SPACE-BASED SOLAR POWER CONVERSION AND DELIVERY SYSTEMS STUDY

VOLUME V

ECONOMIC ANALYSIS

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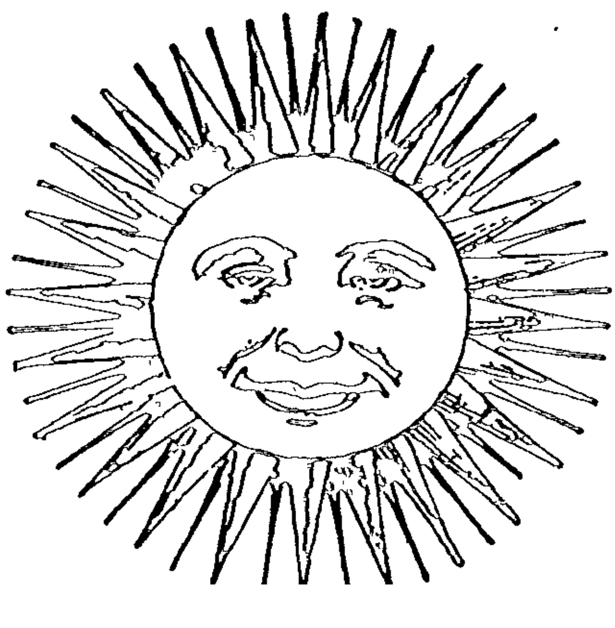

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SPACE-BASED SOLAR POWER CONVERSION AND DELIVERY SYSTEMS STUDY

FINAL REPORT

VOLUME V

ECONOMIC ANALYSIS

Prepared for

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

Under Contract No. NAS8-31308

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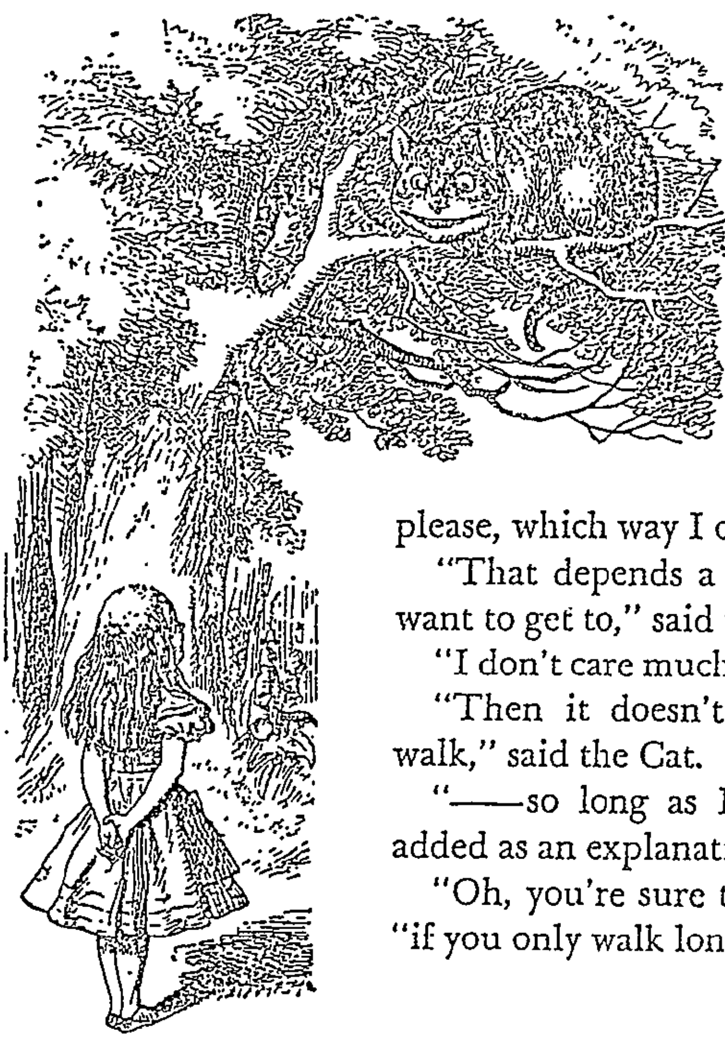

"Would you tell me, please, which way I ought to walk from here?"

"That depends a good deal on where you want to get to," said the Cat.

"I don't care much where——" said Alice.

"Then it doesn't matter which way you walk," said the Cat.

"——so long as I get *somewhere,*" Alice added as an explanation.

"Oh, you're sure to do that," said the Cat, "if you only walk long enough."

Lewis Carroll

ALICE IN WONDERLAND

IF MAN CAN DECIDE WHERE HE WANTS TO GO, SCIENCE CAN TELL HIM THE BEST WAY TO GET THERE

ABSTRACT

This study of space-based solar power conversion and delivery systems addresses a variety of economic and programmatic issues relevant to their development and deployment. Specifically, the study focuses on the costs, uncertainties and risks associated with the current photovoltaic Satellite Solar Power System (SSPS) configuration, and with issues affecting the development of an economically viable SSPS development program. In particular, the desirability of low earth orbit (LEO) and geosynchronous (GEO) test satellites is examined and critical technology areas are identified.

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

An assessment of LEO and GEO test satellites as components of the SSPS development program was performed using a decision tree approach. Five development program options were examined. This work serves as a benchmark for the formulation of effective program plans and establishes the value of test satellites of the proper scale. It is shown that the probability of successfully implementing the current configuration SSPS appears to be sufficiently high so that an economically justifiable program plan for the pursuit of the SSPS concept can be developed.

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

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

NOTE OF TRANSMITTAL

The economic analyses of space-based solar power conversion and delivery systems developed and reported in this volume have been prepared for NASA, George C. Marshall Space Flight Center, under Contract NAS8-31308. ECON study manager for this effort was Dr. George A. Hazelrigg, Jr. Data for the analyses were provided by the Grumman Aerospace Corporation, the Raytheon Company and Arthur D. Little, Inc. as subcontractors to ECON. The study managers for these organizations were Mr. Rudolph J. Adornato, Mr. Chet Wendell and Dr. Peter E. Glaser, respectively.

ECON also recognizes the assistance and substantial contributions of Mr. Gregg R. Fawkes of ECON in the preparation of this report, and the guidance of Dr. Bette M. Winer of Arthur D. Little, Inc. and Mr. Owen E. Maynard of Raytheon Company. Special recognition is due to Mr. Walter E. Whitacre of the Payload Studies Office of Marshall Space Flight Center as the COR for this study.

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Approved by: Klaus P. Heiss

Klaus P. Heiss
President

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF TABLES

1. INTRODUCTION

This report provides a detailed documentation of the economic studies that ECON performed under Contract No. NAS8-31308 for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center. The purpose of this study is to provide an economic assessment of both satellite solar power and power relay satellite concepts. Specifically, the study addresses three questions, sequentially, relevant to each concept:

1. Can it be done?

2. Should it be done?

3. How should it be done?

The first question addresses the technical and economic feasibility of each concept. To do this, system configurations were selected and studied in some detail. Critical technology areas were identified and futuristic but plausible technology goals were assumed to be met in each area. The systems were then costed (deterministically) subject to the above technology assumptions, and compared to the projected costs for alternative systems. The results of this effort show that satellite solar power is technically feasible and has economic potential, and that a power relay satellite is technically feasible but would be of no identifiable economic benefit over the foreseeable future. As a result of this outcome, no further attention was given to the power relay satellite concept in this study. The technical and economic feasibility studies are documented in Section 2.

The second question, addressed only to the satellite solar power concept, asks for a determination of the economic justification for proceeding with a satellite solar power system development program. To answer this question, a classical risk/decision analysis was performed. This analysis acknowledges first that it is not possible, today, to know:

1. What a satellite solar power system built with 1990's technology 20 years hence will cost

   a. to produce and

   b. to operate and maintain.

2. What the price of electric power will be from alternative energy sources available in the same period.

Secondly, the analysis recognizes that any satellite solar power system development program will be a segmented program where the "economic" purpose of each program segment will be to buy information to make the decision either to continue the program or to terminate it, thereby controlling risk.

To perform this analysis, a system cost model suitable for a risk analysis was developed and implemented into a risk analysis model. The risk analysis model was used to assess cost-risk associated with both the unit production cost and the operation and maintenance costs for a number of satellite solar power system alternatives. These data were then used as inputs to a decision analysis performed on the development program. A number of alternative programs were analyzed and several of them found to be "economic". That is, a preliminary economic justification is presented for undertaking the initial phase of one of these programs. It is shown that an effective level of effort would be $25 million per year through 1979, leading to a decision to conduct a space-based test using a 150 kW satellite. It is also shown that alternative solar cell materials, besides single crystal silicon, warrant attention. These studies are documented in Sections 3, 4, 5 and 7.

Finally, the question, How should it be done? was addressed. Critical technology areas and issues were identified and flagged as appropriate for emphasis in future studies. The major areas that were identified as both containing a significant amount of uncertainty and being key cost and/or cost-risk drivers are fabrication and assembly of large structures in space, and solar energy conversion technology. This effort is documented in Section 6.

Section 8 provides some comments on programmatic risks and Section 9 identifies and analyzes some key economic issues relevant to the utility interface area.

2. THE ECONOMIC FEASIBILITY OF SPACE-BASED SOLAR POWER CONVERSION AND DELIVERY SYSTEMS

In performing an economic analysis of any system which might be developed over a 20- to 30-year time period, and which has inherent in it a variety of uncertainties, the economist should first ask, Is it feasible? This question was asked in the first phase of the ECON study. To answer it, futuristic (which is to say, optimistic) but plausible technology goals were assumed to be met in each critical technology area for the two systems under study, a Satellite Solar Power System (SSPS), and a Power Relay Satellite (PRS). Based upon these assumptions, the SSPS and PRS systems were costed and then compared with terrestrial power generation and transmission systems of equal output capability. Deterministic cost models of the space-based systems were used along with conventional sensitivity analysis (including a variety of assumptions about price escalations of the terrestrial systems) in order to gain insight into which factors seemed to be the major cost drivers. The format that was used to do comparative economic analysis of the space-based systems with terrestrial systems is found in Sections 2.1.4 and 2.2.4 for the SSPS and the PRS, respectively.

2.1 Economic Feasibility of a Space-Based Solar Power System

Discussion of the economic feasibility of a space-based solar power system is divided into four main areas: system costs (Section 2.1.1), development program costs (Section 2.1.2), costs of terrestrial alternatives (Section 2.1.3), and a comparative economic analysis of space-based versus terrestrial systems (Section 2.1.4). The results of this section are based on the SSPS configuration as obtained at the end of the first study phase. The configuration changes somewhat through the remainder of the study.

2.1.1 Space-Based Solar Power System Costs

Table 2.1 provides an annual cost summary of an operational 5 GW SSPS. This summary presents only the recurring unit and operations and maintenance costs and does not include DDT&E. Also, these costs are for a representative operational unit after "learning" has been accomplished. The "serial number" is not specified. With an assumed operational life of 30 years, the busbar cost of energy generated by a 5 GW SSPS would be 26.7 mills/kwh. This includes 15.0 mills for capital recovery at a 7.5 percent discount rate, 3.1 mills for maintenance and 8.6 mills for taxes and insurance.

Table 2.2 contains a summary of the major 5 GW SSPS unit cost elements. As seen, the satellite hardware accounts for only about 30 percent of the total cost. Transportation is the major cost element (43.2 percent) and the ground station accounts for 18 percent.

Table 2.3 contains the detailed cost summary of the elements that comprise the capital investment component (satellite and receiving antenna) of the 5 GW SSPS. As noted above, a relatively minor proportion of the total cost is represented by "space hardware" (31 percent), the rest consisting

Table 2.1 Annual Cost of an Operational 5 GW SSPS

Element	Annual Cost, $ millions (1974)	Power Cost, 1974 mills/kWh
• Satellite	657	15.0
• Maintenance	136	3.1
• Taxes, Insurance	377	8.6
TOTAL	1156	26.7

Table 2.2 Five Gigawatt SSPS Unit Cost Summary

Element	Cost, $ billions (1974)	Percent
• Solar Array	1.798	24.0
Solar Blankets	(1.501)	(20.0)
• Transmitting Antenna	0.495	6.5
• Propellants and Miscellaneous Supplies	*	*
• Fabrication and Assembly Equipment	0.573	7.6
• Transportation	3.278	43.3
Space Shuttle Fleet	(0.240)	(3.2)
HLLV Fleet	(1.074)	(14.2)
Space Shuttle Flights	(0.879)	(11.6)
HLLV Flights	(1.013)	(13.4)
• Personnel	0.077	1.0
• Receiving Antenna	1.345	17.8
TOTAL	7.566	100.0

*Cost is negligible, weight has been accounted for in transportation charges.

