.19	7.83
SOLAR CELL EFFICIENCY	38.69	6.96	39.54	7.18	43.61	8.93
RF-DC CONVERTER EFFICIENCY	38.37	6.78	39.59	7.45	43.21	7.78
PHASE CONTROL EFFICIENCY	39.37	6.41	38.76	7.14	44.17	8.44
RATIO: COST OF GRID INTERFACE PROVISIONS TO POWER THROUGHPUT	38.58	7.64	40.12	7.63	43.12	7.89

* "COST RISK" IS THE STANDARD DEVIATION OF THE COST ESTIMATE

occurred in the area of space construction. Owing to the fact that there is no real difference between the expected value of the two programs, only the results of the anlaysis of the second program, which corresopnds more closely to the Rockwell program for purposes of comparison, will be presented here. This second Boeing development program is represented as a decision tree in Figure 2.12. The expected value of the program is substantial and positive ($570.5 billion (1977) present value as of January 1, 1980), for the same reasons as pertained to the Rockwell program. To wit, the modest assessment of system risk and the low discount rate applied in this analysis combined to produce virtual certainty of success at each decision point. It should be noted that the low discount rate used in this analysis is appropriate only if a valid risk assessment has been conducted. This requirement is described in further detail in Section 3.

2.4 Comparison and Conclusions

The cost-risk profiles of the Boeing and Rockwell configurations are compared on an installed cost basis in Figure 2.13. An unthoughtful examination of the data presented in these cost-risk profiles would lead one to the conclusion that the Boeing configuration is very likely to be the less costly alternative. In fact, the cost differences are not likely to be statistically significant and are likely to be due to differences in the people who made the estimates. This is a type of "calibration" error described in an important article by Harrison [1]. Whereas it is important to model systems such as SPS at an appropriate level of detail so that the basic probability assessments being conducted are done so on a level that is easily grasped by the participants, it is precisely this practice which, according to Harrison, "opens up the possibility of series error through unwarranted independence assumptions." Harrison concludes, "Whenever an analyst does things right, I believe that he must worry to some extent over the potential effect of the decision

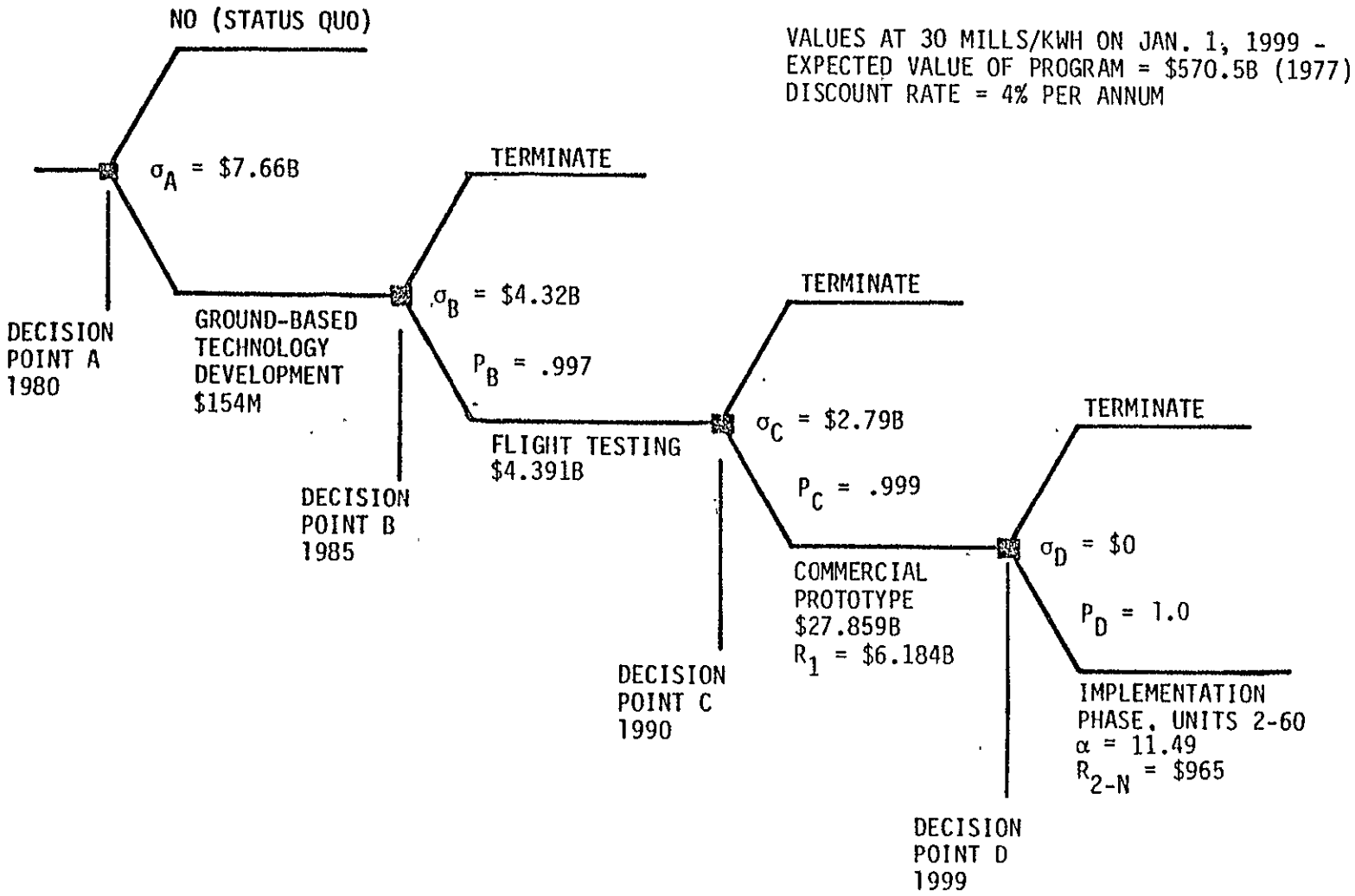

FIGURE 2.12 DECISION TREE FOR THE BOEING SPS DEVELOPMENT PROGRAM

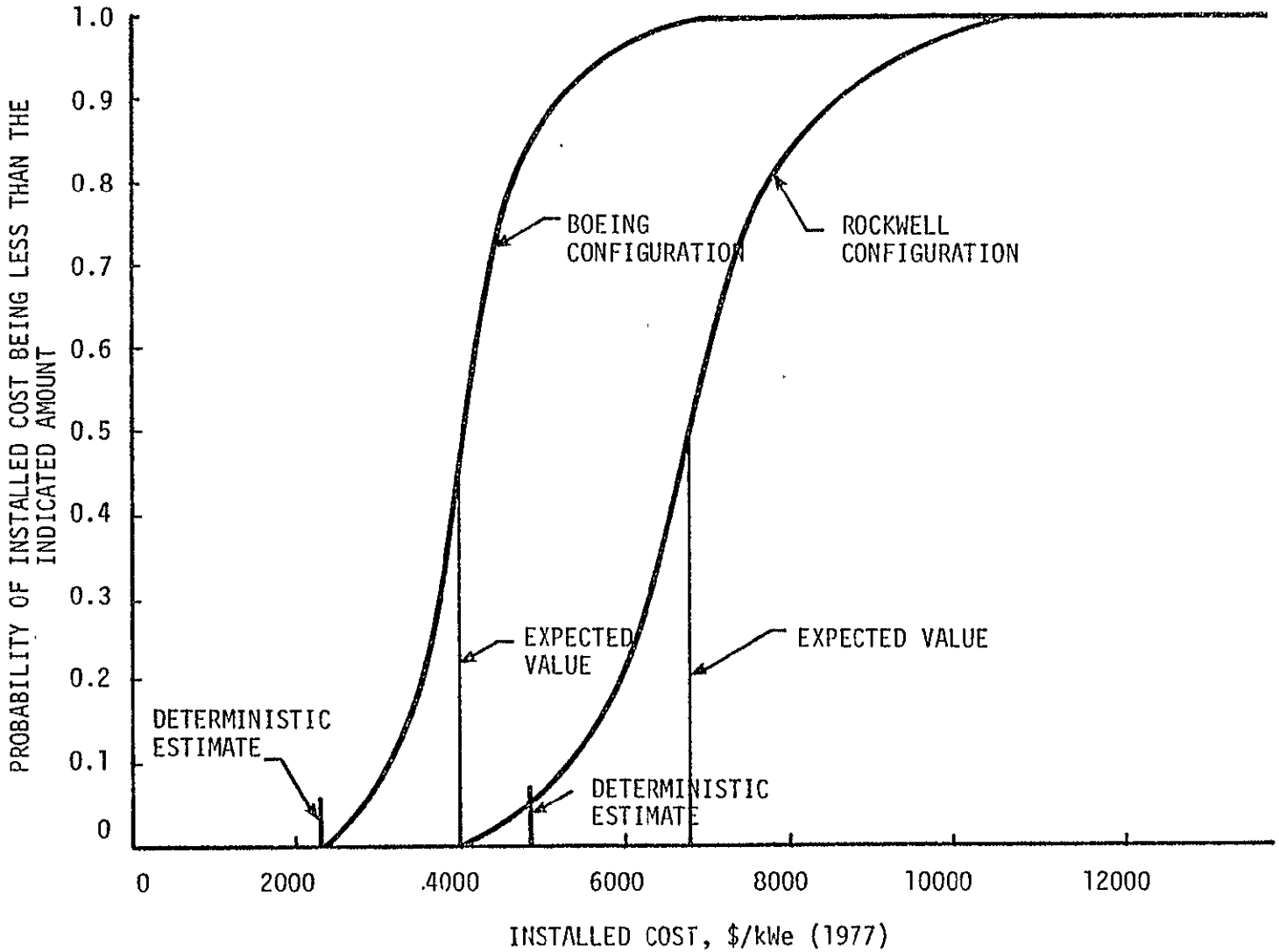

FIGURE 2.13 TFU COST COMPARISON OF BOEING AND ROCKWELL SPS CONFIGURATIONS

maker's uncertainty about his own calibration." The fact that the "critical" technologies are much the same for both configurations and that cost-risk analyses of both configurations exhibit extreme sensitivity to alternative assessments of the current state-of-knowledge tends to support the conclusion that much of the difference between the cost estimates presented here is actually due to calibration errors among the individuals making the underlying estimates. Consequently, it would be highly desirable for a panel of experts to be established to support the development of consensus on the basic technical and economic issues underlying a cost estimating procedure such as that required for SPS. It is also highly desirable that such a panel have available the services of an economist or operations research scientist to assure that a consistent, mathematically correct framework is established within which to elicit expert opinion.

A second conclusion which can be drawn from an examination of Figure 2.13 is that, in spite of the substantial positive expected values calculated for both configurations above, neither configuration has a sufficiently high probability of being economic to justify commitment to an entire SPS development program prior to substantial reduction of existing uncertainties. This can be accomplished with further studies, analyses and technology programs which, at the proper level, appear economically justifiable under the existing state of uncertainty. Economically successful SPS development will depend upon successful completion of the various component technology programs. It should be noted that the deterministic estimates of the cost of the two systems lie at the tip of the low-side tail of the cost-risk profiles for the two systems. Further, both cost-risk profiles demonstrated considerable sensitivity to alternative expert estimates of the current high-side risk on solar cell parameters. These continue to remain inconsistencies in the evaluation of system costs and the risk analysis procedures

used by both NASA contractors seem to fall short of properly evaluating the uncertainty existing in many, if not most, cost elements. If the uncertainty associated with other system parameters besides solar cell efficiency, cost and mass were equivalently evaluated, the cost-risk profiles may well turn out to be much "flatter" than even those shown above for the higher risk cases, with expected values possibly considerably higher than those shown in Figure 2.13.

The sensitivity of the programmatic evaluations to several of the assumptions on which the analyses are based was conducted. The expected value of the Rockwell program is charted in Figure 2.14 as a function of both the assumed rate of escalation for the price of power and the rate of learning applied to the costs of successive SPS units. It is clear from this figure that the economic value of SPS programs is extremely dependent upon both of these factors. Consequently, the value of information provided by the next phase of SPS development will be highly dependent upon the expected price of power and the rate of power price escalation in the year 2000 and beyond. Furthermore, if rates of learning as high as the 90 percent learning curve assumed in the programmatic evaluations here or higher are to be used, justification will have to be forthcoming in terms of production scenarios and techniques which allow for such learning from unit to unit. A more conservative 95 percent learning relationship substantially reduces the expected value of the program, and as the assumed rate of power price escalation declines, the value of the program actually becomes negative. Another assumption underlying the programmatic evaluations which was examined was the implementation rate; however, this factor was found to have very little effect on program expected value compared with the effect of the assumed rates of learning and power price escalation.

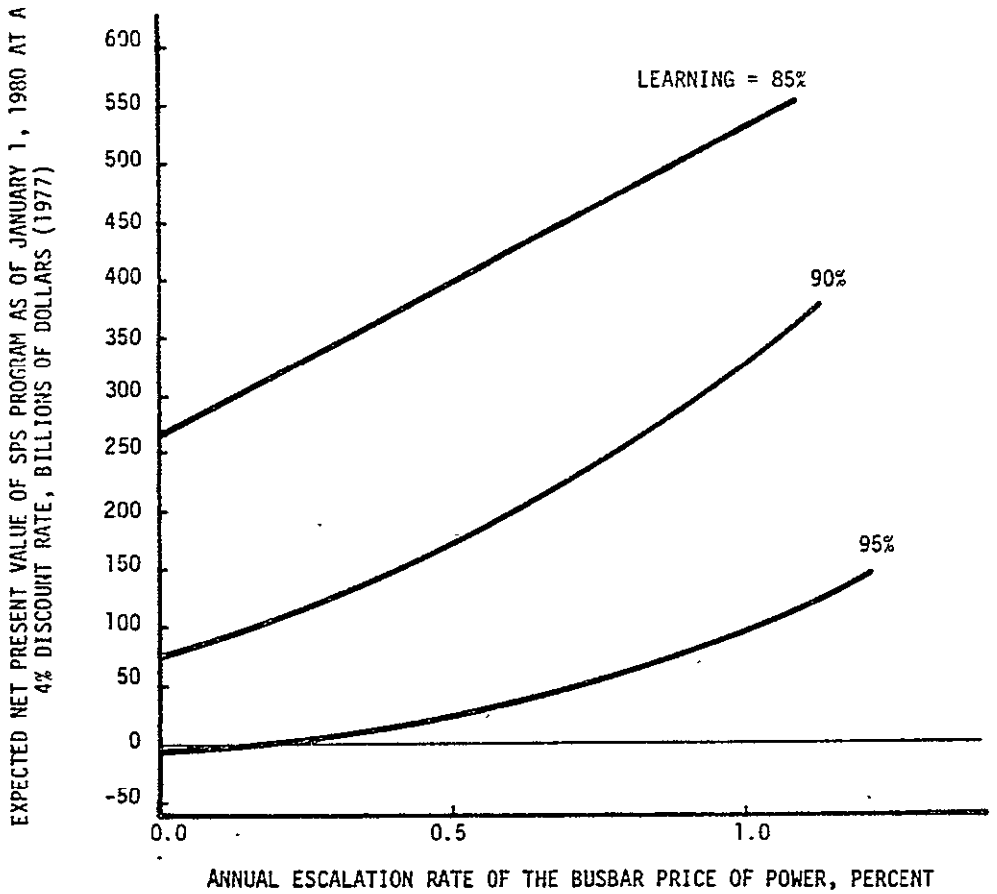

FIGURE 2.14 EXPECTED NET VALUE OF THE ROCKWELL SPS PROGRAM VS. ASSUMED RATES OF LEARNING AND PRICE OF POWER ESCALATION

3. THE PROPER RATE OF INTEREST FOR USE IN SPS SYSTEM DEFINITION STUDIES

The social rate of interest, or the discount rate, is a key parameter in the optimization of SPS system design. It is also a widely misunderstood and misused parameter. The purpose of the work reported here is to establish and substantiate a recommended rate of interest for use in SPS system definition studies.

Several theorists argue that the social rate of time preference is the relevant parameter in advocating the social rate of discount. Most economists, however, recognize private sector rates of return as opportunity costs for government investment. Such arguments have led to the recommended 10 percent rate by the Office of Management and Budget (OMB).

In light of recent private sector performance, a 10 percent rate appears considerably too high. Figures 3.1 and 3.2 show some bond yield and interest rate statistics for the 20th century (Figure 3.1) and over the last 13 years (Figure 3.2). The important point to notice is that the nominal rates in the late 1960s and early 1970s are high--higher than those which have prevailed historically--but the real rates have remained consistent with or lower than historical levels. In looking for a "true" measure of the cost of capital to the government, as argued by Stockfisch [2], it would be hard to find a better candidate than the return on treasury bonds, the vehicle by which the federal government finances its debt. Since 1965 the real rate of return on treasury bonds has not exceeded 2.5 percent per year. On the other hand, however, since OMB's recommended rate was based in part upon evidence of industry performance records, it is also appropriate to examine this performance over the last several, inflation-ridden years.

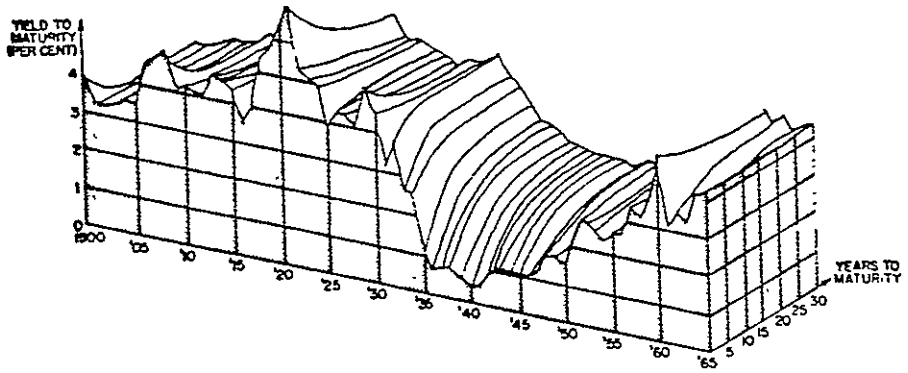

FIGURE 3.1 BASIC YIELDS OF CORPORATE BONDS BY MATURITY, 1900-1965 (SOURCE: MALKIEL, BURTON GORDON, THE TERM STRUCTURE OF INTEREST RATES: EXPECTATIONS AND BEHAVIOR PATTERNS, PRINCETON UNIVERSITY PRESS, PRINCETON, NEW JERSEY, 1966, p. 9)

The only data available for examination of industry performance are profit and loss statements which have been prepared in accordance with Internal Revenue Service guidelines. These guidelines dictate the use of current dollar values for tax accounting. Furthermore, they were established during and for a period of relatively low inflation and no particular care was taken to assure that they would provide an accurate measure of real (corrected for inflation) performance. But the objective here is, in fact, to establish real performance. Hence, these profit and loss data must be adjusted to account for the distorting effects of inflation on real performance as measured by the profit and loss statements prepared under IRS guidelines. Thus, the bulk of the discussion below centers on identifying the distortions which inflation causes in reported corporate performance and the correction of these distortions to yield real performance data. It is not the intent here to criticize or even critique the IRS guidelines, but merely to adjust the available data to correct for inflation.

3.1 Methodological Background

3.1.1 Depreciation, Capital Formation and Inflation: Nominal Versus Real Depreciation

Depreciation is an artificial acounting tool whereby the costs of physical assets acquired in one accounting period are spread over subsequent accounting

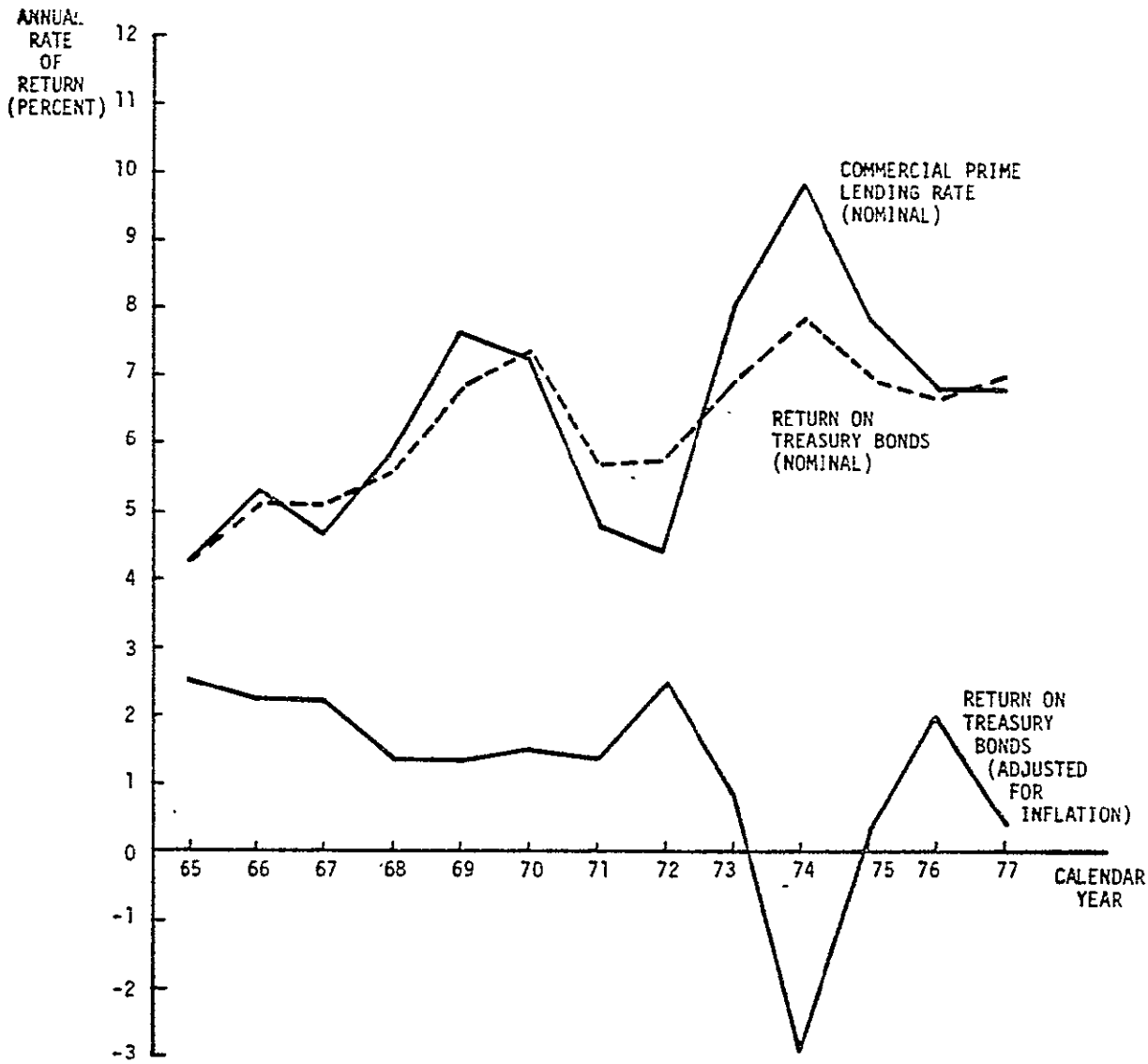

FIGURE 3.2 NOMINAL INTEREST RATES, NOMINAL AND REAL TREASURY BOND YIELDS, 1965-77

periods according to the "useful" lifetime of the assets. For example, a firm spends $30 million in 1975 for new machinery that will be in use for ten years. The money is spent in 1975, but the machinery is not used up in the process of generating 1975 production. Depreciation allocates the $30 million investment against the production revenues that will be obtained over the ten years the machinery is used.

Depreciation thus allows the recovery of funds to make up for the initial investment of resources. Depreciation is a valid "cost" in measuring corporate performance in a current year, whether or not the recovered funds are actually used to replace the asset at the end of its useful life. Asset values not yet depreciated are carried forward to future years. The concept of depreciation is recognized in U.S. tax law and procurement regulations, which define depreciation broadly as a "reasonable deduction" for the wear-and-tear on capital stock in a given accounting period. Funds recovered by such deductions should assure the corporation of the opportunity to make a similar investment at the end of the useful life of the asset.

Figure 3.3 describes the current accounting procedures invovled in the acquisition of additional capital stock. In this example, a firm acquires $30 million worth of new machinery. Of the total, $10 million is funded through depreciation. The remaining $20 million is funded half by debt ($10 milion) and half by issuing new shares to raise equity ($10 million). Had there been no inflation over the past ten years, $10 million worth of the newly acquired machinery would replace equivalent machinery bought ten years ago at a cost of $10 million. The other $20 million would be correctly measured as added capital stock, providing new capacity for corporate growth. This is the way U.S. accounting rules determine depreciation and new capital formation--without regard to inflation. Obviously, these

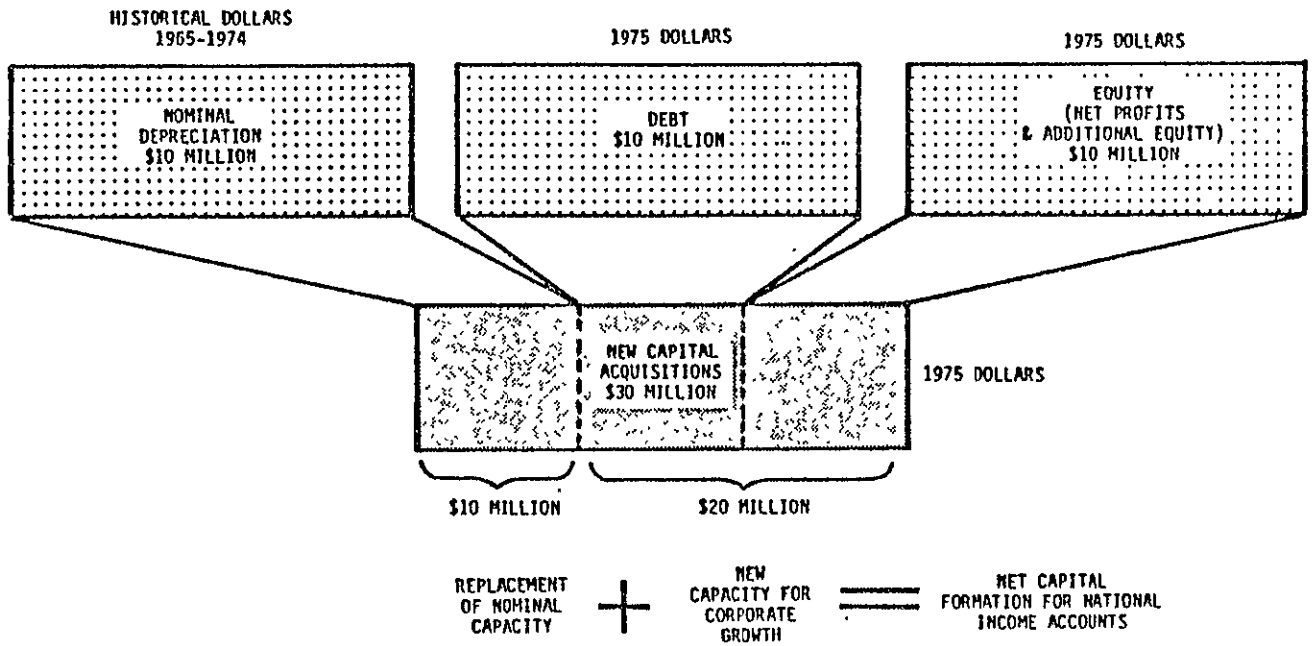

FIGURE 3.3 EXAMPLE OF CURRENT ACCOUNTING PROCEDURES FOR FUNDING NEW CAPITAL ACQUISITIONS

accounting rules and regulations were formulated during a period of monetary stability.

When one looks at the same transaction and assumes a 10 percent annual rate of inflation, a completely different picture emerges. Table 3.1 illustrates the effect; it shows the follows:

Column A: The ten years of the asset history.

Column B: The annual nominal depreciation under existing U.S. accounting procedures. In this case the straight line depreciation methods is employed and depreciation is listed at $1 million a year, or one-tenth of the original value of the $10 million worth of machinery acquired ten years ago.

Column C: The reacquisition cost of the asset at the end of each year, assuming a 10 percent rate of inflation. After ten years it would cost $25.9 million to replace the original $10 million worth of machinery.

Column D: Depreciation computed on the basis of the reacquisition cost in Column C rather than on the original cost. (Other methods suggest that the price the corporation might realize for the machinery on the market could be used as a depreciation base.)

Column E: The overstatement of profits resulting from the use of nominal rather than real depreciation costs. Over the ten year period, the corporation will report a total of $7.6 million in profits which are not really profits; they are in fact part of the cost of capital, that is, depreciation.

Column F: The corporate income taxes on that portion of the profit that has been overstated due to the use of nominal depreciation charges. Over the ten years the corporation will pay $3.6 million in taxes on profits which in fact do not exist.

Column G: The dividend distributions that the corporation will make, based on overstated profits. The 27 percent figure roughly represents available dividend taxes and retained profits.

Column H: The retained portion of the overstated profit, amounting to a total of $1.9 million over the ten-year span.

Had there been no inflation during the period covered in the table, each of the columns D through H would "zero out." The fact that positive entries are shown is due to the illusory effect of inflation when capital assets are evaluated in terms of original costs.

TABLE 3.1 FINANCIAL HISTORY OF A CAPITAL ASSET--TEN YEAR USELIFE (MILLIONS OF DOLLARS)

ASSUMPTIONS Acquisition price $10
Expected uselife 10 years
Rate of inflation 10 percent annually
Corporate income tax 48 percent
25 percent of profits before taxes retained; balance distributed

A	B	C	D	E	F	G	H
Year	Depreciation 10% Annually	Reacquisition Cost Calculation		Overstated Profit D–B	Corporate Income Tax 48% on E	Distributed Overstated Profit 27% on E	Retained Overstated Profit 25% on E
		Asset Price 10% Inflation	Depreciation 10% on C				
1	$ 1.0	$ 11.0	$ 1.1	$ 0.1	$ .048	$ .027	$ .025
2	1.0	12.1	1.2	0.2	.096	.054	.050
3	1.0	13.3	1.3	0.3	.144	.081	.075
4	1.0	14.6	1.5	0.5	.240	.135	.125
5	1.0	16.1	1.6	0.6	.288	.162	.150
6	1.0	17.7	1.8	0.8	.384	.216	.200
7	1.0	19.5	2.0	1.0	.480	.270	.250
8	1.0	21.4	2.1	1.1	.528	.297	.275
9	1.0	23.6	2.4	1.4	.672	.373	.350
10	1.0	25.9	2.6	1.6	.763	.432	.400
Σ	$10.0	$ na	$ na	$ 7.6	$3.600	$2.100	$1.900

TEN YEAR SUMMARY: Reacquisition price $25.9
Total overstated profit $7.6
Tax paid on overstated profit $3.6
Distributed overstated profit $2.1
Total cash outflow due to overstated profits $5.7

na Not applicable

In summary, the table shows:

- An overstated profit of $7.6 million
- Payment of $3.6 million in corporate income tax on the overstated profit
- Distribution of $2.1 million in dividends
- "Equity" amounting to $1.9 million in retained profits.

Figure 3.4 shows the new picture of the transaction that emerges when real cost accounting, which considers the 10 percent inflation factor, is employed. To maintain its productive base by replacing the original $10 million worth of machinery, the corporation now has to lay out $25.9 million. Thus, in investing the

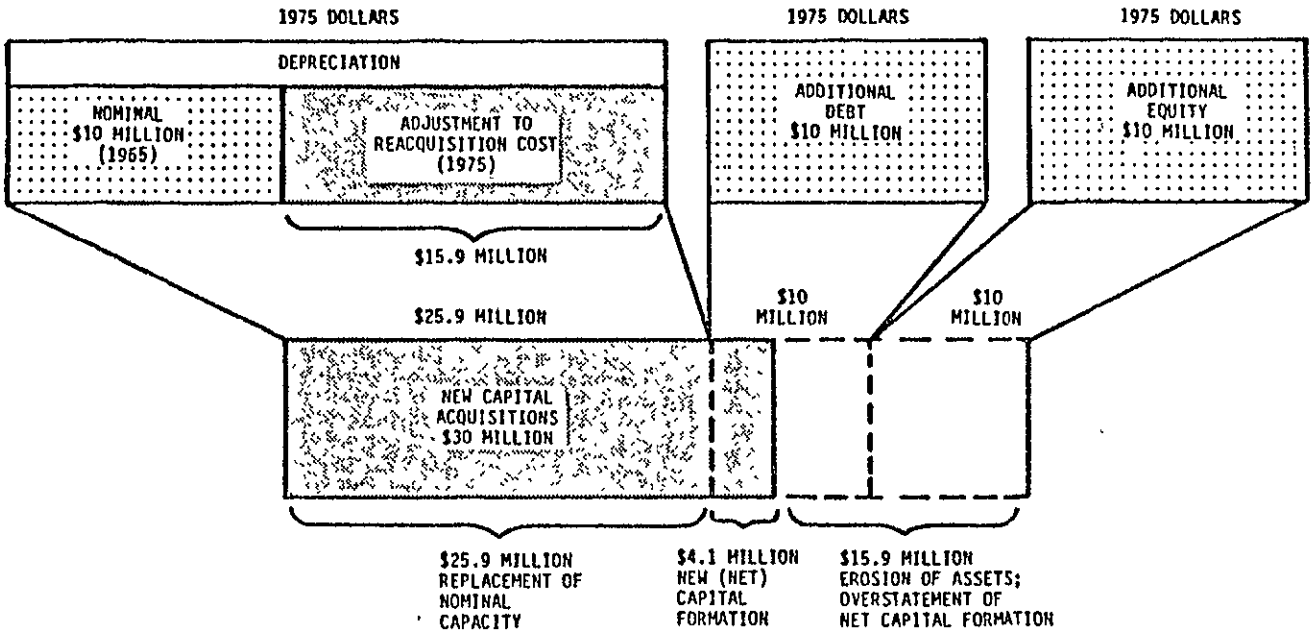

FIGURE 3.4 EXAMPLE OF REAL COST ACCOUNTING PROCEDURES FOR FUNDING NEW CAPITAL ACQUISITIONS (ASSUMING 10% INFLATION AND 10-YEAR USELIFE)

earlier-mentioned $30 million, the corporation incurs $10 million in new debt and has to issue new shares for $10 million, but $25.9 million of the $30 million goes to replace the original $10 million worth of 1965 vintage machinery. Only $4.1 million is net added investment. The new financing needed in addition to available depreciation funds to replace the 1965 machinery--$15.9 million--represents an erosion of corporate assets. Where the prices of products are also determined by "historical" costs, or by government-regulated pricing procedures (exemplified by public utilities, Department of Defense, the National Aeronautics and Space Administration, and the Department of Energy), investments for maintaining the capital base for the production of these products cannot be continued for long.

The current U.S. practice of historical depreciation causes extensive distortion in the accounting process. Real depreciation, based on reacquisition costs, must be used to insure a correct reflection of market principles and prices.

3.1.2 Monetary and Real Capital

In the minds of the public and also of some economists, the term capital denotes wealth, posessions, money, plant and equipment. However, in the context of capital and capital formation in an economic system, two fundamentally different terms of "capital" have to be distinguished:

- Real capital denotes physical goods in the form of machinery, plant and equipment which are used with labor to produce goods and services. Since these items are quite often used beyond a single accounting period--say one year--the term durable goods is often used synonymously for real (production) capital.

- Monetary capital denotes simply any accumulation of paper bills or entries on banking accounts which convey purchasing power or potential title to dispose of resources, that is, labor, equipment, plant or consumer goods.

Even though in market economies, except in times of crisis, monetary capital can readily be exchanged into real capital through purchases, the two terms are

strictly different. When account entries cannot be changed into paper bills and paper bills cannot be transformed into goods and services, the crucial distinction between real capital and monetary capital is clearly discernible.

Monetary capital can instantly be transferred worldwide at little cost. On the other hand, real capital in the form of equipment, plants, transport fleets and networks may take months, years or decades to transfer, and some forms of real capital, such as interstate highways and other "fixed" investments, can never be transferred. This distinction is most apparent today in the Organization of Petroleum Exporting Countries. While highly endowed with financial capital amounting to billions of dollars, it is extremely difficult--if not impossible--for them to obtain real capital within their boundaries. During the years in which this transfer of real capital is taking place, they hold only paper or account entries.

These distinctions between monetary and real capital are emphasized because of their importance in understanding real capital formation in any economic system. Monetary savings in an economic system is not the same as real capital. Real capital is formed only if new plants and equipment are produced, procured and put into productive use. While accumulation of monetary capital can be equated with savings, there is no reason why such savings must lead to the creation of real capital--an assumption all too readily made by macroeconomists. Such savings may be diverted into the public sector and may be used instead for defense expenditures, local, state or federal government services or lost by inefficiencies in nonmarket services.

3.1.3 Interest, Debt, Equity and the Cost of Capital

In the context of determining the "true" profitability of firms in an economy with inflation, several factors have to be considered before interfirm comparability

of real rates of return are possible--in addition to the depreciation cost adjustment. First, the debt to equity ratio between firms can vary widely. While the debt and equity structure of the firm simply has to do with the ownership of the enterprise--a matter of book entries and legal documents having little if anything to do with the substantive flow of resources and revenues to the firm--this differing ownership structure is recognized in a totally distorted and misleading way in today's U.S. accounting and tax practices: interest paid on debt, that is the cost of outside financing, is recognized as a cost, while the interest cost on the equity portion is treated as profit--that is, as if provided to the firm "free of charge." This leads to seriously distorted profit and loss reports from firms that in fact (that is, in substance, real flow or resources) show identical performances. A firm financed 100 percent by equity may show a profit of 9 or 10 percent on its account while the identical firm financed 100 percent by debt could show zero profit--or even a loss--depending on the conditions at which it can obtain financing. In the former case the firm would have the "privilege" of paying corporate income tax on its "profit," while in the latter case no tax liability to the firm arises. This in turns leads to an overdue emphasis of "self-financing" through retained profits as well as an overexpansion of investments by firms that are heavily equity financed.

The economically correct way of accounting for profit is to allow also for an interest cost for the equity portion of a firm's financing, something long and widely advocated and implemented, for example, in German Cost Accounting Standards. To correct for this arbitrary distortion in U.S. accounting procedures, the total fixed charges (that is, interest payments and related expenses) are added back into gross profits before calculating rates of return on assets irrespective of the financial structure of firms. Through this method, the real gross rate of return on

total assets for each firm, and for each sector of U.S. industry, is calculated in the program used in this study.

Second, in addition to depreciation cost adjustment and the adjustment for fixed charges, other losses occur to any firm in an inflationary economy: to the extent that any firm needs a minimum of monetary assets to conduct its business these nominal, monetary holdings are subject to the erosion of inflation. In the calculations performed it is assumed that the monetary asset structure of firms is efficient in the sense that no substantial reduction could be obtained in those monetary assets without endangering the conduct of business by that firm. This simplifying assumption has to be made for purposes of this analysis; otherwise each firm would have to be analyzed case by case to determine the optimum monetary asset balances needed and it would only be on those optimum balances that losses due to inflation could and should be computed. This task is clearly beyond the purposes of this exercise.

Third, additional losses through inflation occur to the firm on inventories held by the firm again in the conduct of its business: the acquisition of inventories two or three months in advance of sales again leads to arbitrary, fictitious profits included in today's profit and loss account which would not be shown were it not for inflation. To determine the inventory-related fictitious profit a detailed analysis of each firm and its inventory structure would be needed. A fair approximation of the inventory-related fictitious profits can, however, be obtained by determining the turn-over rate of sales to inventories: the higher the turn-over rate, the smaller the inventory in relation to total sales transacted by a firm, and the smaller the inflation-related distortion of profits. With the adjustments of inventory losses by the turn-over rate of inventory, fictitious profits due to

inventory valuation were also adjusted for under the "fully impacted" earnings calculations for each firm, and for each sector of U.S. industry.

3.2 Results

The results of the inflation impact analysis show clearly that reported (nominal) returns by industry significantly overstate the real returns being earned. For example, in 1977 while reported annual returns on assets (ROA) were 12.9 percent (asset-weighted average for 1600 corporations in 25 industries), the actual return on assets was only 6.1 percent. Further, it was the asset owners, those who held equity in the corporations, who suffered the most due to inability to depreciate properly: while adjustments for inflation dropped ROA by 6.7 percent (roughly equal to the increase in the consumer price index), returns on equity fell from 12.1 percent down to 1.2 percent when adjusted for inflation. Clearly the lenders are only feeling the first-order effects of inflation while the equity holders are bearing the brunt of the inadequate asset-depreciation burden. The disturbing results found in terms of real rates of return on equity is an additional finding that, for purposes of this analysis, can be ignored but which, in a larger context, has to be addressed in economic accounting and tax practices. One should not, however, advocate such low or even negative rates of return for purposes of evaluating public investment projects. The rates of return on assets are the relevant results and these indicate real interest rates of about 6 percent, as stated.

Table 3.2 shows actual and reported earnings and returns on assets and equity for 25 industries for 1977. In general, nominal returns on assets deviate from the actual by approximately the rate of inflation, while returns on equity were more severely affected. Table 3.3 shows actual returns on assets and equity for the 25 industries for 1974-77 and real return rates on treasury bonds for those same years.

TABLE 3.2 REPORTED AND ACTUAL (FULLY ADJUSTED FOR INFLATION) PERFORMANCE RECORDS BY INDUSTRY FOR 1977 FOR 1600 COMPANIES

INDUSTRY	PERFORMANCE RECORDS (MILLIONS OF DOLLARS OR PERCENT PER YEAR)					
	REPORTED EARNINGS ($)	ACTUAL EARNINGS ($)	REPORTED RETURN ON EQUITY (%)	ACTUAL RETURN ON EQUITY (%)	REPORTED RETURN ON ASSETS (%)	ACTUAL RETURN ON ASSETS (%)
AGRICULTURE	2.92	-0.75	5.69	-0.86	9.03	4.47
MINING	13.51	0.97	6.72	0.29	8.20	3.88
DRILLING AND EXPLORATION	24.89	7.10	14.47	2.40	17.96	9.97
BUILDERS AND CONSTRUCTION	17.33	7.01	16.55	4.27	12.69	7.59
FOOD	32.22	13.38	13.02	3.50	14.69	8.46
TOBACCO	129.11	92.12	14.44	8.37	15.38	12.21
TEXTILE AND LUMBER	17.56	1.38	11.83	0.49	12.59	4.84
PRINTING	18.53	9.73	14.59	5.72	18.47	12.02
CHEMICALS AND DRUGS	63.24	23.50	14.54	3.42	15.14	8.19
REFINING AND ROOFING	293.22	28.15	13.33	0.68	18.11	9.15
RUBBER AND PLASTIC	14.03	-4.90	9.25	-1.81	11.22	4.34
GLASS, CLAY AND CEMENT	22.84	2.58	12.70	0.76	11.99	4.87
IRON AND STEEL	11.08	-35.79	2.83	-4.00	3.56	-1.23
HARDWARE	8.08	1.09	14.15	1.13	15.19	6.92
MACHINERY	45.74	15.80	16.44	4.14	17.87	10.38
ELECTRIC	28.92	8.31	15.06	3.04	14.32	8.11
CARS, TRUCKS AND AIRCRAFT	79.13	32.12	16.43	4.38	16.19	9.41
INSTRUMENTS	35.53	19.00	14.70	6.03	18.52	11.96
JEWELRY AND TOYS	6.72	0.40	12.06	0.46	14.52	7.17
RAILS	84.22	15.82	8.64	0.72	7.61	3.08
TRANSPORTATION	17.29	-7.20	13.46	-2.41	9.54	2.19
COMMUNICATION	232.13	-30.51	12.00	-0.51	11.35	3.54
UTILITIES	49.98	16.04	11.28	1.37	9.70	4.81
WHOLESALE	10.05	3.73	14.60	3.80	12.68	7.92
RETAIL	20.34	6.90	12.80	2.69	12.81	7.16

TABLE 3.3 ACTUAL RETURNS ON ASSETS, EQUITY AND REAL RETURNS ON TREASURY BONDS, 1974-77

	RETURN ON ASSETS*	RETURN ON EQUITY*	RETURN ON TREASURY BONDS
	PERCENT PER YEAR		
1974	6.3	0.5	-3.0
1975	5.1	-0.6	0.3
1976	5.9	1.1	2.0
1977	6.1	1.2	0.4

*ASSET-WEIGHTED AVERAGES FOR 25 INDUSTRIES.

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Based upon these considerations, the use of a 10 percent discount rate is clearly unwarranted for the evaluation of long-term projects, that is, projects for which the return on investment is realized many years into the future. High discount rates strongly favor the selection of short-term projects and nearly doom competing long-range projects, despite the potential benefits offered. When risks have not been properly accounted for (for example, the risk that a component may cost ten times as much as estimated, or the risk that the system will not work at all), it has been argued that the use of a high discount rate such as 10 percent is justified as a type of risk premium, accounting for the improper or incomplete assessment. This point underscores the need for the use of proper risk assessments in the evaluation of long-range energy R&D, for such projects cannot bear the burden of the higher discount rate.

Given that the 1 to 6 percent range established above is rather wide, where within this range would one advocate as "the" social rate of discount? As treasury bonds are very liquid and compete with regulated bank interest rates, their rates of return might be somewhat too low. On the other hand, return rates on corporate assets contain a risk premium, probably beyond that which is appropriate for public project evaluation. Still further, Von Neumann [3] gave a mathematical proof that, in an expanding, linear, economic system, the real rate of interest is less than or equal to the real rate of technological growth of that system. As that proof has remained unrefuted since 1937, it stands as an argument for advocating a discount rate approximately equal to the growth rate of the economy, between 3 and 4 percent. The rate of interest thus recommended here for use in SPS systems definition studies is 4 percent, the midpoint of the range of 3 to 5 percent which represents the "resolution" of the results obtained above. It is important to note that this represents a "risk-free" interest rate, that is, that comparisons or

evaluations made using this rate should include an explicit risk assessment. The separate consideration of these two factors is demonstrated in an example below.

One of the major impacts of this recommended interest rate is that it enhances the economic value of all long-range energy RD&D, including SPS. In the evaluation of energy research, some of the benefits which result, particularly from research into long-range technologies, are realized several decades from now. The use of high discount rates almost totally denies any value to pursuing such research, not only today but also in the future since the long lead times required between the earliest development and implementation will remain. As an example of the limitations which a high discount rate places upon energy R&D, consider two hypothetical projects, A and B, the former of which provides immediate returns with no risk and the latter of which provides returns which, while substantially greater in dollar value than the other project's, are offset in the future and are subject to uncertainty. This uncertainty in returns may derive either from uncertainties in the technical performance of the system or from uncertainties in the markets for inputs and outputs of the system. Figure 3.5 shows the comparison of the value of these two projects at a high discount rate (10 percent) and a lower discount rate (5 percent). The total area for Project B (both shaded and unshaded areas) shows the potential return of B, and if risk were not taken into account, Project B would clearly be more desirable than Project A at either high or low discount rates because its potential return exceeds that of Project A in both cases. However, as noted in the foregoing discussion, the issue of the effect of uncertainty on the value of a program should be dealt with separately from the effect of interest rates; consequently, it is the expected value of projects which must be compared, that is, the potential payoffs weighted by the corresponding probabilities of success. When the potential return of Project B is weighted by its

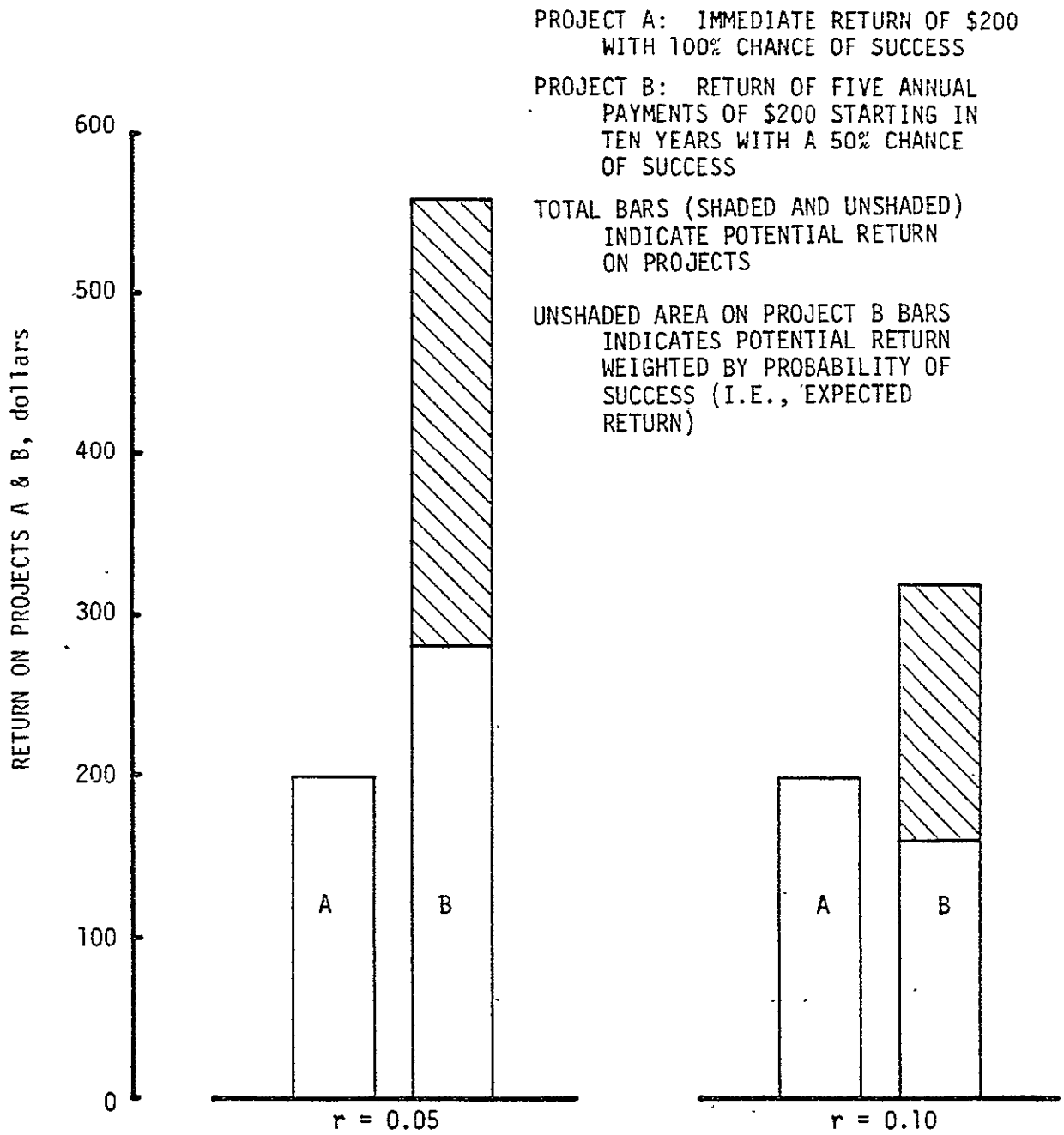

FIGURE 3.5 COMPARISON OF TWO HYPOTHETICAL PROJECTS SHOWING THE PENALTY IMPOSED ON FUTURE RETURNS BY A HIGH DISCOUNT RATE (r)

probability of success (50 percent), then Project B's expected value (unshaded area only) is lower than the expected value of Project A at a discount rate of 10 percent, in spite of the fact that Project B offers a return that is five times greater in (undiscounted) dollar value. Clearly, it is the high discount rate that makes Project B appear less desirable. When a lower discount rate (such as the 5 percent used in this example), appropriate for situations where risk is considered explicitly, is employed in the comparison, then Project B offers a higher return, even after risk has been accounted for.

A somewhat more realistic representation of the effects of different discount rates on the revenues (benefits) of an SPS implementation program is shown in Figure 3.6. Under the assumption of 120 five GW satellites, each having a lifetime of 30 years, being built at the rate of four satellites per year starting in 1996, and producing power whose price escalates in real terms at the rate of 1 percent per year, a revenue profile like the one shown in Figure 3.6 would be generated. Overlaid on this revenue profile are trajectories representing the ratio between the value of the revenue stream in a given year to its corresponding present value in 1980, at discount rates from 1 to 10 percent per year. The diagram demonstrates the dramatic effect that high discount rates have on the value of future revenues: for instance, in the first year that satellites are constructed (1996), any revenues accruing that year would be worth, expressed as a present value in 1980, only 20 percent of their value in 1996 at a 10 percent discount rate, whereas revenues from that year would retain over 50 percent of their value (again, expressed as a present value in 1980) at a discount rate of 4 percent. The situation is even more dramatic in 2026, the year in which the satellite fleet is completed, when only about 1 percent of the value of revenues from that year are reflected in a 1980 present value if discounted at 10 percent, whereas a still significant 16 percent of the

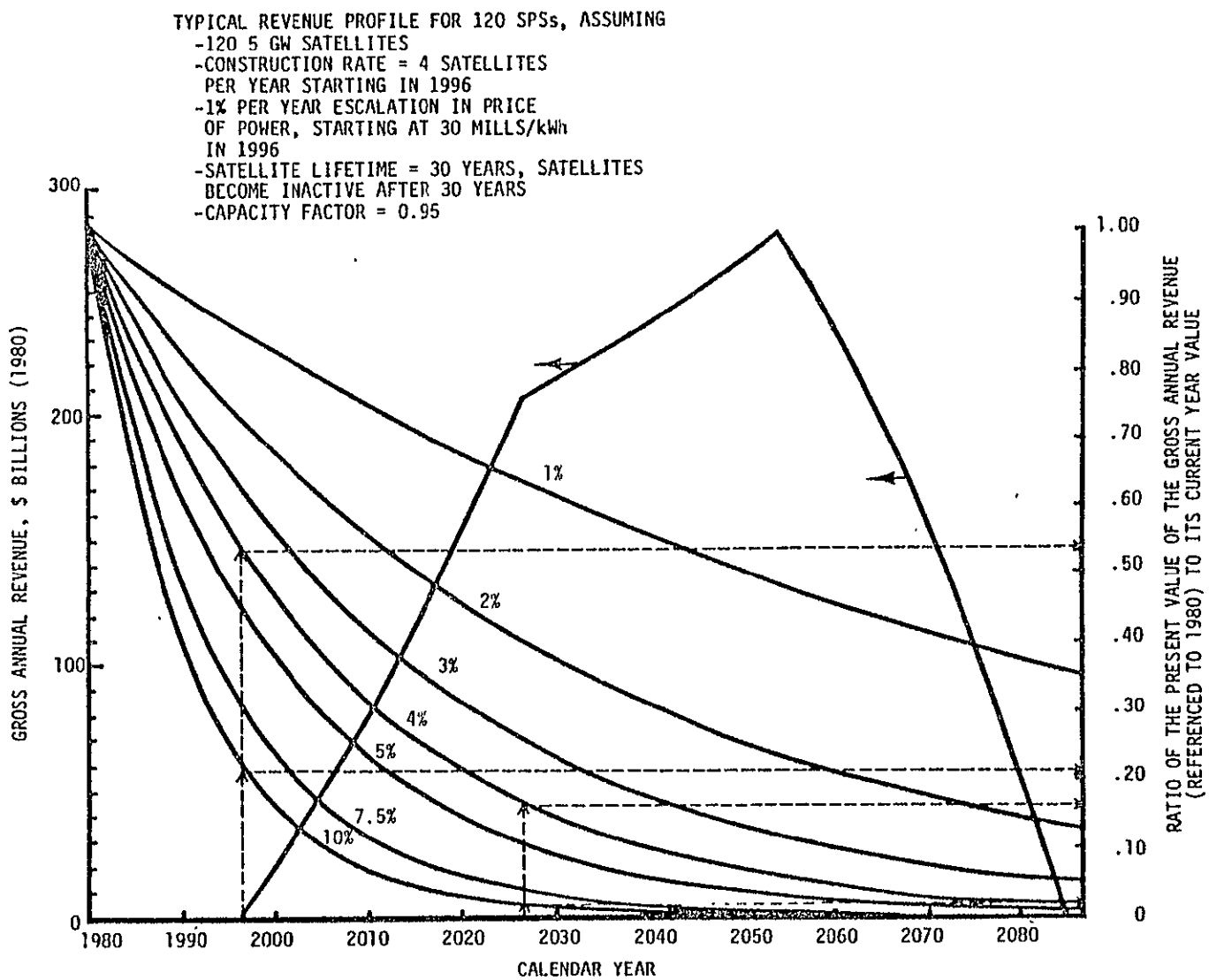

FIGURE 3.6 THE EFFECT OF DISCOUNT RATE ON THE PRESENT VALUE OF GROSS SPS REVENUES FOR 120 SATELLITES

value of the revenues would be reflected in a 1980 present value if discounted at 4 percent.

The effect described above of a larger percentage of revenues (benefits) "clearing the hurdle" of a lower discount rate is a major determining factor in the difference in expected values of an SPS program evaluated at different discount rates. The exponential nature of the discounting process, as reflected in the curvature of the trajectories of value in Figure 3.6, takes a particularly high toll when operating at high rates over the long period of time involved in the implementation of SPS. Another aspect of the exponential nature of discounting is that the "upfront" costs, such as satellite RDT&E, are less affected than the later occurring revenues in an exponential relationship to the discount factor owing to their relative proximity in time to the discounting reference point. This difference between the upfront costs and later revenues in terms of discounted values is shown in Figure 3.7. The "gap" which exists between the discounted sunk costs of the program and the discounted revenues constitutes the allowable discounted investment costs for the program. Clearly, the revenues are far more sensitive to the discount rate, occurring as they do much farther in the future. Consequently, the "gap" representing allowable costs narrows as the discount rate employed in evaluation increases.

To demonstrate the effect of different discount rates on the value of actual proposed programs, the Rockwell program which is analyzed in Section 2 was evaluated at a range of discount rates and the results are presented in Figure 3.8. As in Section 2, two cases have been analyzed: one using the original Rockwell TFU cost data, and a second using TFU cost data with the values for solar cell specific cost and mass modified to reflect a more uncertain state-of-knowledge on

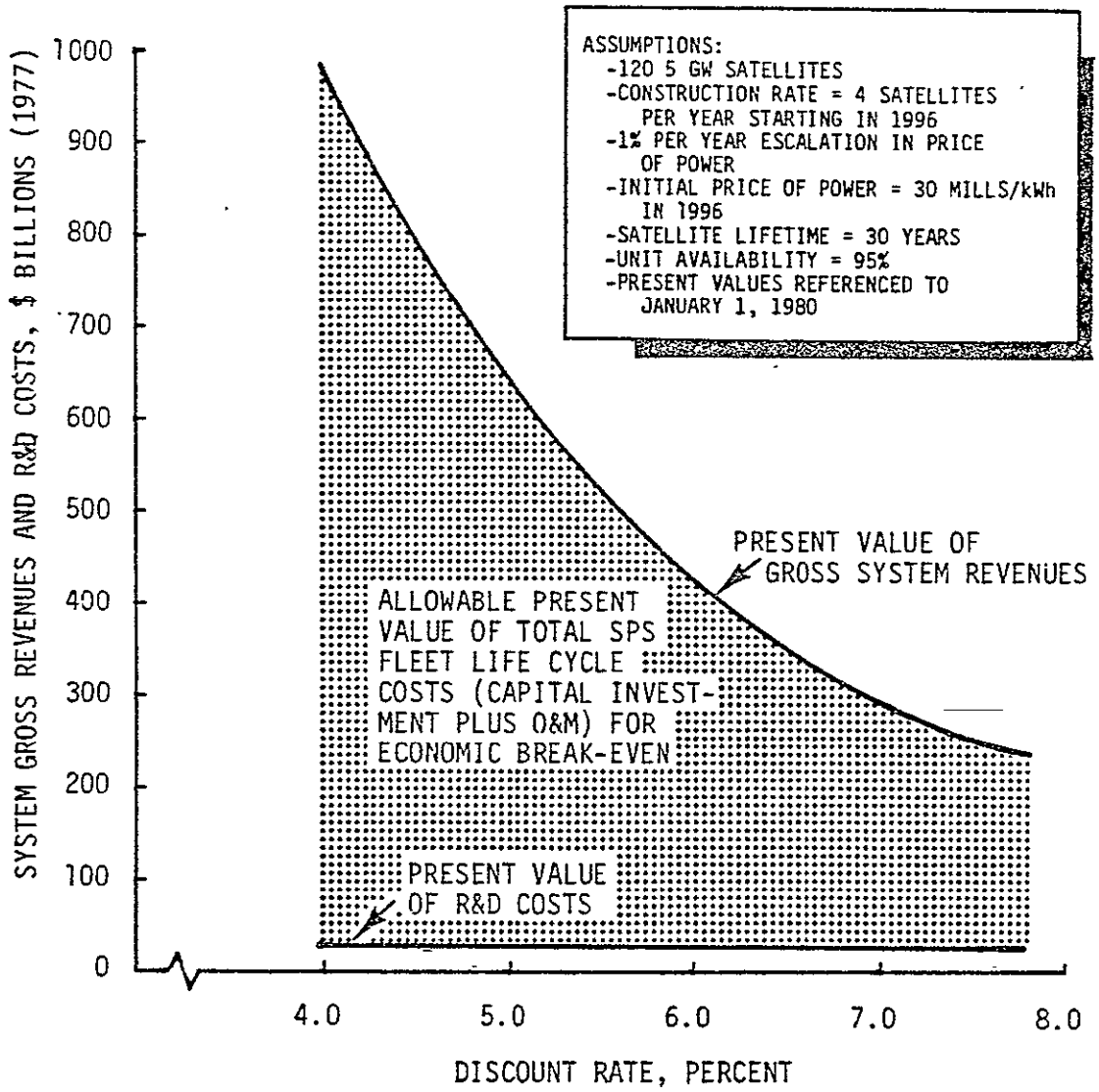

FIGURE 3.7 THE EFFECT OF DISCOUNTING ON THE ALLOWABLE PRESENT VALUE OF TOTAL SPS FLEET LIFE CYCLE COSTS FOR THE ROCKWELL PROGRAM

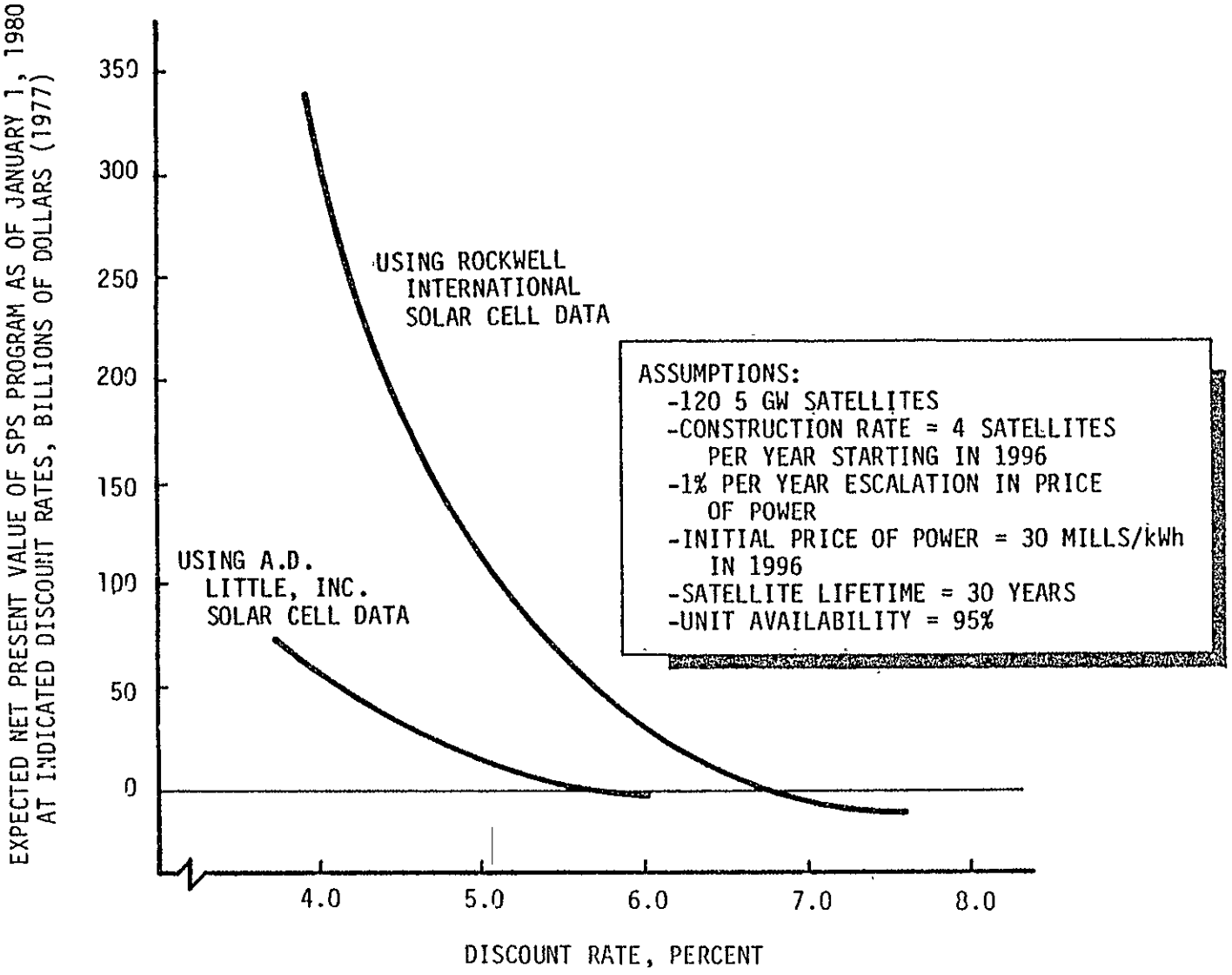

FIGURE 3.8 EFFECT OF DISCOUNT RATE ON EXPECTED NET VALUE OF ROCKWELL SPS PROGRAM

these parameters, based upon information developed by Arthur D. Little, Inc.* The substantial effect on program value, which was noted in Section 2, resulting from the increase in risk on these two parameters indicates a necessity for better solar cell data as a prelude to economic justification for the program if the program is to be evaluated at higher discount rates. Indeed the economic value of the program becomes clearly negative at inappropriately high discount rates. Whereas 4 percent is the discount rate which is recommended for SPS systems definition studies, this rate corresponds to a risk-free interest rate, and it is crucial that a proper assessment of risk be conducted, in order for the results being evaluated at a 4 percent discount rate to represent a valid assessment of the economic value of the program under consideration. This has been done here and, with the data supplied by the Rockwell and Boeing studies, evaluated at a 4 percent discount rate, an SPS program appears economically justified (note that noneconomic considerations are not taken into account here--these could either increase or decrease the desirability of an SPS program).

A second effect which the discount rate has on the value of a program is that it shifts the "prior distribution" of unit cost on which the decision analytic evaluation of the program is based. This occurs because the cost of each unit is incurred over some period of time prior to the initial operation date (IOD) of the system, and a cost of capital or interest rate is applied to these incurred costs so that the cost of an SPS unit which must be recovered during the operation of the unit includes the capital cost itself as well as interest charges on it. For the purposes of this study, the cost profile for each unit has been characterized as a

*"Space-Based Solar Power Conversion and Delivery Systems Study--Vol. IV, Energy Conversion Systems Studies," prepared by A. D. Little, Inc. for ECON, Inc., under Contract No. NAS8-31308, March 29, 1977.

beta distribution beginning four years before the IOD and peaking six months before the IOD. The difference between applying a 4 percent as opposed to a 7-1/2 percent interest rate to this cost profile is an almost 4 percent reduction in cost of the unit referenced to its IOD date. By thus reducing the cost of the unit the chances of its being economically competitive are increased. This is reflected in higher probabilities of success in the decision tree representing the program. With higher probabilities of success occurring at each branch of the tree, the revenues which obtain at the final branch of the tree are more heavily weighted, that is, a larger percentage of the positive returns of the program are included in the calculation of the net expected value of the program.

A final note which should be made on the issue of the proper discount rate to be used for comparison of SPS system tradeoffs is that the use of high discount rates in energy policy is particularly inconsistent with the emphasis placed on conservation of existing, conventional energy resources. Pursuit of policies which result in increases in the discount rate beyond that already present in the economy would also result in increased consumption rates of the available, nonrenewable resources. The emphasis in federal policy on energy conservation above and beyond that amount which would already be realized by the market economy implies a special role to energy commodities (for national security or macroeconomic reasons, perhaps) in the form of a lower discount rate. If this is indeed warranted, it should be applied to evaluation of SPS alternatives as well.