Table 2.3 Five Gigawatt Operational SSPS Unit Cost

System Components	Mass, $\times 10^6$ kg	Design Variable	Specific Cost, \$ (1974)	Unit Cost, \$ billions (1974)
Satellite				2.293
• Solar Array	12.3			1.826
- Blankets	(7.83)	27.8 km²	54/m²	1.501
- Concentrators	(1.23)	61.1 km²	1.1/m²	.067
- Structure	2.23	2.23×10^6 kg	81/kg	.180
- Mast	0.64	0.64×10^6 kg	81/kg	.050
- Buses, Switches	(0.27)			
• Transmitting Antenna	5.72	5×10^6 kW[1,2]	99/kW	.495
- Power Distrib.	(0.54)		(18/kW)	.090
- Phase Front Control	(0.13)		(26/kW)	.130
- Waveguide	(2.31)		(14/kW)	.070
- DC-RF Converters	(2.33)		(26/kW)	.130
- Structure	(0.41)		(15/kW)	.075
Supplies	2.53			
o Cryo Propellants	(.981)			Neg
o Ion Propellants	(.772)			Neg
• S/S Resupply	(.772)			Neg
Equipment				.573
• 12 LEO Space Stations[3]	(.920)			.217
• 1 GEO Space Station	(.076)			.062
• Assembly Equipment[3]				
- Manned Manipulators	(.023)			.038
- Teleoperators	(.039)			
- EVA Equipment	(.018)			.089
• Fabrication Module[3]	(.016)			.015
• Crew Module[3]	(.012)			.007
• Orbit Maintenance Module[3]	(.002)			.005
Transportation				3.278
• Launch Vehicle Fleet[4]				1.314
- Space Shuttles		2 for 2 years	$60 $\times 10^6$/yr	240
- HLLVs		3 for 2 years	\$179 $\times 10^6$/yr	1.074
• Large Cryo Tug[3]				.009
• Support Tugs[3]				.008
• Advanced Ion Stage[3]				055
• HLLV Flights			\$9 $\times 10^6$/flt	1.013
- Satellite		99		.391
- Supplies		13		.117
- Equipment[3]		17		.005
• Shuttle Flights			\$12 $\times 10^6$/flt	.379
- Crew Rotation		72		864
- Teleoperator Equipment		3		311
- Crew Module		1		004
Personnel		1711 Man Years	\$45 $\times 10^3$/yr	.077
Receiving Antenna		5×10^6 kW[1,2]		1.345
• Real Estate				.095
• Site Preparation				.040
• Support Structure				.570
• RF-DC Subarrays				.380
• Power Interface				.235
• Phase Front Control				.025
TOTAL SSPS Mass/Cost	18.36			7.566 (5)

[1] Net power output at busbar.

[2] Efficiency losses have been accounted for

[3] Amortized over five SSPS units.

[4] 100 flight use-life was assumed

[5] Equivalent to \$1513/kW or 15.34 mills/kWh.

[6] Satellite mass.

of the equipment required for orbital fabrication and assembly, transportatio and the rectenna.

The costs of fabrication and assembly equipment as well as high energy stages (for transport of equipment and personnel from LEO to GEO) have been amortized over five SSPS units. It has been assumed that five SSPS units can be fabricated and assembled over a 10-year period, and the amortization formula repays the original capital with interest (7.5 percent) with equal annual payments. The launch vehicle fleet, space shuttles and HLLV have been costed in a similar manner but in these cases the amortization is based upon use-life of 100 flights and a 2-week turn-around. Assuming that the launch vehicle fleet will be dedicated to the SSPS program, there exists a "cushion" of extra flights that would incur only operations costs. The three HLLVs are capable of 156 flights in a 2-year period and the two space shuttles are capable of 104 flights. One hundred twelve HLLV flights and 76 shuttle flights are estimated to be required for each SSPS, or 56 and 38 per year, respectively. With 2-week turn-around the fleets are capable of 78 and 52 flights annually, respectively, allowing 22 and 14 additional flights, respectively. This result allows for sizable growth in the activity level of launches or reduction in the average launch vehicle load factor (to 75 percent) without significant cost impact.

As given above, the fleet was costed assuming a 100-use life and this resulted in \$1.31 billion (2.6 mills/kWh). Were the use-life 150 flights, the charges would be \$0.94 billion; use-life 200 flights, \$0.75 billion; use-life 500 flights, \$0.43 billion.

The annual maintenance cost estimate shown in Table 2.1 includes both the cost of subsystem units which fail and must be replaced as well as the cost of maintenance support equipment and personnel. Tables 2.4 through 2.6 list the definition of the Lowest Replaceable Unit (LRU) for the solar array, the microwave antenna, the rotary joint and the array control system.

Included are estimates of the failure rates and the corresponding number of LRUs replaced over the power station's 30-year life. The recurring maintenance cost for the array is estimated at \$3.99 million/yr while the cost to maintain the antenna is \$0.99 million/yr. The control system, mainly the ion engines for pointing of the array and antenna rotary joint, requires the most maintenance, \$39.10 million/yr.

The nonrecurring (excluding development costs) and the recurring costs for maintenance support have been analyzed assuming the following scenario:

- A six-man space station is required for monitoring the satellite and for use as a repair shop and garage for maintenance teleoperators
- Maintenance is performed using ground-controlled teleoperators
- Space station crews are rotated four times per year, using the Shuttle and a chemical tug

Table 2.4 Microwave Antenna Maintenance Cost

Element	LRU Description	LRU Mass, kg	LRU Failures Over 30 Years	Cost Over 30 Years, $ M	Average Cost Per Year, $ M
1. MW Tube	1670 - 18 x 18m Subarray	3017	4	5.73	0.19
2. Power Dist.	18 x 18m Subarray	3017	1	1.43	0.05
3. Command Electronics	1670 Units	467	3%	20.56	0.69
4. Trans. Antenna (Exclude tubes)	1670 - 18 x 18m Subarray	3107	1	1.43	0.05
5. Structure	To Design	--	--	--	--
6. Contour Control	6680 Units	22	1404	0.35	0.01
TOTALS MILLS/KWH					0.99 0.02

Assumptions:

1. MW Tube - MTBF = 1.14×10^{-6} hours projected (no moving parts, no seals and low temperature cathode).
2. Power Dist. - Highly redundant system expected to meet 30 year life requirement, one subarray failure assumed.
3. Command Electronics - 30 year life achieved with high level of redundancy, 3 percent failure assumed.
4. Trans. Antenna - Waveguides considered structure with low failure rate. One subarray failure assumed.
5. Structure - Assumed not to fail.
6. Contour Control - Failure rate = 0.8 F/10^{-6} (1 percent duty factor) for brushless DC motor operating 500°K.

Table 2.5 Rotary Joint and Array Control System

Element	LRU Description	LRU Mass, kg	LRU Failures Over 30 Years	Cost Over 30 Years, $ M	Average Cost Per Year, $ M
Rotary Joint					
• Slip Ring	24 Brushes, 4 Slip Rings				
- Brush		10	72	0.24	0.01
- Slip Ring		63	12	0.26	0.01
• Drive	8 Brushless Motors/Gear Train Units (4 Active, 4 Standby)				
- Motor/Gears		1367	24	11.0	0.37
- LIM		1086	--	--	--
Control System					
• Actuators	64 Electric Engines	203	640	1010	33
• Propellant	24,000 KG/Year	--	--	--	5.7
TOTALS MILLS/KWH					39.09 0.9

Assumptions:

1. Slip Ring - Previous space station studies indicate MTBF = 10 years within reach.
2. Drive - Same as slip ring.
3. Actuators - Current estimates place ion engine failure rate at 3800F/10^6 hour. Assume order magnitude improvement and a 10 percent duty factor. Cost assumes $7500/KG for engine and power conditioning.

Table 2.6 Solar Array Maintenance Cost

Element	LRU Description	LRU Mass, kg	LRU Failures Over 30 Years	Cost Over 30 Years, $ M	Average Cost Per Year, $ M
1. Blanket	80-1670 x 207m Modules	97,484	1	41.90	1.40
2. Concentrator	160-1670 x 207m Modules	768	1	0.23	0.01
3. Nonconducting Structure	To Design	-	-	-	-
4. Buses	400 m	26,000	1	8.29	0.28
5. Switches	59 Blocking DIO DES/Blanket LRU	97,484	1	41.90	1.40
6. Mast	6(+), 6(-) Buses/Panel	85,000	1	27.12	0.9
TOTALS MILLS/KWH					$3.99M 0.09

Assumptions:

1. Blanket - Cell open circuit failure = 2.6 x 10^{-4}/year. The probability of 5.6 percent LRU power loss over 30 years is less than 10^{-99}. One LRU replacement assumed over 30 years.
2. Concentrator - Mirror failure less likely than blanket failure, one LRU replacement assumed over 30 years.
3. Nonconducting Structure - Assumed not to fail.
4. Buses - Bus/connector failure rate (OAO) = 10^{-9} F/year. One LRU replacement assumed over 30 years.
5. Switches - Blocking diode failure rate (OAO) = 10^{-7} F/year. Assumes one blanket LRU replaced because of diode failure.
6. Mast - Same as for buses.

- An HLLV/Ion stage (payload = 181,600 kg to LEO) is used to initially place the space station and to resupply the station once each year.

The maintenance support costs are summarized in Table 2.7.

2.1.2 Development Program Costs

A three-phase SSPS development program was assumed for initial analysis: Phase I, a 15 MW low-earth-orbit satellite with an initial operation date (IOD) of 1 January 1985; Phase II, a 1 GW SSPS with an IOD of 1 January 1990; and Phase III, a 5 GW SSPS with an IOD of 31 December 1995. Presumably, the first 5 GW unit (1995) would be "grown" from the earlier 1 GW unit. The cost estimates for the above program are summarized in Tables 2.8 and 2.9. The costs associated with each of the program phases have been organized by expenditure period within three different development program categories: Direct Development, Design, Testing and Evaluation (DDT&E); related DDT&E; and Support Programs.

The direct DDT&E programs pertain to those program elements which would not be developed were it not for the decision to develop the SSPS. These total approximately $19.3 billion, and the costs are distributed over the

Table 2.7 Maintenance Support Cost, $ millions (1974)

Nonrecurring (Excludes Development)	
• Space Base	
- Hardware	$490
- Transport	$ 8
• Manipulator Modules	
- 50 Units at	$400
- Transport	$ 1
• Mission Control Facility	$ 20
	$919
Recurring/Year	
• Crew Rotation (4 flights)	
- Shuttle Flights	$ 42.0
- Shuttle Amortization	$ 1.8
- Tug Flights	$ 4.0
- Tug Amortization	$ 0.6
- Crew Transport Module	$ 4.0
- Crew Transport Module Amortization	$ 0.7
• Resupply Crew and Manipulator Consum.	
- HLLV (1/Year)	$ 9.0
- Amortization	$ 6.0
- Ion Stage	$ 1.0
- Amortization	$ 4.6
• Mission Control	
- Personnel (320)	$ 14.0/Year
	$ 87.7

Table 2.8 SSPS Direct and Related Development Programs, $ millions (1974)

Development Item	Expenditure Period			Total
	1981-1985	1986-1990	1991-1995	
DIRECT				
• Solar Array	1108	2453	3104	6665
• Rotary Joint	383	446	149	978
• Transmitting Antenna	616	464	260	1340
• Receiving Antenna	75	1610	403	2088
• 15 MW Demo Sat	427			427
Subtotal	2609	4973	3916	11071
• Management, S&I (@ 40%)	1044	1989	1566	4566
Subtotal	3653	6962	5482	15981
• 20% Uncertainty Factor	731	1392	1096	3196
Subtotal Direct	4384	8354	6579	19319
RELATED				
• Assembly Equipment	410			
• Logistics Equipment	44			
• Maintenance Equipment		44		
• Fabrication Module	271			
Subtotal	725	44		769
• Management, S&I (@ 40%)	290	18		308
Subtotal	1015	62		1077
• 20% Uncertainty Factor	203	12		215
Subtotal Related	1218	74		1292
TOTAL	5602 (3394)	8428 (3557)	6579 (1931)	20609 (8882)

Note: ( ) indicates 1975 present value, r = 7.5 percent.

Table 2.9 Support Programs, $ millions (1974)

Technology Development	IOD Year 1986	IOD Year 1992	Total
• LEO Transport			
- Shuttle Derivative	380		380
- Heavy Lift Launch Vehicle		6540	6540
• GEO Transport			
- Largy Cryo Tug	166		166
- Advanced Ion Stage		3847	3847
- Propellant Depot	223		223
- Tug for Depot	215		215
• GEO Crew Training Module	190		190
• LEO Space Station	2225		2225
• GEO Space Station	224		224
Subtotal	3623	10387	14010
• Management, S&I (@ 40%)	1449	4155	5604
Subtotal	5072	14542	19614
• 20% Uncertainty	1014	2908	3993
TOTAL	6086 (2570)	17450 (5130)	23536 (7701)

Note: ( ) indicates 1975 present value, r = 7.5 percent.

three phases of the program plan. The heaviest funding requirements occur over the period 1986 through 1990. The development costs in this period could provide for the installation of a 1 GW pilot plant in synchronous orbit. The purpose of this plant would be to provide a final decision point on the technical and economic feasibility of an operational plant. The unit cost of this pilot plant would be approximately $16 billion, allowing for management and uncertainty as provided in Tables 2.8 and 2.9. A major component of the pilot plant's cost would be transportation. This is because the HLLV and ion orbit transfer stage are not expected to be developed until 1990. The plant would not be strictly a development item since it is expected that some of the unit cost could be offset by revenues from the sale of power. The decision to install a 1 GW plant should be based upon its economic merit. This is assessed in Section 7 of this volume.