4. A METHODOLOGY FOR SPS COSTING TO DEAL WITH "DIFFERENTIAL INFLATION"

The development of a cost estimate for any system that has yet to be built represents a prediction of the future. As such, it is fraught with a number of potential perils. Costs of any technological system are a function of both the prices and the quantities of the inputs (labor, resources, capital) involved. The "quantity" part of the cost estimate involves a quantification of the required inputs for different levels of system performance, based upon expectations of technology advancement. The uncertainties inherent in such estimates are greatly amplified if the system is to be built 20 to 30 years in the future and if it is to be based on technologies not yet developed. Even if precise knowledge of the quantities of the inputs were possible, however, system costs could still be quite difficult to predict accurately due to uncertainties in the prices of the inputs. Examples of this problem can be observed in the aircraft industry. Boeing has recently produced the 1500th Boeing 727 aircraft. Suppose, with the production of this aircraft, the line were shut down and dismantled. Then, suppose 30 years from now Boeing reopened the line and began producing precisely the same aircraft again. Certainly there is very little technical uncertainty in the design or production of this aircraft. Yet, it is unlikely that the cost of the 727 produced in the year 2008 could be estimated today with an error that could be confidently expected to be less than ± 50 percent, even setting aside the effects of inflation (that is, even expressing the cost in 1978 dollars). This uncertainty is a result of the fact that the national economy with its diverse markets and sectors will have continued to operate in the intervening 30 years with the result of continuously adjusting prices for (and quantities produced of) the inputs which would be used to produce a 727 in 2008. Driving this continual

process of market adjustments are factors such as technological innovation, changing incomes and preferences, changing real prices (for instance, as a result of increasing scarcity) of related goods and substitution, as well as interaction in international trade.

Sometimes the capability of a system changes so that it becomes quite difficult to historically compare such costs over a moderate period of time, but an illustrative attempt is nonetheless in order. Consider the case of the Beechcraft Bonanza. The model 35 Bonanza was introduced in 1947 with a price tag of $7900. The base sticker price of the V35B model Bonanza in 1977, 30 years later, was $65,950. Inflation over this period accounts for a factor of 2.84 of this increase, bringing the 1947 price up to $22,463 in 1977 dollars. (More will be said about inflation below.) Of the remaining gap, about 50 percent might be allowed for increased capability: higher speed, higher payload, engine improvements, etc. Although the 50 percent is quite subjective, it is also probably a generous allotment for such improvements. This 50 percent increment brings the price up to $33,695. There is a remaining factor of 1.96, or an annual real price increase of 2.26 percent, yet to be explained. If one had estimated the cost of producing the 1977 V35B in 1947, it is unlikely that this factor would have been included and, thus, it is likely that the cost estimate would have been in error by a factor of at least two, even given excellent knowledge of the technical aspects of the system.

It is clear from the above example that there are a number of economic factors which must be taken into consideration when estimating costs of projects in the mid- to long-term (greater than 20 years in the future). These effects derive from market interactions which may be expected to occur in the intervening period. In the case of near-term cost estimation, such market phenomena are frequently ignored as not having a significant impact on design-cost tradeoffs.

However, over the time period during which the SPS will be developed, market interactions may have a very substantial effect on the relative prices of inputs for SPS production and therefore must be considered explicitly in design-cost analyses. Two types of market-induced effects will be discussed below: first, general inflation which affects the "money price" (but not the real price) of goods and services; and second, relative price changes (sometimes called differential inflation) which represent changes in the real prices of goods and services. Relative price changes will be discussed in terms of the three types of economic inputs (resources, capital and labor) with recommendations being made in each area as to how to approach projections of these changes and the likely limits on the accuracy of such forecasts.

4.1 General Inflation and the Desirability of "Constant Dollar" Analysis

The value of a dollar at any point in time (that is, the relationship between the dollar and real goods and services) is arbitrary. Furthermore, it is constantly changing to reflect the complex interactions among different markets and sectors within an economy and the interactions among national economies in international trade. The dollar is simply a convenient medium of exchange in these processes of economic interaction, and its value (whether measured in relation to other currencies or real goods) continuously changes to equilibrate imbalances which exist in different types of economic activity (savings, investment, government spending, consumption), imbalances which exist in the demand for and supply of goods and services in the various sectors of the economy, as well as imbalances in the amount of goods traded between different national economies.

Inflation is the name given to an adjustment in the value of a unit of currency such that the ratio of real goods to the unit of currency decreases. Conversely, the (less familiar) process of deflation is one in which the ratio of real goods to a unit

of currency increases.* If one does not bear in mind the fact that the dollar is an arbitrary unit of measure whose value changes continuously, then in periods of continuing high inflation one might mistakenly conclude that inflation is actually an important "cost-driver." In reality, measuring the cost of something at two different points in time without correcting for the changing value of the dollar is equivalent to measuring the length of something in meters one time and feet the next time and concluding that the length has changed because the numbers are different.

Correcting for inflation can lead to surprising results. For example, over the period 1950 to 1974, the real price (corrected for inflation) of new cars decreased by 35 percent, the real price of dairy products decreased by 4 percent, and the real price of fuel and utilities decreased by 16 percent (even after the large jump in prices in the 1973-1974 period). One of the most surprising areas is the cost of borrowing money. While the interest rates increase together with the inflation rate, there is often a lag in this increase. Thus, the real cost of capital is usually lower during periods of high and increasing inflation than it is during periods of relatively low inflation, despite the illusion that is created by the numerical rates.**

Several different theories of the cause of inflation have been develoed to account for the continued upward march of price indices in different economic circumstances. One explanation applied to an economy at full production describes what is called "demand-pull" inflation, in which total aggregate demand in the economy is greater than the output that can be produced even at full employment.

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*The 1930s are a prime example in U.S. economic history of a period of deflation.

**This issue of "money illusion" is discussed in Section 3, where the rates of return for corporations have been adjusted for inflation, resulting, in some cases, in <u>negative</u> rates of return.

This excess demand drives up prices, but since no more goods can be produced because the economy is at full capacity, all that changes are the prices--in an inflationary spiral. An alternative description has been applied to the recent situation of high inflation even though there has been simultaneous high unemployment, that is, the economy is not at full capacity. This type of inflation has been called "cost-push" or sellers' inflation whereby the sellers' of all of the inputs to production demand remuneration greater than the total product generated. An example of this would be a labor union demanding a wage increase greater than the value of whatever increases in productivity had been achieved that year. The result of a settlement along such lines can only be an increase in prices, if the industry is going to continue to exist.

The phenomenon of inflation is further complicated by the action of government to achieve certain socially desirable ends, such as low unemployment, by direct attempts to control or modify economic behavior through regulation, tax incentives, government spending, interest rate and money supply control, among others. Thus, if one were to try to predict the rate of inflation over time, he would be faced not only with modeling the myriad actors and decisions of the marketplace, but also with trying to model or predict the actions of government as it interacts with the economy when the actions of government are essentially arbitrary in nature and timing.* Consequently, it has proven to be extremely difficult to predict with any accuracy the course of inflation in the short run; mid-term predictions of inflation have been notoriously inaccurate; and it is pointless to try to predict how the value of the dollar will vary over the potential time period of SPS development and implementation.

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*In addition, the actions of other governments and economies would have to be accounted for because of the considerable effect they can have on the value of the U.S. dollar as demonstrated so vividly over the past several years.

More important than the intractability of forecasting inflation is the fact that, even if it were possible to make such a prediction with perfect accuracy, it would provide no useful information for the purposes of SPS program decision making. To estimate costs either at the present or for the future one need only be concerned with real costs (that is, measured against real goods) referenced to a specific point in time. A cost estimate is referenced to a specific point in time by specifying at what point in time the value of the dollar is taken to be fixed. For instance, all of the cost estimates in this report are expressed in "mid-1977" dollars, which says that the relationship which existed between real goods and dollars in mid-1977 is the one to be used for the purposes of cost estimation in this study. If one wishes to incorporate together or compare estimates made in different year dollars, it is necessary to adjust all of the estimates to a single reference point in time, making use of relationships between the dollar and real goods, that is, convert all of the estimates to one particular year's dollars, so that like elements are being combined or compared.

A number of price indices exist to aid in making intertemporal comparisons of the value of the dollar. Three of the most familiar are shown in Figure 4.1. The most generally used tool for adjustment of the changing value of the dollar is the GNP (gross national product) implicit price deflator which is an all-encompassing indicator that measures the "overall" value of the dollar against a "standard" dollar, such as 1972. To convert (in this case inflate) a cost estimate made in 1960 dollars to 1975 dollars, one would multiply the earlier estimate by the ratio of the index of the later year (123.5) to the index of the earlier year (68.5). Thus, an estimate of a cost of 100 dollars in 1960 is equivalent to an estimate of approximately 180 1975 dollars. The other two familiar price indices shown in Figure 4.1 are the consumer price index and the wholesale price index. The former

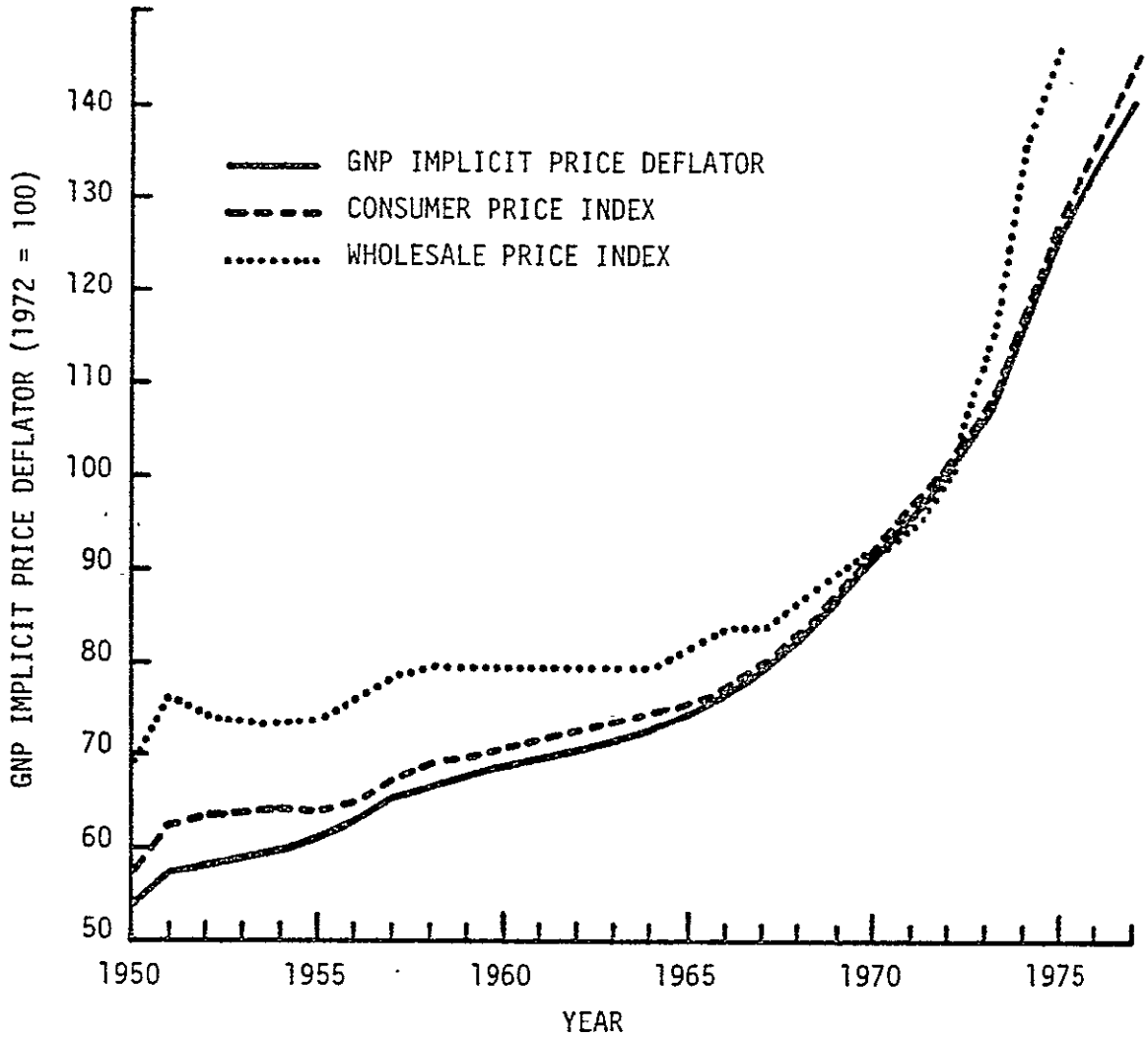

FIGURE 4.1 THREE TYPICAL PRICE INDICES

tracks the total price of a standard market basket of consumer goods and the latter tracks the total price of a standard market basket of wholesale items. As these latter two indices are tied to specific sets of products, the GNP price deflator is generally regarded as a more desirable index for general adjustments in the value of the dollar. In any event, it can be seen from Figure 4.1 that the three indices remain closely related over time.

If the GNP index is to be used to define the value of the dollar, then the use of the GNP implicit price deflator is also appropriate for adjusting historical costs in order to obtain data for cost estimates of future projects. The effects of inflation must always be removed from historical costs before these costs are to be used for forecasting future costs. Also, long-term cost trends, such as an increasing cost of labor, must be properly taken into account. Proper adjustments for the cost of capital are also necessary and can be quite difficult to make properly. All of these factors make it quite difficult to use historical costs as a basis for estimates of future costs over substantial time periods. The cost estimator must take extreme caution not to fall into any of several potential "accounting traps."

The techniques described above are appropriate for adjusting historical cost estimates to a single reference point. That reference point for the value of the dollar is then used in forecasts of relative price changes, as described below, and it is this single reference point for the value of the dollar used both for aggregating historical cost estimates and for making estimates of future costs which is indicated by the term "constant dollar" analysis. Before proceeding with a discussion of techniques for the forecasting of future relative price changes, however, a few more comments on the relative desirability of constant dollar analysis and the appropriate role of inflation in economic analysis are needed. The desire to include an inflation effect in future cost estimation may be motivated by some sense of "realism," that is, inflation is a real effect and, therefore, if it is not included in an analysis, it is perhaps thought that something is missing. Indeed, inflation is of concern to macrolevel decision makers because high levels of inflation can be destabilizing to an economic system and because inflation acts to degrade the capital base of the country if it is not properly taken into account, as

discussed in Section 3.1. And clearly, inflation is of concern to individuals, particularly individuals on fixed incomes, for if their wages do not keep pace with price increases, then their real purchasing power decreases over time. However, for those interested in cost estimation, inflation does not matter, for costs exist in terms of real goods, and the actual number of dollars corresponding to an amount of real goods at any point in time is unimportant and does not affect any decisions which might, for instance, be made on the ordering of the costs of alternative approaches.

In addition, there are several advantages to constant dollar analysis over attempts to include the effect of inflation. First, since it is impossible to predict accurately the course of inflation over the time period of SPS development and implementation for reasons described above, one is forced to assume a rate of inflation. Consequently, all of the results from an analysis including an assumed rate of inflation are dependent, at least in magnitude, upon what value was assumed for inflation and therefore may not be compared with any other results unless the same technique and values were used with respect to inflation. By contrast, constant dollar analysis is equivalent to assuming an inflation rate of zero, a simplification which is possible without sacrificing any useful information. For example, the results of that analysis can readily be updated and correctly compared to later year data by bringing them "forward" at an objective, historical inflationary rate as it occurred. Analyses that are an amalgam of assumed or predicted rates, etc. are close to impossible to disentangle in later years for purposes of updating or checking. Second, by dealing with a constant dollar value corresponding, for example, to 1977 dollars, one is working with units for which one has some intuitive sense of value and with which he or she can measure the reasonableness of cost estimates within his or her area of expertise. Who could

have any sense of what a dollar will be worth in 2005--again, measured in real goods--assuming a 4, 5 or 6 percent rate of inflation? The application of subjective judgment is crucial in future cost estimation, a process which is difficult enough without introducing the artificial and unnecessary complication of assumed rates of inflation which add nothing to the analysis.

4.2 Projecting Relative Price Changes

In general economic terms, three types of inputs are required to produce a good: resources, capital and labor. Figure 4.2 shows a cost tree depicting, by economic category, these cost components. The resources branch of this tree may be further divided into resources which are practically infinite and resources which are discernably finite. Practically infinite resources can be further subdivided into resources for which there is a constant cost of recovery and those for which, due to depletion of easily recovered reserves, the cost of recovery is increasing with time or, due to improved technology or economies of scale, is decreasing with time. The cost of capital is discussed extensively in Section 3 of this report. Suffice it to say

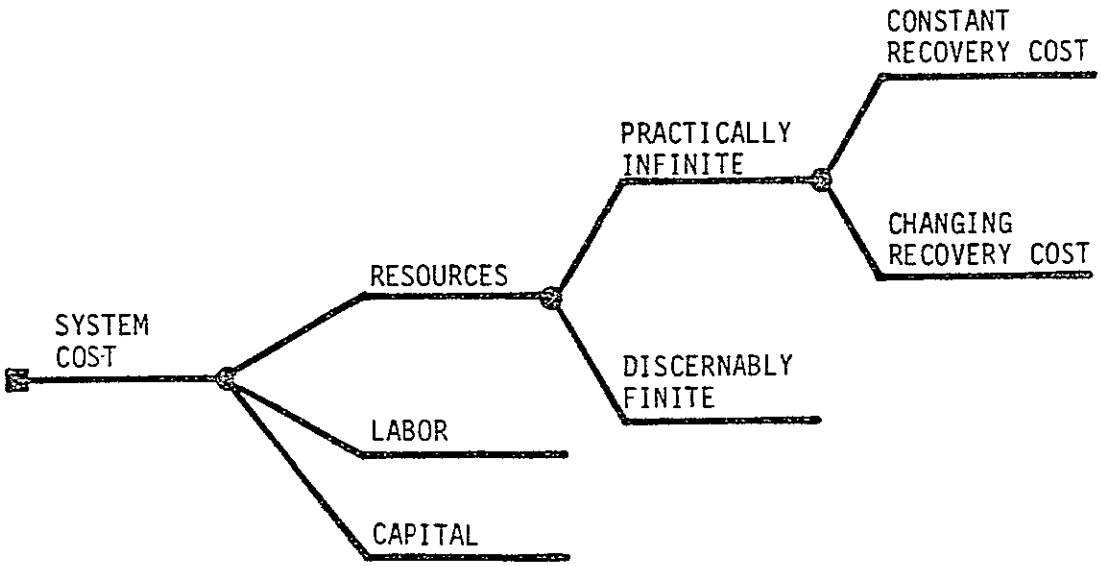

FIGURE 4.2 A SYSTEM COST TREE

here that there exists a certain volatility in the cost of capital which affects the precise cost of capital at any given point in time. This is simply another component of uncertainty in the total cost of an SPS system. The remaining cost components are treated individually below.

4.2.1 Labor

As a direct result of technology innovation, the productivity of labor has increased steadily throughout this century. The productivity of labor over the past 23 years is detailed in Figure 4.3. Over this period, there has been an average annual increase of 3.8 percent. The result of increasing productivity is that, each successive year, there is an increasing per capita supply of goods available for distribution. Hence, there is an increasing real income, on the average, across all employees. The magnitude of this increase is illustrated in Figure 4.4. Over the past 23 years there has been an average annual increase of 3.2 percent in real compensation for all nonfarm business employees. (The slightly lower rate of increase in real income compared to productivity is due in part to the fact that a decreasing fraction of the total work force is productive. This occurs, for example, as more and more people become employed in the regulation of industry.)

In the "average" industry, the increased real cost of labor is precisely offset by the increase in productivity so that the real cost of labor to produce the "average" good remains constant in time and hence the real cost of the "average" good remains constant. The "average" employee improves his standard of living because he obtains an increasing real income with time. Averages, however, do not apply in specific cases. For example, the productivity of labor in producing hand-held calculators is increasing very rapidly, resulting even in a declining price for the resulting good. On the other hand, the construction industry shows a very low rate of technology innovation with commensurately increasing construction costs.

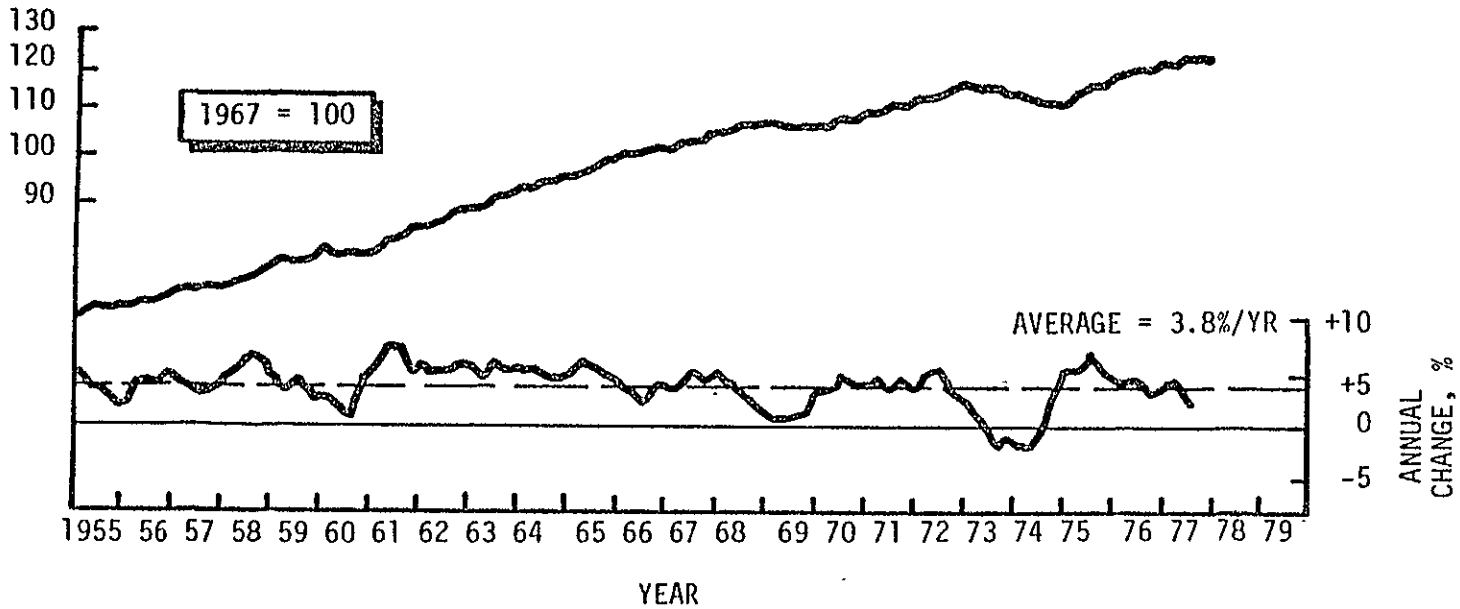

FIGURE 4.3 PRODUCTIVITY, ALL EMPLOYEES, NONFARM BUSINESS SECTOR

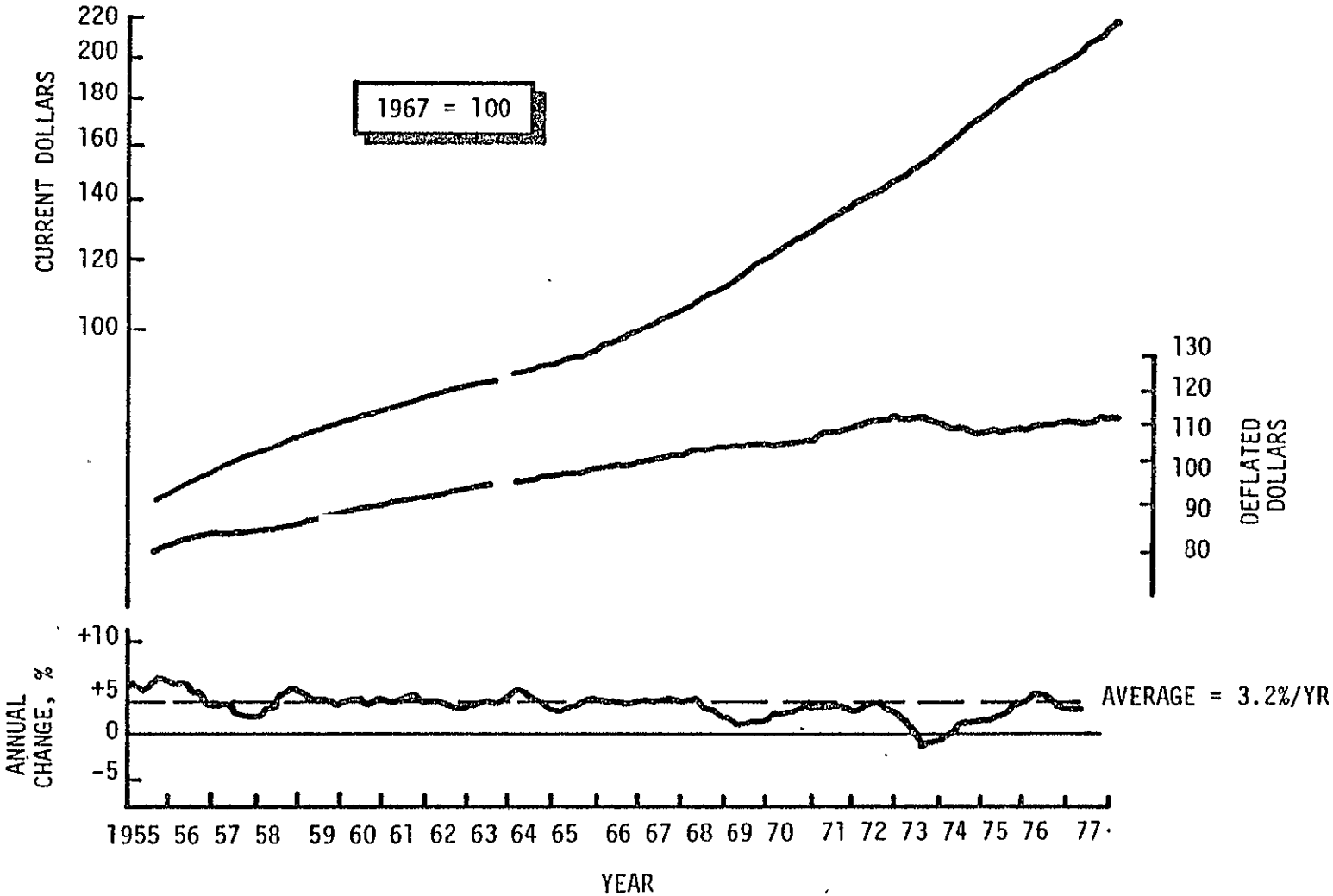

FIGURE 4.4 COMPENSATION, ALL EMPLOYEES, NONFARM BUSINESS SECTOR

The fact that prices vary, as in the above examples, rather than wage rates is due to the fact that long-term effects of technology innovation in one industry versus no innovation in another would result in widely disparate wage rates if the adjustments went totally into labor rate changes. This effect would cause an abundance of labor in areas where technology innovation is high and a shortage of labor where innovation is low. The resulting labor supply would then force wage rates to equalize across the industries with resulting impacts on prices. Returning to the example of the Beechcraft Bonanza, the technology for producing the airplane has changed very little over the past 30 years. Thus, at a 3.2 percent per year real wage increase, the real labor cost to produce the airplane has increased by a factor of about 2.57 during this period. Since much of the cost of producing the airplane is in labor, this largely explains the remaining factor of 1.96 between 1947 and 1977 production costs.

The implication of the above notions on SPS costing are as follows:

1. The real wage rate can be expected to increase at about 2 to 3 percent per year. Thus, the real cost of labor to build an SPS in the year 2000 will be about twice the cost of the same labor in 1978. Of course such increases also apply for costing other energy alternatives.

2. The productivity of labor for building an SPS cannot be expected to increase since expected increases have already been accounted for in estimating the manpower requirements.

3. There is no guarantee that the wage rate will continue to increase at 3.2 percent per year just because it has historically done so. Thus, one should acknowledge that there exists a rather substantial uncertainty in the real cost of labor 20 years or more into the future.

4.2.2 Resources

Resources comprise the basic building (or raw) materials for an SPS. They may include materials such as aluminum, copper, silicon, gallium, graphite, and so on. These materials are converted into SPS components such as solar cells,

structural members, etc., by the use of capital and labor. When component production rates are low, the capital and labor costs for producing components are generally much larger than the resource costs. But when production rates are high, the component costs can approach the sum of the resource and energy costs which the components require. (In fact, the energy cost may also be reduced by technology innovation.) To be sure, much of the resource costs can be tied to capital and labor for resource recovery in which case the above principles apply. However, it is more convenient here to deal with resources as raw material inputs to the SPS construction process. The mining industry is one in which there has been a significant level of technology innovation to offset rising real labor costs.

Not all of the costs associated with resources can be tied to capital and labor, at least not in the conventional sense. This fact has recently been made quite clear by the behavior of the OPEC (Organization of Petroleum Exporting Countries) cartel's behavior relative to the price of crude oil. The present OPEC price, some 65 times the marginal cost of recovery,* includes an economic "rent" which the holders of the resource charge to the users of the resource to compensate for the resource's finiteness. There are clearly times when these rents become the dominant cost.

The discussion below deals first with resources that are perceived to be infinite and second with resources that are discernably finite. The major distinguishing feature that determines whether a resource is perceived to be finite or infinite is the way in which the resource is priced. Of course, all resources are ultimately finite. However, a particular resource may be widely distributed and

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*This was the relationship calculated for the marginal cost of recovery (average for all the OPEC countries) and the market price in 1977.

may have a runout horizon of thousands of years. Under such circumstances, the resource is generally priced at a rate which reflects its production cost. If, on the other hand, the resource reserves are controlled by a few nations or individuals, or if the runout horizon is short, say less than 100 years, then quite often economic rents are charged for depletion of the resource. In the former case, long-term price forecasting is best done by examining the historical prices and the current and projected production costs. In the latter case, prices may fluctuate over a wide range as the result of politics and policies, however, the long-term economic forces drive the price toward an "equilibrium" level which maximizes the value of the resource to its holders. Such appears to be the case, for example, with respect to petroleum.

4.2.2.1 Practically Infinite Resources

Table 4.1 shows the reserve and resource* situation for a number of minerals. While ultimate resources for many minerals may be extremely large, the reserves of these resources may be quite finite. Such is the case for iron ore and domestic bauxite reserves. The core of the earth may be made of iron and iron may be present in vast quantities in the earth's crust, but easily recovered ore, by current technology is quite limited. Similarly, the total domestic supply of aluminum is virtually unlimited, but not in the form of bauxite. This could become important if it became desirable to limit aluminum imports. Thus, looking at the index of reserves divided by annual production gives some indication of the time horizon to the point at which significant peturbations in production costs might be expected. Where this index is on the order of hundreds to thousands of years, historical cost trends probably yield the best information on future price expectations. Where this

*Reserves are defined as those resources which have been identified and delineated as viable in the context of the current economic and technological conditions.

TABLE 4.1 PRODUCTION, RESERVES AND ULTIMATE RESOURCES FOR SELECTED MINERALS

MINERALS	ESTIMATED PRODUCTION 1977			RESERVES 1977				
	TOTAL U.S.	LARGEST PRODUCING NATION	TOTAL WORLD	TOTAL U.S.	NATION W/LARGEST RESERVES	TOTAL WORLD	U.S. RESERVES 1977 PRODUCTION	WORLD RESERVES 1977 PRODUCTION
ARGON*	296 ST	U.S.	536 ST	UNLIMITED RESERVES			NA	NA
ARSENIC*	W	NA	1/39 ST	500 ST	NA	4,100 ST	NA	105 YRS.
BAUXITE**	2,000 LT	AUSTRALIA 24,800 LT	81,000 LT	40,000 LT	GUINEA 8,200,000 LT	24,500,000 LT	20 YRS.	302 YRS.
BERYLLIUM	W	NA	1/113 ST	28,000 ST	NA	NA	NA	NA
BORON*	1,436 ST	NA	NA	350,000 ST	TURKEY 500,000 ST	1,100,000 ST	243 YRS.	NA
CHROMIUM*	W	NA	9,250 ST	——	S. AFRICA 2,000,000	2,700,000 ST	NA	291 YRS.
COPPER*	1,490 ST	U.S.	8,320 ST	93,000 ST	U.S. CHILE	503,000 ST	62 YRS.	60 YRS.
GALLIUM	NA	NA	14,000-20,000 kg	NA	NA	NA	NA	NA
GERMANIUM	35,000 LB	ZAIRE 54,000 LB	100,000 LB	850,000 LB	NA	4,000,000 LB	24 YRS.	22 YRS.
IRON ORE	57 MLT	USSR 240 MLT	840 MLT	17,000 MLT	USSR 108,800 MLT	254,700 MLT	290 YRS.	303 YRS.
MAGNESIUM*	W	NA	1/148 ST	VAST SUPPLIES IN WELL, LAKE BRINES & SEAWATER			NA	NA
MANGANESE*	——	CEC 10,500	26,400 ST	——	CEC 3,000,000	6,000,000 ST	NA	227 YRS.
MOLYBDENUM***	120,000 LB	U.S.	200,700 LB	7,600,000	U.S.	19,800,000 LB	63 YRS.	98 YRS.
NICKEL	17,000 ST	CANADA 250,000 ST	800,300 ST	200,000 ST	28,000,000 ST	60,000,000 ST	11 YRS.	74 YRS.
SILCON*	510 ST	U.S.	2,377 ST	AMPLE IN RELATION TO DEMAND			NA	NA
TITANIUM	W	NA	2/9,400 ST	3/21,000 ST	3/CEC 35,000 ST	3/72,400 ST	NA	NA
VANADIUM***	12,400 LB	S. AFRICA 22,000 LB	62,300 LB	230,000 LB	S. AFRICA 4,000,000 LB	21,400,000 LB	18 YRS.	343 YRS.

*DATA IN THOUSAND SHORT TONS.
**DATA IN THOUSAND LONG TONS.
***DATA IN THOUSAND POUNDS.
W WITHHELD TO AVOID DISCLOSING INDIVIDUAL COMPANY CONFIDENTIAL DATA.
NA INFORMATION NOT AVAILABLE.
1 EXCLUDES U.S. PRODUCTION.
2 EXCLUDES CENTRAL ECONOMY COUNTRIES; U.S.
3 ESTIMATED CAPACITY.