Of smaller magnitude are the development costs referred to as "related DDT&E." These are developments that are necessary for the realization of an SSPS but which <u>might</u> be required by other space programs as well. It is not unreasonable to anticipate that other programs will require the development of assembly, logistics and maintenance equipment. These developments require relatively small funding amounting to approximately $1.1 billion through the first operational SSPS unit. In total, the direct and related costs are equal to $20.5 billion.

The DDT&E designated "support programs" are required for the launch assembly and orbital transfer of the SSPS. Unlike the other technology developments, these are likely to be required--in part or entirety--by other space programs. If the only "customer" for these systems were the SSPS, then the SSPS should bear the full burden of repaying their development, but one would not expect this to be the case.

It is likely that other space programs will require these systems but that the SSPS will have specific requirements of a technical or programmatic nature. In this case, the SSPS should bear the economic burden caused by its specific requirements.

2.1.3 Alternative Power System Costs

Studies of the economic feasibility of the SSPS concept must be made in comparison with terrestrial power generation systems currently in use or likely to be in use before the year 2000.

For the purposes of this study, terrestrial power generation systems have been designated as either "existing" or "future" systems. Although the present form of existing systems may not be installed in the time frame when SSPS could become operational, these systems provide the most reliable data base for the purposes of an economic comparison.

Existing systems include oil-fired and coal-fired fossil fuel plants and light water reactor nuclear (LWR) plants. The technical characteristics of these systems are well-known. The major uncertainties associated with these systems are: the availability and price of fuels for the oil-fired and nuclear systems, the environmental hazards associated with all terrestrial systems, and the economic (investment) problems resulting from the social and environmental challenges currently being placed before nuclear systems.

The pollution problems and costs associated with the current methods of using coal to directly fire a steam generator have led to the development of several entirely different future approaches and processes for using coal either directly (as in the case of fluidized bed combustion) or after the significant amount of processing required for coal gasification or liquefaction. For this study, enumeration of the costs and system efficiencies associated with future coal processing plants was conducted for: two coal liquefaction techniques (Consol Synthetic Fuel and Solvent Refined Coal), 6 high-BTU coal gasification techniques (Lurgi, Hygas-Electrothermal, Hygas-Steam-Oxygen, Bigas, Synthane, CO_2 Acceptor) and 3 low-BTU techniques (BOM Atmospheric, BOM Pressurized, Lurgi). Two future advanced nuclear fission reactor systems considered to be representative of the developing nuclear technology were studied (i.e., the Liquid Metal Fast Breader Reactor (LMFBR) and the High Temperature Gas Cooled Reactor (HTGR).

The operating characteristics and capital cost estimates summarized in Table 2.10 have been derived from the literature on each of the generation systems used here for comparison. They are "representative" numbers for each type of system, acknowledging that significant cost variations occur from one site to another.

Table 2.10 Cost Estimates for Terrestrial Power Generation Plants
$ (1974); Discount Rate = 7.5%

Plant Type	Direct Coal-Fired	Direct Oil-Fired	Fluidized-Bed Coal-Fired	Low-BTU Coal-Gas Fired	High-BTU Coal-Gas Fired	Liquefied-Coal Fired	Light Water Reactor	High-Temperature Gas-Cooled Reactor	Liquid Metal Fast Breeder Reactor
Mature Plant Availability Factor	.75	.75	.75	.8	.8	.75	.8	.75	.75
Lead Time(1)									
Preconstruction	2.5	2.5	2.5	-	-	-	5	5	5
Construction	4	3.5	3	4(5)	4(5)	4(5)	6	4	6
Heat Rate(2)									
Environmentally Unregulated	8,960	8,962	-	-	-	-	10,200	-	-
Environmentally Regulated	9,558	9,053	9,614	11,590 (BOM Pres)	15,050 (Synthane)	13,790 (average)	10,300	8,740	8,650
Solid Waste(3)									
Environmentally Unregulated (lbs./kWh)	0.091	-	-	-	-	-	1.94	-	-
Environmentally Regulated (lbs./kWh)	0.279	-	.105	.120	.157	.116	1.94	1.09	-
Capital Cost ($/kW(1974))									
Environmentally Unregulated	274	240	-	-	-	-	342	-	-
Environmentally Regulated	330	253	258	236	340	445 (average)	363(6)	300	477
Cost of Capital(4) (1974 mills/kWh)	4.8	3.6	3.6	3.2	4.6	6.6	5.3	5.5	7.4
O and M Cost(4) (1974 mills/kWh)	2.1	0.7	1.3	2.4	2.3	3.6	1.2	1.3	1.9
Fuel Cost(4)	6.3	14.5	6.1	7.6	10.4	9.0	2.9	5.0	-
Taxes and Insurance (1974 mills/kWh)	2.5	1.9	2.1	1.7	2.4	3.5	2.6	2.9	3.6
BUSBAR Cost (1974 mills/kWh)	15.7	20.7	13.1	14.9	19.7	22.7	12.0	14.7	12.9

(1) Capital Expenditures assumed to occur in uniform increments during construction phase (See Economic Methodology).
(2) Cost of operating pollution control equipment reflected in heat rate, not O and M cost.
(3) Cost of solid waste disposal not included in total BUSBAR cost.
(4) For environmentally regulated plants only (See Appendix A, Section A.7)
(5) Data not available; conservative assumption made for purposes of economic analysis.
(6) The method of analysis used by utility companies (6% inflation, 10% discount rates) yields an equivalent cost of $951/kW for this plant in 1985 dollars (See Appendix A).

The components of the total "cost at the busbar" include the costs of: capital; operation and maintenance; fuel; and taxes, insurance and depreciation (an annual charge of 5 percent of the capital investment). The fuel and O&M costs are taken from the literature; the method for determining the cost of capital as a user charge is described in Appendix A (to wit, determining the equivalent annuity over the 30-year plant lifetime at a 7.5 percent discount rate to repay the capital expenditures made in equal increments during the construction phase). All cost estimates are expressed in 1974 dollars.

2.1.4 Comparative Economic Analysis

At existing relative prices, the SSPS would not be cost effective compared with terrestrial systems but, at expected future relative prices, it may well be cost effective. Figure 2.1 illustrates the comparative economic analysis for an SSPS operational in 1995.

The x-axis (abscissa) contains average values for the cost of electric generation over the 30-year period (1995-2025) in mills/kWh. The y-axis contains the "economically justifiable" 5 GW SSPS unit cost, evaluated at a 7.5 percent discount rate. The method by which this has been estimated, and the rationale for the choice of discount rate, is described in Appendix A.

The analysis compares the 5 GW SSPS with terrestrial fossil fuel systems. (i.e., oil and coal-fired generation plants).

The line, R, in Figure 2.1 relates the generation cost in mills/kWh of terrestrial coal and oil-fired systems over the period 1995-2025, as indicated on the x-axis. A range of cost estimates resulting from the study performed by University of California, Berkeley for JPL is also provided.

The coal and oil system values are based on three projections of the future:

- Relative fuel prices* remain constant (C_0, O_0)
- The relative prices of coal increase by 2.6 percent per year, and the relative price of oil increases by 0.67 percent (C_A, O_A)
- The relative prices of coal and oil increase by 5.0 percent per year (C_B, O_B).

As indicated by the suggested probability distributions, the first projections have a very low expectation. Regarding coal, the cost of production

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*"Relative prices" refer to the price relationship of all goods and services to each other. The usual practice is to consider one good as the baseline and calculate all prices relative to it. Obviously, generalized inflation would not affect relative prices.

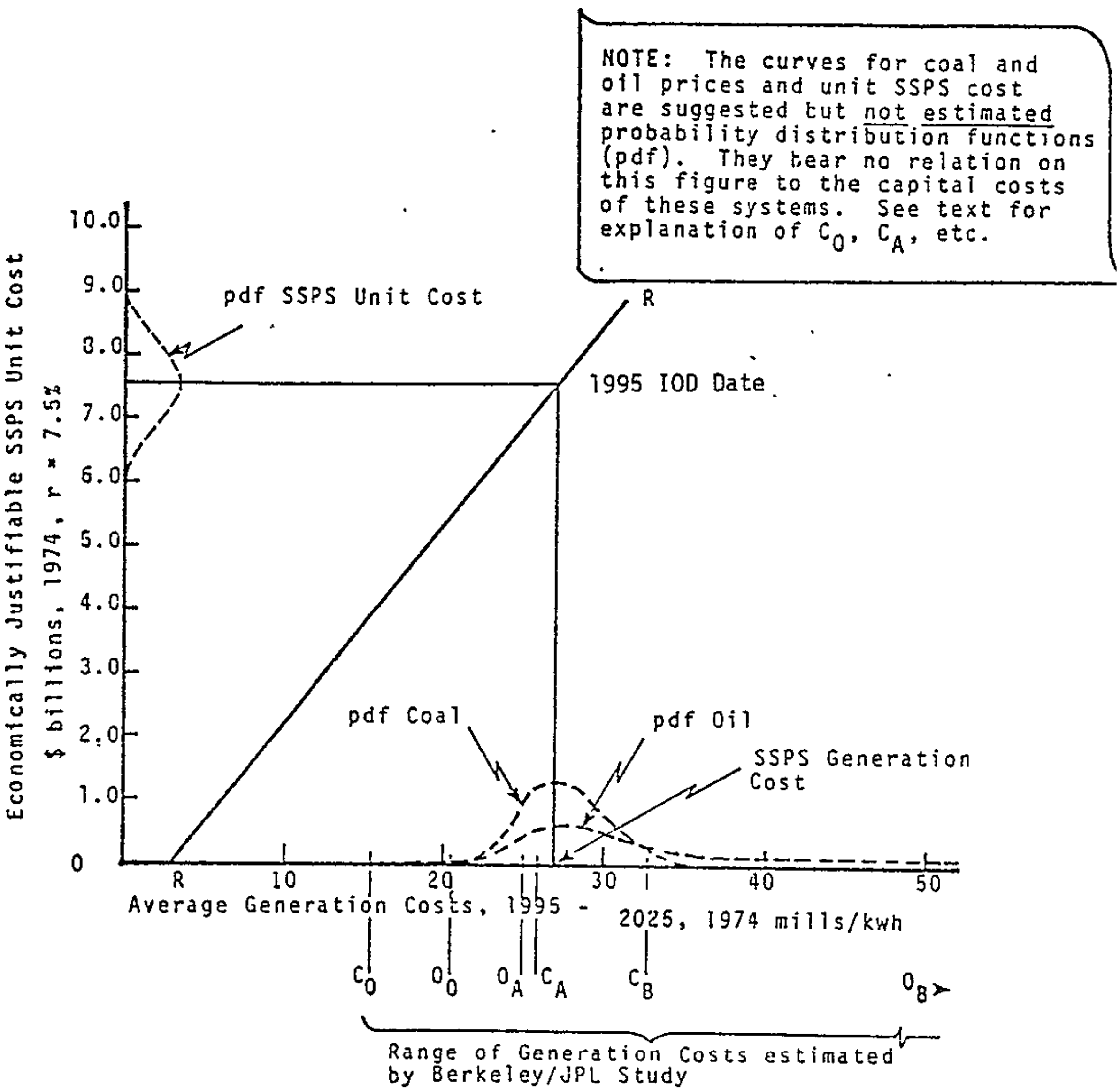

Figure 2.1 Comparative Economic Analysis of a 5GW SSPS Operating Over the Period 1955-2025

will rise as it becomes necessary to mine deeper veins and provide the expected environmental and human safeguards. Regarding oil, increased scarcity will no doubt raise relative prices. In fact, new oil-fired capability may not be installed after 1995.

The second projection has been adapted from the work of E.A. Hudson and D.W. Jorgenson and is highly regarded in the economic energy literature.* The estimates were derived from their analysis of a scenario in which the government does not intervene with respect to energy prices.

The third projection has been derived from the Hudson-Jorgenson scenario, in which the United States government levies a "BTU" tax of $0.05/million BTU (to encourage fuel conservation), over the period 1975-1980 and $1.35/million BTU over the period 1980-1985.** The goal of this action is United States energy independence by 1985.

Based upon projection of the Hudson-Jorgenson estimates of relative price changes to the year 2025, the typical coal-fired plant would generate electric power at an average price of 25.1 mills/kWh over the period 1995-2025. If a vigorous policy of energy independence were to be pursued, the average generation price would be about 33 mills/kWh.