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TABLE 4.1 PRODUCTION, RESERVES AND ULTIMATE RESOURCES FOR SELECTED MINERALS (CONTINUED)

		U.S. PRICE (1972 $)					ULTIMATE RESOURCES	
MINERALS	UNITS	1973	1974	1975	1976	1977	U.S.	WORLD
ARGON	$/ST	147.28	168.67	217.64	195.69	205.20	UNLIMITED	
ARSENIC	¢/LB	5.90-6.37	11.18	15.82-18.20	14.93-15.68	14.15-14.85	1,750 ST*	45 MST
BAUXITE	$/ST	4.72-14.16	4.30-12.90	3.95-11.87	3.73-11.20	3.53-10.6	325 MST	40 BST
BERYLLIUM	$/LB	66.08	64.54	59.35	56.02	53.07	80,000 ST	NA
BORON	$/ST	75.52	68.84	79.14	78.42	83.49	NA	ADEQUATE
CHROMIUM	1/$/LT 2/$/MT	34.93 32.09	55.93 43.02	108.42 27.70	102.33 29.13	96.94 41.74	8 MST	18 BST
COPPER	¢/LB	56.17	66.52	50.81	51.98	47.19	NA	156 MST
GALLIUM	$/KG	708.08	645.43	593.58-633.16	373.46	389.16	15 MKG	1 BKG
GERMANIUM	¢/GM	27.66	25.21	23.18	21.88	22.36	SEVERAL BILLION POUNDS	
IRON ORE	$/LT	11.24-11.62	13.55-13.76	14.64-14.83	15.13-15.16	14.98-15.16	108 BLT	800 BLT
MAGNESIUM	¢/LB	36.11	35.49-64.54	64.89	64.98-67.22	67.93-70.05	UNLIMITED	
MANGANESE	$/LTU	.54-.75	.68-1.22	1.09-1.14	1.03-1.14	1.00-1.08	NA	VERY LARGE
MOLYBDENUM	$/LB	1.62	1.97	2.07	2.57	2.83	37 BLB	70 BLB
NICKEL	$/LB	1.44	1.31-1.72	1.59-1.74	1.64-1.80	1.70-1.55	1.4 BST	143 MST
SILCON	¢/LB	26.8	38.72	34.03	31.74	30.07	ABUNDANT	
TITANIUM	$/LB	1.34	1.93	2.13	2.01	2.10	**	
VANADIUM	$/LB	1.41	1.82	2.18	2.16	2.15	NA	62 MST

*DATA IN THOUSAND SHORT TONS.

**SOURCE OF TITANIUM IS RUTILE (TOTAL WORLD RESOURCE: 220 MST).

1TURKISH (DELIVERED U.S. PORTS).

2SOUTH AFRICAN (DELIVERED U.S. PORTS).

SOURCE: MINERAL COMMODITY SUMMARIES, BUREAU OF MINES, 1978.

index is on the order of decades to, say, 100 years, significant changes in price structure could occur during the SPS program. For these resources, it would be prudent to cost production from alternative sources. It could be useful to do this, for example, for aluminum.

A reasonable approach to costing many resources is to simply examine the historical cost trends. Figures 4.5 and 4.6 show 28-year trends for aluminum and copper. To use long-term data, one must first convert all prices to a common unit, say 1972 dollars. This can be done using a deflator index such as the GNP price deflator given in Figure 4.2. The deflated prices can then be analyzed statistically. Unless there is a clear upward (or downward) trend in the price, it is generally adequate to simply use the long-term average price as the "best guess" of the future price (beyond the next few years).

Beyond estimating the long-term average price, it is useful to examine the volatility of the price over time. For example, the standard deviation of the price about the long-term average is an interesting parameter. It provides an estimate of potential variability of the price at any future time and thus measures inability to predict future prices. Because long-term (secular) price trends are difficult to predict in advance, and because they may be present today, it is probably wise to consider the three-standard- deviation range as the bound on one's ability to forecast future resource prices. As the price volatilities for aluminum and copper indicate, the three-standard-deviation band can be on the order of the resource's long-term average price. Thus, it is very plausible that many resources will not be priceable to better than a factor of plus or minus two over the time period when such resources would be needed for SPS. However, it should be emphasized that this is strictly a plus or minus situtation, not one that is biased one way or the other.

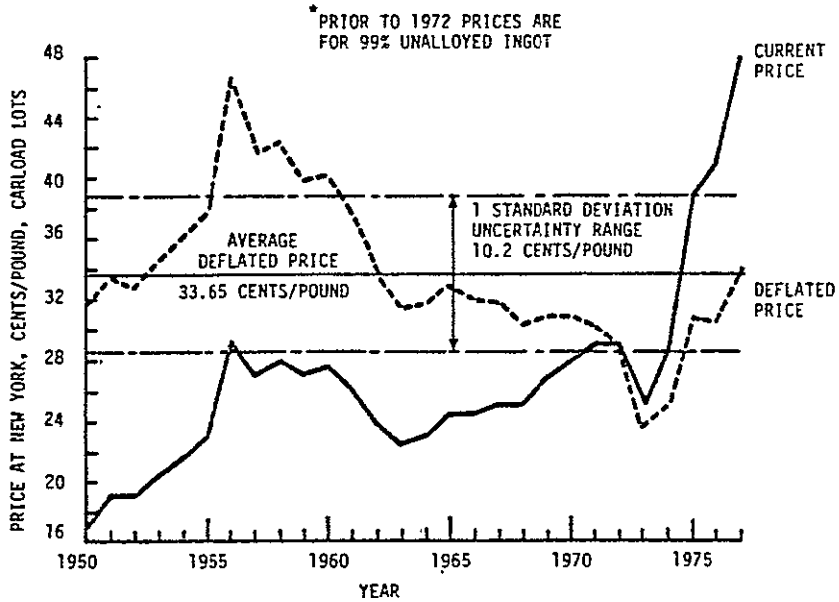

FIGURE 4.5 PRICE OF ALUMINUM--VIRGIN 99.5%* UNALLOYED INGOT--JANUARY

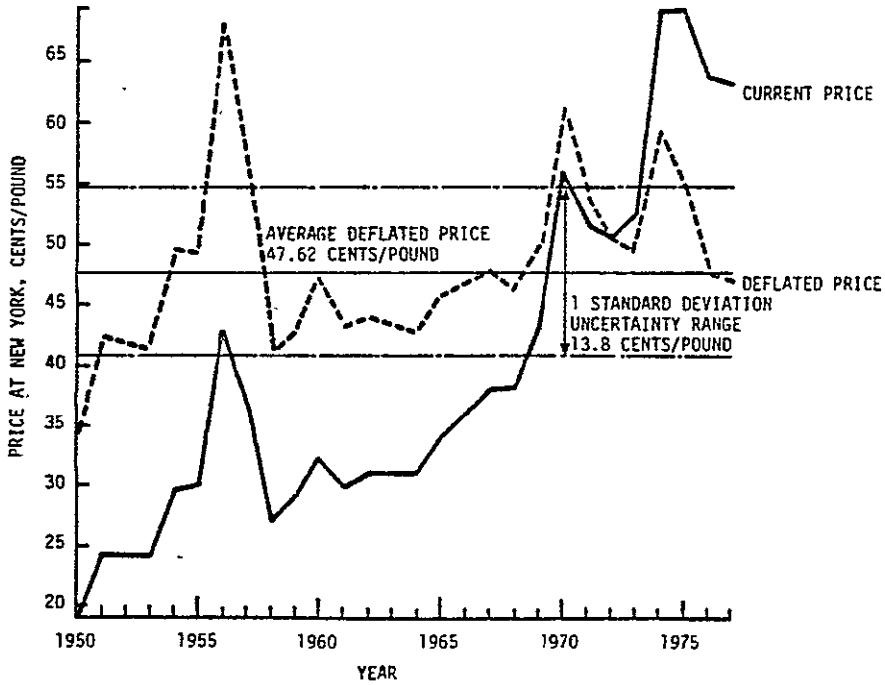

FIGURE 4.6 PRICE OF WIREBAR COPPER--N.Y. REFINERY EQUIVALENT--JANUARY

Another problem in resource pricing that shows up in the data of Figures 4.5 and 4.6 is that the prices of many minerals are correlated in time. Thus, if the price of one mineral goes up, it is likely that others will also. This means that cost uncertainties are not necessarily reduced by using a variety of materials in the system design.

Finally, it is again worth emphasizing that this state of price forecasting applies to all future energy systems, not just SPS. It is not a good nor a bad feature of SPS that such prices cannot be predicted accurately, it is just a fact of life that must be accepted and dealt with accordingly.

4.2.2.2 Discernably Finite Resources

To round out this discussion, it is necessary to discuss the pricing of discernably finite resources. To be sure, one should recognize that resources are, in general, quite vast and widespread. However, there is an energy cost associated with their recovery that is difficult to escape. The same is true of energy resources and, hence, one might say that they are limited to the extent that, at some point, the energy cost for recovering these resources will equal the energy contained in the resources recovered. In this context, fossil and nuclear fuels are, indeed, limited. From this it follows that other resources are limited, but only by the economics, and particularly the energy costs, of their recovery. Thus, the discussion which follows applies fully to energy resources, and to other resources within the context that, at some price, the resource supply becomes very large. At such high prices, monopolies and cartels give way to competition from other sources.

The basic notion employed in the development of a mathematical model for medium- to long-range pricing of finite resources is that the holders of these resources wish to maximize the value of their resource to themselves. This

assumption leads to an economically optimal price as a function of time. Short-term variations may occur around the economically optimal price due to political factors and due to uncertainty in economic parameters such as the demand elasticity and the resource reserves. However, considerable pressure is exerted by the economic forces tending to drive the price towards its "equilibrium" value. Thus, in the long run, we believe that the economically optimal price is the "best guess" of future resource price. Certainly, this seems to be the case with unregulated oil prices at the present time.

The mathematical model is formulated as follows: It is desired to maximize J, where

$$J = \int_0^\infty e^{-\rho t}\, u(Q,q,t)dt \tag{4-1}$$

where t is time, ρ is the resource holder's discount rate, Q is the magnitude of the reserve at time, t, and q is the rate of downdrawal of the reserve. The maximization is subject to the constraints:

$$\frac{dQ}{dt} = -q$$

$$\left.\begin{array}{l} q \geq 0 \\ Q \geq 0 \end{array}\right\} \text{ for all } t$$

and it is assumed that $Q(t=0) = Q_0$ (today's reserve) is known. This problem is read: select the functional q(t) which maximizes the present value of present and future utilities (that is, worth), U(Q,q,t), to the resource holders from resource production subject to the constraints that total resource inventory diminishes at the rate at which the resource is produced for consumption and that the resource is nonrenewable.

It is appropriate to consider that the utility of resource production may be given as the net revenues generated by the resource, that is, the gross revenues minus extraction costs. For example, let $S(Q,q,t)$ be the per unit cost of extraction of the resource and $D(P,t)$ be the demand for the resource at price P. Assuming that production equals demand,

$$q = D(P,t)$$

yields price as a function of production and time,

$$P = P(q,t)$$

Then, the utility of production can be written

$$U(Q,q,t) = q\left[P(q,t) - S(Q,q,t)\right]$$

This is an optimal control problem where the control variable is q and the state variable is Q. The solution to this problem depends on the form of $P(q,t)$ and $S(Q,q,t)$. A typical solution is given in Appendix A of ECON Report No. 77-146-1, "A Study of Some Economic Factors Relating to the Development and Implementation of a Satellite Power System." For convenience, this solution is repeated in this report in Appendix A. The solution yields q as a function of time which can then be translated into price as a function of time. Substantial variability might be expected around the optimal price at any point in time. In the long term, such variability cannot be forecast.

4.3 Caveats

The methods for forecasting future costs presented above assume a "business as normal" environment. Any number of events could occur to create large cost variations. These include mainly factors which could cause major changes in the supply or demand picture for resources or labor: a major economic recession,

war,* drastically new technologies, political changes, etc. The major thing one should be aware of is the new demand for resources which SPS will create. If this demand is a significant fraction of the total resource demand, large changes in resource cost can be expected. These are likely, but not necessarily, to be upward.

*War should not be discounted. The possibility of war in the South African nations which hold much of the world's mineral resources is very real. Resulting changes in political structures (or even the threat of change) can result in drastically changed resource price structures. Such was recently the case with cobalt in Zaire.

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2. Stockfisch, J. A., The Social Rate of Discount: Some Issues in the Theories of Cost and Public Finance, Institute for Defense Analysis Research Paper P-536, October 1969.

3. Von Neumann, J., A Model of General Equilibrium, reprinted in P. Newnan (ed.), Readings in Mathematical Economics, Baltimore: Johns Hopkins Press, 1968.

APPENDIX A

A NONRENEWABLE RESOURCE PRICE MODEL

This appendix develops a solution to the nonrenewable price model described in Section 4. Consider the problem of selecting a functional q(t) so as to maximize J,

$$J = \int_0^T U[q(t), Q(t), t]\, e^{-\rho t}\, dt,$$

subject to the constraints:*

$$\dot{Q}(t) = -q(t)$$

$$q(t), Q(t) \geq 0.$$

Specify a priori the following conditions on U:

$$U_q, U_Q > 0$$

$$U_{qq} \leq 0,$$

and that $Q(t_0) = Q_0$. These conditions, in particular that on U_q, guarantee that

(i) the control inequality constraint $q \geq 0$ will never be active, and

(ii) there exists some time, T, $T < \infty$, where $Q = 0$ and the state inequality constraint $Q \geq 0$ becomes active.

Although the problem is properly considered as an infinite horizon one, the nonrenewability of the resource Q and condition (ii) above make it such that the control problem ends at time T; there exist no more options.

---

*The following notations are used: $\dot{x} = \frac{dx}{dt}$ and for F(x,y), $F_x = \frac{\partial F}{\partial x}$. By $\hat{x}(t)$ is meant the optimal time path of x.

From Takayama* (Theorem 8.A.3, p. 613), the necessary conditions for the optimality of the functional $\hat{q}(t)$ are:

(i) $\dot{Q} = \frac{\partial \hat{H}}{\partial s}$, $\dot{s} = -\frac{\partial \hat{H}}{\partial Q}$,

where $\hat{H} = H[\hat{q}(t), \hat{Q}(t), t, s(t), v(t)]$

$= v(t)u[\hat{q}(t), \hat{Q}(t), t]e^{-\rho t} - s(t)\hat{q}(t)$;

(ii) $H[\hat{q}(t), \hat{Q}(t), t, s(t), v(t)] \geq H[q(t), \hat{Q}(t), t, s(t), v(t)]$, for all admissable $q(t)$;

(iii) $H[\hat{q}(T), \hat{Q}(T), T, s(T), v(T)] = 0$;

(iv) $v(t) = \text{constant} \geq 0$.

$s(t)$ and $v(t)$ are Lagrangian multipliers or adjoint variables.

Condition (ii) requires

$$vU[\hat{q}(t), \hat{Q}(t), t]e^{-\rho t} - s(t)\hat{q}(t) \geq vU[q(t), \hat{Q}(t), t]e^{-\rho t} - s(t)q(t),$$

given the constant v as specified in condition (iv). Now if $v = 0$, then

$$s(t)\hat{q}(t) \leq s(t)q(t).$$

Since v and $s(t)$ cannot vanish simultaneously ("Fritz John's theorem"; see Takayama, p. 612), $s(t) \neq 0$. If $s(t) < 0$, this implies $\hat{q}(t) \geq q(t)$ for all $q(t) \geq 0$, and thus $q(t)$ would be unbounded above. But an infinite rate of downdrawal is clearly not optimal.** If $s(t) > 0$, and letting $q(t) = 0$, the implication is that $\hat{q}(t) = 0$ for all t, which is clearly not optimal given the condition $U_q > 0$. Thus, $v \neq 0$. Without loss of generality we can set $v = 1$. Condition (ii) also yields the condition $\frac{\partial H}{\partial q} = 0$ up to time T since $q(t)$ will be in the interior of the admissable region.

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*Takayama, A., Mathematical Economics, The Dryden Press, 1974.

**That an infinite rate of downdrawal were optimal would imply that buyers could absorb Q_0 in an infinitessimal amount of time; and this would occur without letting demand become more elastic than -1.

From the above conditions, the following equations are obtained:

$$\dot{s} = -U_Q e^{-\rho t} \tag{A-1}$$

$$\dot{Q} = -q(t) \tag{A-2}$$

$$s(t) = U_q e^{-\rho t} \tag{A-3}$$

$$s(T)\hat{q}(T) = U\left[\hat{q}(T), \hat{Q}(T), T\right] e^{-\rho T}. \tag{A-4}$$

Equations A-1 to A-3 describe the movement of the system up until the entry into the constraint, i.e., $0 \leq t \leq T^-$. Equation (A-4) describes the transversality condition at T^+. (A-1) to (A-4) is a system of two first-order differential equations, (A-1) and (A-2), with two boundary conditions known: $Q(T_o) = Q_o$ and $Q(T) = 0$. The system also contains the unknown T and two independent equations, (A-3) and (A-4). Henceforth, it will be understood that q(t) and Q(t) refer to the optimal time paths.

The effect of the state variable inequality constraint, $Q(t) \geq 0$, has not yet been considered. Doing so yields an additional necessary condition for optimality, called the jump condition. This provides an expression for $\dot{s}(T)$. According to Pontryagin et al.,* at the time that the optimal path enters into the constraint boundary [here, time T where $Q(t) = 0$], the following condition holds:

$$\left.\begin{aligned} v^+(T) &= v^-(T) \\ s^+(T) &= s^-(T) \end{aligned}\right\}. \tag{A-5}$$

(A-5) permits equating $s^+(T)$ from (4) with $s^-(T)$ from (A-3). Before proceeding further, the form of $U\left[q(t),q(t),t\right]$ must be specified. The analysis up to this point is quite general in nature. A special case is dealt with below.

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*L. S. Pontryagin, V. G. Boltyanskii, R. V. Gramkrelidze, and E. F. Mishchenko, The Mathematical Theory of Optimal Processes, New York, Wiley Interscience, 1962 (tr. by K. N. Trirogoff from Russian original), p. 302.

An Exponentially Increasing Demand Case

Consider a linear demand function in which the quantity demanded as a function of price grows exponentially. Such a function has the following form:

$$q(t) = \left[\frac{p(t) - a_1}{a_2}\right] \quad e^{\gamma t}$$

Solving for p(t) yields

$$p(t) = a_1 + a_2 e^{-\gamma t} q(t) \tag{A-6}$$

Take the cost of recovery to be given by the expression

$$c(t) = b_1 q(t) + \frac{b_2}{2} q(t)^2 + b_2 \left[Q_o - Q(t)\right] q(t) \tag{A-7}$$

Now we define the (undiscounted) rate of utility increase as net revenue:

$$U\left[q(t), Q(t)\right] = q(t) \cdot p(t) - c(t)$$
$$= (a_1 - b_1 - b_2 Q_0) q(t) + \left(a_2 e^{-\gamma t} - \frac{b_2}{2}\right) q(t)^2 + b_2 Q(t) q(t)$$

or, simplifying coefficients,*

$$U\left[q(t), Q(t)\right] = C_1 q(t) + h(t) q(t)^2 + C_3 Q(t) q(t) \tag{A-8}$$

From this the following obtains

$$U_q = C_1 + 2h(t) q(t) + C_3 Q(t) \tag{A-9}$$

$$U_Q = C_3 q(t). \tag{A-10}$$

Substitute (A-9) into (A-3)

$$s(t) = \left[C_1 + 2h(t) q(t) + C_3 Q(t)\right] e^{-\rho t} \tag{A-11}$$

and solve for q(t)

$$q(t) = \frac{1}{2h(t)} \left[s(t) e^{\rho t} - C_1 - C_3 Q(t)\right] \tag{A-12}$$

Consider now equation (A-4) which describes the transversality conditions. Substituting (A-8)

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*Although it is specified that $h(t) = a_2 e^{-\gamma t} - \frac{b_2}{2}$, there is no actual restriction on the form of h(t) in what follows.

$$s^+(T)q(T) = -q(T)\left[C_1 + h(T)q(T) + C_3Q(T)\right] e^{-\rho T}.$$

Now, if $q(T) \neq 0$, divide through by $q(T)$, noting that, by definition $Q(T) = 0$:

$$s^+(T) = -C_1 e^{-\rho T} - h(t)e^{-\rho T} q(T).$$

Substitute (A-11)

$$s^+(T) = -C_1 e^{-\rho T} \; 1/2\, s^-(T) + 1/2\, C_1 e^{-\rho T}$$

Noting that $s^+(T) = s^-(T)$ (the jump condition),

$$s^-(T) = C_1 e^{-\rho T}.$$

If, on the other hand, $q(T) = 0$, solve (A-11) directly for $s^-(T)$, finding

$$s^-(T) = C_1 e^{-\rho T}. \tag{A-13}$$

Thus obtains the final necessary condition for optimality.

One can now proceed to solve the system of differential equations. Recalling $\dot{Q} = -q$, differentiate (A-11) to obtain

$$\begin{aligned}\dot{S} &= -\rho e^{-\rho t}\left[C_1 - 2h(t)\dot{Q} + C_3Q(t)\right] \\ &\quad + e^{-\rho t}\left[-2h'(t)\dot{Q} - 2h(t)\ddot{Q} + C_3\dot{Q}\right]\end{aligned} \tag{A-14}$$

Substitute (A-10) into (A-1)

$$\begin{aligned}\dot{S} &= -C_3 q(t) e^{-\rho t} \\ &= C_3\dot{Q}e^{-\rho t}\end{aligned} \tag{A-15}$$

Equate (A-14) and (A-15)

$$-\rho C_1 + 2\rho h(t)\dot{Q} - \rho C_3 Q(t) - 2h'(t)\dot{Q} - 2h(t)\ddot{Q} + C_3\dot{Q} = C_3\dot{Q}$$

Thus,

$$-2h(t)\ddot{Q} + 2\left[h(t) - h'(t)\right]\dot{Q} - \rho C_3 Q(t) = C_1 \tag{A-16}$$

or

$$\ddot{Q} - \left[\rho - \frac{h'(t)}{h(t)}\right]\dot{Q} + \frac{\rho C_3}{2h(t)} = -\frac{\rho C_1}{2h(t)} \tag{A-17}$$

Thus, a second-order ordinary differential equation in $Q(t)$ is obtained. The boundary conditions $Q(0) = Q_0$ and $Q(T) = 0$ are known. Additionally, from (A-13) and (A-11), $q(T) = 0$. T, however, is not known. Equation A-17 can be solved either

by choosing some initial consumption rate q(0) and solving until Q(T) = 0 or by a Frobenius series solution of the form

$$q(t) = -\frac{C_1}{C_3} + \sum_{k=0}^{\infty} A_k \left(E^{-\gamma t}-1\right)^k$$

Unfortunately, the series solution requires the use of about 100 terms to obtain adequate accuracy and thus holds no computational advantage over the numerical solution. The numerical computations of the first procedure are minimized by noting that any two solutions to a linear DE (such as A-17) can be linearly combined to form a third solution. Thus iteration on q(0) is not necessary; one simply combines two arbitrary solutions in the manner which yields q(T) = 0 where Q(T) = 0 and uses this same linear combination to find the optimal q(0).

APPENDIX B

THEORETICAL FIRST UNIT (TFU) AND OPERATION AND MAINTENANCE (O&M) COST MODELS FOR THE ROCKWELL INTERNATIONAL SPS CONFIGURATION

The following is a listing of the equations incorporated in the TFU and O&M cost models of the Rockwell International SPS configuration as described in "Satellite Power Systems (SPS) Concept Definition Study" of April 1978. The equations are organized here to correspond to the structure delineated in "Satellite Power System Work Breakdown Structure Dictionary," NASA TM 78155, January 1978. Where discrepancies exist in the level of detail developed or the elements identified between the Rockwell report and the suggested WBS structure in the NASA document, an attempt has been made to reconcile the differences and to report the cost equations at the lowest possible level of detail corresponding to the NASA WBS structure. The definitions of the variables used in these equations have been gathered together at the end of each cost model in order to avoid repetition.

It should be noted that the cost model is designed to calculate the cost of a single satellite. The data listed in Appendix D correspond to the TFU of the Rockwell configuration, and therefore the cost of a single satellite calculated by the models listed below is for the cost of the TFU. Where costs or masses below relate to facilities or equipment used to construct more than one satellite, these costs and masses are amortized in the model so that each satellite pays an equal portion of the common cost. For example, in the case of the space bases, whose lifetime is equal to the total time required to build the SPS fleet, the cost of the space bases has been spread over all the satellites, such that each satellite pays an annuity at its IOD, the sum of all of which annuities discounted at the indicated discount rate equals the present value of the space base at the IOD of the first

production unit. Hence, any variable which corresponds the total procurement cost of equipment which is used for the construction of more than one satellite is the amount of the cost of such equipment which has been amortized to each satellite. A similar amortization process has also been applied to the masses of space-based equipment (used for the construction of more than one satellite) for the purpose of calculating total transportation cost associated with the construction of one satellite.

B.1 The TFU Cost Model of the Rockwell International Configuration

01-00-00 Satellite System

$$C_{SAT} = C_{SPM} + C_{SSEI} + C_{ST} + C_{PS} + C_{ANT} + C_{PDC}$$
$$C_{MISC} + C_{GAI} + C_{SGTH} + C_{SGTO} + C_{GSE} + C_{OPS}$$
$$M_{SAT} = M_{ST} + M_{PS} + M_{ANT} + M_{PDC} + M_{MISC}$$

01-01-00 Structure

$$C_{ST} = C_{AST} + C_{PSST} + C_{MECHS} + C_{SEST}$$
$$M_{ST} = M_{AST} + M_{PSST} + M_{MECHS} + M_{SEST}$$

01-01-01 Antenna Structure

$$C_{AST} = SC_{AST}\, P_{ANT\ PD}$$
$$M_{AST} = SM_{AST}\, P_{ANT\ PD}$$

01-01-02 Power Source Structure

$$AB = \frac{P_{SAPD}}{\eta_{SC}\, F\, n_{EFF}\, f_{SFSC}\, f_{AD}\, f_{ED}}$$

$$AC = \frac{(n_{EFF} - 1)\, AB}{\eta_{CONC}}$$

$$C_{PSST} = SC_{PSST}\, (A_B + A_C)$$

$M_{PSST} = SM_{PSST} (A_B + A_C)$

01-01-03 Mechanisms

$C_{MECHS} = SC_{MECHS} (A_B + A_C)$

$M_{MECHS} = SM_{MECHS} (A_B + A_C)$

01-01-04 Secondary Structure

$C_{SEST} = SC_{SEST} (A_B + A_C)$

$M_{SEST} = SM_{SEST} (A_B + A_C)$

01-02-00 Power Source

$C_{PS} = C_{SB} + C_{SC} + C_{PDC}$

$M_{PS} = M_{SB} + M_{SC} + M_{PDC}$

01-02-01 Solar Blankets

$C_{SB} = SC_{SB} A_B$

$M_{SB} = SM_{SB} A_B$

01-02-02 Solar Concentrators

$C_{SC} = SC_{SC} A_C$

$M_{SC} = SM_{SC} A_C$

01-03-00 Power Distribution and Conditioning

$C_{PDC} = (SC_{CNDC} + SC_{SWT} + SC_{BATT} + SC_{BPC}) P_{SAPD}$
$+ SC_{SR} P_{ANT\ INT}$

$M_{PDC} = (SM_{CNDC} + SM_{SWT} + SM_{BATT} + SM_{BPC}) P_{SAPD}$
$+ SM_{SR} P_{ANT\ INT}$

01-04-00 Microwave Antenna

$C_{HP} = SC_{HP} P_{DC-RF}$

$M_{HP} = SM_{HP} P_{DC-RF}$

$C_{MWA} = SC_{MWA} P_{DC-RF}$

$M_{MWA} = SM_{MWA} P_{DC-RF}$

$C_{ANT} = C_{HP} + C_{MWA}$

$M_{ANT} = M_{HP} + M_{MWA}$

01-05-00 Rotary Joint

[Hardware elements in this category have been included elsewhere.]

01-06-00 Propulsion

[Hardware elements in this category have been included in Miscellaneous Equipment below.]

01-07-00 Energy Storage

[Hardware elements in this category have been included elsewhere.]

01-08-00 Avionics

[Hardware elements in this category have been included in Miscellaneous Equipment below.]

Miscellaneous Equipment

$C_{MISC} = SC_{MISC} (M_{ST} + M_{PS} + M_{ANT} + M_{PDC})$

$M_{MISC} = SM_{MISC} (M_{ST} + M_{PS} + M_{ANT} + M_{PDC})$

[NOTE: Miscellaneous equipment in the Rockwell configuration includes thermal control equipment which is not included in the NASA WBS dictionary.]

01-09-00 Ground Assembly and Integration

$C_{SUPC} = C_{ST} + C_{ANT} + C_{PS} + C_{PDC}$

$C_{GAI} = f_{GAI} C_{SUPC}$

01-10-00 System Ground Test Hardware

$$C_{SGTH} = f_{SGTH}\, C_{SUPC}$$

01-11-00 System Ground Test Operations

$$C_{SGTO} = f_{SGTO}\, C_{SUPC}$$

01-12-00 Ground Support Equipment

$$C_{GSE} = f_{GSE}\, C_{SUPC}$$

01-13-00 Satellite System Program Management

$$C_{SPM} = f_{SPM}\,(C_{ST} + C_{PS} + C_{ANT} + C_{MISC} + C_{MISC} + C_{GAI} + C_{SGTH} + C_{SGTO} + C_{GSE} + C_{OPS})$$

01-14-00 Satellite System Systems Engineering and Integration (SE&I)

$$C_{SSEI} = f_{SSEI}\,(C_{ST} + C_{PS} + C_{ANT} + C_{MISC} + C_{GAI} + C_{SGTH} + C_{SGTO} + C_{GSE} + C_{OPS})$$

02-00-00 Ground Station System

$$C_{GS} = C_{GSPM} + C_{GSSEI} + C_{RECT} + C_{SATCON} + C_{UTINT} + C_{S\&F}$$

02-01-00 Rectanna

$$C_{RECT} = C_{DIPREC} + C_{RECPDC} + C_{GPS}$$

02-01-01 Dipole/Rectifier Elements

$$C_{DIPREC} = {}^{SC}C_{DIPREC}\, P_{RF\text{-}DC}$$

02-01-02 Rectenna Power Distribution and Conditioning

$$C_{RECPDC} = {}^{SC}C_{RECPD}\, P_{RECT\ PD}$$

02-01-03 Rectenna Support and Ground Plane Structure

$C_{GPS} = {}^{SC}C_{GPS}\ P_{RF-DC}$

02-02-00 Satellite Control

C_{SATCON} = [Input Value]

02-03-00 Utility Interface

$C_{UTINT} = {}^{SC}C_{UTINT}\ P_{RECT}\ PD$

02-04-00 Site and Facilities

$C_{S\&F} = C_{LP} + C_{RF} + C_{UT} + C_B + C_{ME}$

02-05-00 Ground Station Program Management

$C_{GSPM} = f_{GSPM}\ (C_{RECT} + C_{SATCON} + C_{UTINT} + C_{S\&F})$

02-06-00 Ground Station SE&I

$C_{GSSEI} = f_{GSSEI}\ (C_{RECT} + C_{SATCON} + C_{UTINT} + C_{S\&F})$

03-00-00 Manpower Operations

$C_{GROPS} = C_{SGO} + C_{GCONST} + C_{GLOGS}$

$C_{OROPS} = C_{CCREW} + C_{CPROV}\ C_{CEMS}$

$C_{OPS} = C_{GROPS} + C_{OROPS} + C_{GSOPS}$

04-00-00 Orbital Assembly and Support

$C_{SPAST} = C_{LEOSB} + C_{GEOSB}$

$M_{SPAST} = M_{LEOSB} + M_{GEOSB}$

04-01-00 Construction Base and
04-03-00 O&M Support Base

$N_{GEO} = f_{SHPD} \cdot f_{NPPS}$

$$C_{GEOSB} = \frac{N_{GEO}}{f_{NGEO}} \cdot \frac{1}{R_{CONST}\, f_{DIGEO}} \quad (N_{ADM}\, SC_{ADM} +$$

$$N_{CHM}\, SC_{CHM} + N_{CLM}\, SC_{CLM} + N_{OM}\, SC_{COM} +$$

$$N_{CSM}\, SC_{CSM} + N_{POWM}\, SC_{POWM} + N_{PSM}\, SC_{PSM}$$

$$N_{SDA}\, SC_{SDH} + N_{SM}\, SC_{SM} + C_{FIX})$$

$$M_{GEOSB} = \frac{N_{GEO}}{f_{NGEO}} \cdot \frac{1}{R_{CONST}\, f_{DLGEO}} \quad (N_{ADM}\, SM_{ADM} +$$

$$N_{CHM}\, SM_{CHM} + N_{CLM}\, SM_{CLM} + N_{OM}\, SM_{COM} +$$

$$N_{CSM}\, SM_{CSM} + N_{POWM}\, SM_{POWM} + N_{PSM}\, SM_{PSM} +$$

$$N_{SDH}\, SM_{SDH} + N_{SM}\, SM_{SM} + M_{FIX})$$

<u>04-02-00 Logistics Base</u>

$$C_{LEOSB} = \frac{N_{LEO}}{f_{NLEO}} \cdot \frac{1}{R_{CONST}\, f_{DLLEO}} \quad (SC_{CHM} + SC_{CSM} +$$

$$SC_{COM} + SC_{POWM})$$

$$M_{LEOSB} = \frac{N_{LEO}}{f_{NLEO}} \cdot \frac{1}{R_{CONST}\, f_{DLLEO}} \quad (SM_{CHM} + SM_{CSM} +$$

$$SC_{COM} + SM_{POWM})$$

<u>05-00-00 Assembly and Support Equipment</u>

$$C_{ASE} = \frac{N_{BM}\, SC_{BM}}{R_{CONST}\, f_{DLBM}} + \frac{N_{C}\, SC_{C}}{R_{CONST}\, f_{DLC}} + \frac{N_{CAM}\, SC_{CAM}}{R_{CONST}\, f_{DLCAM}} +$$

$$\frac{N_{RM}\, SC_{RM}}{R_{CONST}\, f_{DLPM}} + \frac{N_{BD}\, SC_{BD}}{R_{CONST}\, f_{DLBD}} + \frac{N_{RD}\, SC_{RD}}{R_{CONST}\, f_{DLRD}} +$$

$$\frac{N_{CD}\, SC_{CD}}{R_{CONST}\, f_{DLCD}} + \frac{N_{API}\, SC_{API}}{R_{CONST}\, f_{DLAPI}}$$

$$M_{ASE} = \frac{N_{BM}\, SM_{BM}}{R_{CONST}\, f_{DLBM}} + \frac{M_C\, SM_C}{R_{CONST}\, f_{DLC}} + \frac{N_{CAM}\, SM_{CAM}}{R_{CONST}\, f_{DLCAM}} +$$

$$\frac{N_{RM}\, SM_{RM}}{R_{CONST}\, f_{DLRM}} + \frac{N_{BD}\, SM_{BD}}{R_{CONST}\, f_{DLBD}} + \frac{N_{RD}\, SM_{RD}}{R_{CONST}\, f_{DLRD}} +$$

$$\frac{N_{CD}\, SM_{CD}}{R_{CONST}\, f_{DLCD}} + \frac{N_{API}\, SM_{API}}{R_{CONST}\, f_{DLARI}}$$

06-00-00 Heavy Lift Launch Vehicle (HLLV)

$$C_{HLLV} = C_{HLVPR} + C_{HLVOP}$$

06-01-00 HLLV Fleet

$$M_{LEO} = M_{ST} + M_{PS} + M_{ANT} + M_{MISC} + M_{SPAST} + M_{ASE} + M_{COTV} + M_{IOV}$$

$$N_{LVFLT} = \frac{M_{LEO}}{M_{P/L}\, f_{LOAD}} + f_{P-LV} \left(\frac{N_{GEO} \frac{f_{ROT}}{R_{CONST}}}{f_{POTV}} \right)$$

$$N_{HLLV} = \frac{N_{LVFLT}}{f_{DLLV}}$$

$$C_{HLVPR} = SC_{HLLV}\, N_{HLLV}$$

06-02-00 HLLV Operations

$$C_{HLVOP} = SC_{LVFLT}\, N_{LVFLT}$$

07-00-00 Space Transportation System (STS)*

$$C_{IOV} = C_{IOVPR} + C_{IOVOP}$$

*This category refers to the Rockwell Intra-Orbit Vehicle (IOV) which transfers payloads from HLLVs to the LEO Space Base.