The same analysis for oil indicates that the projections of the Hudson-Jorgenson estimates of "no policy change" would not affect the relative standing of oil-fired systems. With an "energy independence" policy, the price of electric power from oil-fired plants might be driven off the scale.

Based upon these results, there is some expectation--the probability of which is discussed in Section 5--that the SSPS will be cost effective with respect to fossil fuel systems by 1995. Furthermore, since fossil fuel systems depend upon nonrenewable sources of energy, the economic viability of SSPS should be enhanced relative to these beyond 1995.

While every attempt has been made to cost the systems on a consistent basis, one major element of cost has not been addressed: the systems' relative social and environmental impacts. Within this study we have begun to develop a framework for evaluating these impacts. This will, however, require much further study before our level of understanding is adequate for the purpose of decision making.

A second issue that could impact total systems cost is the relative acceptable distance between population and industrial centers for SSPS rectennas and conventional electric power generators. This is an important determinant of the cost of energy transmission, and hence, the delivered

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*Hudson, E. A. and D. W. Jorgenson, "U.S. Energy Policy and Economic Growth, 1975-2000," The Bell Journal of Economics and Management Science, Vol. 5, No. 2, Autumn 1974.

**It is to be stressed that the 5 percent value is not that of Hudson-Jorgenson. It is our projection of the constant dollar impact estimated in their analysis.

cost of electric power to the user. Based on current trends in plant siting, it does not seem likely that major energy-intensive industries--such as metals processing--would locate near 5 to 10 GW nuclear sites. The rectenna site, on the other hand, would appear to be amenable to such activity. These issues, however, await future study.

Finally, it should be noted that the U.S. Energy Research and Development Administration (ERDA) is currently funding research in electric generation technologies, such as ocean thermal and solar power towers that are expected to produce energy in the range of 30-50 mills/kWh, as well as fusion power, the potential cost of which is more difficult to estimate.

The conclusions of the feasibility study are: given appropriate technological advances and continued increases in the real cost of generating electrical power by terrestrial systems, satellite solar power systems might become economically viable by the mid to late 1990s; however, an SSPS is not cost effective compared to fossil fuel alternatives at the present time even given the futuristic technological advances assumed.

Had the results of the feasibility study indicated that the SSPS would not be economically viable in the 1995 and beyond time period, even given that futuristic technology goals would be achieved, then it would be appropriate to discontinue further studies related to this particular configuration of space power system. Until such time that an economically viable space power system concept can be found, the pursuit of a space power system concept would have to be based upon justification other than its ability to compete, on a cost-effectiveness basis, with alternative methods of electrical power generation. Since the indication in this study is that the space power system concept examined could become cost effective in the 1990-2000 time period, it is appropriate to continue the economic analysis of this system, not with the focus on what optimistically could happen but, rather, with the focus on what might likely happen. Thus, the second phase of economic study involves a risk analysis of the space power system concept.

2.2 Economic Feasibility of a Power Relay Satellite

Discussion of the economic feasibility of a Power Relay Satellite is divided into four main areas: PRS system costs (Section 2.2.1); development program costs (Section 2.2.2); terrestrial power transmission system costs (Section 2.2.3); and a comparative economic analysis of space-based versus terrestrial systems (Section 2.2.4).

2.2.1 Power Relay Satellite System Cost

The Power Relay Satellite (PRS) Microwave Power Transmission concept uses a reflector in synchronous orbit to provide power transfer from a transmitting antenna at one ground location to a ground receiving and rectifying antenna at a distant location. The transmitting antenna is a phased array radiating through slotted waveguides and the receiving antenna is a rectenna similar to that used for SSPS.

The economic and technical issues for transportation, assembly and maintenance are the same for the PRS as for the SSPS. The same array of transportation options should be considered in the assessment of PRS economics, though the use of a Heavy Lift Launch Vehicle (HLLV) may not be found to be cost effective. Simple derivatives of a Shuttle may be found to be adequate.

The cost trends for the PRS are illustrated in Figure 2.2 for a 5 GW case plotted as functions of peak power density at the transmitting antenna. There is a tradeoff between the transmitting antenna cost and the reflector cost. The totals for a range of ground power outputs in Figure 2.3 show that capital cost decreases with increasing total power output and, depending upon the power output, decrease with peak ground power density.

The environmental/biological levels shown in Figure 2.3 make it clear that the economics of the PRS drive the acceptance of greater environmental risk in going to higher power densities than the SSPS.

Figures 2.4, 2.5, and 2.6 illustrate that the basic cost trends noted above are relatively insensitive to assumptions on equipment manufacturing cost, orbital transportation and assembly costs, and system efficiency. The transportation and assembly cost is a relatively minor factor in this example.

A PRS design point was selected at a peak power density of 50 mW/cm^2 for 5 GW and 10 GW systems because this is at the "knee" of the total cost curve. Lower power densities imply great risk of cost escalation due to the steepness of the cost curve in that area; and higher power densities increase the biological/environmental risk without a commensurate reduction in cost.

Table 2.11 summarizes the maintenance costs for the PRS. The major maintenance cost drivers for PRS are similar to the SSPS, namely, the contour control actuators and the electric propulsion units used for attitude control and stationkeeping.

Maintenance support costs for PRS are similar to those required for SSPS, namely, costs associated with resupply and recycling crews of $86M/yr. The cost of equipments replaced each year is small, approximately $4M/year. Subsection 4.4 discusses in detail the assumptions used to establish maintenance support costs.

2.2.2 Development Program Costs

Figure 2.7 is a PRS development plan used as a strawman schedule for economic analysis. A geosynchronous demonstration satellite is scheduled for 1985. The transportation/assembly modes assumed available in this time frame are:

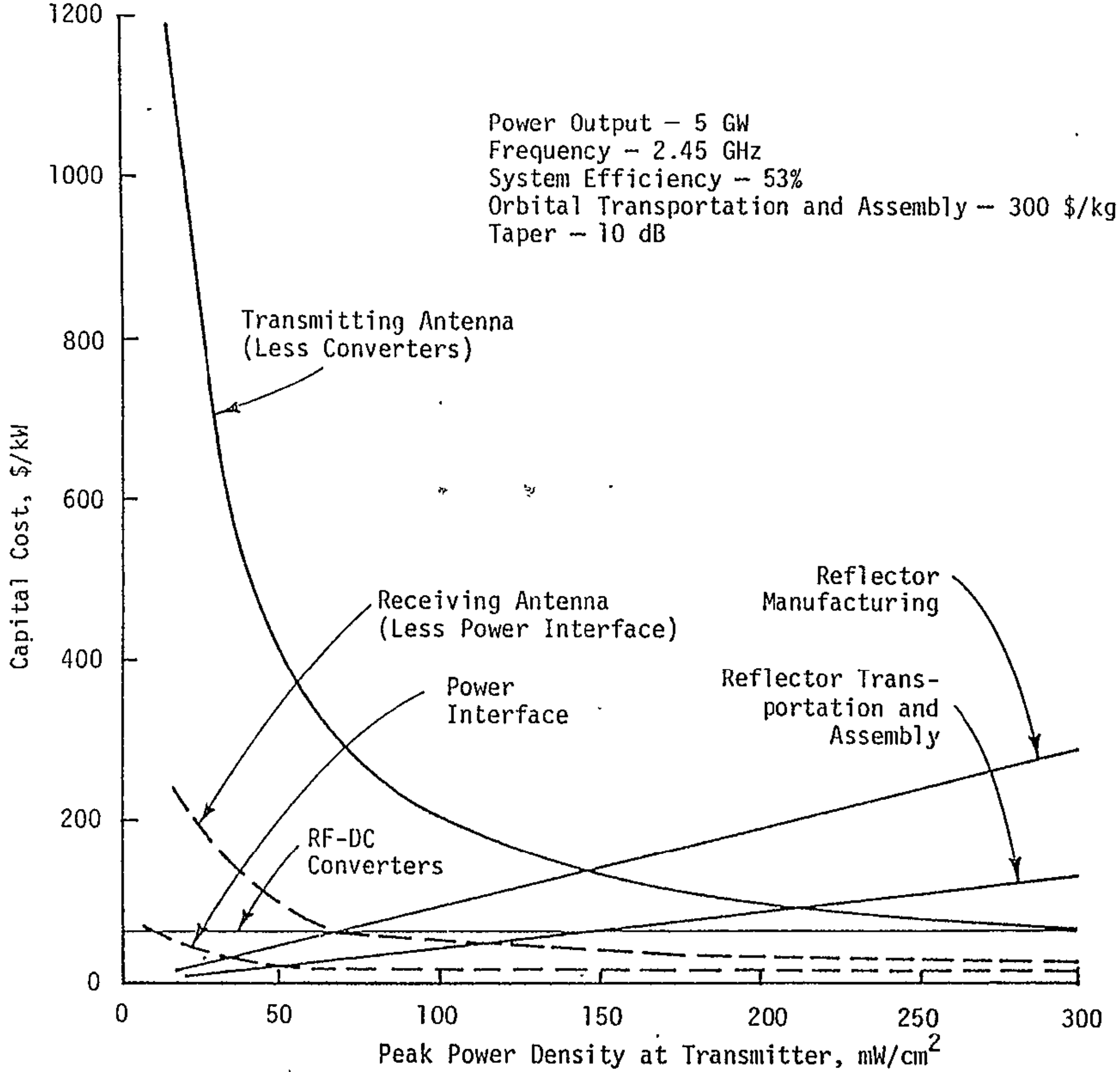


Figure 2.2 PRS Cost Elements Versus Peak Power Density at Transmitter

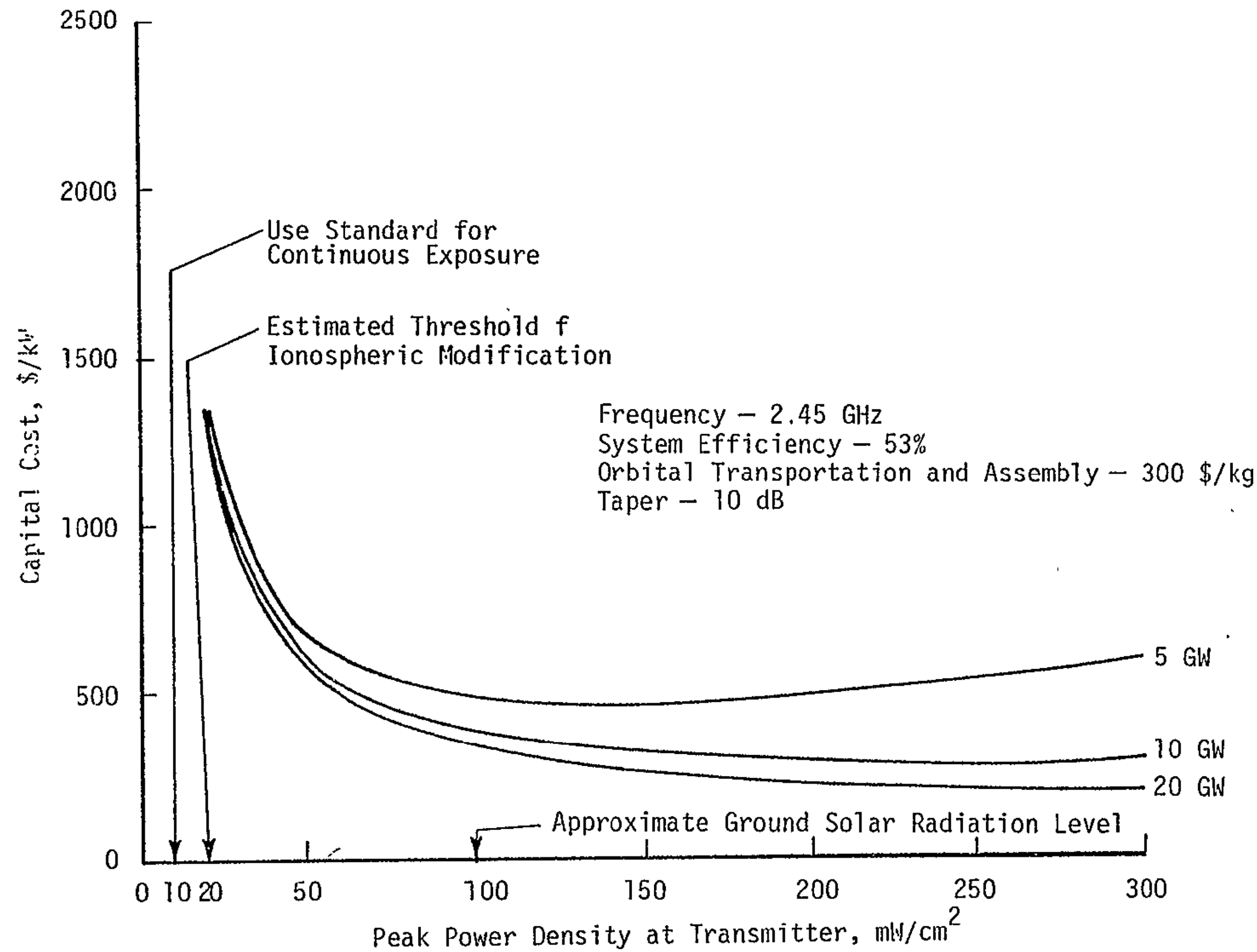


Figure 2.3 PRS Cost for Various Power Outputs

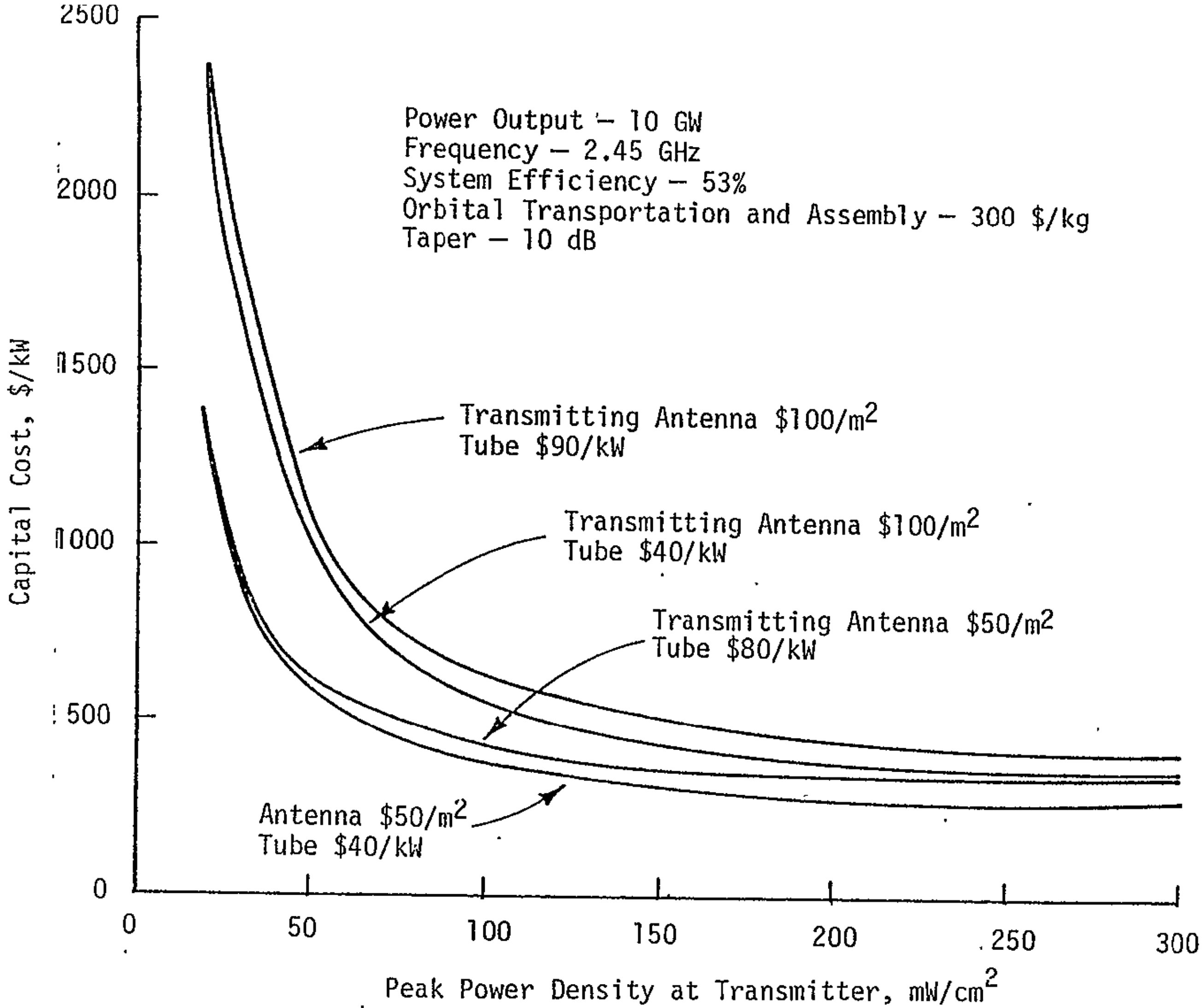


Figure 2.4 PRS Cost for Several Transmitter Cost Factors

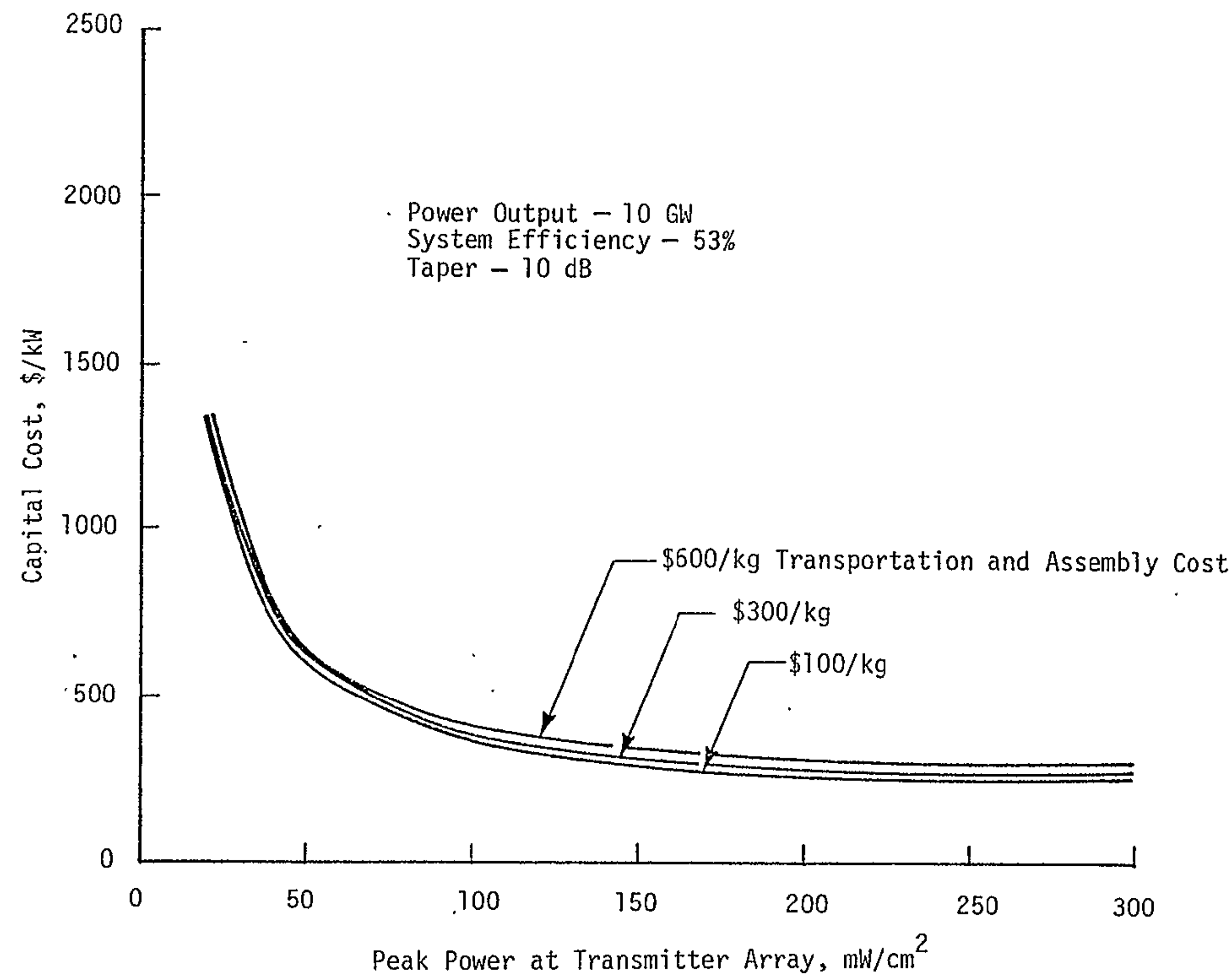


Figure 2.5 PRS Cost for Several Transportation/Assembly Cost Factors

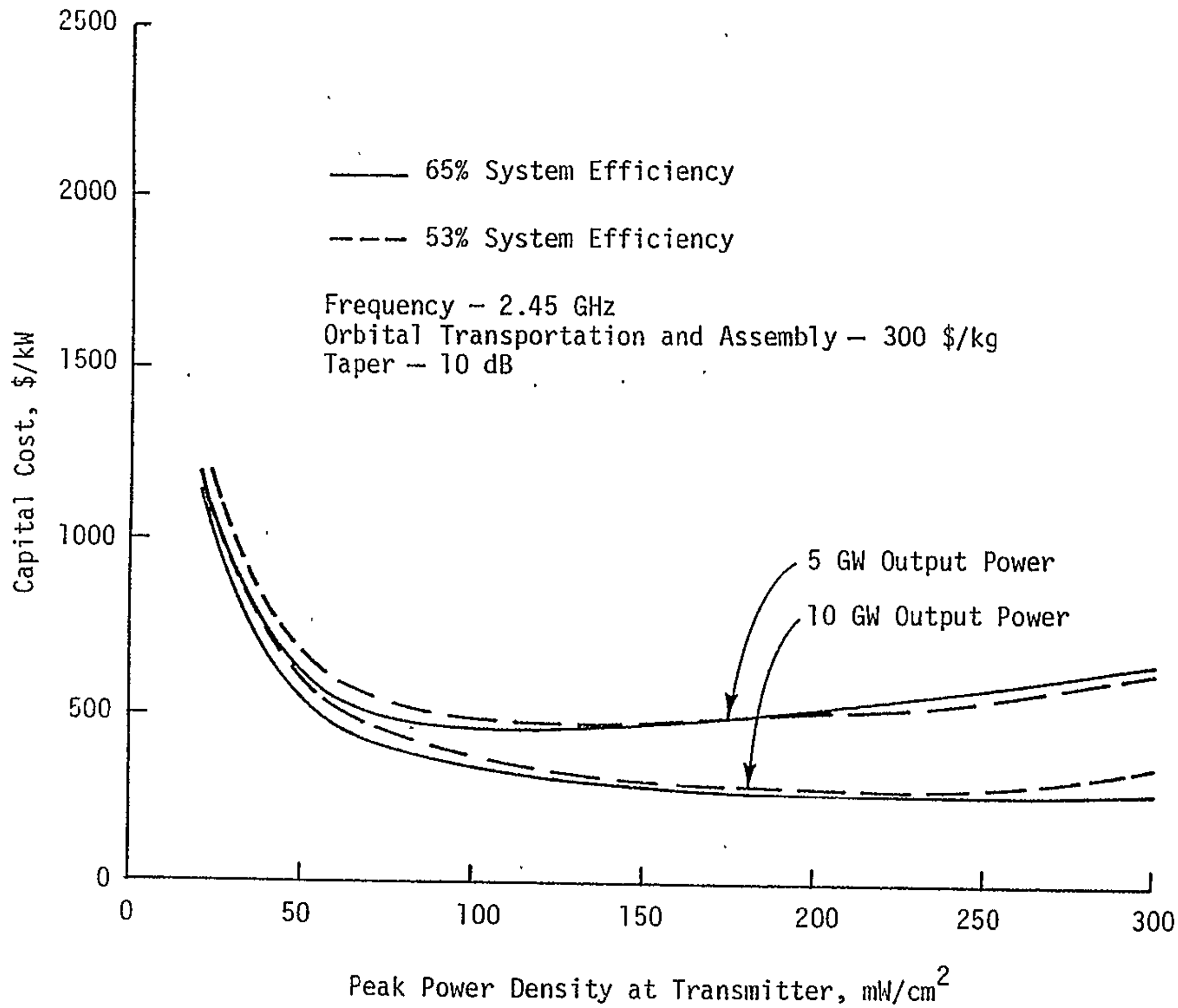
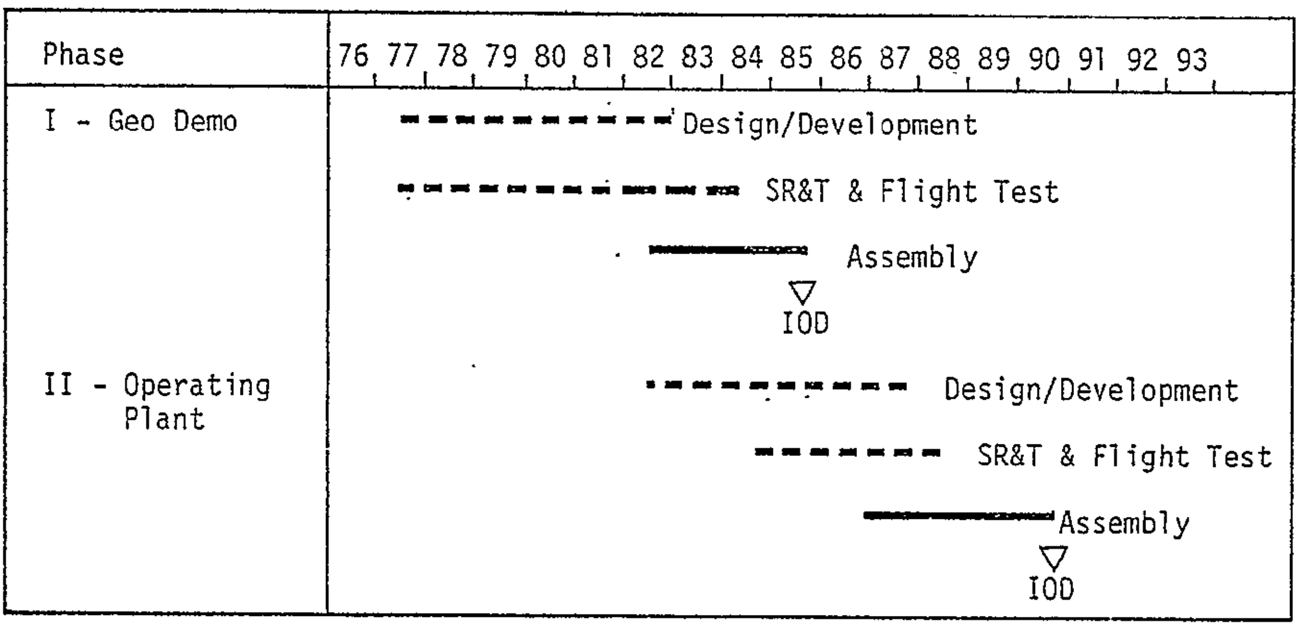