07-01-00 STS Fleet

$$M_{LEO} = M_{SAT} + M_{COTV} + M_{ASE} + M_{SPAST}$$

$$N_{IOV} = \frac{M_{LEO}}{M_{P/L}\, f_{LOAD}\, f_{DLIOV}}$$

$$C_{IOVPR} = SC_{IOV}\, N_{IOV}$$

$$M_{IOV} = SM_{IOV}\, N_{IOV} + SM_{IPRP} \left(\frac{M_{LEO}}{M_{P/L}\, f_{LOAD}} \right)$$

07-02-00 STS Operations

$$C_{IOVOP} = \frac{SC_{IVFT}\, M_{LEO}}{M_{P/L}\, f_{LOAD}}$$

08-00-00 Orbit Transfer Vehicle (OTV)*

$$C_{COTV} = C_{COTVPR} + C_{COTVOP}$$

08-01-00 OTV Fleet

$$N_{CFLTS} = \frac{M_{SAT} + M_{SPAST} + M_{ASE} + M_{GEOSB}}{f_{LOAD}\, M_{P/L}\, f_{COTV}}$$

$$N_{COTV} = \frac{N_{CFLTS}}{f_{DLCOTV}}$$

$$C_{COTVPR} = SC_{COTV}\, N_{COTV}$$

$$M_{COTV} = SM_{COTV}\, N_{COTV}$$

08-02-00 OTV Operations

$$C_{COTVOP} = SC_{COTVFLT}\, N_{CFLTS}$$

*This category refers to the Rockwell Cargo Orbit Transfer Vehicle (COTV) which transfers materials (delivered to LEO by HLLVs) out to the GEO construction base.

09-00-00 Personnel Module*

$$C_{POTV} = C_{POTVPR} + C_{POTVOP}$$

09-01-00 Personnel Module Fleet

$$N_{PFLTS} = \frac{N_{GEO} \frac{f_{ROT}}{R_{CONST}}}{f_{POTV}}$$

$$N_{POTV} = \frac{N_{PFLTS}}{f_{DLPOTV}}$$

$$C_{POTVPR} = {}^{SC}C_{POTV} \, N_{POTV}$$

09-02-00 Personnel Module Operations

$$C_{POTVOP} = {}^{SC}C_{POTVFLT} \, N_{PFLTS}$$

10-00-00 Facilities

$$C_{FACS} = \frac{{}^{SC}C_{FACS}}{R_{CONST} \, f_{DLFACS}}$$

11-00-00 Taxes

C_{TXS} = [Input Value]

12-00-00 Insurance

C_{INS} = [Input Value]

13-00-00 Program Management

$$C_{PM} = f_{PM} (C_{SAT} + C_{GS} + C_{SPAST} + C_{ASE} + C_{HLLV} + C_{IOV} + C_{COTV} + C_{POTV})$$

*This category has been used to include the entire personnel transportation system.

14-00-00 Program SE&I

$$C_{SEI} = f_{SEI}(C_{SAT} + C_{GS} + C_{SPAST} + C_{ASE} + C_{HLLV} + C_{IOV} + C_{COTV} + C_{POTV})$$

Definitions of TFU Cost Model Variables

Following is a listing of the definitions of the variables used in the TFU Cost Model of the Rockwell configuration, in the order of their initial appearance in the model.

C_{SAT}	=	total procurement cost of an operational satellite ($)
C_{SPM}	=	total cost of program management for the satellite system ($)
C_{SSEI}	=	total cost of systems engineering and integration (SE&I) for the satellite system ($)
C_{ST}	=	total cost of the structure of the satellite system ($)
C_{PS}	=	total cost of the power source of the satellite system ($)
C_{ANT}	=	total procurement cost of the transmitting antenna ($)
C_{MISC}	=	total procurement cost of miscellaneous equipment (propulsion, avionics, thermal control, et al.) ($)
C_{GAI}	=	total cost of ground assembly and integration ($)
C_{SGTH}	=	total procurement cost of system ground test hardware ($)
C_{SGTO}	=	total cost of system ground test operations ($)
C_{GSE}	=	total cost of ground support equipment ($)
C_{OPS}	=	total cost of operations associated with the production of the TFU ($)
M_{SAT}	=	total mass of an operational TFU satellite (kg)
M_{ST}	=	total mass of the structure of the satellite system (kg)
M_{PS}	=	total mass of the power source of the satellite system (kg)
M_{ANT}	=	total mass of the microwave transmitting antenna of the satellite system (kg)

M_{MISC} = total mass of the miscellaneous equipment of the satellite system (propulsion, avionics, thermal control, et al.) (kg)

C_{AST} = total cost of the antenna structure ($)

C_{PSST} = total cost of the power source structure ($)

C_{MECHS} = total cost of structural mechanisms ($)

C_{SEST} = total cost of secondary structure ($)

M_{ST} = total mass of the structure of the satellite system (kg)

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

M_{PSST} = total mass of the power source structure (kg)

M_{MECHS} = total mass of structural mechanisms (kg)

M_{SEST} = total mass of secondary structure (kg)

SC_{AST} = ratio of the cost of the antenna structure to the power throughput of the antenna power distribution system ($/kW)

$P_{ANT\ PD}$ = power input to the antenna power distribution system (kW);

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

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

$\eta_{ANT\ PD}$ = 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)

SM_{AST} = ratio of the mass of the antenna structure to the power throughput of the antenna power distribution system (kg/kW)

A_B = area of the solar blanket (km^2)

P_{SAPD} = power input to the solar array power distribution system (kW);

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

where $\eta_{ANT\ INT}$ = antenna power distribution efficiency

η_{SAPD} = solar array power distribution efficiency

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

F = solar flux constant ($1353 \times 10^3 kW/km^2$)

η_{EFF} = effective concentration ratio

f_{SFSC} = seasonal correction factor for solar flux constant

f_{ED} = environmental degradation factor for solar cells over design life

f_{AD} = array design factor (includes "packing factor," that is, the ratio of solar cell area to total array area)

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

η_{CONC} = efficiency of the concentrator

SC_{PSST} = ratio of the cost of the power source structure to the planform area (that is, the area as seen by the sun) of the solar array and concentrator ($\$/km^2$)

SM_{PSST} = ratio of the mass of the power source structure to the planform area of the solar array and concentrators (kg/km^2)

SC_{MECHS} = ratio of the cost of structural mechanisms to the planform area of the solar array and concentrators ($\$/km^2$)

SM_{MECHS} = ratio of the mass of structural mechanisms to the planform area of the solar array and concentrators (kg/km^2)

SC_{SEST} = ratio of the cost of secondary structure to the planform area of the solar array and concentrators ($\$/km^2$)

SM_{SEST} = ratio of the mass of secondary structure to the planform area of the solar array and concentrators (kg/km^2)

C_{SB} = total cost of the solar blankets ($)

C_{SC} = total cost of the solar concentrators ($)

C_{PDC} = total cost of the power distribution and conditioning system of the solar array ($)

M_{SB} = total mass of the solar blankets (kg)

M_{SC} = total mass of the solar concentrators (kg)

M_{PDC} = total mass of the power distribution and conditioning system of the solar array (kg)

SC_{SB} = specific cost of the solar blankets ($/km^2)

SM_{SB} = specific mass of the solar blankets (kg/km^2)

SC_{SC} = specific cost of the solar concentrators ($/km^2)

SM_{SC} = specific mass of the solar concentrators (kg/km^2)

SC_{CNDC} = ratio of the cost of conductors and switches to the solar array power throughput ($/kW)

SC_{SWT} = ratio of the cost of switching to the solar array power throughput ($/kW)

SC_{BATT} = ratio of the cost of batteries to the solar array power throughput ($/kW)

SC_{BPC} = ratio of the cost of battery power conditioning to the solar array power throughput ($/kW)

SC_{SR} = ratio of the cost of slip rings and brushes to the antenna interface power throughput ($/kW)

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

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

SM_{CNDC} = ratio of the mass of conductors and switches to the solar array power throughput (kg/kW)

SM_{SWT} = ratio of the mass of switching equipment to the solar array power throughput (kg/kW)

SM_{BATT} = ratio of the mass of batteries to the solar array power throughput (kg/kW)

SM_{BPC} = ratio of the mass of battery power conditioning equipment to the solar array power throughput (kg/kW)

SM_{SR} = ratio of the mass of slip rings and brushes to the antenna interface power throughput (kg/kW)

C_{HP} = total cost of microwave heat pipes ($)

SC_{HP} = ratio of the cost of microwave heat pipes to the DC-RF power throughput ($/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_{HP} = total mass of microwave heat pipes (kg)

SM_{HP} = ratio of the mass of microwave heat pipes to the DC-RF power throughput (kg/kW)

C_{MWA} = total cost of microwave antenna elements ($)

SC_{MWA} = ratio of the cost of the microwave antenna elements to DC-RF power throughput ($/kW)

M_{MWA} = total mass of the microwave antenna elements (kg)

SM_{MWA} = ratio of the mass of the microwave antenna elements to the DC-RF power throughput (kg/kW)

SC_{MISC} = ratio of the cost of miscellaneous equipment to the mass of the satellite structure, power source, antenna and power distribution and conditioning equipment ($/kg)

SM_{MISC} = ratio of the mass of miscellaneous equipment to the mass of the satellite structure, power source, antenna and power distribution and conditioning equipment (fraction)

C_{SUPC} = total procurement cost of the satellite system

f_{GAI} = ratio of ground assembly and integration cost to the satellite system procurement cost (fraction)

f_{SGTH} = ratio of the cost of system ground test hardware to the satellite system procurement cost (fraction)

f_{SGTO} = ratio of the cost of system ground test operations to the satellite system procurement cost (fraction)

f_{GSE} = ratio of the cost of ground support equipment to the satellite system procurement cost (fraction)

f_{SPM} = ratio of the cost of satellite system program management to all other TFU costs (fraction)

f_{SSEI} = ratio of the cost of satellite system SE&I to all other TFU costs (fraction)

C_{GSPM} = total cost of ground station program management ($)

C_{GSSEI} = total cost of ground station SE&I ($)

C_{RECT} = total cost of the rectenna ($)

C_{SATCON} = total cost of ground station satellite control facilities ($)

C_{UTINT} = total cost of the ground station utility interface ($)

$C_{S\&F}$ = total cost of the ground station site and facilities ($)

C_{DIPREC} = total cost of the dipole/rectifier elements ($)

C_{REDPDC} = total cost of rectenna power distribution and conditioning equipment ($)

C_{GPS} = total cost of the rectenna ground plane and support structure ($)

SC_{DIPREC} = specific cost of the dipole/rectifier elements ($/kW)

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

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

SC_{RECPD} = specific cost of the rectenna power distribution and conditioning equipment ($/kW)

$P_{RECT\ PD}$ = power input to the rectenna power distribution and conditioning equipment (kW);

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

SC_{GPS} = specific cost of the rectenna support and ground plane structure ($/kW)

SC_{UTINT} = specific cost of the utility interface ($/kW)

C_{LP} = total cost of the ground station land and preparation ($)

C_{RF} = total cost of the ground station roads and fences ($)

C_{UT} = total cost of the ground station utilities ($)

C_B = total cost of the ground station buildings ($)

C_{ME} = total cost of the ground station maintenance equipment ($)

f_{GSPM}	=	ratio of ground station program management costs to ground station procurement costs (fraction)
f_{GSSEI}	=	ratio of the cost of ground station SE&I to ground station procurement costs (fraction)
C_{GROPS}	=	total cost of ground operations ($)
C_{SGO}	=	total cost of satellite operations at the ground station ($)
C_{GCONST}	=	total cost of construction for satellite operations facilities at the ground station ($)
C_{GLOGS}	=	total cost of ground logistics for satellite operations ($)
C_{OROPS}	=	total cost of orbital operations ($)
C_{CCREW}	=	total cost of the construction crew for orbital operations ($)
C_{CPROV}	=	total cost of construction crew provisions for orbital operations ($)
C_{CEMS}	=	total cost of expendable maintenance supplies for orbital operations ($)
C_{SPAST}	=	total cost of the orbital assembly facilities ($)
M_{SPAST}	=	total mass of the orbital assembly facilities (kg)
C_{GSOPS}	=	total cost of ground station system operations ($)
C_{LEOSB}	=	total cost of the low earth orbit (LEO) space base ($)
C_{GEOSB}	=	total cost of the geosynchronous orbit (GEO) space base ($)
M_{LEOSB}	=	total mass of the LEO space base (kg)
M_{GEOSB}	=	total mass of the GEO space base (kg)
N_{GEO}	=	total crew size of the GEO space base (number) *[Note: this input varies over the range of the expected value of the crew size, and the cost and mass of the space base are scaled accordingly, in reference to the point design number f_{NGEO} below.]*
f_{NGEO}	=	reference point number for the total crew size of the GEO space base (number)
f_{SHPD}	=	number of shifts per day (number)

f_{NNPS}	=	number of personnel per shift (number)
R_{CONST}	=	satellite fleet construction rate (number of satellites/year)
f_{DLGEO}	=	design life of GEO space base equipment (years)
N_{ADM}	=	number of airlock docking modules in the GEO space base (number)
SC_{ADM}	=	unit cost of an airlock docking module ($)
N_{CHM}	=	number of crew habitability modules in the GEO space base (number)
SC_{CHM}	=	unit cost of a crew habitability module ($)
N_{CLM}	=	number of consumables logistics modules in the GEO space base (number)
SC_{CLM}	=	unit cost of a consumables logistics module ($)
N_{COM}	=	number of base management modules in the GEO space base (number)
SC_{COM}	=	unit cost of a base managemnet module ($)
N_{CSM}	=	number of crew support modules with EVA unit in the GEO space base (number)
SC_{CSM}	=	unit cost of a crew support module with EVA unit ($)
N_{POWM}	=	number of power modules in the GEO space base (number)
SC_{POWM}	=	unit cost of a power module ($)
N_{PSM}	=	number of pressurized storage modules in the GEO space base (number)
SC_{PSM}	=	unit cost of a pressurized storage module ($)
N_{SDH}	=	number of shielding units in the GEO space base (number)
SC_{SDH}	=	unit cost of a shielding unit ($)
N_{SM}	=	number of crew support modules without EVA unit (number)
SC_{SM}	=	unit cost of a crew support module without EVA unit ($)
C_{FIX}	=	cost of the fabrication fixture ($)
SM_{ADM}	=	unit mass of an airlock docking module (kg)

SM_{CHM}	=	unit mass of a crew habitability module (kg)
SM_{CLM}	=	unit mass of a consumables logistics module (kg)
SM_{COM}	=	unit mass of a base management module (kg)
SM_{CSM}	=	unit mass of a crew support module with EVA unit (kg)
SM_{POWM}	=	unit mass of a power module (kg)
SM_{PSM}	=	unit mass of a pressurized storage module (kg)
SM_{SDH}	=	unit mass of a shielding unit (kg)
SM_{SM}	=	unit mass of a crew support module without EVA unit (kg)
M_{FIX}	=	mass of the fabrication fixture
N_{LEO}	=	total crew size of the LEO space base (number) *[Note: this input varies over the range of the expected value of the crew size, and the cost and mass of the space base are scaled accordingly, in reference to the point design number f_{NLEO} below.]*
f_{NLEO}	=	reference point number for the total crew size of the LEO space base (number)
f_{DLLEO}	=	design life of the LEO space base equipment (years)
C_{ASE}	=	total cost of assembly and support equipment ($)
N_{BM}	=	total number of beam machines (number)
SC_{BM}	=	unit cost of a beam machine ($)
f_{DLBM}	=	design life of a beam machine (years)
N_C	=	total number of cassettes (number)
SC_C	=	unit cost of a cassette ($)
f_{DLC}	=	design life of a cassette (years)
N_{CAM}	=	total number of cable attaching machines (number)
SC_{CAM}	=	unit cost of a cable attaching machine ($)
f_{DLCAM}	=	design life of a cable attaching machine (years)
N_{RM}	=	total number of remote manipulators (number)
SC_{RM}	=	unit cost of a remote manipulator ($)
f_{DLRM}	=	design life of a remote manipulator (years)

N_{BD}	=	total number of blanket dispensers (number)
SC_{BD}	=	unit cost of a blanket dispenser ($)
f_{DLBD}	=	design life of blanket dispenser (years)
N_{RD}	=	number of reflector dispensers (number)
SC_{RD}	=	unit cost of a reflector dispenser ($)
f_{DLRD}	=	design life of a reflector dispenser (years)
N_{CD}	=	number of cable dispensers (number)
SC_{CD}	=	unit cost of a cable dispenser ($)
f_{DLCD}	=	design life of a cable dispenser (years)
N_{API}	=	number of antenna panel installers (number)
SC_{API}	=	unit cost of an antenna panel installer ($)
f_{DLAPI}	=	design life of an antenna panel installer (years)
M_{ASE}	=	total mass of assembly and support equipment (kg)
SM_{BM}	=	unit mass of a beam machine (kg)
SM_{C}	=	unit mass of a cassette (kg)
SM_{CAM}	=	unit mass of a cable attaching machine (kg)
SM_{RM}	=	unit mass of a remote manipulator (kg)
SM_{BD}	=	unit mass of a blanket dispenser (kg)
SM_{RD}	=	unit mass of a reflector dispenser (kg)
SM_{CD}	=	unit mass of a cable dispenser (kg)
SM_{API}	=	unit mass of an antenna panel installer
C_{HLLV}	=	total cost associated with the heavy lift launch vehicle (HLLV) ($)
C_{HLVPR}	=	total procurement cost of the HLLV fleet ($)
C_{HLVOP}	=	total operations cost of the HLLV fleet ($)
M_{LEO}	=	total mass launched to LEO (kg)
M_{COTV}	=	total mass of the cargo orbit transfer vehicle (COTV) (kg)

M_{IOV}	=	total mass of the intra-orbit vehicles (IOVs) (kg)
$M_{P/L}$	=	total mass of the payload of an HLLV to LEO (kg)
f_{LOAD}	=	average load factor for an HLLV (what percentage of the payload is used)
f_{P-LV}	=	ratio of the number of HLLV flights for each Personnel Orbit Transfer Vehicle (POTV) flight (number)
f_{ROT}	=	crew rotation rate (number of rotations per year)
f_{POTV}	=	number of people carried per POTV flight (number)
N_{HLLV}	=	total number of HLLVs procured (number)
f_{DLLV}	=	design life of an HLLV (number of flights)
SC_{HLLV}	=	unit cost of an HLLV ($)
SC_{LVFLT}	=	cost per flight of an HLLV ($)
C_{IOV}	=	total cost of the intra-orbit vehicles (IOV) ($)
C_{IOVPR}	=	total procurement cost of the IOV fleet ($)
C_{IOVOP}	=	total operations cost of the IOV fleet ($)
N_{IOV}	=	total number of IOVs procured (number)
f_{DLIOV}	=	design life of an IOV (number of flights)
SC_{IOV}	=	unit cost of an IOV ($)
SM_{IOV}	=	unit mass of an IOV (kg)
SM_{IPRP}	=	mass of IOV propellant consumed per flight (kg)
SC_{IVFT}	=	cost per flight of an IOV ($)
C_{COTV}	=	total cost of the COTV fleet ($)
C_{COTVPR}	=	total procurement cost of the COTV fleet ($)
C_{COTVOP}	=	total operations cost of the COTV fleet ($)
N_{CFLTS}	=	total number of COTV flights
f_{COTV}	=	ratio of the number of HLLV flights to one COTV flight (number)
N_{COTV}	=	total number of COTVs procured (number)

f_{DLCOTV}	=	design life of a COTV (number of flights)
SC_{COTV}	=	unit cost of a COTV ($)
SM_{COTV}	=	unit mass of a COTV (kg)
$SC_{COTVFLT}$	=	cost per COTV flight ($)
C_{POTV}	=	total cost of the POTV fleet ($)
C_{POTVPR}	=	total procurement cost of the POTV fleet ($)
C_{POTVOP}	=	total operations cost of the POTV fleet ($)
N_{PLFTS}	=	total number of POTV flights (number)
N_{POTV}	=	total number of POTVs procured (number)
f_{DLPOTV}	=	design life of a POTV (number of flights)
SC_{POTV}	=	unit cost of a POTV ($)
$SC_{POTVFLT}$	=	cost per POTV flight ($)
SC_{FACS}	=	total cost of ground facilities associated with the construction of the SPS fleet ($)
C_{FACS}	=	total cost of ground facilities associated with the construction of a single SPS satellite ($)
f_{DLFACS}	=	design life of the ground facilities (number of years)
C_{TXS}	=	total cost of taxes ($)
C_{INS}	=	total cost of insurance ($)
C_{PM}	=	total cost of SPS program management ($)
f_{PM}	=	ratio of overall program management cost to TFU initial investment cost (fraction)
C_{SEI}	=	total cost of SPS program SE&I ($)
f_{SEI}	=	ratio of overall program SE&I cost to TFU initial investment cost (fraction)

B.2 The O&M Cost Model of the Rockwell International Configuration

Orbital Operations

$$C_{OROMP} = N_{ORC}\, SC_{ORC} + M_{ORPR}\, SC_{ORPR} + M_{EMS}\, SC_{EMS} + \frac{SC_{ADM}\, N_{OMADM}}{f_{DLADM}} + \frac{SC_{CHM}\, N_{OMCHM}}{f_{DLCHM}}$$

$$\frac{SC_{CLM}\, M_{OMCLM}}{f_{DLCLM}} + \frac{SC_{COM}\, N_{OMCOM}}{f_{DLCSM}}$$

Ground Operations

$$C_{GSOM} = C_{GSC} + C_{GSMAT}$$

O&M Transportation

$$M_{OM} = M_{ORPR} + M_{EMS} + \frac{SM_{ADM} + N_{OMADM}}{f_{DLADM}} + \frac{SM_{CHM}\, N_{OMCHM}}{f_{DLCHM}} + \frac{SM_{CLM}\, N_{OMCLM}}{f_{DLCLM}} + \frac{SM_{COM}\, N_{OMCOM}}{f_{DLCOM}} + \frac{SM_{PSM}\, N_{OMPSM}}{f_{DLPSM}} + \frac{SM_{CSM}\, N_{OMCSM}}{f_{DLCSM}}$$

$$N_{OMCFT} = \frac{M_{OM}}{M_{PL}\, f_{LOAD}\, f_{COTV}}$$

$$N_{OMCV} = \frac{N_{OMCFT}}{f_{DLCTV}}$$

$$M_{OMCV} = SM_{COTV}\, N_{OMCV}$$

$$C_{OMCV} = C_{CTVFT}\, N_{OMCFT} + N_{OMCV}\, SC_{COTV}$$

$$N_{OMIFT} = \frac{M_{OM} + M_{OMCV}}{M_{PL}\, f_{LOAD}}$$

$$N_{OMIV} = \frac{M_{OM} + M_{OMCV}}{M_{PL}\, f_{LOAD}\, f_{DLIOV}}$$

$$M_{OMIV} = SM_{IOV}\, N_{OMIV}$$

$$C_{OMIV} = N_{OMIV}$$

$$N_{OMLVF} = \frac{M_{OM} + M_{OMCV} + M_{OMIV}}{M_{PL}\, f_{LOAD}}$$

$$N_{OMLV} = \frac{N_{OMLVF}}{f_{DLLV}}$$

$$C_{OMLV} = SC_{HLLV}\, N_{OMLV} + SC_{LVFL}\, N_{OMLVF}$$

$$N_{OMPFT} = \frac{N_{ORC} \cdot f_{ROT}}{f_{POTV}}$$

$$N_{OMPV} = \frac{N_{OMPFT}}{f_{DLPTV}}$$

$$C_{OMPV} = N_{OMPV}\, SC_{POTV} + N_{OMPFT} \cdot P_{OTVFT}$$

$$C_{OMST} = C_{OMLV} + C_{OMCV} + C_{OMIV} + C_{OMPV}$$

<u>Total Annual O&M Cost</u>

$$C_{OM} = C_{OROMP} + C_{GSOM} + C_{OMST}$$

Definitions of O&M Model

C_{OROMP}	=	total cost of orbital O&M personnel ($)
N_{ORC}	=	total number of O&M crew members (number)
SC_{ORC}	=	annual cost per person of O&M crew members ($/person)
M_{ORPR}	=	total mass of annual O&M refurbishment procurements (kg)
SC_{ORPR}	=	average specific cost of annual O&M refurbishment procurements ($/kg)
M_{EMS}	=	total mass of expendable maintenance supplies (kg)
SC_{EMS}	=	average specific cost of expendable maintenance supply materials ($/kg)
C_{GSOM}	=	total cost of ground station O&M
C_{GSC}	=	annual cost of ground station crew ($)
M_{OM}	=	total mass to be transported to GEO for O&M (kg)
C_{GSMAT}	=	annual cost of ground station materials ($)
N_{OMADM}	=	number of O&M airlock docking modules (number)
N_{OMCHM}	=	number of O&M crew habitability modules (number)
N_{OMCLM}	=	number of O&M consumables logistics modules (number)
N_{OMCOM}	=	number of O&M base management modules (number)
N_{OMPSM}	=	number of pressurized storage modules (number)
N_{OMCSM}	=	number of O&M crew support modules (number)
N_{OMCFT}	=	total number of COTV flights to support O&M (number)
N_{OMCV}	=	total number of COTVs "consumed" by O&M (number)
M_{OMCV}	=	total mass of COTVs "consumed" by O&M (kg)
C_{OMCV}	=	total cost of COTVs "consumed" by O&M ($)
N_{OMIFT}	=	total number of IOV flights to support O&M (number)
N_{OMIV}	=	total number of IOVs "consumed" by O&M (number)
M_{OMIV}	=	total mass of IOVs "consumed" by O&M (kg)

C_{OMIV}	=	total cost of IOVs "consumed" by O&M ($)
N_{OMLVF}	=	total number of launch vehicles flights (number)
N_{OMLV}	=	total number of launch vehicles "consumed" by O&M (number)
C_{OMLV}	=	total cost of launch vehicles "consumed" by O&M ($)
C_{OMST}	=	total cost of O&M space transportation ($)
N_{OMPFT}	=	total number of personnel transfer flights (number)
N_{OMPV}	=	total number of personnel transfer vehicles "consumed" by O&M (number)
C_{OMPV}	=	total cost of personnel transfer vehicles "consumed" by O&M ($)
C_{OM}	=	total annual cost of O&M per satellite ($)

APPENDIX C

THEORETICAL FIRST UNIT (TFU) AND OPERATION AND MAINTENANCE (O&M) COST MODELS FOR THE BOEING CO. SPS CONFIGURATION

The following is a listing of the equations incorporated in the TFU and O&M cost models of the Boeing Co. SPS configuration as described in "Solar Power Satellite--System Definition Study, Part III" of March 1978. The equations are organized here to correspond to the structure delineated in "Satellite Power System Work Breakdown Structure Dictionary," NASA TM 78155, January 1978. Where discrepancies exist in the level of detail developed or the elements identified between the Boeing report and the suggested WBS structure in the NASA document, they have been noted, and an attempt has been made to reconcile the differences and to report the cost equations at the lowest possible level of detail corresponding to the NASA WBS structure. The definitions of the variables used in these cost equations have been gathered together at the end of each cost model in order to avoid repetition.

It should be noted that the cost model is designed to calculate the cost of a single satellite. The data listed in Appendix E correspond to the TFU of the Boeing configuration, and therefore the cost of a single satellite calculated by the models listed below is for the cost of the TFU. Where costs or masses below relate to facilities or equipment used to construct more than one satellite, these costs and masses are amortized in the model so that each satellite pays an equal portion of the common cost. For example, in the case of the space bases, whose lifetime is equal to the total time required to build the SPS fleet, the cost of the space bases has been spread over all the satellites, such that each satellite pays an annuity at its IOD, the sum of all of which annuities discounted at the indicated discount rate

equals the present value of the space base at the IOD of the first production unit. Hence, any variable which corresponds the total procurement cost of equipment which is used for the construction of more than one satellite is the amount of the cost of such equipment which has been apportioned to each satellite. A similar amortization process has also been applied to the masses of space-based equipment (used for the construction of more than one satellite) for the purpose of calculating total transportation cost associated with the construction of more than one satellite) for the purpose of calculating total transportation cost associated with the construction of one satellite.

C.1 The TFU Cost Model of the Boeing Co. Configuration

01-00-00 Satellite System

$$C_{SAT} = C_{SSS} + C_{PS} + C_{PODS} + C_{MPTS} + C_{RT} + C_{AVS} + C_{GAI} + C_{SGTH} + C_{SGTO} + C_{GSE} + C_{SPM} + C_{SSEI}$$

$$M_{SAT} = M_{SSS} + M_{PS} + M_{PODS} + M_{MPTS} + M_{AVS}$$

01-01-00 Structure

$$C_{CSSS} = C_{AST} + C_{PSTR} + C_{SEST}$$

$$M_{SSS} = M_{AST} + M_{PSTR} + M_{SEST}$$

01-01-01 Antenna Structure

$$C_{AST} = P_{PAPD} \left(SM_{WWPS}\, SC_{MWS} + SM_{MWST}\, SC_{MWST}\right)$$

$$M_{AST} = P_{PAPD} \left(SM_{MWPS} + SM_{MWST}\right)$$

01-01-02 Power Source Structure

$$A_B = \frac{P_{SAPD}}{\eta_{SC}\, F\, \eta_{EFF}\, t_{SFSC}\, t_{AD}\, t_{ED}}$$

$$M_{PSTR} = SM_{PSTR}\, A_B$$

$C_{PSTR} = SC_{PSTR} M_{PSTR}$

01-01-03 Mechanisms

[Hardware elements in this category have been reported elsewhere.]

01-01-04 Secondary Structure

$C_{SEST} = (SC_{CSS} + SC_{BSUP}) A_B$

$M_{SEST} = (SM_{CSS} + SM_{BSUP}) A_B$

01-02-00 Power Source

$C_{PS} = SC_{SB} A_B$

$M_{PS} = SM_{SB} A_B$

[Note: This configuration has no concentrators for the solar array; therefore, $C_{ECOL} = 0$.]

01-03-00 Power Distribution and Conditioning

$M_{IBJ} = SM_{IBJ} P_{SAPD}$

$M_{MB} = SM_{MB} P_{SAPD}$

$M_{SWTG} = SM_{SWTG} P_{SAPD}$

$C_{PODS} = SC_{SWTG} M_{SWTG} + SC_{MB} M_{MB} + SC_{IBJ} M_{IBJ}$

01-04-00 Microwave Antenna

$C_{MPTS} = C_{MWTA} + C_{MWPD}$

$M_{MPTS} = M_{MWTA} + M_{MWPD}$

01-04-01 RF Generator and Beam Control

01-04-02 Waveguides

$C_{MWTA} = (SC_{TASG} + SC_{TAPA} + SC_{TATC} + SC_{TACC} + SC_{TAH}) P_{DCRF}$

$$M_{MWTA} = (SM_{TASG} + SM_{TAPA} + SM_{TATC} + SM_{TACC} + SM_{TAH})\, P_{DCRF}$$

01-04-03 Power Distribution and Conditioning

$$C_{MWPD} = (SC_{MWPD}\, SM_{MWPP} + SC_{MWTC}\, SM_{MWTC} + SC_{MWTC}\, SM_{MWBC} + SC_{MWSG}\, SM_{MWSG})\, P_{APD}$$

$$M_{MWPD} = (SM_{MWPP} + SM_{MWTC} + SM_{MWSG} + SM_{WWBC})\, P_{APD}$$

01-05-00 Rotary Joint

$$M_{AYT} = SM_{AYT}\, P_{AINT}$$

$$C_{AYT} = SC_{AYT}\, M_{AYT}$$

$$M_{RJ} = M_{AYT} + SM_{ERT}\, P_{AINT}$$

$$C_{RJ} = C_{AYT} + SC_{ERJ}\, M_{ERJ}$$

01-06-00 Propulsion

[Hardware elements in this category have been included elsewhere.]

01-07-00 Energy Storage

[Hardware elements in this category have been included elsewhere.]

01-08-00 Avionics

$$C_{AVS} = C_{DM} + C_{CM} + C_{AC}$$

$$M_{AVS} = M_{DM} + M_{CM} + M_{AC}$$

01-08-01 Data Mangement

$$C_{DM} = SC_{MWDP}\, P_{APD} + C_{CC}$$

$$M_{DM} = SM_{DP}\, P_{APD} + M_{CC}$$

01-08-02 Communications and Tracking

$$C_{CM} = C_{COMM} + SC_{MWC}\, P_{APD}$$

$$M_{CM} = M_{COMM} + SM_{MWC}\, P_{APD}$$

01-08-03 Instrumentation

[Hardware elements in this category have been included elsewhere.]

01-08-04 Attitude Control

$$C_{AC} = C_{THR} + C_{ACPP} + C_{ACIN} + C_{ACTS} + C_{ACCN} + SC_{MWAC}\, P_{APD}$$

$$M_{AC} = M_{THR} + M_{ACPP} + M_{ACIN} + M_{ACTS} + M_{ACCN} + SM_{MWAC}\, P_{APD}$$

01-09-00 Ground Assembly and Integration

$$C_{SUPC} = C_{SSS} + C_{PS} + C_{PODS} + C_{MPTS} + C_{RJ} + C_{AVS}$$

$$C_{GAI} = f_{GAI}\, C_{SUPC}$$

01-10-00 System Ground Test Hardware

$$C_{SGTH} = f_{SGTH}\, C_{SUPC}$$

01-11-00 System Ground Test Operations

$$C_{SGTO} = f_{SGTO}\, C_{SUPC}$$

01-12-00 Ground Support Equipment

$$C_{GSE} = f_{GSE}\, C_{GSE}$$

01-13-00 Satellite System Program Management

$$C_{SPM} = f_{SPM}\,(C_{SSS} + C_{PS} + C_{PODS} + C_{MPTS} + C_{RJ} + C_{AVS} + C_{GAI} + C_{SGTH} + C_{SGTO} + C_{GSE})$$

01-14-00 Satellite System Systems Engineering and Integration (SE&I)

$$C_{SSEI} = f_{SSEI}\,(C_{SSS} + C_{PS} + C_{PODS} + C_{MPTS} + C_{RJ} + C_{AVS} +$$

$$C_{GAI} + C_{SGTH} + C_{SGTO} + C_{GSE})$$

02-00-00 Ground Station Systems*

$$C_{GS} = 2(C_{GSEC} + C_{GSCC} + C_{GSGI} + C_{RE} + C_{GSPM} + C_{GSSEI})$$

02-01-00 Rectenna

$$C_{GSEC} = C_{GSRF} + C_{GSPD} + C_{RPS}$$

02-01-01 Dipole/Rectifier Elements

$$C_{GSRF} = (SC_{RFDI} + SC_{RFCR} + SC_{RFSC} + SC_{RECP} + SC_{RFDC})\, P_{RFDC}$$

02-01-02 Power Distribution and Conditioning

$$C_{GSPD} = (SC_{GSLB} + SC_{GSDP})\, P_{RECPD}$$

02-01-03 Support and Ground Plane Structures

$$C_{RPS} = (SC_{RPS} + SC_{GSGP})\, P_{RFDC}$$

02-02-00 Satellite Control

$$C_{GSCC} = C_{GSPC} + C_{SOPS}$$

02-03-00 Utility Interface

$$C_{GSGI} = P_{RECPD}\, SC_{GSGI}$$

02-04-00 Site and Facilities

$$C_{RE} = [\text{input}]$$

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*The plural "systems" is used because for this configuration there are two 5 GW ground receiving stations for each 10 GW satellite.

02-05-00 Ground Station Program

$$C_{GSPM} = f_{GSPM} (C_{GSEC} + C_{GSCC} + C_{GSGI} + C_{RE})$$

02-06-00 Ground Station Systems Engineering and Integration

$$C_{GSSEI} = f_{GSSEI} (C_{GSEC} + C_{GSCC} + C_{GSGI} + C_{RE})$$

03-00-00 Manpower Operations

[Costs associated with this category have been included elsewhere.]

04-00-00 Orbital Assembly and Support

$$C_{SPCN} = C_{LCB} + C_{GCB}$$

$$M_{SPCN} = M_{LCB} + M_{GCB}$$

04-01-00 Construction Base

$$C_{LCB} = \frac{N_{LEO}}{f_{NLEO}} \cdot \frac{C_{LCBFR} + C_{LCBCM} + C_{LCBWM} + C_{LCBCH} + C_{LCBBS}}{R_{CONST}\, f_{DLLEO}} + C_{LMP}$$

$$M_{LCB} = \frac{N_{LEO}}{f_{NLEO}} \cdot \frac{M_{LCBFR} + M_{LCBCM} + M_{LCBWM} + M_{LCBCH} + C_{LCBBS}}{R_{CONST}\, f_{DLLEO}} + M_{MP}$$

04-02-00 Logistics Base and
04-03-00 O&M Base

$$C_{GCB} = \frac{N_{GEO}}{f_{NGEO}} \cdot \frac{C_{GCBFR} + C_{GCBCM} + C_{GCBWM} + C_{GCBCH} + C_{GCBBS}}{R_{CONST}\, f_{DLGEO}} + C_{GMP}$$

$$M_{GCB} = \frac{N_{GEO}}{f_{NGEO}} \cdot \frac{M_{GCBFR} + M_{GCBCM} + M_{GCBWM} + M_{GCBH} + M_{GCBBS}}{R_{CONST}\, f_{DLGEO}} + M_{GMP}$$

05-00-00 Orbital Assembly and Support

$$C_{ORBAS} = \frac{C_{LSA}}{R_{CONST}\, f_{DLLSA}} + \frac{C_{LEC}}{R_{CONST}\, f_{DLLEC}} + \frac{C_{LPD}}{R_{CONST}\, f_{DLLPD}} + \frac{C_{LAS}}{R_{CONST}\, f_{DLLAS}} + \frac{C_{LC}}{R_{CONST}\, f_{DLLC}} + \frac{C_{LI}}{R_{CONST}\, f_{DLLI}} + \frac{C_{GSA}}{R_{CONST}\, f_{DLGSA}} + \frac{C_{GEC}}{R_{CONST}\, f_{DLGEC}} + \frac{C_{GPD}}{R_{CONST}\, f_{DLGPD}} + \frac{C_{GAS}}{R_{CONST}\, f_{DLGAS}} + \frac{C_{GC}}{R_{CONST}\, f_{DLGC}} + \frac{C_{GI}}{R_{CONST}\, f_{DLGI}}$$

$$M_{ORBHS} = \frac{M_{LSA}}{R_{CONST}\, f_{DLLSH}} + \frac{M_{LEC}}{R_{CONST}\, f_{DLLEC}} + \frac{M_{LPD}}{R_{CONST}\, f_{DLLPD}} + \frac{M_{LAS}}{R_{CONST}\, f_{DLLAS}} + \frac{M_{LC}}{R_{CONST}\, f_{DLLC}} + \frac{M_{LI}}{R_{CONST}\, f_{DLLI}} + \frac{M_{GSA}}{R_{CONST}\, f_{DLGSA}} + \frac{M_{GEC}}{R_{CONST}\, f_{DLGEC}} + \frac{M_{GPD}}{R_{CONST}\, f_{DLGPD}} + \frac{M_{GAS}}{R_{CONST}\, f_{DLGAS}} + \frac{M_{GC}}{R_{CONST}\, f_{DLGC}} + \frac{M_{GI}}{R_{CONST}\, f_{DLGI}}$$

06-00-00 Heavy Lift Launch Vehicle (HLLV)

$$C_{HLLV} = C_{HLVPR} + C_{HLVOP}$$

06-01-00 HLLV Fleet

$$M_{LEO} = M_{SAT} + M_{SPCN} + M_{ORBAS} + M_{OTV}$$

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

$$N_{HLLV} = \frac{N_{LVFLT}}{f_{DLLV}}$$

$$C_{HLVPR} = SC_{HLLV}\, N_{HLLV}$$

06-02-00 HLLV Operations

$$C_{HLVOP} = SC_{LVFLT}\, N_{LVFLT}$$

07-00-00 Space Transportation System (STS) and
09-00-00 Personnel Module

$$C_{POTV} = C_{POTVPR} + C_{POTVOP}$$

07-01-00 STS Fleet and
09-01-00 Personnel Module Fleet

$$N_{PFLTS} = \frac{N_{GEO}\, \frac{f_{ROT}}{R_{CONST}}}{f_{POTV}}$$

$$N_{POTV} = \frac{N_{PFLTS}}{f_{DLPOTV}}$$

$$C_{POTVPR} = SC_{POTV}\, N_{POTV}$$

07-02-00 STS Operations and
09-02-00 Personnel Module Operations

$$C_{POTVOP} = SC_{POTVFLT}\, N_{PFLTS}$$

08-00-00 Orbit Transfer Vehicle*

$$C_{SOTV} = M_{SAT}\,(SC_{STHR} + SC_{SOT} + SC_{AR} + SC_{LOX})$$

$$M_{SOTV} = M_{SAT}\,(SM_{STHR} + SM_{SOT} + SM_{AR} + SM_{LOX})$$

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*This category accounts for the costs associated with the self-orbit transfer concept employed in the Boeing configuration.

10-00-00 Facilities

$$C_{FACS} = \frac{SC_{FACS}}{R_{CONST}\, f_{DLFACS}}$$

11-00-00 Taxes

C_{TXS} = [Input Value]

12-00-00 Insurance

C_{INS} = [Input Value]

13-00-00 Program Management

$$C_{PM} = f_{PM}\,(C_{SAT} + C_{GS} + C_{SPCN} + C_{ORBAS} + C_{HLLV} + C_{POTV} + C_{SOTV})$$

14-00-00 Program SE&I

$$C_{SEI} = f_{SEI}\,(C_{SAT} + C_{GS} + C_{SPCN} + C_{ORBAS} + C_{HLLV} + C_{POTV} + C_{SOTV})$$

Definitions of TFU Cost Model Variables

Following is a listing of the definitions of the variables used in the TFU Cost Model of the Boeing configuration, in the order of their initial appearance in the model.

C_{SAT}	=	total procurement cost of an operational satellite ($)
C_{SSS}	=	total cost of the structure of the satellite system ($)
C_{PS}	=	total cost of the power source of the satellite system ($)
C_{PODS}	=	total cost of the satellite power distribution and conditioning system ($)
C_{MPTS}	=	total procurement cost of the transmitting antennae ($)
C_{RJ}	=	total cost of the rotary joints ($)
C_{AVS}	=	total cost of avionics for the satellite system ($)

C_{GAI}	=	total cost of ground assembly and integration ($)
C_{SGTH}	=	total procurement cost of system ground test hardware ($)
C_{SGTO}	=	total cost of system ground test operations ($)
C_{GSE}	=	total cost of ground support equipment ($)
C_{SPM}	=	total cost of program management for the satellite system ($)
C_{SSEI}	=	total cost of systems engineering and integration (SE&I) for the satellite system ($)
M_{SAT}	=	total mass of an operational TFU satellite (kg)
M_{SSS}	=	total mass of the structure of the satellite system (kg)
M_{PS}	=	total mass of the power source of the satellite system (kg)
M_{PODS}	=	total mass of the satellite power distribution and conditioning system (kg)
M_{MPTS}	=	total mass of the microwave transmitting antenna of the satellite system (kg)
C_{AST}	=	total cost of the antenna structure ($)
C_{PSTR}	=	total cost of the power source structure ($)
C_{SEST}	=	total cost of secondary structure ($)
M_{SSS}	=	total mass of the structure of the satellite system (kg)
M_{AST}	=	total mass of the antenna structure (kg)
M_{PSTR}	=	total mass of the power source structure (kg)
M_{SEST}	=	total mass of secondary structure (kg)
SM_{MWPS}	=	ratio of the mass of microwave antennae primary structure to power throughput (kg/kW)
SC_{MWPS}	=	specific cost of the microwave antennae primary structure ($/kW)
SM_{MWPS}	=	ratio of the mass of microwave antennae secondary structure to power throughput (kg/kW)
SC_{MWPS}	=	specific cost of the microwave antennae secondary structure ($/kW)

P_{APD} = power input to the antenna power distribution system (kW);

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

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

$\eta_{ANT\ PD}$ = 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)

A_B = area of the solar blanket (km^2)

P_{SAPD} = power input to the solar array power distribution system (kW);

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

where $\eta_{ANT\ INT}$ = antenna power distribution efficiency

η_{SAPD} = solar array power distribution efficiency

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

F = solar flux constant ($1353 \times 10^3 kW/km^2$)

n_{EFF} = effective concentration ratio

f_{SFSC} = seasonal correction factor for solar flux constant

f_{ED} = environmental degradation factor for solar cells over design life

f_{AD} = array design factor (includes "packing factor," that is, the ratio of solar cell area to total array area)

SM_{PSTR}	=	ratio of the mass of the power source structure to the planform area of the solar array and concentrators (kg/km^2)
SC_{PSTR}	=	specific cost of the power source structure ($/kg)
SC_{CSS}	=	ratio of the cost of catenary support system to the planform area of the solar array and concentrators ($/$km^2$)
SC_{BSUP}	=	ratio of the cost of the catenary support system to the planform area of the solar array and concentrators ($/$km^2$)
SM_{CSS}	=	ratio of the mass of the catenary support system to the planform area of the solar array (kg/km^2)
SM_{BSUP}	=	ratio of the mass of the bus supports to the planform area of the solar array (kg/km^2)
SC_{SB}	=	specific cost of the solar blankets ($/$km^2$)
SM_{SB}	=	specific mass of the solar blankets (kg/km^2)
M_{IBJ}	=	total mass of the interbay jumpers (kg)
SM_{IBJ}	=	ratio of the mass of interbay jumpers to the power throughput (kg/kW)
M_{MB}	=	total mass of the main buses (kg)
SM_{MB}	=	ratio of the mass of the main buses to the power throughput (kg/kW)
M_{SWTG}	=	total mass of switchgear (kg)
SM_{SWTG}	=	ratio of the mass of the switchgear to the power throughput (kg/kW)
SC_{SWTG}	=	specific cost of the switchgear ($/kg)
SC_{MB}	=	specific cost of the main buses ($/kg)
SC_{IBJ}	=	specific cost of the interbay jumpers ($/kg)
C_{MWTA}	=	total cost of the microwave transmitting arrays ($)
C_{MWPD}	=	total cost of microwave antenna power distribution system ($)
M_{MWTA}	=	total mass of the microwave transmitting arrays (kg)
M_{MWPD}	=	total mass of the microwave antenna power distribution system (kg)

SC_{TASG} = ratio of the cost of antennae structure and waveguides to power throughput ($/kW)

SC_{TAPA} = ratio of the cost of the transmitter power amplifiers to power throughput ($/kW)

SC_{TATC} = ratio of the cost of transmitter thermal control to power throughput ($/kW)

SC_{TACC} = ratio of the cost of phase control to power throughput ($/kW)

SC_{TAH} = ratio of the cost of transmitter harnesses to power throughput ($/kW)

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

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

SM_{TASG} = ratio of the mass of antennae structure and waveguides to power throughput (kg/kW)

SM_{TAPA} = ratio of the mass of transmitter power amplifiers to power throughput (kg/kW)

SM_{TATC} = ratio of the mass of transmitter thermal control to power throughput (kg/kW)

SM_{TACC} = ratio of the mass of phase control equipment to power throughput (kg/kW)

SM_{TAH} = ratio of the mass of transmitter harnesses to power throughput (kg/kW)

SC_{MWPP} = specific cost of microwave antennae power processors ($/kg)

SM_{MWPP} = ratio of the mass of microwave antennae power processors to power throughput (kg/kW)

SC_{MWTC} = specific cost of the microwave power processor thermal control ($/kg)

SM_{MWTC} = ratio of the mass of microwave antennae power processor thermal control equipment to power throughput (kg/kW)

SC_{MWBC} = specific cost of microwave antennae busing and cabling ($/kg)

SM_{BC} = ratio of the mass of microwave antennae busing and cabling to power throughput (kg/kW)

SC_{MWSG} = specific cost of microwave antennae switchgear ($/kg)

SM_{MWSG} = ratio of the mass of microwave antennae switchgear to power throughput (kg/kW)

M_{AYT} = total mass of the antenna yokes and turntables (kg)

SM_{AYT} = ratio of the mass of the antenna yokes and turntables to the power throughput (kg/kW)

P_{AINT} = power input to the antenna interface (kw);

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

C_{AYT} = total cost of the antenna yokes and turntables ($)

SC_{AYT} = specific cost of the antenna yokes and turntables ($/kg)

SM_{ERJ} = ratio of the mass of the electrical rotary joints to the power throughput (kg/kW)

SC_{ERJ} = specific cost of the electrical rotary joints ($/kg)

C_{DM} = total cost of data management ($)

C_{CM} = total cost of communications ($)

C_{AC} = total cost of attitude control ($)

M_{DM} = total mass of data management equipment (kg)

M_{CM} = total mass of communications equipment (kg)

M_{AC} = total mass of attitude control equipment (kg)

SC_{MWDP} = ratio of the cost of microwave antennae data processing to power throughput ($/kW)

C_{CC} = cost of central computing complex ($)

SM_{MWDP} = ratio of the mass of microwave antenna data processing equipment to power throughput (kg/kW)

M_{CC} = total mass of the central computing complex (kg)

C_{COMM} = total cost of the communications subsystem ($)

SC_{MWC} = ratio of the cost of microwave antennae communications equipment to power throughput ($/kW)

M_{COMM}	=	total mass of the communications subsystem (kg)
SM_{MWC}	=	ratio of the mass of the microwave antennae communications equipment to power throughput (kg/kW)
C_{THR}	=	total cost of the attitude control thrusters ($)
C_{ACPP}	=	total cost of the attitude control power processors ($)
C_{ACIN}	=	total cost of the attitude control installation ($)
C_{ACTS}	=	total cost of the attitude control propellant tanks ($)
C_{ACCN}	=	total cost of the attitude control propellant feed and thrust control system ($)
SC_{MWAC}	=	specific cost of the microwave antenna attitude control equipment ($/kg)
M_{THR}	=	total mass of the attitude control thrusters (kg)
M_{ACPP}	=	total mass of the attitude control power processors (kg)
M_{ACIN}	=	total mass of the attitude control installation (kg)
M_{ACTS}	=	total mass of the attitude control propellant tanks (kg)
M_{ACCN}	=	total mass of the attitude control propellant feed and thrust control system (kg)
SM_{MWAC}	=	ratio of the mass of microwave antennae attitude control equipment to power throughput (kg/kW)
C_{SUPC}	=	total procurement cost of the satellite system
f_{GAI}	=	ratio of ground assembly and integration cost to the satellite system procurement cost (fraction)
f_{SGTH}	=	ratio of the cost of system ground test hardware to the satellite system procurement cost (fraction)
f_{SGTO}	=	ratio of the cost of system ground test operations to the satellite system procurement cost (fraction)
f_{GSE}	=	ratio of the cost of ground support equipment to the satellite system procurement cost (fraction)
f_{SPM}	=	ratio of the cost of satellite system program management to all other TFU costs (fraction)
f_{SSEI}	=	ratio of the cost of satellite system SE&I to all other TFU costs (fraction)

C_{GSEC} = total cost of a rectenna ($)

C_{GSCC} = total cost of a satellite control facility ($)

C_{GSGI} = total cost of a utility interface ($)

C_{RE} = total cost of site and facilities ($)

C_{GSPM} = total cost of ground station system program management ($)

C_{GSSEI} = total cost of ground station system SE&I ($)

C_{GSRF} = total cost of the dipole/rectifier elements for a ground station ($)

C_{GSPD} = total cost of rectenna power distribution and conditioning for a ground station ($)

C_{RPS} = total cost of support and ground plane structure for a ground station ($)

SC_{RFDI} = ratio of the cost of RF assembly dipoles to power throughput ($/kW)

SC_{RFCR} = ratio of the cost of RF assembly circuitry to power throughput ($/kW)

SC_{RFSC} = ratio of the cost of RF assembly shields and covers to power throughput ($/kW)

SC_{RECP} = ratio of the cost of rectenna panels to power throughput ($/kW)

SC_{RFDC} = ratio of the cost of RF-DC conversion units to power throughput ($/kW)

$P_{RF\text{-}DC}$ = power input to the RF-DC converters (kW);

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

SC_{GSLB} = ratio of the cost of ground station local busing to power throughput ($/kW)

SC_{GSDP} = ratio of the cost of ground station distributed processing to power throughput ($/kW)

P_{RECPD} = power input to the rectenna power distribution system (kW);

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

SC_{RPS}	=	ratio of the cost of rectenna primary structure to power throughput ($/kW)
SC_{GSGP}	=	ratio of the ground station planes to power throughput ($/kW)
C_{GSPC}	=	total cost of a ground station phase control facility ($)
C_{SOPS}	=	total ground station cost of SPS operations
SC_{GSGI}	=	ratio of the cost of grid interface provisions to power throughput ($/kW)
f_{GSPM}	=	ratio of ground station program management costs to ground station procurement costs (fraction)
f_{GSSEI}	=	ratio of the cost of ground station SE&I to ground station procurement costs (fraction)
C_{SPCN}	=	total cost of orbital assembly and support ($)
C_{LCB}	=	total cost of the low earth orbit (LEO) construction base ($)
C_{GCB}	=	total cost of the geosynchronous earth orbit (GEO) construction base ($)
M_{SPCN}	=	total mass of orbital assembly and support equipment (kg)
M_{LCB}	=	total mass of the LEO construction base (kg)
M_{GCB}	=	total mass of the GEO construction base (kg)
N_{LEO}	=	total crew size of the LEO space base (number *[Note: this input varies over the range of the expected value of the crew size, and the cost and mass of the space base are scaled accordingly, in reference to the point design number f_{NLEO} below.]*
f_{NLEO}	=	reference point for the total crew size of the LEO space base (number)
f_{DLLEO}	=	design life of the LEO space base equipment (years)
R_{CONST}	=	satellite fleet construction rate (number of satellites/year)
C_{LCBRF}	=	total cost of LEO space base framework ($)
C_{LCBCM}	=	total cost of LEO space base crew modules ($)
C_{LCBWM}	=	total cost of LEO space base work modules ($)

C_{LCBCH}	=	total cost of LEO space base cargo handling and distribution equipment ($)
C_{LCBBS}	=	total cost of LEO space base subsystems ($)
C_{LMP}	=	total cost of LEO space base maintenance provisions ($)
M_{LCBFR}	=	total mass of the LEO space (kg)
M_{LCBCM}	=	total mass of the LEO space base crew modules (kg)
M_{LCBWM}	=	total mass of the LEO space base work modules (kg)
M_{LCBCH}	=	total mass of the LEO space base cargo handling and distribution equipment (kg)
M_{LCBBS}	=	total mass of the LEO space base subsystems (kg)
M_{LMP}	=	total mass of LEO space base maintenance provisions (kg)
N_{GEO}	=	total crew size of the GEO space base (number) *[Note: this input varies over the range of the expected value of the crew size, and the cost and mass of the space base are scaled accordingly, in reference to the point design number f_{NGEO} below.]*
f_{NGEO}	=	reference point number for the total crew size of the GEO space base (number)
f_{DLGEO}	=	design life of GEO space base equipment (years)
C_{GCBFR}	=	total cost of the GEO space base framework ($)
C_{GCBCM}	=	total cost of the GEO space base crew modules ($)
C_{GCBWM}	=	total cost of the GEO space base work modules ($)
C_{GCBCH}	=	total cost of the GEO space base cargo handling and distribution equipment ($)
C_{GCBBS}	=	total cost of the GEO space base subsystems ($)
C_{GMP}	=	total cost of the GEO space base maintenance provisions ($)
M_{GCBFR}	=	total mass of the GEO space base framework (kg)
M_{GCBCM}	=	total mass of the GEO space base crew modules (kg)
M_{GCBWM}	=	total mass of the GEO space base work modules (kg)
M_{GCBCH}	=	total mass of the GEO space base cargo handling and distribution equipment (kg)

C_{GI}	=	total cost of GEO space base indexers ($)
f_{DLGI}	=	design life of GEO space base indexers (years)
M_{LSA}	=	total mass of LEO space base structural assembly equipment (kg)
M_{LEC}	=	total mass of LEO space base energy conversion installation equipment (kg)
M_{LPD}	=	total mass of LEO space base power distribution installation equipment (kg)
M_{LAS}	=	total mass of LEO space base antenna installation equipment (kg)
M_{LC}	=	total mass of LEO space base cranes and manipulators (kg)
M_{LI}	=	total mass of LEO space base indexers (kg)
M_{GSA}	=	total mass of GEO space base structural assembly equipment (kg)
M_{GEC}	=	total mass of GEO space base energy conversion installation equipment (kg)
M_{GPD}	=	total mass of GEO space base power distribution installation equipment (kg)
M_{GAS}	=	total mass of GEO space base antenna installation equipment (kg)
M_{GC}	=	total mass of GEO space base cranes and manipulators (kg)
M_{GI}	=	total mass of GEO space base indexers (kg)
C_{HLLV}	=	total cost associated with the heavy lift launch vehicle (HLLV)($)
C_{HLVPR}	=	total procurement cost of the HLLV fleet ($)
C_{HLVOP}	=	total operations cost of the HLLV fleet ($)
M_{LEO}	=	total mass launched to LEO (kg)
N_{LVFLT}	=	total number of HLLV flights required (number)
$M_{P/L}$	=	total mass of the payload of an HLLV to LEO (kg)
f_{LOAD}	=	average load factor for an HLLV (what percentage of the payload is used)

N_{HLLV}	=	total number of HLLVs procured (number
f_{DLLV}	=	design life of an HLLV (number of flights)
SC_{HLLV}	=	unit cost of an HLLV ($)
SC_{LVFLT}	=	cost per flight of an HLLV ($)
M_{GCBBS}	=	total mass of the GEO space base subsystems (kg)
C_{ORBAS}	=	total cost of orbital assembly and support equipment ($)
C_{LSA}	=	total cost of LEO space base structural assembly equipment ($)
f_{DLLSA}	=	design life of LEO space base structural assembly equipment (years)
C_{LEC}	=	total cost of LEO space base energy conversion installation equipment ($)
f_{DLLEC}	=	design life of LEO space base energy conversion installation equipment (years)
C_{LPD}	=	total cost of LEO space base power distribution installation equipment ($)
f_{DLLPD}	=	design life of LEO space base power distribution installation equipment (years)
C_{LAS}	=	total cost of LEO space base antenna installation equipment ($)
f_{DLLAS}	=	design life of LEO space base antenna installation equipment (years)
C_{LC}	=	total cost of LEO space base cranes and manipulators ($)
f_{DLLC}	=	design life of LEO space base cranes and manipulators (years)
C_{LI}	=	total cost of LEO space base indexers ($)
f_{DLLI}	=	design life of LEO space base indexers (years)
C_{GSA}	=	total cost of GEO space base structural assembly equipment ($)
f_{DLGSA}	=	design life of GEO space base structural assembly equipment ($)

C_{GEC}	=	total cost of GEO space base energy conversion installation equipment ($)
f_{DLEC}	=	design life of GEO space base energy conversion installation equipment (years)
C_{GPD}	=	total cost of GEO space base power distribution installation equipment ($)
f_{DLPD}	=	design life of GEO space base power distribution installation equipment ($)
C_{GAS}	=	total cost of GEO space base antenna installation equipment ($)
f_{DLGAS}	=	design life of GEO space base antenna installation equipment (years)
C_{GC}	=	total cost of GEO space base cranes and manipulators ($)
f_{DLC}	=	design life of GEO space base cranes and manipulators (years)
C_{POTV}	=	total cost of the POTV fleet ($)
C_{POTVPR}	=	total procurement cost of the POTV fleet ($)
C_{POTVOP}	=	total operations cost of the POTV fleet ($)
N_{PLFTS}	=	total number of POTV flights (number)
f_{ROT}	=	crew rotation rate (number of rotations per year)
f_{POTV}	=	number of people carried per POTV flight (number)
N_{POTV}	=	total number of POTVs procured (number)
f_{DLPOTV}	=	design life of a POTV (number of flights)
SC_{POTV}	=	unit cost of a POTV ($)
$SC_{POTVFLT}$	=	cost per POTV flight ($)
C_{SOTV}	=	total cost of self-orbit transfer ($)
SC_{STHR}	=	ratio of the cost of self-orbit transfer thrusters to total satellite mass ($/kg)
SC_{SOT}	=	ratio of the cost of self-orbit transfer propellant tanks to satellite mass ($/kg)

SC_{AR}	=	ratio of cost of argon propellant for self-orbit transfer to satellite mass ($/kg)
SC_{LOX}	=	ratio of the cost of chemical propellant for self-orbit transfer to satellite mass ($/kg)
SM_{STHR}	=	ratio of the mass of self-orbit transfer thrusters to the satellite mass (kg/kg)
SM_{SOT}	=	ratio of the mass of self-orbit transfer propellant tanks to the satellite mass (kg/kg)
SM_{AR}	=	ratio of the mass of the argon propellant for self-orbit transfer to the satellite mass (kg/kg)
SM_{LOX}	=	ratio of the mass of chemical propellant for self-orbit transfer to the satellite mass (kg/kg)
SC_{FACS}	=	total cost of ground facilities associated with the construction of the SPS fleet ($)
C_{FACS}	=	total cost of ground facilities associated with the construction of a single SPS satellite ($)
f_{DLFACS}	=	design life of the ground facilities (number of years)
C_{TXS}	=	total cost of taxes ($)
C_{INS}	=	total cost of insurance
C_{PM}	=	total cost of SPS program management ($)
f_{PM}	=	ratio of overall program management cost to TFU initial investment cost (fraction)
C_{SEI}	=	total cost of SPS program SE&I ($)
f_{SEI}	=	ratio of overall program SE&I cost to TFU initial investment cost (fraction)

C.2 The O&M Cost Model of the Boeing Co. Configuration

Personnel

$$C_{OMC} = \frac{(N_{ORC}\, SC_{ORC})}{f_{NSOM}}$$

O&M Equipment Cost

$$C_{OME} = \sum_{i=1}^{9} \frac{N_{OMi}\, C_{OMi}}{f_{DLOMi}} + \frac{C_{CH}}{f_{DLCH}}$$

O&M Space Transportation Cost

$$M_{OME} = \sum_{i=1}^{9} \frac{N_{OMi}\, M_{OMi}}{f_{DLOMi}}$$

$$M_{OM} = M_{CPM} + \frac{N_{ORC}}{f_{NSOM}} \cdot \frac{M_{CH}}{f_{DLCH}}$$

$$N_{OMPPT} = \frac{N_{ORC}\, f_{ROT}}{f_{POTV}}$$

$$N_{OMPV} = \frac{N_{OMPFT}}{f_{DLPTV}}$$

$$C_{OMPV} = N_{OMPV}\, SC_{POTV} + N_{OMPFT}\, P_{OTVFT}$$

$$N_{OMCFT} = \frac{M_{OM}}{f_{COTV}}$$

$$N_{OMCV} = \frac{N_{OMCFT}}{f_{DLCTV}}$$

$$M_{OMCV} = SM_{COTV}\, N_{OMCV}$$

$$C_{OMCV} = C_{OTVFT}\, N_{OMCFT} + N_{OMCV}\, SC_{COTV}$$

$$N_{OMLVF} = \frac{M_{OM} + M_{OMCV} + M_{OME}}{M_{PL}\, f_{LOAD}}$$

$$N_{OMLV} = \frac{N_{OMLVF}}{f_{DLLV}}$$

$$C_{OMLV} = SC_{HLLV} N_{OMLV} + SC_{LVFL} N_{OMLVF}$$

$$C_{OMST} = C_{OMLV} + C_{OMCV} + C_{OMPV}$$

<u>Total Annual O&M</u>

$$C_{OM} = C_{OMC} + C_{OME} + C_{OMST}$$

Definitions of O&M Model

C_{OMC}	=	total cost of O&M personnel ($)
N_{ORC}	=	total number of orbital O&M personnel (number)
SC_{ORC}	=	annual cost per O&M crew member ($/person)
F_{NSOM}	=	number of satellites maintained by a single O&M base (number)
C_{OME}	=	total cost of O&M equipment ($)
N_{OM1}	=	number of maintenance gantry and manipulation units (number)
N_{OM2}	=	number of crew module docking ports (number)
N_{OM3}	=	number of crew buses (number)
N_{OM4}	=	number of crane manipulators (number)
N_{OM5}	=	number of component transporters (number)
N_{OM6}	=	number of turntables (number)
N_{OM7}	=	number of laser annealing units (number)
N_{OM8}	=	number of gantry/repair vehicles (number)
C_{OM1}	=	unit cost of a maintenance gantry and manipulation units ($)
C_{OM2}	=	unit cost of crew module docking ports ($)
C_{OM3}	=	unit cost of crew buses ($)
C_{OM4}	=	unit cost of crane manipulators ($)
C_{OM5}	=	unit cost of component transporters ($)
C_{OM6}	=	unit cost of turntables ($)
C_{OM7}	=	unit cost of laser annealing units ($)
C_{OM8}	=	unit cost of gantry/repair vehicles ($)
f_{DLOM1}	=	design life of maintenance gantry and manipulation units (years)
f_{DLOM2}	=	design life of crew module docking ports (years)

f_{DLOM3}	=	design life of crew buses (years)
f_{DLOM4}	=	design life of crane manipulators (years)
f_{DLOM5}	=	design life of component transporters (years)
f_{DLOM6}	=	design life of turntables (years)
f_{DLOM7}	=	design life of laser annealing units (years)
f_{DLOM8}	=	design life of gantry/repair vehicles (years)
C_{CH}	=	unit cost of an O&M crew habitability module ($)
f_{DLCH}	=	design life of an O&M crew habitability module (kg)
M_{OME}	=	total mass of O&M equipment (kg)
M_{OM1}	=	unit mass of maintenance gantry and manipulation units (kg)
M_{OM2}	=	unit mass of crew module docking ports (kg)
M_{OM3}	=	unit mass of crew buses (kg)
M_{OM4}	=	unit mass of crane manipulators (kg)
M_{OM5}	=	unit mass of component transporters (kg)
M_{OM6}	=	unit mass of turntables (kg)
M_{OM7}	=	unit mass of laser annealing units (kg)
M_{OM8}	=	unit mass of gantry/repair vehicles (kg)
M_{OM}	=	total mass of O&M material to GEO (kg)
M_{CPM}	=	mass of annual refurbishment components for a single SPS satellite (kg)
M_{CH}	=	mass of an O&M crew habitability module (kg)
N_{OMPPT}	=	total number of personnel transfer flights (number)
N_{OMPV}	=	total number of personnel transfer vehicles "consumed" by O&M (number)
C_{OMPV}	=	total cost of personnel transfer vehicles "consumed" by O&M ($)
N_{OMCFT}	=	total number of COTV flights to support O&M (number)
N_{OMCV}	=	total cost of COTVs "consumed" by O&M (kg)

f_{DLCTV}	=	design life of a cargo orbit transfer vehicle (number of flights)
M_{OMCV}	=	total mass of COTVs "consumed" by O&M (kg)
SC_{COTV}	=	unit cost of a cargo orbit transfer vehicle (number of flights)
C_{OMCV}	=	total cost of COTVs "consumed" by O&M ($)
COTVFT	=	cost per flight of a cargo orbit transfer vehicle ($/flight)
N_{OMLVF}	=	total number of launch vehicle flights to support .O&M (number)
N_{OMLV}	=	total number of launch vehicles "consumed" by O&M (number)
C_{OMLV}	=	total cost of launch vehicles "consumed" by O&M ($)
C_{OMST}	=	total cost of O&M space transportation ($)
C_{OM}	=	total annual O&M cost per satellite ($)

APPENDIX D

ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE ROCKWELL INTERNATIONAL CONFIGURATION

The current state-of-knowledge relative to the Rockwell configuration is reflected by the ranges of input variables to the risk analysis model. These ranges have been subjectively assessed and are given in Table D.1 for the TFU cost model and in Table D.2 for the O&M cost model. Table D.2 lists only those O&M cost model inputs whose values are not already listed in Table D.1. The current state-of-knowledge corresponds to Decision Point A (DPA) in the Rockwell SPS Development program analyzed in Section 2. It should be noted that the date for DPA is given as 1980 because no experimentation that might reduce uncertainty on any of the listed cost model elements is likely to occur before then.