Figure 2.6 PRS Cost and System Efficiency

Table 2.11 PRS Maintenance Cost

Element	LRU Description	LRU Mass kg	LRU Failures Over 30 Yrs	Cost Over 30 Yrs $M	Avg. Per Yr. $M
1 Structure	To Design	--	--	--	--
2 Reflectors	18 x 18m Subarray		1		
3 Contour Control Actuators	6680 Units	22	1404	0.35	0.01
4 Contour System Actuators	64 Electric Engines	203	640	1010	3.3
Propellant	885 Kg/Yr	--	--	--	0.21
				Total	3.52



	1985 System	1990 System
Mass	.581 x 10^6 kg	0.505 x 10^6 kg
DDT&E	$1696M	$264M
Unit Cost	$2491M	$567M
Maintenance	-	$ 90M/Year

Total Program through first operation unit = $5.1B

Figure 2.7 PRS Orbital System Program Schedule and Cost

- Shuttle
- Full Capability Tug
- LEO Space Station
- GEO Space Station

Based on these major system elements the cost for transportation and assembly is approximately $4190/kg. The 1990 system, which is an improved version of the demonstration satellite, was analyzed, assuming the following transportation and assembly system elements:

- Deploy Only Launch Vehicle derivative of Shuttle
- Large Cryo Tugs which are derivatives of the Shuttle External Tanks
- LEO Space Station
- GEO Space Station.

Based on these major elements, the transportation and assembly costs are $1080/kg.

2.2.3 Terrestrial Power Transmission System Costs

In order to compare the PRS transmission concept with terrestrial alternatives, use has been made of available data on representative terrestrial systems in order to design transmission systems that would provide a capability equal to that of the PRS. While these systems provide such a capability, it is unlikely that they would in fact be built under any foreseeable circumstances.

The categories of terrestrial alternatives studied include transmission via conventional circuits and super conducting transmission lines (all of which are considered to be "existing" systems even though some currently exist only in experimental application), and hydrogen transmission and microwave transmission via waveguides (which are classified as "future" systems).

In order to design the most economic terrestrial power delivery systems that would provide a capability equal to that of the PRS, it was necessary to make the following basic design assumptions:

- Power input--AC electric power would be at the appropriate voltage level.
- Power output--AC electric power would be at the appropriate voltage level.

- All transmission systems would have the capacity required to most economically deliver 5,000 or 10,000 MW. Additional capacity would be added at the source to provide the capability of economically carrying that power which would be lost along the route.

- Designs would be those which were most economical in 1974.

- The cost of the energy lost because of transmission would be based on a 1974 cost of \$0.02/kwh = \$175 x 10^3/MW-year.

- All transmission systems would be in use 100 percent of the time.

- Overland circuits would range from 2,000 to 5,000 miles long. This is independent of the great circle distance between the transmitting and receiving points.

- Only transmission capability would be considered. No credit would be given for the potential benefit of energy storage, since the PRS does not provide any energy storage option.

- Systems having a transmission efficiency of less that 50 percent would not be considered.

The costs of the transmission systems have been calculated in a consistent mills/kWh user charge format (as a function of transmission distance) for comparison with the PRS.

Conventional Transmission Systems

There is no single cost per circuit or single effective resistance/circuit-km for any particular system. The resistance/circuit-km can be reduced (within limits), but only with a corresponding increase in capital costs. Designing the optimum system requires knowing the detailed relationship between the capital costs and resistance and a specific transmission route. Since these data are not generally available, it was necessary to use a representative capital cost and representative effective resistance per circuit-km for each system considered.

The capital costs and effective resistances/circuit-km that were used in this part of the study have been garnered from a variety of sources published in various years. The costs have all been adjusted to 1974 dollars using the Handy-Whitman Index and the resulting values then compared to each other, to make sure they were reasonable and consistent. These values represent the best estimate of the costs that can be made, given the limitations of this study.

The total transmission costs for all the terrestrial systems are not sensitive to the cost of the land required for the right-of-way (ROW). The ROW costs have been included as part of the capital costs of the various conventional transmission systems and assumed to average $1000/acre--low for flat land near cities and high for mountainous or desert terrain. This is equivalent to about $11,200/circuit-km for the 765-kV ac overhead line, just 3.6 percent of the total costs of the circuit.

The cost of delivering energy is the sum of the fixed costs and the operating costs of the system used. The systems had to be designed to minimize this sum. However, the operating costs and the fixed costs are related. The higher the loading of each transmission circuit, the fewer the circuits required to deliver the same amount of power and the lower the capital costs and, thereby, the fixed costs. On the other hand, the higher the loading of the circuit (except the Superconducting Power Transmission Line), the higher the percentage of power that is lost, and this loss must be paid for (20 mills/kWh).

Each transmission system was then designed to achieve minimum total cost, while not exceeding a 50 percent transmission loss. It was necessary to do this type of economic analysis for each of the candidate transmission systems. However, as a result of the high capital costs for underground systems, the minimums for the naturally cooled underground systems always occur when the circuit is loaded above the thermal limit. For that reason, extra underground circuits are added only when it is necessary to carry more power than the existing circuit can physically accommodate. A minimum does exist for the forced-cooled conventional underground systems.

The costs for the nine different conventional systems have been summarized in Figure 2.8. This figure serves as the basis for comparison to the PRS (Section 2.2.4).

Hydrogen Transmission

The cost of transmission by pipeline compares unfavorably with the ± 500 kV dc overhead line. In addition, one of the basic design parameters was that no system would be considered if the transmission losses were greater than 100 percent of the delivered energy. Hydrogen transmission clearly does not qualify for overland transmission; however, cost estimates for LH_2 transport by tanker have been included in Figure 2.8 for the purpose of comparison of international energy transfer costs.

2.2.4 Comparative Economic Analysis

The PRS system in its current configuration has been compared with terrestrial electric transmission systems that currently exist or that might exist in the 1990-2020 time frame. Transmission costs for PRS systems with output powers ranging from 5 to 10 GW have been compared with terrestrial systems delivering comparable outputs. This comparison is summarized in Figure 2.8.

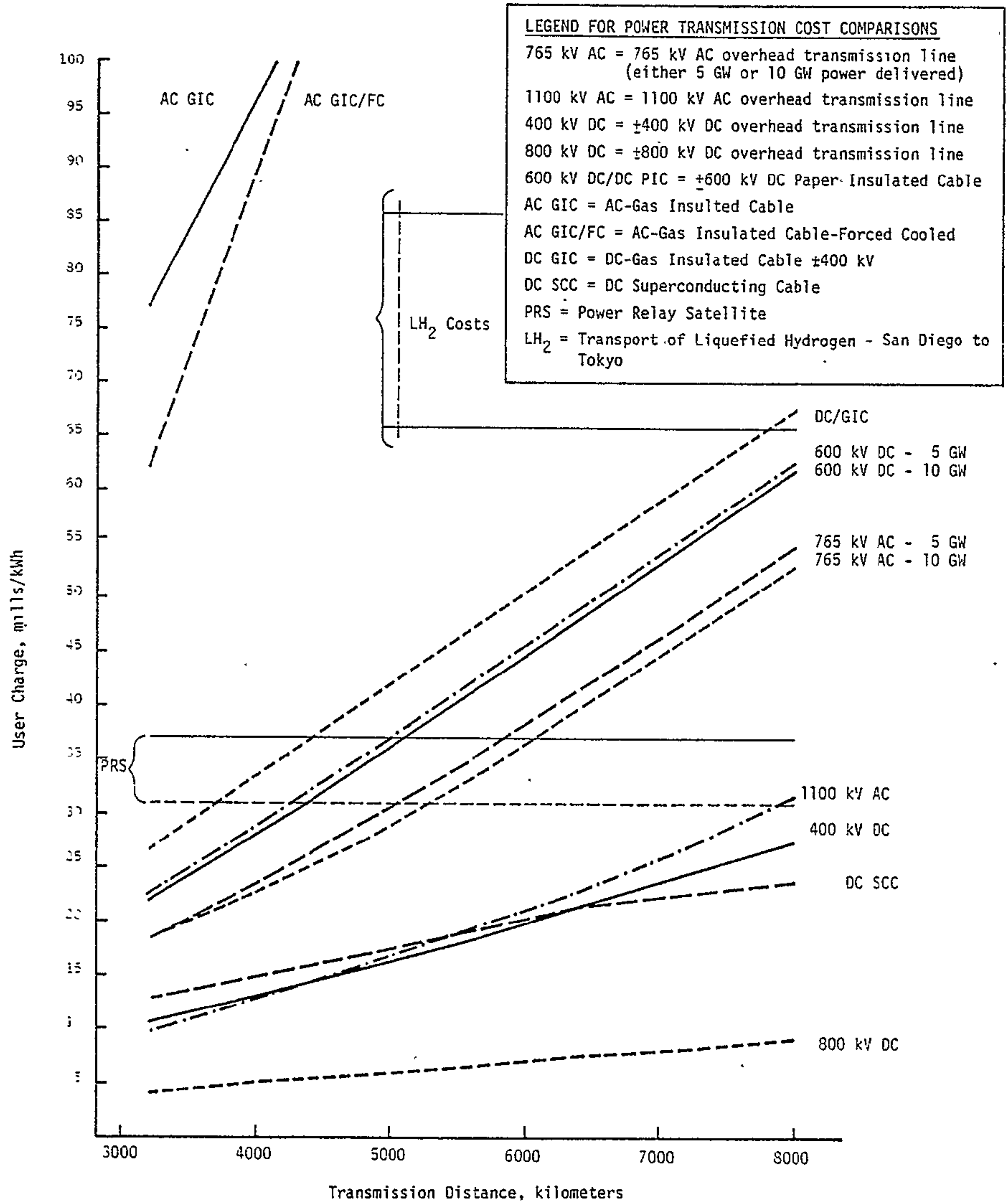


Figure 2.8 Power Transmission Cost Comparisons

The PRS would provide less costly energy transmission than current or projected underground cables, and would be less costly for distances greater than 5,600 km than the current 765 kV ac overhead lines. It offers higher costs than currently existing ± 400 kV dc overhead lines or several other systems already in limited application (such as the dc superconducting cable) or those expected to be utilized (such as the ± 800 kV dc overhead line). The relatively higher costs of the PRS are the result of both high capital costs and unavoidably high transmission losses. Specifically, at an output level of 10 GW the cost of the PRS transmission losses, calculated at a representative generation cost of 20 mills/kWh, are almost 50 percent greater than the capital costs.

Sensitivity analyses were conducted to determine the effects of decreases in antenna efficiency, phase control, and beam control efficiency in the PRS system. Ten percent decreases in each of these individually were found to increase transmission costs on the order of 2 mills/kWh.

The PRS concept is limited to overall system efficiencies of 50 to 60 percent, even with individual system elements developed to the highest practicable limits. If there existed the political requirement for large intercontinental energy transfers, the PRS seems to be economically superior to bulk energy transport _via_ liquid hydrogen.

Based upon the results obtained in this section, the PRS was not studied in the second or third study phases.

3. COST, UNCERTAINTY AND RISK ANALYSIS OF SPACE SYSTEMS

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

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

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

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

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

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

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

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

Figure 3.1 places risk analysis in perspective with typical engineering analyses. Most engineering analyses are point estimates. A point estimate is obtained by inputting the "best guess" or estimate of the various system parameters into a model to obtain "single number" estimates of system cost or performance. Point estimating procedures seek an answer to the question, What do you think? It is often recognized that point estimates can be wrong. Thus, a next step is generally to conduct a sensitivity analysis. A sensitivity analysis considers variations around the "best guess" parameters of the point estimate and thus addresses the question, What if you are wrong? Risk analysis, on the other hand, adds a new dimension by addressing the question, What do you know? To do this, it provides a framework for adding ranges and probability distributions of system parameters for input to system models and provides, as output, ranges and probability distributions of system cost and performance rather than single number estimates of these values.

The answer to the question, What do you know?, incorporates the answer to the question, What do you think? As shown in Figure 3.2, the answer to the question, What do you think?, is typically the most likely value for a parameter to take on. That is, it is the value of the parameter for which the probability density function* obtains a maximum. In addition, however, it includes information such as the minimum and maximum values which the parameter can assume (that is, the range of the parameter outside of which there is zero probability of occurrence of the parameter) and confidence bounds which serves to establish the form of the probability density function.

As an adjunct to the above discussion, it can be observed that, in general, for continuous distribution functions such as the one shown in Figure 3.2, there is a zero probability that exactly the most likely value will occur. In other words, there is probability one that the answer to the question, What do you think?, is wrong.

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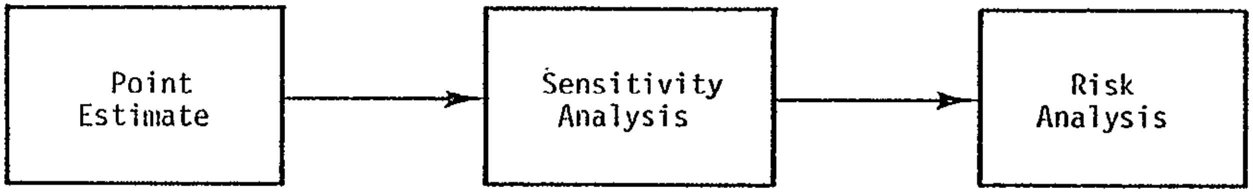
*The probability density function, $p(x)$, gives the probability per unit of x that a random variable, x, lies between the value x_0 and $x_0+\Delta x$ for very small Δx. That is, the probability that x takes on a value between x_0 and $x+\Delta x_0$ is

$$p(x_0)\Delta x$$



"Best Guess" of System Parameters

- Masses
- Efficiencies
- Reliabilities
- Costs

Provides "Single Number" Estimate

What Do You Think?

Variations of System Parameters Around the "Best Guess"

- Δ Masses
- Δ Efficiencies
- Δ Reliabilities
- Δ Costs

Provides "Sensitivity" of Single Number Estimate to Input Data

What If You Are Wrong?

Ranges and Distributions of System Parameters

Provides Expected Value and Distribution of "Single Number" Estimate

What Do You Know?

Figure 3.1 Risk Analysis

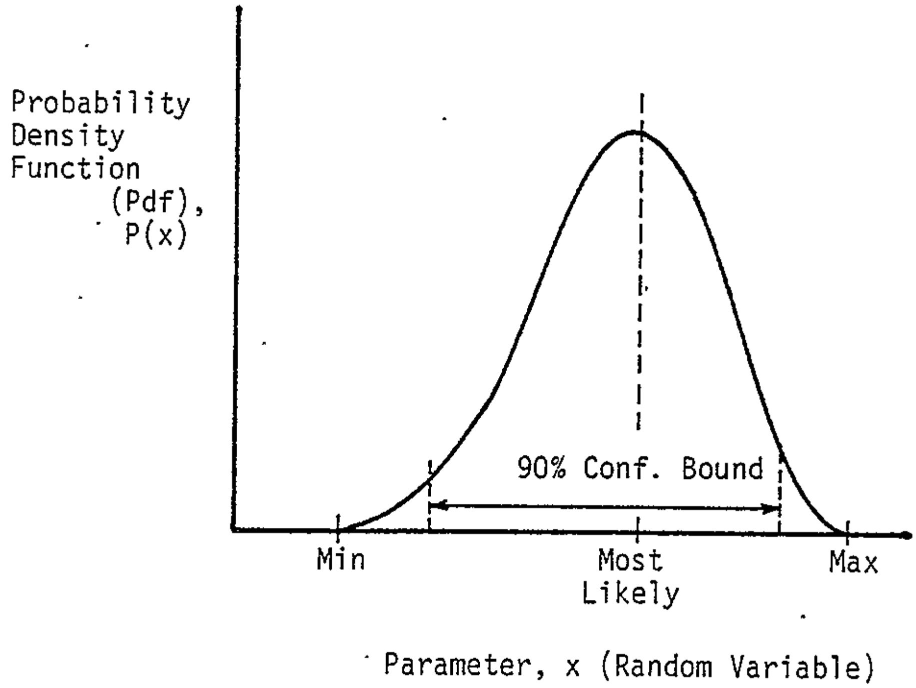


Figure 3.2 Quantifying the State-of-Knowledge Relative to a Parameter, x

One is thus led to question the validity of point cost estimates. Indeed, without performing a risk analysis, cost estimates are generally wrong and almost invariably low. The reason for this is easily explained within the context of risk analysis. System cost estimates are generally performed by dividing the system into subsystems, costing the subsystems individually and summing these costs to obtain the total system cost. However, it must be recognized that a cost estimate is a forecast of the future and thus can be expressed only as a probability distribution. Hence, single point estimates are, in fact, samples from such distributions. A characteristic of most aerospace subsystem cost probability distributions is that they are skewed such that the mean or expected value of the distribution is higher than the most likely value. But it is the most likely value that is generally obtained by soliciting point estimates. Now, when one adds the subsystem costs together to obtain the total system cost, whether it is explicitly recognized or not, one is adding probability distributions; and the mean value theorem asserts that, if one adds together a number of probability distributions, the resulting distribution tends to approach a normal (Gaussian) distribution for which the expected value and the most likely value are the same, and these are equal to the sum of the expected values of the component distributions, not the sum of the most likely values. Thus, in the summation process, the increment of cost between the most likely value and the expected value for each subsystem is left out and the resulting sum is low by the sum of these increments.

Figure 3.3 illustrates this phenomenon. A, B and C are component subsystems of the total system. Solicitations of point cost estimates result in the most likely values, L_A, L_B and L_C. The sum of the cost differences between the most likely values and the expected values, E_A, E_B and E_C, namely $\Delta_A+\Delta_B+\Delta_C$, is neglected in point cost estimates. Thus, the estimate of E_{SYS} or L_{SYS}, the expected or most likely values of total system cost, is low by this amount. This explains why most cost estimates are low. Of course, in general, one does not obtain expected values anyway and the cost of any particular system may deviate from the expected value by some amount that can be estimated only by performing a risk analysis.

3.1 Uncertainty, Risk and Decision Making

Decision makers are often confronted with a wide range of alternatives from which they must select one or a few alternatives to pursue. The selection of the "best" alternative must invariably consider the risks inherent in each candidate alternative. For example, consider the investment of private savings. Clearly, a vast number of alternatives exist ranging all the way from placing the savings in a government insured bank account to placing the total sum on Crazy Horse to win in the fifth at Belmont. In between these extremes (and maybe beyond them) are all the opportunities present in the stock market. Obviously, the private investor who puts his entire savings into the investment that offers the possibility of the highest return is rare.* Most investors readily admit foregoing significant potential returns to obtain added security (reduced risk) in an investment. The same philosophy must also apply for the federal government in the selection of alternative courses of action to meet the energy needs of the nation in the year 2000 and beyond.

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

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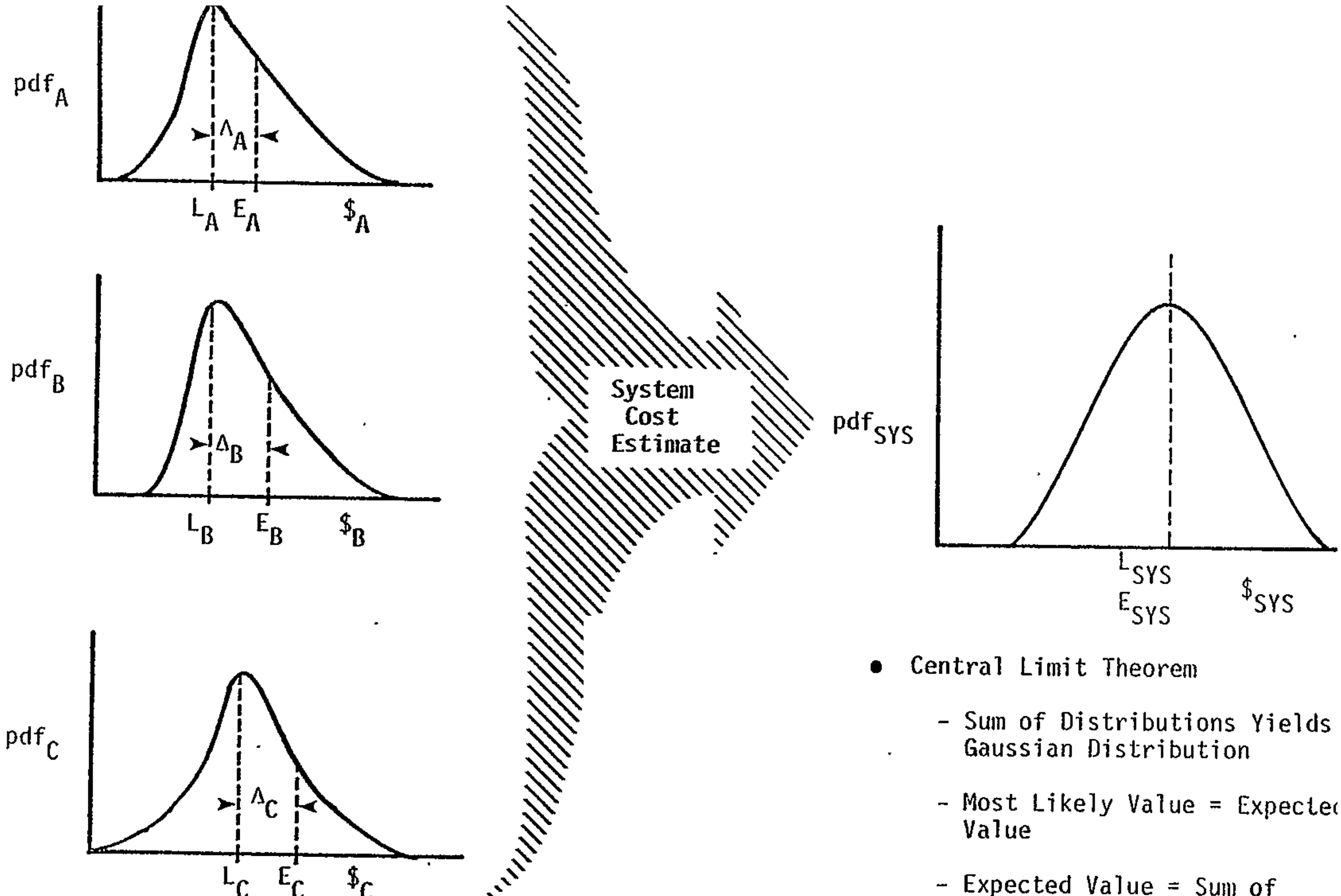
*For good reason. Few such investors exist who have nonnegative savings.



- Central Limit Theorem
  - Sum of Distributions Yields Gaussian Distribution
  - Most Likely Value = Expected Value
  - Expected Value = Sum of Expected Values of Component Distributions

Figure 3.3 Illustration that Point Cost Estimates Are Generally Low

A simple game serves to illustrate this principle. A player must pay $100 to enter the game. Then a thumbtack is flipped 20 times. If it lands point up 15 or more times, the player wins and his prize is $250 ($150 net). Otherwise the player loses. The key to the value of the game is, of course, the probability of the thumbtack landing point up on any particular toss, R. Unlike a fair coin, however, one can only guess about the value of R. But rather than to guess only a single number for R, the player is wise to describe his state-of-knowledge about R, $P_R(R)$. For example, see Figure 3.4 which is one individual's guess at $P_R(R)$. Independent of the state-of-knowledge about R, it is possible to assess the chance of winning the game, $P_W(R)$, as a function of R.* This is shown in Figure 3.5. Then, it is straightforward to compute the players expectation of winning the game,

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

and from this computing the expected value of the game.