The sources for these input data are the "Satellite Power Systems (SPS) Concept Definition Study" final report of April 1978, prepared by Rockwell International for the George C. Marshall Space Flight Center under NASA Contract NAS8-32475 and numerous telephone conversations and two series of meetings with Rockwell International personnel.

The states-of-knowledge at the decision points of the SPS development plan proposed by Rockwell have been subjectively assessed and are also shown in Table D.1. The numbers shown represent the percent reduction in uncertainty (that is, the range) in each variable over the state-of-knowledge today. 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 D 1 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON TFL COST MODEL INPUTS AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE ROCKWELL INTERNATIONAL CONFIGURATION

INPUT ELEMENT	VARIABLE NAME	UNITS	CURRENT STATE-OF-KNOWLEDGE RANGE OF VALUES (DPA)			IMPROVEMENT IN STATE-OF-KNOWLEDGE %	
			BEST	MOST LIKELY	WORST	DPA	DPC
RATIO OF OVERALL PROGRAM MANAGEMENT COST TO OTHER UNIT PRODUCTION COST	f_{PM}	FRACTION	.01	01	.01	--	--
RATIO OF OVERALL PROGRAM SYSTEMS ENGINEERING AND INTEGRATION COST TO OTHER UNIT PRODUCTION	f_{SEI}	FRACTION	.02	.02	.02	--	--
RATIO OF SATELLITE SYSTEM PROGRAM MANAGEMENT COST TO SATELLITE SYSTEM COST	f_{SPM}	FRACTION	.01	.01	.01	--	--
RATIO OF SATELLITE SYSTEM SYSTEMS ENGINEERING AND INTEGRATION COST TO SATELLITE SYSTEM COST	f_{SSEI}	FRACTION	.0455	07	.10	50%	100%
SPECIFIC COST OF THE TRANSMITTING ANTENNA STRUCTURE	SC_{AST}	$/kW	3.65	4.72	5 9	50%	100%
POWER OUTPUT AT RECTENNA BUSBAR (EOL)	P_{OUT}	kW	*	5×10^6	*	--	--
SOLAR CELL EFFICIENCY, GaAlAs CELLS (EOL)	ETA1	FRACTION	.193	.132	.10	65%	100%
SOLAR ARRAY POWER DISTRIBUTION EFFICIENCY	ETA2	FRACTION	.96	.93	.855	60%	100%
ANTENNA INTERFACE EFFICIENCY	ETA3	FRACTION	.999	.999	.99	--	--
ANTENNA POWER DISTRIBUTION EFFICIENCY	ETA4	FRACTION	.98	.92	.734	75%	100%
DC-RF CONVERTER EFFICIENCY	ETA5	FRACTION	.9	.85	.65	80%	100%
PHASE CONTROL EFFICIENCY	ETA6	FRACTION	.97	.925	.75	75%	100%
IONOSPHERIC PROPAGATION EFFICIENCY	ETA7	FRACTION	.98	.98	.95	100%	--
ATMOSPHERIC PROPAGATION EFFICIENCY	ETA8	FRACTION	1.0	1 0	1.0	--	--
BEAM COLLECTION EFFICIENCY	ETA9	FRACTION	.98	.92	.80	45%	100%
RF-DC CONVERTER EFFICIENCY	ETA10	FRACTION	.91	89	.85	45%	100%
RECTENNA POWER DISTRIBUTION EFFICIENCY	ETA11	FRACTION	.98	.93	.85	40%	100%
SPECIFIC MASS OF THE TRANSMITTING ANTENNA STRUCTURE	SM_{AST}	kg/kW	.0858	.0944	.1178	75%	100%
SPECIFIC COST OF THE POWER SOURCE STRUCTURE	SC_{PSST}	$/km^2	17189	25278	33750	50%	100%
ARRAY DESIGN FACTOR (INCLUDES SOLAR CELL PACKING FACTOR)	f_{AD}	FRACTION	.89	.855	81	40%	100%
SOLAR FLUX CONSTANT	F	kW/km^2	*	1353×10^3	*	--	--
EFFECTIVE CONCENTRATION RATIO	n_{EFF}	FRACTION	1.90	1.72	1.60	40%	100%
SEASONAL CORRECTION FACTOR FOR SOLAR FLUX CONSTANT	f_{SFSC}	FRACTION	*	.91	*	--	--
ENVIRONMENTAL DEGRADATION FACTOR FOR SOLAR CELLS OVER DESIGN LIFE	f_{ED}	FRACTION	.96	.96	.84	100%	--
SOLAR CONCENTRATOR EFFICIENCY	n_{CONC}	FRACTION	.9	.72	.6	85%	100%
RATIO. MASS OF THE POWER SOURCE STRUCTURE TO THE ARRAY AREA	SM_{PSST}	kg/km^2	35000	60000	80888	45%	100%
RATIO COST OF STRUCTURE MECHANISMS TO ARRAY AREA	SC_{MECHS}	$/km^2	10847	18078	36156	85%	100%
RATIO· MASS OF STRUCTURE MECHANISMS TO ARRAY AREA	SM_{MECHS}	kg/km^2	6089	8524	12032	50%	100%
RATIO· COST OF SECONDARY STRUCTURE TO ARRAY AREA	SC_{SEST}	$/km^2	3.157×10^6	4.385×10^6	5.017×10^6	60%	100%
RATIO MASS OF SECONDARY STRUCTURE TO ARRAY AREA	SM_{SEST}	kg/km^2	22346	25815	38636	70%	100%
SPECIFIC COST OF THE SOLAR BLANKET	SC_{SB}	$/km^2	51.725×10^6	64.656×10^6	130.0×10^6	35%	100%
SPECIFIC MASS OF THE SOLAR BLANKET	SM_{SB}	kg/km^2	230×10^3	304×10^3	450×10^3	45%	100%
SPECIFIC COST OF THE SOLAR CONCENTRATORS	SC_{SC}	$/km^2	1.494×10^6	1.942×10^6	3.137×10^6	35%	100%
SPECIFIC MASS OF THE SOLAR CONCENTRATORS	SM_{SC}	kg/km^2	9200	18460	36700	45%	100%
RATIO· COST OF CONDUCTORS AND SWITCHES TO ARRAY POWER THROUGHPUT	SC_{CHDC}	$/kW	.372	.465	.9895	45%	100%
RATIO. COST OF SLIP RINGS AND BRUSHES TO ANTENNA INTERFACE POWER THROUGHPUT	SC_{SR}	$/kW	17.395	22.888	48.705	45%	100%
RATIO COST OF SWITCHING TO ARRAY POWER THROUGHPUT	SC_{SWT}	$/kW	11.438	15.856	19.575	70%	100%
RATIO COST OF BATTERIES TO ARRAY POWER THROUGHPUT	SC_{BATT}	$/kW	.148	.205	.252	70%	100%

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TABLE D.1 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON TFU COST MODEL INPUTS AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE ROCKWELL INTERNATIONAL CONFIGURATION (CONTINUED)

INPUT ELEMENT	VARIABLE NAME	UNITS	CURRENT STATE-OF-KNOWLEDGE RANGE OF VALUES (DPA)			IMPROVEMENT IN STATE-OF-KNOWLEDGE, %	
			BEST	MOST LIKELY	WORST	DPS	DPC
RATIO COST OF BATTERY POWER CONDITIONING OF ARRAY POWER THROUGHPUT	SC_{BPC}	$/kW	.029	.040	.049	65%	100%
RATIO MASS OF CONDUCTORS AND SWITCHES TO ARRAY POWER THROUGHPUT	SK_{CNDC}	kg/kW	.093	.116	.163	65%	100%
RATIO MASS OF SWITCHING EQUIPMENT TO ARRAY POWER THROUGHPUT	SK_{SWT}	kg/kW	.030	.0375	.0525	65%	100%
RATIO. MASS OF BATTERIES TO ARRAY POWER THROUGHPUT	SK_{BATT}	kg/kW	.0026	.00325	.00455	70%	100%
RATIO. MASS OF BATTERY POWER CONDITIONING EQUIPMENT TO ARRAY POWER THROUGHPUT	SK_{BPC}	kg/kW	.0013	.00163	.00224	70%	100%
RATIO MASS OF SLIP RINGS AND BRUSHES TO ANTENNA INTERFACE POWER THROUGHPUT	SK_{SR}	kg/kW	.048	.0625	.077	75%	100%
RATIO COST OF MICROWAVE HEAT PIPES TO DC-RF POWER THROUGHPUT	SC_{HP}	$/kW	.583	1.029	1.6464	50%	100%
RATIO MASS OF MICROWAVE HEAT PIPES TO DC-RF POWER THROUGHPUT	SK_{HP}	kg/kW	.109	.192	.3075	50%	100%
RATIO COST OF MICROWAVE ANTENNA ELEMENTS TO DC-RF POWER THROUGHPUT	SC_{MWA}	$/kW	196 028	345.937	553.451	50%	100%
RATIO MASS OF MICROWAVE ANTENNA ELEMENTS TO DC-RF POWER THROUGHPUT	SK_{MWA}	kg/kW	.527	.93	1.95	45%	100%
RATIO COST OF MISCELLANEOUS EQUIPMENT TO MASS OF SATELLITE	SC_{MISC}	$/kg	13.659	18.0	25.0	50%	100%
RATIO. MASS OF MISCELLANEOUS EQUIPMENT TO MASS OF SATELLITE	SK_{MISC}	FRACTION	.0646	.08	.09	10%	100%
RATIO GROUND ASSEMBLY AND INTEGRATION COST TO SATELLITE UNIT PROCUREMENT COST	f_{GAI}	FRACTION	.022	.022	.022	--	--
RATIO SYSTEM GROUND TEST HARDWARE COST TO SATELLITE UNIT PROCUREMENT COST	f_{SGTH}	FRACTION	0	0	0	--	--
RATIO SYSTEM GROUND TEST OPERATIONS COST TO SATELLITE UNIT PROCUREMENT COST	f_{SGTO}	FRACTION	0	0	0	--	--
COST OF SATELLITE GROUND OPERATIONS	C_{SGO}	$	54.679×10^6	75.184×10^6	90.221×10^6	25%	100%
COST OF GROUND CONSTRUCTION FOR SATELLITE OPERATIONS	C_{GCRST}	$	52×10^6	71.5×10^6	85.8×10^6	25%	100%
COST OF GROUND LOGISTICS FOR SATELLITE OPERATIONS	C_{GLOGS}	$	2.679×10^6	3.684×10^6	4.421×10^6	25%	100%
COST OF CONSTRUCTION CREW FOR SATELLITE ORBITAL OPERATIONS	C_{CCREW}	$	9.984×10^6	17.971×10^6	23.962×10^6	85%	100%
COST OF CONSTRUCTION CREW PROVISIONS FOR SATELLITE ORBITAL OPERATIONS	C_{CPROV}	$	18.586×10^6	33.455×10^6	44.606×10^6	85%	100%
COST OF EXPENDABLE MAINTENANCE SUPPLIES FOR SATELLITE ORBITAL OPERATIONS	C_{CEMS}	$	7.008×10^6	9.811×10^6	$13 456 \times 10^6$	75%	100%
COST OF GROUND SUPPORT EQUIPMENT	C_{GSE}	$	0	0	0	--	--
COST OF SATELLITE CONTROL EQUIPMENT AT GROUND STATION	C_{SATCN}	$	42.558×10^6	55.075×10^6	68.844×10^6	50%	100%
COST OF GROUND STATION SYSTEM OPERATIONS	C_{GSOPS}	$	0	0	0	--	--
RATIO GROUND STATION PROGRAM MANAGEMENT COSTS TO OTHER GROUND STATION COSTS	f_{GSPM}	FRACTION	.01	.01	.02	40%	100%
RATIO. GROUND STATION SYSTEM ENGINEERING AND INTEGRATION COSTS TO OTHER GROUND STATION COSTS	f_{GSSEI}	FRACTION	.06	.07	.09	40%	100%
SPECIFIC COST OF DIPOLE/RECTIFIER ELEMENTS	SC_{DRE}	$/kW	85.98	157.63	268.688	30%	100%
SPECIFIC COST OF RECTENNA POWER DISTRIBUTION	SC_{RPDC}	$/kW	5.816	11.146	18.173	30%	100%
SPECIFIC COST OF RECTENNA SUPPORT AND GROUND PLANE STRUCTURE	SC_{RPS}	$/kW	90	117.809	176.714	35%	100%
SPECIFIC COST OF UTILITY INTERFACE	SC_{UTNT}	$/kW	50.47	63.090	75.71	35%	100%
COST OF GROUND STATION LAND AND PREPARATION	C_{LP}	$	82.676×10^6	105.512×10^6	125.048×10^6	25%	100%
COST OF GROUND STATION ROADS AND FENCES	C_{RF}	$	8.90×10^6	8.90×10^6	8.90×10^6	--	--
COST OF GROUND STATION UTILITIES	C_{UT}	$	10×10^6	10×10^6	10×10^6	--	--
COST OF GROUND STATION BUILDINGS	C_B	$	4.8×10^6	4.8×10^6	4.8×10^6	--	--

TABLE D.1 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON TFU COST MODEL INPUTS AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE ROCKWELL INTERNATIONAL CONFIGURATION (CONTINUED)

INPUT ELEMENT	VARIABLE NAME	UNITS	CURRENT STATE-OF-KNOWLEDGE RANGE OF VALUES (DPA)			IMPROVEMENT IN STATE-OF-KNOWLEDGE $	
			BEST	MOST LIKELY	WORST	DPB	DPC
COST OF GROUND STATION MAINTENANCE EQUIPMENT	C_{ME}	$	4.0×10^6	4.0×10^6	4.0×10^6	--	--
UNIT COST OF CREW HABITABILITY MODULE	SC_{CHM}	$	44.045×10^6	88.089×10^6	264.267×10^6		
UNIT COST OF CREW SUPPORT MODULE/EVA	SC_{CSM}	$	78.273×10^6	156.546×10^6	469.638×10^6		
UNIT COST OF BASE MANAGEMENT MODULE	SC_{COM}	$	181.083×10^6	362.165×10^6	1086.495×10^6		
UNIT COST OF POWER MODULE	SC_{POWM}	$	129.92×10^6	259.83×10^6	779.49×10^6		
NUMBER OF PEOPLE IN LEO SPACE BASE	N_{LEO}	NUMBER	30	30	75		
NUMBER OF PEOPLE IN BASELINE LEO SPACE BASE DESIGN	f_{NLEO}	NUMBER	*	30	*	--	--
DESIGN LIFE OF LEO SPACE BASE EQUIPMENT	f_{DLLEO}	YEARS	*	30	*	--	--
NUMBER OF PEOPLE IN BASELINE GEO SPACE BASE DESIGN	f_{NGEO}	NUMBER	*	680	*	--	--
SATELLITE FLEET CONSTRUCTION RATE	R_{CONST}	#/YEAR	*	4	*	--	--
DESIGN LIFE OF GEO SPACE BASE EQUIPMENT	f_{DLGEO}	YEARS	*	30	*	--	--
NUMBER OF AIRLOCK DOCKING MODULES IN GEO SPACE BASE	N_{ADM}	NUMBER	*	36	*	--	--
UNIT COST OF AIRLOCK DOCKING MODULE	SC_{ADM}	$	7.739×10^6	15.477×10^6	46.431×10^6		
NUMBER OF CREW HABITABILITY MODULES IN GEO SPACE BASE	N_{CHM}	NUMBER	*	25	*	--	--
NUMBER OF CONSUMABLES LOGISTICS MODULES	N_{CLM}	NUMBER	*	14	*	--	--
UNIT COST OF CONSUMABLES LOGISTICS MODULES	SC_{CLM}	$	32.744×10^6	65.487×10^6	196.461×10^6		
NUMBER OF BASE MANAGEMENT MODULES	N_{COM}	NUMBER	*	4	*	--	--
NUMBER OF CREW SUPPORT MODULES/EVA	N_{CSM}	NUMBER	*	0	*	--	--
NUMBER OF POWER MODULES	N_{POWM}	NUMBER	*	4	*	--	--
NUMBER OF PRESSURIZED STORAGE MODULES	N_{PSM}	NUMBER	*	4	*	--	--
UNIT COST OF PRESSURIZED STORAGE MODULES	SC_{PSM}	$	142.74×10^6	285.48×10^6	570.96×10^6		
UNIT COST OF SHIELDING	SC_{SDM}	$	13.696×10^6	27.391×10^6	82.173×10^6		
NUMBER OF SHIELDING UNITS	N_{SDM}	NUMBER	*	12	*	--	--
NUMBER OF CREW SUPPORT MODULES	N_{SM}	NUMBER	*	4	*	--	--
UNIT COST OF CREW SUPPORT MODULES	SC_{SM}	$	41.086×10^6	82.172×10^6	246.516×10^6		
COST OF THE FABRICATION FIXTURE	C_{FIX}	$	4.2375×10^6	8.475×10^6	25.425×10^6		
NUMBER OF SHIPS PER DAY	f_{SHPD}	#/DAY	*	4	*	--	--
NUMBER OF PEOPLE PER SHIFT	f_{NPPS}	NUMBER	170	170	196		
UNIT MASS OF CREW HABITABILITY MODULE	SM_{CHM}	kg	13500	27000	40500		
UNIT MASS OF CREW SUPPORT MODULE/EVA	SM_{CSM}	kg	13500	27000	40500		
UNIT MASS OF BASE MANAGEMENT MODULES	SM_{COM}	kg	13500	27000	40500		
UNIT MASS OF POWER MODULES	SM_{POWM}	kg	125	250	375		
UNIT MASS OF AIRLOCK DOCKING MODULE	SM_{ADM}	kg	1250	2500	3750		
UNIT MASS OF CONSUMABLES LOGISTICS MODULES	SM_{CLM}	kg	2500	5000	7500		
UNIT MASS OF PRESSURIZED STORAGE MODULES	SM_{PSM}	kg	7500	15000	22500		
UNIT MASS OF SHIELDING UNITS	SM_{SDM}	kg	5500	11000	16500		
UNIT MASS OF CREW SUPPORT MODULES	SM_{SM}	kg	7500	15000	22500		
DESIGN LIFE OF BEAM MACHINE	f_{DLBM}	YEARS	12	10	10		
NUMBER OF BEAM MACHINES	N_{BM}	NUMBER	234	234	234		
UNIT COST OF BEAM MACHINES	SC_{BM}	$	0.89×10^6	1.78×10^6	5.34×10^6		
UNIT MASS OF BEAM MACHINES	SM_{BM}	kg	350	700	1050		
NUMBER OF CASSETTES	N_C	NUMBER	1206	1206	1206		
DESIGN LIFE OF CASSETTES	f_{DLC}	YEARS	10	10	10	--	--
UNIT COST OF CASSETTES	SC_C	$	13000	26000	52000		
UNIT MASS OF CASSETTES	SM_C	kg	100	200	300		

TABLE D 3 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON TFL COST MODEL INPUTS AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE ROCKWELL INTERNATIONAL CONFIGURATION (CONTINUED)

INPUT ELEMENT	VARIABLE NAME	UNITS	CURRENT STATE-OF-KNOWLEDGE RANGE OF VALUES (DPA)			IMPROVEMENT IN STATE-OF-KNOWLEDGE, %	
			BEST	MOST LIKELY	WORST	DPE	DPC
DESIGN LIFE OF CABLE ATTACHING MACHINES	t_{DLCAM}	YEARS	10	10	10	--	--
UNIT COST OF CABLE ATTACHING MACHINES	SC_{CAM}	$	376.5×10^6	753×10^6	2259×10^6		
NUMBER OF CABLE ATTACHING MACHINES	N_{CAM}	NUMBER	76	76	76	--	--
UNIT MASS OF CABLE ATTACHING MACHINES	SM_{CAM}	kg	250	500	750		
DESIGN LIFE OF REMOTE MANIPULATORS	t_{DLRM}	YEARS	30	30	30	--	--
NUMBER OF REMOTE MANIPULATORS	N_{RM}	NUMBER	36	36	36	--	--
UNIT COST OF REMOTE MANIPULATORS	SC_{RM}	$	148×10^6	296×10^6	888×10^6		
UNIT MASS OF REMOTE MANIPULATORS	SM_{RM}	kg		800			
DESIGN LIFE OF BLANKET DISPENSERS	t_{DLBD}	YEARS	*	6 3	*	--	--
NUMBER OF BLANKET DISPENSERS	N_{BD}	NUMBER	*	76	*	--	--
UNIT COST OF BLANKET DISPENSERS	SC_{BD}	$	274500	549000	$1\ 647 \times 10^6$		
UNIT MASS OF BLANKET DISPENSERS	SM_{BD}	kg	1000	2000	3000		
DESIGN LIFE OF REFLECTOR DISPENSERS	t_{DLRD}	YEARS	*	6	*	--	--
NUMBER OF REFLECTOR DISPENSERS	N_{RD}	NUMBER	*	6	*	--	--
UNIT COST OF REFLECTOR DISPENSERS	SC_{RD}	$	123500	247000	741000		
UNIT MASS OF REFLECTOR DISPENSERS	SM_{RD}	kg	5000	10000	15000		
DESIGN LIFE OF CABLE DISPENSERS	t_{DLCD}	YEARS	*	20	*	--	--
NUMBER OF CABLE DISPENSERS	N_{CD}	NUMBER	*	307	*	--	--
UNIT COST OF CABLE DISPENSERS	SC_{CD}	$	26500	53000	106000		
UNIT MASS OF CABLE DISPENSERS	SM_{CD}	kg	100000	200000	300000		
DESIGN LIFE OF ANTENNA PANEL INSTALLERS	t_{DLAPI}	YEARS	*	10	*	--	--
NUMBER OF ANTENNA PANEL INSTALLERS	N_{API}	NUMBER	*	1	*		
UNIT COST OF ANTENNA PANEL INSTALLERS	SC_{API}	$	6.070×10^6	12.139×10^6	24.278×10^6		
UNIT MASS OF ANTENNA PANEL INSTALLERS	SM_{API}	kg	225000	450000	675000		
UNIT COST OF HLLV	SC_{HLLV}	$	$549 9 \times 10^6$	611×10^6	763.75×10^6		
DESIGN LIFE OF HLLV	t_{DLLV}	# OF FLTS	400	300	200		
HLLV PAYLOAD TO EQUATORIAL LEO	$M_{P/L}$	kg	*	91000	*	--	--
HLLV LOAD FACTOR (AVERAGE % OF PAYLOAD CAPACITY USED)	f_{LOAD}	FRACTION	.95	.90	.70		
RATIO: NUMBER OF HLLV FLIGHTS FOR EACH POTV FLIGHT	f_{P-LV}	NUMBER	*	3	*	--	--
CREW ROTATION RATE	f_{ROT}	#/YEAR	*	4	*	--	--
NUMBER OF PEOPLE CARRIED PER POTV FLIGHT	f_{POTV}	NUMBER	72	48	24		
COST PER HLLV FLIGHT	SC_{LVFL}	$	0.624×10^6	1.248×10^6	2.496×10^6		
UNIT COST OF IOV	SC_{IOV}	$	4.95×10^6	9.9×10^6	19.8×10^6		
DESIGN LIFE OF IOV	t_{DLIOV}	# OF FLTS	*	500	*	--	--
COST PER IOV FLIGHT	SC_{IVFT}	$	500	1000	2000		
UNIT COST OF COTV	SC_{COTV}	$	345×10^6	690×10^6	1380×10^6		
DESIGN LIFE OF COTV	t_{DLCTV}	# OF FLTS	*	20	*	--	--
RATIO NUMBER OF HLLV FLIGHTS PER COTV FLIGHT	f_{COTV}	NUMBER	*	44	*	--	--
COST PER COTV FLIGHT	COTVFT	$	0.71×10^6	1.42×10^6	$2 84 \times 10^6$		
UNIT COST OF POTV	SC_{POTV}	$	31.5×10^6	63×10^6	126×10^6		
DESIGN LIFE OF POTV	t_{DLPTV}	# OF FLTS	*	300	*	--	--
COST PER POTV FLIGHT	POTVFT	$	21500	90000	.180000		
BASELINE DESIGN COST FOR FACILITIES	SC_{FAC}	$	2600×10^6	3250×10^6	3900×10^6		
DESIGN LIFE FOR FACILITIES	t_{DLFAC}	YEARS	*	30	*	--	--
COST OF TAXES	C_{TXS}	$	0	0	0	--	--
COST OF INSURANCE	C_{INS}	$	0	0	0	--	--
UNIT MASS OF IOV	SM_{IOV}	kg	1350	2700	4050		
UNIT MASS OF COTV	SM_{COTV}	kg	929600	1050000	1172000		
PROPELLANT MASS PER IOV FLIGHT	SM_{IPRP}	kg	*	1500	*	--	--

TABLE D.2 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON O&M COST MODEL INPUTS FOR THE ROCKWELL INTERNATIONAL CONFIGURATION

INPUT ELEMENT	VARIABLE NAME	UNITS	RANGE OF VALUES		
			BEST	MOST LIKELY	WORST
TOTAL NUMBER OF O&M CREW MEMBERS	N_{ORC}	NUMBER	*	285	*
ANNUAL COST PER PERSON OF O&M CREW MEMBERS	SC_{ORC}	$/PERSON	*	62500	*
TOTAL MASS OF ANNUAL O&M REFURBISHMENT PROCUREMENTS	M_{ORPR}	kg	1.2×10^6	1.498×10^6	2.2×10^6
AVERAGE SPECIFIC COST OF ANNUAL O&M REFURBISHMENT PROCUREMENTS	SC_{ORPR}	$/kg	5.00	5.52	8.50
TOTAL MASS OF EXPENDABLE MAINTENANCE SUPPLIES	M_{EMS}	kg	800×10^3	832200	900×10^3
AVERAGE SPECIFIC COST OF EXPENDABLE MAINTENANCE SUPPLY MATERIALS	SC_{EMS}	$/kg	3.00	3.75	5.00
ANNUAL COST OF GROUND STATION CREW	C_{GSC}	$	100×10^3	114×10^3	250×10^3
ANNUAL COST OF GROUND STATION MATERIALS	C_{GSMAT}	$	75×10^3	100×10^3	200×10^3
NUMBER OF O&M AIRLOCK DOCKING MODULES	N_{OMADM}	NUMBER	*	4	*
NUMBER OF O&M CREW HABITABILITY MODULES	N_{OMCHM}	NUMBER	*	1	*
NUMBER OF O&M CONSUMABLES LOGISTICS MODULES	N_{OMCLM}	NUMBER	*	1	*
NUMBER OF O&M BASE MANAGEMENT MODULES	N_{OMCOM}	NUMBER	*	1	*
NUMBER OF PRESSURIZED STORAGE MODULES	N_{OMPSM}	NUMBER	*	1	*
NUMBER OF O&M CREW SUPPORT MODULES	N_{OMCSM}	NUMBER	*	1	*

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APPENDIX E

ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE BOEING CO. CONFIGURATION

The current state-of-knowledge relative to the Boeing configuration is reflected by the ranges of input variables to the risk analysis model. These ranges have been subjectively assessed and are given in Table E.1 for the TFU cost model and in Table E.2 for the O&M cost model. Table E.2 lists only those O&M cost model inputs whose values are not already listed in Table E.1. The current state-of-knowledge corresponds to Decision Point A (DPA) in the Boeing SPS Development programs analyzed in Section 2. It should be noted that the date for DPA is given as 1980 because no experimentation that might reduce uncertainty on any of the listed cost model elements is likely to occur before then.

The sources for these input data are the "Solar Power Satellite System Definition Study" final report of March 1978, prepared by Boeing Co. for the Lyndon B. Johnson Space Center under NASA Contract NAS9-15196 and numerous telephone conversations and two series of meetings with Boeing Co. personnel, headed by Mr. Gordon Woodcock.

The states-of-knowledge at the decision points of the SPS development plan proposed by Boeing have been subjectively assessed and are also shown in Table E.1. The numbers shown represent the percent reduction in uncertainty (that is, the range) in each variable over the state-of-knowledge today. 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 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON TFU COST MODEL INPUTS AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE BOEING CO. CONFIGURATION

INPUT ELEMENT	VARIABLE NAME	UNITS	CURRENT STATE-OF-KNOWLEDGE RANGE OF VALUES (DPA)			IMPROVEMENT IN STATE-OF-KNOWLEDGE, %				
						PROGRAM I			PROGRAM II	
			BEST	MOST LIKELY	WORST	DPB	DPC	DPD	DPA, B&C	DPC
RATIO PROGRAM MANAGEMENT COST TO OTHER UNIT PRODUCTION COSTS	f_{PM}	FRACTION	*	.01	*	--	--	--		--
RATIO OVERALL PROGRAM SYSTEM ENGINEERING AND INTEGRATION COST TO OTHER UNIT PRODUCTION COST	f_{SEI}	FRACTION	*	.02	*	--	--	--		--
COST OF SPACE TRAFFIC CONTROL	C_{SCOM}	$	*	0	*	--	--	--		--
SPECIFIC COST OF PRIMARY STRUCTURE	SC_{PSTR}	$/kg	40	55	60			100%		
RATIO PRIMARY STRUCTURE MASS TO AREA OF SOLAR BLANKET	SK_{PSTR}	kg/km^2	44331	64927	119810	75%	87.5%	100%		87.5%
SOLAR CELL EFFICIENCY, SI CELLS (EOL)	ETA1	FRACTION	.10	.173	.140	--	50%	100%		50%
SOLAR ARRAY POWER DISTRIBUTION EFFICIENCY	ETA2	FRACTION	.960	.832	.905	--	--	--		--
ANTENNA INTERFACE EFFICIENCY	ETA3	FRACTION	*	1.0	*	--	--	--		--
ANTENNA POWER DISTRIBUTION EFFICIENCY	ETA4	FRACTION	.98	.97	.95	--	25%	100%		--
DC-RF CONVERTER EFFICIENCY	ETA5	FRACTION	.90	.85	.70	75%	80%	100%		80%
PHASE CONTROL EFFICIENCY	ETA6	FRACTION	.935	.891	.811	50%	75%	100%		75%
IONOSPHERIC PROPAGATION EFFICIENCY	ETA7	FRACTION	*	1.0	*	--	--	--		--
ATMOSPHERIC PROPAGATION EFFICIENCY	ETA8	FRACTION	*	.98	*	--	--	--		--
BEAM COLLECTION EFFICIENCY	ETA9	FRACTION	.98	.95	.90	25%	50%	100%		50%
RF-DC CONVERTER EFFICIENCY	ETA10	FRACTION	.91	.89	.85	75%	80%	100%		80%
RECTENNA POWER DISTRIBUTION EFFICIENCY	ETA11	FRACTION	.98	.97	.96	--	--	--		--
POWER OUTPUT AT RECTENNA BUSBAR (EOL)	P_{OUT}	kW	*	10×10^6	*	--	--	--		--
ARRAY DESIGN FACTOR (INCLUDES SOLAR CELL PACKING FACTOR)	f_{AD}	FRACTION	*	.874	*	--	--	--		--
SOLAR FLUX CONSTANT	F	kW/km^2	*	1353×10^3	*	--	--	--		--
EFFECTIVE CONCENTRATION RATIO	n_{EFF}	FRACTION	*	1	*	--	--	--		--
SEASONAL CORRECTION FACTOR FOR SOLAR FLUX CONSTANT	f_{SFSC}	FRACTION	*	.9765	*	--	--	--		--
ENVIRONMENTAL DEGRADATION FACTOR FOR SOLAR CELLS	f_{ED}	FRACTION	.954	.885	.821	50%	75%	100%	SAME AS PROGRAM I	75%
COST OF ATTITUDE CONTROL THRUSTERS	C_{THR}	$	800×10^3	1.6×10^6	3.2×10^6	25%	50%	100%		50%
MASS OF ATTITUDE CONTROL THRUSTERS	M_{THR}	kg	4440	8000	23640	25%	50%	100%		50%
COST OF ATTITUDE CONTROL POWER PROCESSORS	C_{ACPP}	$	21.42×10^6	42.84×10^6	85.68×10^6	25%	50%	100%		50%
MASS OF ATTITUDE CONTROL POWER PROCESSORS	M_{ACPP}	kg	103785	187×10^3	557.26×10^3	25%	50%	100%		50%
COST OF ATTITUDE CONTROL INSTALLATION	C_{ACIN}	$	12.5×10^6	25×10^6	50×10^6	25%	50%	100%		50%
MASS OF ATTITUDE CONTROL INSTALLATION	M_{ACIN}	kg	33300	60000	178.8×10^3	25%	50%	100%		50%
COST OF ATTITUDE CONTROL PROPELLANT TANKS	C_{ACTS}	$	2.9×10^6	5.8×10^6	11.6×10^6	25%	50%	100%		50%
MASS OF ATTITUDE CONTROL PROPELLANT TANKS	M_{ACTS}	kg	3330	6000	17880	25%	50%	100%		50%
COST OF ATTITUDE CONTROL PROPELLANT FEED AND THRUST CONTROL SYSTEM	C_{ACCR}	$	6.3×10^6	12.6×10^6	25.2×10^6	25%	50%	100%		50%
MASS OF ATTITUDE CONTROL PROPELLANT FEED AND THRUST CONTROL SYSTEM	M_{ACCR}	kg	1	2	6	25%	50%	100%		50%
COST OF CENTRAL COMPUTING COMPLEX	C_{CC}	$	14×10^6	28×10^6	56×10^6	--	50%	100%		50%
MASS OF CENTRAL COMPUTING COMPLEX	M_{CC}	kg	358	775	1163	--	50%	100%		50%
COST OF COMMUNICATIONS SUBSYSTEM	C_{COMM}	$	37×10^6	74×10^6	222×10^6	25%	50%	100%		50%
MASS OF COMMUNICATIONS SUBSYSTEM	M_{COMM}	kg	1360	10×10^3	100×10^3	25%	50%	100%		50%
SPECIFIC COST OF ANTENNA YOKE AND TURNTABLES	SC_{ATT}	$/kg	88.166	176.332	352.664	--	50%	100%		50%
RATIO MASS OF ANTENNA YOKE AND TURNTABLES TO POWER THROUGHPUT	SK_{ATT}	kg/kW	.01138	.0153	.0284	--	50%	100%		50%
COST OF ENERGY COLLECTION SYSTEM	C_{ECOL}	$	*	0	*	--	--	--		--
MASS OF ENERGY COLLECTION SYSTEM	M_{ECOL}	kg	*	0	*	--	--	--		--
SPECIFIC COST OF SOLAR BLANKETS	SC_{SB}	$/km^2$	22×10^6	35×10^6	13.4×10^7	75%	80%	100%		80%
SPECIFIC MASS OF SOLAR BLANKETS	SK_{SB}	kg/km^2	350000	415363	578200	25%	50%	100%		50%
SPECIFIC COST OF CATENARY SUPPORT SYSTEM	SC_{CSS}	$/km^2$	*	0	*	--	--	--		--
SPECIFIC MASS OF CATENARY SUPPORT SYSTEM	SK_{CSS}	kg/km^2	*	0	*	--	--	--		--

TABLE E.1 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON TFU COST MODEL INPUTS AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE BOEING CO CONFIGURATION (CONTINUED)

INPUT ELEMENT	VARIABLE NAME	UNITS	CURRENT STATE-OF-KNOWLEDGE RANGE OF VALUES (DPA)			IMPROVEMENT IN STATE-OF-KNOWLEDGE, %				
						PROGRAM I			PROGRAM II	
			BEST	MOST LIKELY	WORST	DPB	DPC	DPD	DPA, B&C	DPC
SPECIFIC COST OF INTERBAY JUMPERS	SC_{IBJ}	$/kg	22.5	45	135	25%	50%	100%	SAME AS PROGRAM I	50%
RATIO MASS OF INTERBAY JUMPERS TO POWER THROUGHPUT	SR_{IBJ}	kg/kW	.00096	.00192	.00288	25%	50%	100%		50%
SPECIFIC COST OF SWITCHGEAR	SC_{SWTG}	$/kg	207	414	1242	25%	50%	100%		50%
RATIO MASS OF SWITCHGEAR TO POWER THROUGHPUT	SR_{SWTG}	kg/kW	.00228	.00455	.00683	25%	50%	100%		50%
SPECIFIC COST TO MAIN BUSES	SC_{MB}	$/kg	11	22	66	25%	50%	100%		50%
RATIO MASS OF MAIN BUSES TO POWER THROUGHPUT	SR_{MB}	kg/kW	.0699	.1215	.1640	25%	50%	100%		50%
RATIO COST OF BUS SUPPORTS TO AREA OF SOLAR BLANKET	SC_{BSUP}	$/km^2	76 9	123.2	225 6	25%	50%	100%		50%
RATIO. MASS OF BUS SUPPORTS TO AREA OF SOLAR BLANKET	SR_{BSUP}	kg/km^2	838	1239	2244	25%	50%	100%		50%
SPECIFIC COST OF ELECTRICAL ROTARY JOINT	SC_{ERJ}	$/kg	70.5	140 9	422.8	25%	50%	100%		50%
RATIO MASS OF ELECTRICAL ROTARY JOINT TO POWER THROUGHPUT	SR_{ERJ}	kg/kW	.00226	.00271	.00374	25%	50%	100%		50%
SPECIFIC COST OF THE MICROWAVE ANTENNA PRIMARY STRUCTURE	SC_{MWPS}	$/kg	62.85	125.7	377.1	25%	50%	100%		50%
SPECIFIC COST OF THE MICROWAVE ANTENNA SECONDARY STRUCTURE	SC_{MWST}	$/kg	64 6	129.1	387.3	25%	50%	100%		50%
SPECIFIC COST OF THE MICROWAVE ANTENNA ATTITUDE CONTROL	SC_{MWAC}	$/kg	394 8	789.7	2369.0	25%	50%	100%		50%
RATIO COST OF MICROWAVE ANTENNA DATA PROCESSING TO POWER THROUGHPUT	SC_{MWDP}	$/kg	18064 5	36129.0	108387.0	25%	50%	100%		50%
RATIO COST OF MICROWAVE ANTENNA COMMUNICATIONS TO POWER THROUGHPUT	SC_{MWC}	$/kg	1843 7	3687.5	11062.5	25%	50%	100%		50%
RATIO MASS OF MICROWAVE ANTENNA PRIMARY STRUCTURE TO POWER THROUGHPUT	SR_{MWPS}	kg/kW	.0016	.0031	.0237	25%	50%	100%		50%
RATIO MASS OF MICROWAVE ANTENNA SECONDARY STRUCTURE TO POWER THROUGHPUT	SR_{MWST}	kg/kW	.0059	.0119	.0237	25%	50%	100%		50%
RATIO MASS OF MICROWAVE ANTENNA ATTITUDE CONTROL TO POWER THROUGHPUT	SR_{MWAC}	kg/kW	.0038	.0077	.0153	25%	50%	100%		50%
RATIO: MASS OF MICROWAVE ANTENNA DATA PROCESSING TO POWER THROUGHPUT	SR_{MWDP}	kg/kW	.00003	.00005	.00009	25%	50%	100%		50%
RATIO MASS OF MICROWAVE ANTENNA COMMUNICATIONS TO POWER THROUGHPUT	SR_{MWC}	kg/kW	.0006	.0012	.0024	25%	50%	100%		50%
SPECIFIC COST OF MICROWAVE ANTENNA POWER PROCESSOR	SC_{MWPP}	$/kg	67.3	134.6	403.8	25%	50%	100%		50%
SPECIFIC COST OF MICROWAVE POWER PROCESSOR THERMAL CONTROL	SC_{MWTC}	$/kg	164.35	328.7	986.1	25%	50%	100%		50%
SPECIFIC COST OF MICROWAVE ANTENNA SWITCHGEAR	SC_{MWSG}	$/kg	67.3	134 6	403.7	25%	50%	100%		50%
SPECIFIC COST OF MICROWAVE ANTENNA BUSING AND CABLING	SC_{MWBC}	$/kg	80.8	161.6	484.8	25%	50%	100%		50%
RATIO MASS OF MICROWAVE ANTENNA POWER PROCESSOR TO POWER THROUGHPUT	SR_{MWPP}	kg/kW	.0385	.0769	.1539	75%	85%	100%		85%
RATIO MASS OF MICROWAVE PROCESSOR THERMAL CONTROL TO POWER THROUGHPUT	SR_{MWTC}	kg/kW	.0067	.0133	.0266	25%	50%	100%		50%
RATIO MASS OF MICROWAVE ANTENNA SWITCHGEAR TO POWER THROUGHPUT	SR_{MWSG}	kg/kW	.0045	.0095	.0190	25%	50%	100%		50%
RATIO MASS OF MICROWAVE ANTENNA BUSING AND CABLING TO POWER THROUGHPUT	SR_{MWBC}	kg/kW	.0249	.0486	.0995	25%	50%	100%		50%
RATIO COST OF ANTENNA STRUCTURE AND WAVEGUIDES TO POWER THROUGHPUT	SC_{TASG}	$/kg	33.298	66.596	199.789	25%	50%	100%		50%
RATIO COST OF TRANSMITTER POWER AMPLIFIERS TO POWER THROUGHPUT	SC_{TAPA}	$/kg	26.875	53.749	161.247	25%	50%	100%		50%
RATIO COST OF TRANSMITTER THERMAL CONTROL TO POWER THROUGHPUT	SC_{TATC}	$/kg	34 247	68 493	205.479	25%	50%	100%		50%
RATIO COST OF TRANSMITTER PHASE CONTROL TO POWER THROUGHPUT	SC_{TACC}	$/kW	*	0	*	--	--	--		--
RATIO COST OF TRANSMITTER HARNESSES TO POWER THROUGHPUT	SC_{TAH}	$/kg	212.472	424 945	1274 83	25%	50%	100%		50%
RATIO. MASS OF ANTENNA STRUCTURE AND WAVEGUIDES TO POWER THROUGHPUT	SR_{TASG}	kg/kW	.0738	.1477	.2954	25%	50%	100%		50%
RATIO MASS OF TRANSMITTER POWER AMPLIFIERS TO POWER THROUGHPUT	SR_{TAPA}	kg/kW	.1462	.2923	.5847	25%	50%	100%		50%

TABLE E 1 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON TFU COST MODEL INPUTS AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE BOEING CO. CONFIGURATION (CONTINUED)

INPUT ELEMENT	VARIABLE NAME	UNITS	CURRENT STATE-OF-KNOWLEDGE RANGE OF VALUES (DPA)			IMPROVEMENT IN STATE-OF-KNOWLEDGE, %				
						PROGRAM I			PROGRAM II	
			BEST	MOST LIKELY	WORST	DPB	DPC	DPD	DPA BAS	DPA
RATIO MASS OF TRANSMITTER THERMAL CONTROL TO POWER THROUGHPUT	SK_{TATC}	kg/kW	.0600	.1200	.2400	25%	50%	100%	SAME AS PROGRAM I	50%
RATIO MASS OF TRANSMITTER PHASE CONTROL TO POWER THROUGHPUT	SK_{TACC}	kg/kW	*	0	*	--	--	--		--
RATIO MASS OF TRANSMITTER HARNESSES TO POWER THROUGHPUT	SK_{TAH}	kg/kW	.0163	.0326	.0652	25%	50%	100%		50%
RATIO ASSEMBLY AND CHECKOUT COSTS TO UNIT PROCUREMENT COST	f_{ACHE}	FRACTION	.02	.05	.10	25%	50%	100%		50%
RATIO COST OF INITIAL SPARES TO UNIT PROCUREMENT COST	f_{ISPA}	FRACTION	.01	.02	.05	25%	50%	100%		50%
RATIO COST OF GROUND STATION PROGRAM MANAGEMENT TO PRODUCTION COST	f_{GSPM}	FRACTION	.01	.01	.02	25%	50%	100%		50%
RATIO COST OF GROUND STATION SYSTEMS ENGINEERING AND INTEGRATION TO PRODUCTION COST	f_{GSSEI}	FRACTION	.06	.07	.09	25%	50%	100%		50%
COST OF GROUND STATION REAL ESTATE	C_{RE}	$	48×10^6	120×10^6	240×10^6	25%	50%	100%		50%
COST OF GROUND STATION PHASE CONTROL	C_{GSPC}	$	*	0	*	--	--	--		--
GROUND STATION COST OF SPS OPERATIONS	C_{GOPS}	$	*	0	*	--	--	--		--
RATIO COST OF RECTENNA PRIMARY STRUCTURE TO POWER THROUGHPUT	SC_{RPS}	$/kW	63.385	127.77	191.66	50%	70%	100%		70%
RATIO COST OF GROUND STATION GROUND PLANES TO POWER THROUGHPUT	SC_{GSGP}	$/kW	14.202	28.404	42.606	25%	50%	100%		50%
RATIO COST OF RF ASSEMBLY DIPOLES TO POWER THROUGHPUT	SC_{RFDI}	$/kW	9.454	18.907	56.721	25%	50%	100%		50%
RATIO. COST OF RF ASSEMBLY CIRCUITRY TO POWER THROUGHPUT	SC_{RFCR}	$/kW	*	0	*	--	--	--		--
RATIO. COST OF RF ASSEMBLY SHIELDS AND COVERS TO POWER THROUGHPUT	SC_{RFSC}	$/kW	*	0	*	--	--	--		--
RATIO COST OF RECTENNA PANELS TO POWER THROUGHPUT	SC_{RECP}	$/kW	*	0	*	--	--	--		--
RATIO COST OF RF-DC CONVERSION UNITS TO POWER THROUGHPUT	SC_{RFDC}	$/kW	*	0	*	--	--	--		--
RATIO COST OF GROUND STATION LOCAL BUSING TO POWER THROUGHPUT	SC_{GSLB}	$/kW	2.765	5.529	16.587	25%	50%	100%		50%
RATIO COST OF GROUND STATION DISTRIBUTED PROCESSING TO POWER THROUGHPUT	SC_{GSDP}	$/kW	2.39	5.335	14.34	25%	50%	100%		50%
RATIO COST OF GRID INTERFACE PROVISIONS TO POWER THROUGHPUT	SC_{GSGI}	$/kW	32.690	65.379	98.064	20%	40%	100%		40%
NUMBER OF PERSONNEL AT LOW EARTH ORBIT (LEO) SPACE BASE	N_{LEO}	NUMBER	239	478	956	25%	75%	100%		75%
NOMINAL NUMBER OF PERSONNEL AT LEO SPACE BASE	N_{NLEO}	NUMBER	*	478	*	--	--	--		--
RATE OF SATELLITE CONSTRUCTION	R_{CONST}	#/YEAR	*	1	*	--	--	--		--
DESIGN LIFE OF LEO SPACE BASE	t_{DLLEO}	YEARS	*	30	*	--	--	--		--
COST OF LEO SPACE BASE FRAMEWORK	C_{LEBFR}	$	175×10^6	350×10^6	1050×10^6	25%	75%	100%		85%
COST OF LEO SPACE BASE CREW MODULES	C_{LEBCM}	$	717.5×10^6	1425×10^6	4305×10^6	25%	75%	100%		85%
COST OF LEO SPACE BASE WORK MODULES	C_{LEBWM}	$	717.5×10^6	1425×10^6	4305×10^6	25%	75%	100%		85%
COST OF LEO SPACE BASE CARGO HANDLING AND DISTRIBUTION EQUIPMENT	C_{LEBCH}	$	165×10^6	330×10^6	990×10^6	25%	75%	100%		85%
COST OF LEO SPACE BASE SUBSYSTEMS	C_{LEBSS}	$	7.5×10^6	15×10^6	45×10^6	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE FRAMEWORK	M_{LEBFR}	kg	1250×10^3	2500×10^3	3750×10^3	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE CREW MODULES	M_{LEBCM}	kg	500×10^3	1000×10^3	1500×10^3	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE WORK MODULES	M_{LEBWM}	kg	500×10^3	1000×10^3	1500×10^3	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE CARGO HANDLING AND DISTRIBUTION EQUIPMENT	M_{LEBCH}	kg	200×10^3	400×10^3	600×10^3	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE SUBSYSTEMS	M_{LEBSS}	kg	100×10^3	200×10^3	300×10^3	25%	75%	100%		85%
DESIGN LIFE OF LEO CONSTRUCTION BASE STRUCTURE ASSEMBLY	t_{DLLSA}	YEARS	*	8	*	--	--	--		--
COST OF LEO CONSTRUCTION BASE STRUCTURAL ASSEMBLY	C_{LSA}	$	175×10^6	350×10^6	1050×10^6	25%	75%	100%		85%
DESIGN LIFE OF LEO CONSTRUCTION BASE ENERGY CONVERSION INSTALLATION EQUIPMENT	t_{DLLEC}	YEARS	*	8	*	--	--	--		--

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TABLE E.1 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON TFU COST MODEL INPUTS AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE BOEING CO. CONFIGURATION (CONTINUED)

INPUT ELEMENT	VARIABLE NAME	UNITS	CURRENT STATE-OF-KNOWLEDGE RANGE OF VALUES (DPA)			IMPROVEMENT IN STATE-OF-KNOWLEDGE, %				
						PROGRAM I			PROGRAM II	
			BEST	MOST LIKELY	WORST	DPB	DPC	DPD	DPA, B&C	DPC
COST OF LEO CONSTRUCTION BASE ENERGY CONVERSION INSTALLATION EQUIPMENT	C_{LEC}	$	82.5×10^6	165×10^6	495×10^6	25%	75%	100%		85%
DESIGN LIFE OF LEO CONSTRUCTION BASE POWER DISTRIBUTION INSTALLATION EQUIPMENT	t_{DLLPD}	YEARS	*	8	*	--	--	--		--
COST OF LEO CONSTRUCTION BASE POWER DISTRIBUTION INSTALLATION EQUIPMENT	C_{LPD}	$	37.5×10^6	75×10^6	225×10^6	25%	75%	100%		85%
DESIGN LIFE OF LEO CONSTRUCTION BASE ANTENNA INSTALLATION EQUIPMENT	t_{DLLAS}	YEARS	*	8	*	--	--	--		--
COST OF LEO CONSTRUCTION BASE ANTENNA INSTALLATION EQUIPMENT	C_{LAS}	$	40×10^6	80×10^6	240×10^6	25%	75%	100%		85%
DESIGN LIFE OF LEO CONSTRUCTION BASE CRANES/MANIPULATORS	t_{DLLC}	YEARS	*	8	*	--	--	--		--
COST OF LEO CONSTRUCTION BASE CRANES/MANIPULATORS	C_{LC}	$	280×10^6	560×10^6	1680×10^6	25%	75%	100%		85%
DESIGN LIFE OF LEO CONSTRUCTION BASE INDEXERS	t_{DLLI}	YEARS	*	8	*	--	--	--		--
COST OF LEO CONSTRUCTION BASE INDEXERS	C_{LI}	$	40×10^6	80×10^6	240×10^6	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE STRUCTURAL ASSEMBLY EQUIPMENT	M_{LSA}	kg	40×10^3	80×10^3	120×10^3	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE ENERGY CONVERSION INSTALLATION EQUIPMENT	M_{LEC}	kg	30×10^3	60×10^3	90×10^3	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE POWER DISTRIBUTION INSTALLATION EQUIPMENT	M_{LPD}	kg	10×10^3	20×10^3	30×10^3	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE ANTENNA INSTALLATION EQUIPMENT	M_{LAS}	kg	15×10^3	30×10^3	45×10^3	25%	75%	100%		85%
MASS OF LEO CONSTRUCTION BASE CRANES/MANIPULATORS	M_{LC}	kg	90×10^3	180×10^3	270×10^3	25%	75%	100%	SAME AS PROGRAM I	85%
MASS OF LEO CONSTRUCTION BASE INDEXERS	M_{LI}	kg	15×10^3	30×10^3	45×10^3	25%	75%	100%		85%
COST OF LEO CONSTRUCTION BASE MAINTENANCE PROVISIONS	C_{LMP}	$	*	0	*	--	--	--		--
NUMBER OF PERSONNEL AT GEO CONSTRUCTION BASE FOR FINAL ASSEMBLY	N_{GEO}	NUMBER	34	67	134	--	--	--		--
NOMINAL NUMBER OF PERSONNEL AT GEO CONSTRUCTION BASE	t_{NGEO}	NUMBER	*	67	*	--	--	--		--
DESIGN LIFE OF GEO CONSTRUCTION BASE	t_{DLGEO}	YEARS	*	30	*	--	--	--		--
COST OF GEO CONSTRUCTION BASE FRAMEWORK	C_{GCBFR}	$	15×10^6	30×10^6	90×10^6	25%	75%	100%		85%
COST OF GEO CONSTRUCTION BASE CREW MODULES	C_{GCBCM}	$	75×10^6	150×10^6	450×10^6	25%	75%	100%		85%
COST OF GEO CONSTRUCTION BASE WORK MODULES	C_{GCBWM}	$	75×10^6	150×10^6	450×10^6	25%	75%	100%		85%
COST OF GEO CONSTRUCTION BASE CARGO HANDLING AND DISTRIBUTION EQUIPMENT	C_{GCBCH}	$	25×10^6	50×10^6	75×10^6	25%	75%	100%		85%
COST OF GEO CONSTRUCTION BASE SUBSYSTEMS	C_{GCBSS}	$	1×10^6	2×10^6	6×10^6	25%	75%	100%		85%
MASS OF GEO CONSTRUCTION BASE FRAMEWORK	M_{GCBFR}	kg	140×10^3	280×10^3	420×10^3	25%	75%	100%		85%
MASS OF GEO CONSTRUCTION BASE CREW MODULES	M_{GCBCM}	kg	83.75×10^3	167.5×10^3	251.3×10^3	25%	75%	100%		85%
MASS OF GEO CONSTRUCTION BASE WORK MODULES	M_{GCBWM}	kg	83.75×10^3	167.5×10^3	251.3×10^3	25%	75%	100%		85%
MASS OF GEO CONSTRUCTION BASE CARGO HANDLING AND DISTRIBUTION EQUIPMENT	M_{GCBCH}	kg	27.5×10^3	55×10^3	82.5×10^3	25%	75%	100%		85%
MASS OF GEO CONSTRUCTION BASE SUBSYSTEMS.	M_{GCBSS}	kg	5×10^3	10×10^3	15×10^3	25%	75%	100%		85%
DESIGN LIFE OF GEO CONSTRUCTION BASE STRUCTURAL ASSEMBLY EQUIPMENT	t_{DLGSA}	YEARS	*	8	*	--	--	--		--
COST OF GEO CONSTRUCTION BASE STRUCTURAL ASSEMBLY EQUIPMENT	C_{GSA}	$	*	0	*	--	--	--		--
DESIGN LIFE OF GEO CONSTRUCTION BASE ENERGY CONVERSION INSTALLATION EQUIPMENT	t_{DLGEC}	YEARS	*	8	*	--	--	--		--
COST OF GEO CONSTRUCTION BASE ENERGY CONVERSION INSTALLATION EQUIPMENT	C_{GEC}	$	*	0	*	--	--	--		--
DESIGN LIFE OF GEO CONSTRUCTION BASE POWER DISTRIBUTION INSTALLATION EQUIPMENT	t_{DLGPD}	YEARS	*	8	*	--	--	--		--

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TABLE E.1 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON TFU COST MODEL INPUTS AND STATES-OF-KNOWLEDGE AT PROGRAM DECISION POINTS FOR THE BOEING CO CONFIGURATION (CONTINUED)

INPUT ELEMENT	VARIABLE NAME	UNITS	CURRENT STATE-OF-KNOWLEDGE RANGE OF VALUES (DPA)			IMPROVEMENT IN STATE-OF-KNOWLEDGE, %				
						PROGRAM I			PROGRAM II	
			BEST	MOST LIKELY	WORST	DPB	DPC	DPD	DPA, BEL	DPC
COST OF GEO CONSTRUCTION BASE POWER DISTRIBUTION INSTALLATION EQUIPMENT	C_{GPD}	$	*	0	*	--	--	--		--
DESIGN LIFE OF GEO CONSTRUCTION BASE ANTENNA INSTALLATION EQUIPMENT	t_{DLGAS}	YEARS	*	8	*	--	--	--		--
COST OF GEO CONSTRUCTION BASE ANTENNA INSTALLATION EQUIPMENT	C_{GAS}	$	82.5×10^6	165×10^6	495×10^6	25%	75%	100%		85%
DESIGN LIFE OF GEO CONSTRUCTION BASE CRANES/MANIPULATORS	t_{DLGC}	YEARS	*	8	*	--	--	--		--
COST OF GEO CONSTRUCTION BASE CRANES/MANIPULATORS	C_{GC}	$	25×10^6	50×10^6	150×10^6	25%	75%	100%		85%
DESIGN LIFE OF GEO CONSTRUCTION BASE INDEXERS	t_{DLGI}	YEARS	*	8	*	--	--	--		--
COST OF GEO CONSTRUCTION BASE INDEXERS	C_{GI}	$	7.5×10^6	15×10^6	45×10^6	25%	75%	100%		85%
MASS OF GEO CONSTRUCTION BASE STRUCTURAL ASSEMBLY EQUIPMENT	M_{GSA}	kg	*	0	*	--	--	--		--
MASS OF GEO CONSTRUCTION BASE ENERGY CONVERSION INSTALLATION EQUIPMENT	M_{GEC}	kg	*	0	*	--	--	--		--
MASS OF GEO CONSTRUCTION BASE POWER DISTRIBUTION INSTALLATION EQUIPMENT	M_{GPD}	kg	*	0	*	--	--	--		--
MASS OF GEO CONSTRUCTION BASE ANTENNA INSTALLATION EQUIPMENT	M_{GAS}	kg	25×10^3	50×10^3	75×10^3	25%	75%	100%		85%
MASS OF GEO CONSTRUCTION BASE CRANES/MANIPULATORS	M_{GC}	kg	59.5×10^3	119×10^3	178.5×10^3	25%	75%	100%		85%
MASS OF GEO CONSTRUCTION BASE INDEXERS	M_{GI}	kg	3×10^3	6×10^3	9×10^3	25%	75%	100%		85%
COST OF GEO CONSTRUCTION BASE MAINTENANCE PROVISIONS	C_{GMP}	$	*	0	*	--	--	--		--
UNIT COST OF HEAVY LIFT LAUNCH VEHICLE (HLLV)	SC_{HLLV}	$	1038.6×10^6	1154×10^6	1442.5	10%	30%	100%	SAME AS PROGRAM I	50%
DESIGN LIFE OF HLLV	t_{DLLV}	# OF FLTS	400	300	200	--	--	--		--
MASS OF HLLV PAYLOAD TO LEO	M_{PL}	kg	500×10^3	400×10^3	300×10^3	--	50%	100%		75%
RATIO: MASS OF HLLV PAYLOAD TO CAPACITY	f_{LOAD}	FRACTION	.95	0.9	0.7	--	50	100%		75%
OPERATIONS COST PER FLIGHT OF HLLV	SC_{LVFL}	$/FLT	4.8×10^6	9.6×10^6	28.2×10^6	10%	30%	100%		60%
DESIGN LIFE OF PERSONNEL LAUNCH VEHICLE	t_{DLPTV}	# OF FLTS	400	300	200	10%	30%	100%		30%
UNIT COST OF PERSONNEL LAUNCH VEHICLE	SC_{POTV}	$	200×10^6	221×10^6	350×10^6	10%	30%	100%		30%
NUMBER OF PERSONNEL CARRIED PER FLIGHT	f_{POTV}	NUMBER	100	75	*	--	30%	100%		30%
RATE OF CREW ROTATION	f_{ROT}	#/YEAR	*	4	*	--	--	--		--
OPERATIONS COST PER PERSONNEL FLIGHT	POTVFT	$	10×10^6	12.62×10^6	20×10^6	25%	50%	100%		50%
RATIO MASS OF SELF-ORBIT TRANSFER THRUSTERS TO SATELLITE MASS	SM_{STHR}	FRACTION	.050	.100	.150	25%	50%	100%		50%
RATIO MASS OF SELF-ORBIT TRANSFER PROPELLANT TANKS TO SATELLITE MASS	SM_{SOT}	FRACTION	.038	.051	.064	25%	50%	100%		50%
RATIO MASS OF ARGON PROPELLANT TO SATELLITE MASS	SM_{AR}	FRACTION	.212	.283	.354	25%	50%	100%		50%
RATIO MASS OF CHEMICAL PROPELLANT TO SATELLITE MASS	SM_{LOX}	FRACTION	.106	.141	.176	25%	50%	100%		50%
RATIO: COST OF SELF-ORBIT TRANSFER THRUSTERS TO SATELLITE MASS	SC_{STHR}	$/kg	8.89	17.780	53.34	25%	50%	100%		50%
RATIO. COST OF SELF-ORBIT TRANSFER PROPELLANT TANKS TO SATELLITE MASS	SC_{SOT}	$/kg	*	0	*	--	--	--		--
RATIO COST OF ARGON PROPELLANT TO SATELLITE MASS	SC_{AR}	$/kg	*	0	*	--	--	--		--
RATIO COST OF CHEMICAL PROPELLANT TO SATELLITE MASS	SC_{LOX}	$/kg	*	0	*	--	--	--		--
RATIO OF SATELLITE SYSTEM PROGRAM MANAGEMENT COST OF SATELLITE COST	f_{SPM}	FRACTION	*	.01	*	--	--	--		--
RATIO OF SATELLITE SYSTEMS ENGINEERING AND INTEGRATION COST TO SATELLITE COST	f_{SSEI}	FRACTION	.0455	.07	.10	25%	50%	100%		50%

TABLE E.2 ESTIMATES OF THE CURRENT STATE-OF-KNOWLEDGE ON O&M COST MODEL INPUTS FOR THE BOEING CO. CONFIGURATION

INPUT ELEMENT	VARIABLE NAME	UNITS	RANGE OF VALUES		
			BEST	MOST LIKELY	WORST
NUMBER OF SATELLITES MAINTAINED BY A SINGLE O&M BASE	f_{NSOM}	NUMBER	20	40	80
COST PER FLIGHT OF A CARGO ORBIT TRANSFER VEHICLE	COTVFT	$/FLT	2.0×10^6	2.6×10^6	4.0×10^6
UNIT COST OF A CARGO ORBIT TRANSFER VEHICLE	SC_{COTV}	$	75×10^6	82×10^6	120×10^6
DESIGN LIFE OF A CARGO ORBIT TRANSFER VEHICLE	f_{DLCTV}	# OF FLTS	75	50	40
MASS OF AN O&M CREW HABITABILITY MODULE	M_{CH}	kg	120×10^3	240×10^3	360×10^3
DESIGN LIFE OF AN O&M CREW HABITABILITY MODULE	f_{DLCH}	YEARS	15	20	30
NUMBER OF MAINTENANCE GANTRY AND MANIPULATION UNITS	N_{OM1}	NUMBER	22	44	66
NUMBER OF CREW MODULE DOCKING PORTS	N_{OM2}	NUMBER	2	4	6
NUMBER OF CREW BUSES	N_{OM3}	NUMBER	2	4	6
NUMBER OF CRANE MANIPULATORS	N_{OM4}	NUMBER	2	4	6
NUMBER OF COMPONENT TRANSPORTERS	N_{OM5}	NUMBER	4	8	12
NUMBER OF TURNTABLES	N_{OM6}	NUMBER	4	8	12
NUMBER OF LASER ANNEALING UNITS	N_{OM7}	NUMBER	4	8	12
NUMBER OF GANTRY/REPAIR VEHICLES	N_{OM8}	NUMBER	1	2	3
UNIT MASS OF MAINTENANCE GANTRY AND MANIPULATION UNITS	M_{OM1}	kg	2500	5000	7500
UNIT MASS OF CREW MODULE DOCKING PORTS	M_{OM2}	kg	*	0	*
UNIT MASS OF CREW BUSES	M_{OM3}	kg	6×10^3	12×10^3	18×10^3
UNIT MASS OF CRANE MANIPULATORS	M_{OM4}	kg	1500	3000	4500
UNIT MASS OF COMPONENT TRANSPORTERS	M_{OM5}	kg	500	1000	1500
UNIT MASS OF TURNTABLES	M_{OM6}	kg	*	0	*
UNIT MASS OF LASER ANNEALING UNITS	M_{OM7}	kg	500	1000	1500
UNIT MASS OF GANTRY/REPAIR VEHICLES	M_{OM8}	kg	2500	5000	7500
UNIT COST OF MAINTENANCE GANTRY AND MANIPULATION UNITS	C_{OM1}	$	10×10^6	20×10^6	60×10^6
UNIT COST OF CREW MODULE DOCKING PORTS	C_{OM2}	$	*	0	*
UNIT COST OF CREW BUSES	C_{OM3}	$	3.5×10^6	7×10^6	21×10^6
UNIT COST OF CRANE MANIPULATORS	C_{OM4}	$	4×10^6	8×10^6	24×10^6
UNIT COST OF COMPONENT TRANSPORTERS	C_{OM5}	$	500×10^3	1×10^6	3×10^6
UNIT COST OF TURNTABLES	C_{OM6}	$	*	0	*
UNIT COST OF LASER ANNEALING UNITS	C_{OM7}	$	7.5×10^6	15×10^6	45×10^6
UNIT COST OF GANTRY/REPAIR VEHICLES	C_{OM8}	$	5×10^6	10×10^6	30×10^6
MASS OF ANNUAL REFURBISHMENT COMPONENTS FOR A SINGLE SPS SATELLITE	M_{CPM}	kg	75×10^3	100×10^3	250×10^3
PAYLOAD OF A COTV	f_{COTV}	kg	*	400×10^3	*
ANNUAL COST PER O&M CREW MEMBER	SC_{ORC}	$/PERSON	*	60×10^3	*
UNIT MASS OF A COTV	SM_{COTV}	kg	400×10^3	490×10^3	600×10^3
DESIGN LIFE OF MAINTENANCE GANTRY AND MANIPULATION UNITS	f_{DLOM1}	YEARS	*	30	*
DESIGN LIFE OF CREW MODULE DOCKING PORTS	f_{DLOM2}	YEARS	*	30	*
DESIGN LIFE OF CREW BUSES	f_{DLOM3}	YEARS	*	30	*
DESIGN LIFE OF CRANE MANIPULATORS	f_{DLOM4}	YEARS	*	30	*
DESIGN LIFE OF COMPONENT TRANSPORTERS	f_{DLOM5}	YEARS	*	30	*
DESIGN LIFE OF TURNTABLES	f_{DLOM6}	YEARS	*	30	*
DESIGN LIFE OF LASER ANNEALING UNITS	f_{DLOM7}	YEARS	*	30	*
DESIGN LIFE OF GANTRY/REPAIR VEHICLES	f_{DLOM8}	YEARS	*	30	*