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

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

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

The thumbtack flip game presented above can be illustrated in terms of a decision tree as shown in Figure 3.6. The decision is

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

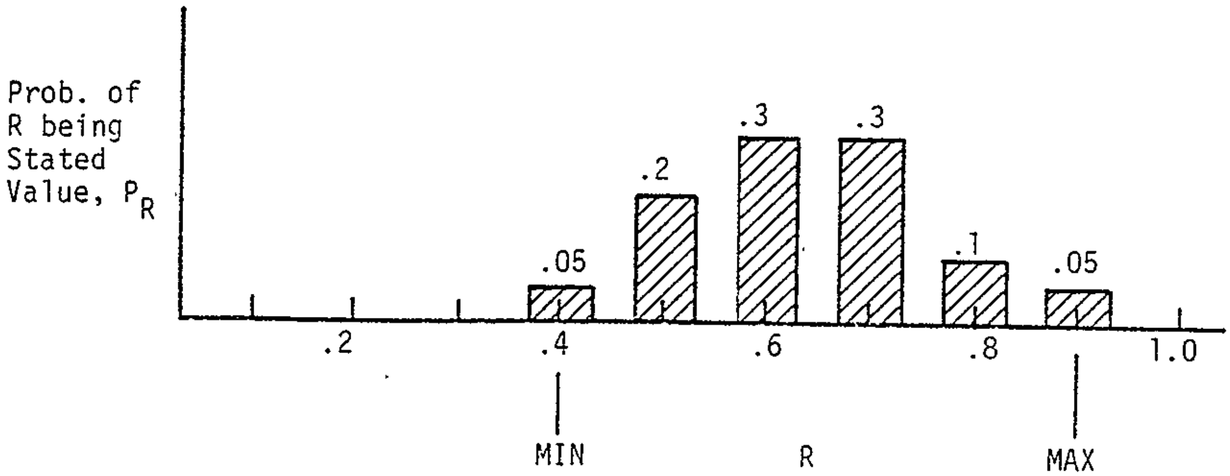
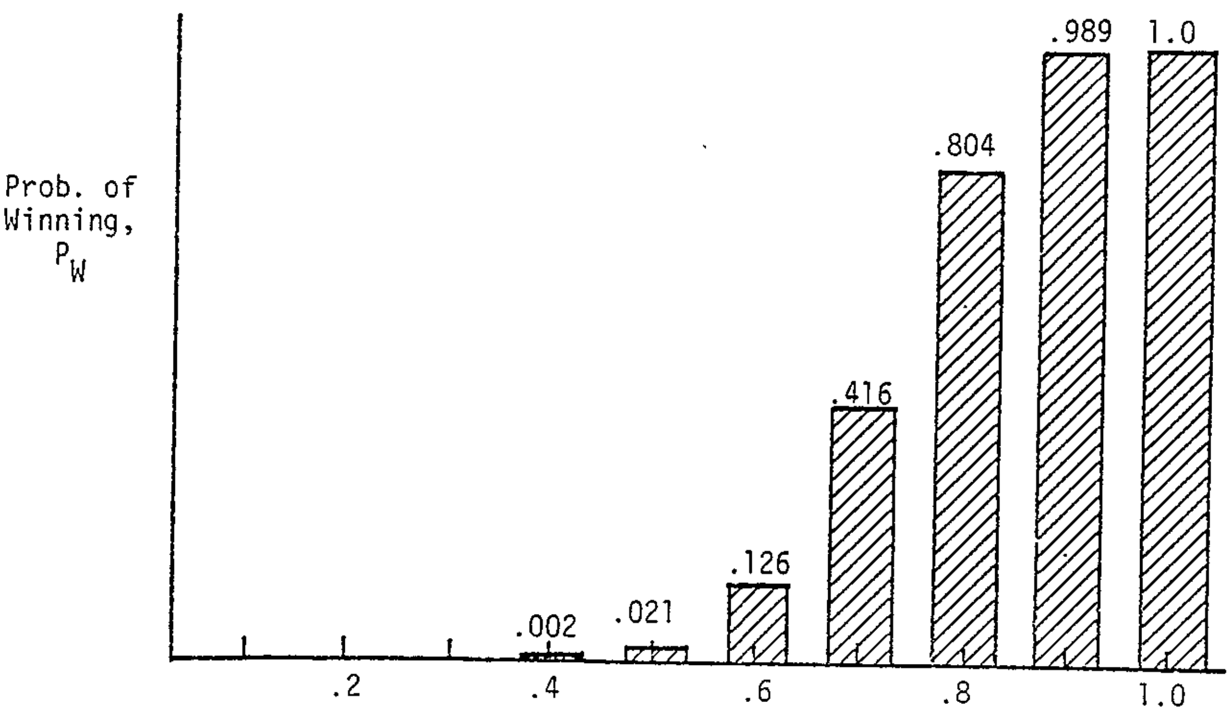


Figure 3.4 The State-of-Knowledge on R



Fi... 3.5 The Chance of Winning as a Function of R

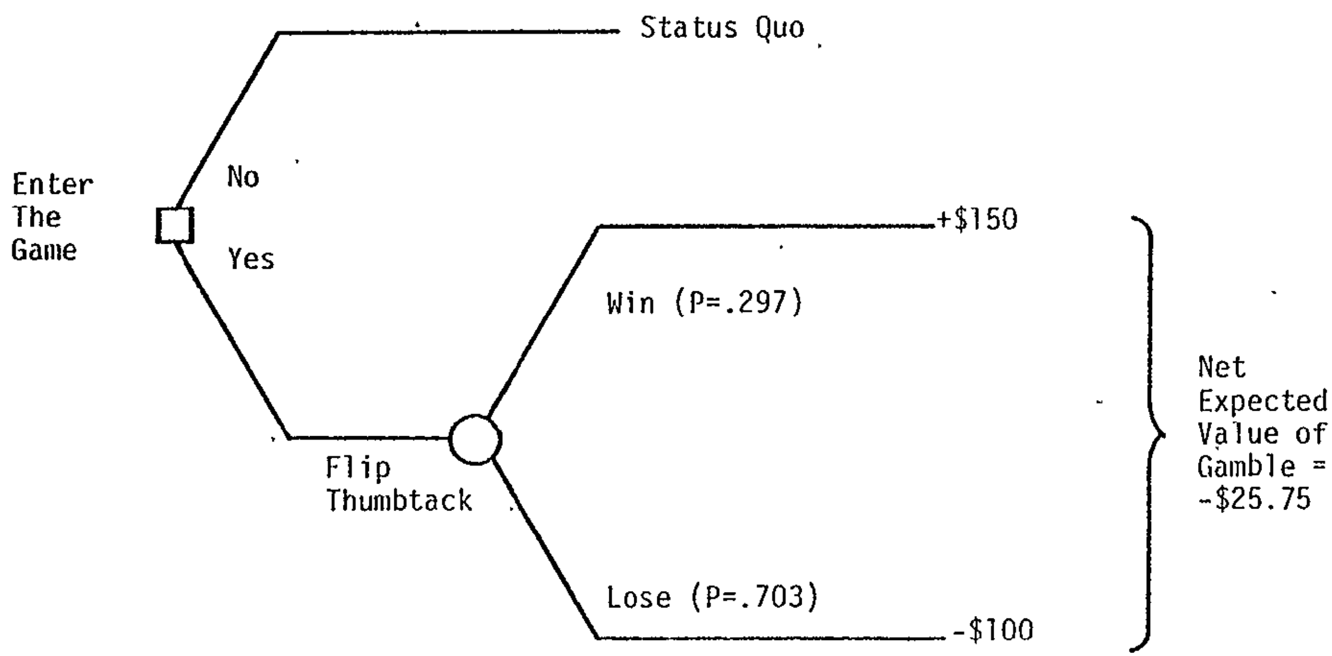


Figure 3.6 A Decision Tree Illustration of the Thumbtack Flip Game

to enter the game or not. If the answer is no, the player remains at his status quo. If the answer is yes, the player encounters a net expected loss of $25.75. Thus, it might well be expected that a prudent player would choose not to enter the game.

Can the game be changed in any way that would lead to a positive net expected payoff? Note that the key to the fact that the game has a net negative payoff is the state-of-knowledge on R, Figure 3.4. Suppose that state-of-knowledge could be improved for a small cost. For example, suppose the player could "rent" the thumbtack for $10, flip it a large number of times and, thus, determine the value of R precisely. Now the decision tree takes on the form shown in Figure 3.7. If the player decides to enter the game, he first commits only $10 to test the thumbtack. Then, and only then, _if_ the thumbtack passes the test, that is, if R is equal to or greater than 0.8 in the decision rule shown, the player enters the game. Because the player is able to determine R at a low cost, he is able to _control_ his risk and thus establish a positive net expected payoff for the game.

The game of technology application and the role of economic studies in this game is very similar to the thumbtack flip game. It is very much a game of information in which the objective is to establish a technology application program plan that controls risk and provides a positive net expected payoff. This is accomplished by a sequence of studies, analyses and tests that provide information necessary to move forward through the program. And like the thumbtack flip game, the ultimate mechanism for controlling risk is the option to exit (or not enter the game. In a technology implementation program, it is the option to recognize that the program has failed and to terminate it. _If a program plan that has a positive net expected payoff cannot be developed, it is a clear indication that the technology is not sufficiently developed to undertake an implementation program and the only thing that can be justified is a low level program of basic research._ Risk analysis provides the mechanism for evaluating the probabilities necessary to _establish_ and _evaluate_ alternative program plans.

3.2 General Procedure

A risk analysis to evaluate the state-of-knowledge relative to space-based solar power systems (SSPS) needs to address the unit production and the operation and maintenance cost risks for SSPS units subsequent to the first unit.* The procedure for doing this is to first develop a deterministic cost model and then to incorporate this cost model in a Monte Carlo simulation computer program as shown in Figure 3.8. The data, consisting of system component costs, efficiencies, masses,

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

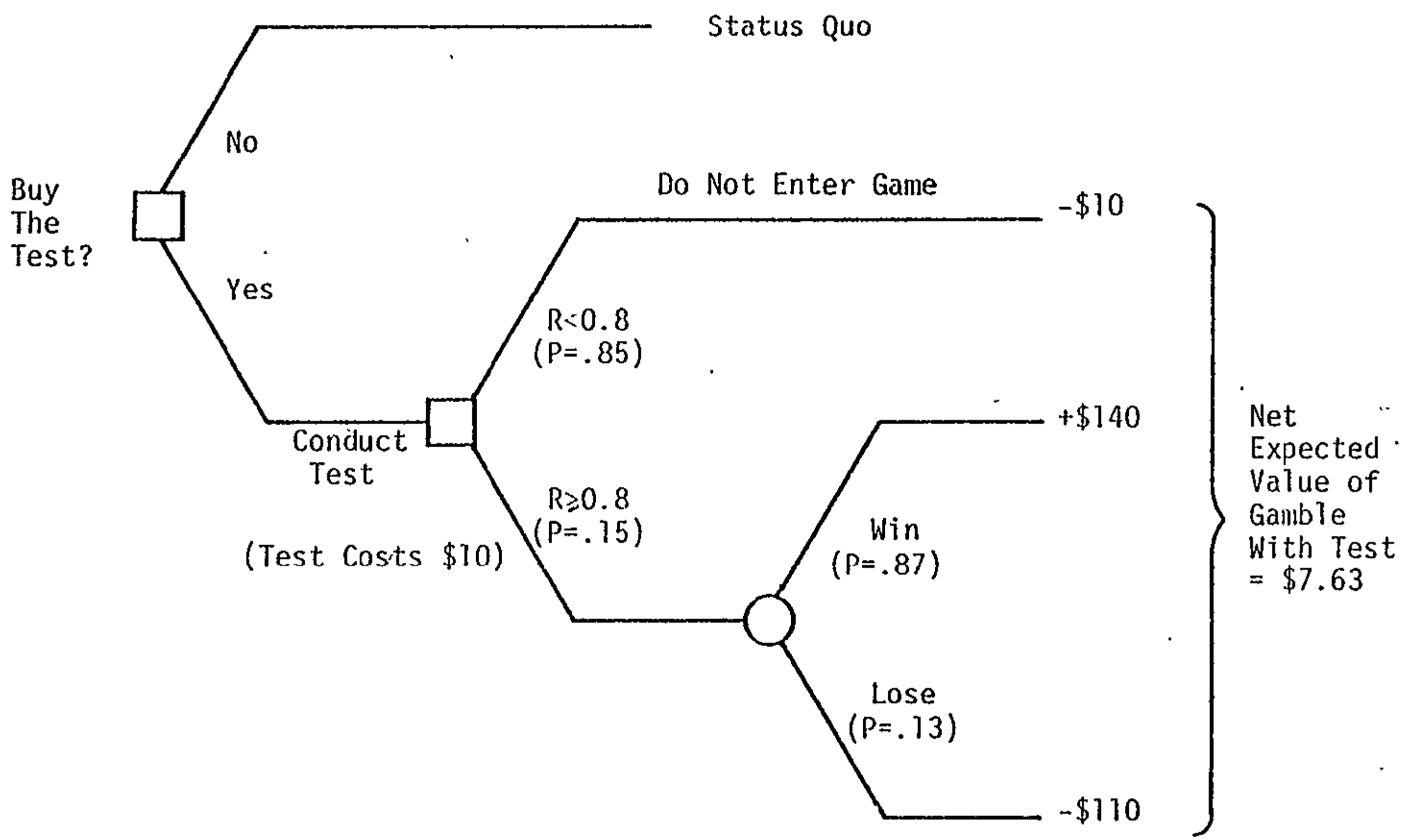


Figure 3.7 Decision Tree for the Thumbtack Flip Game with a Test

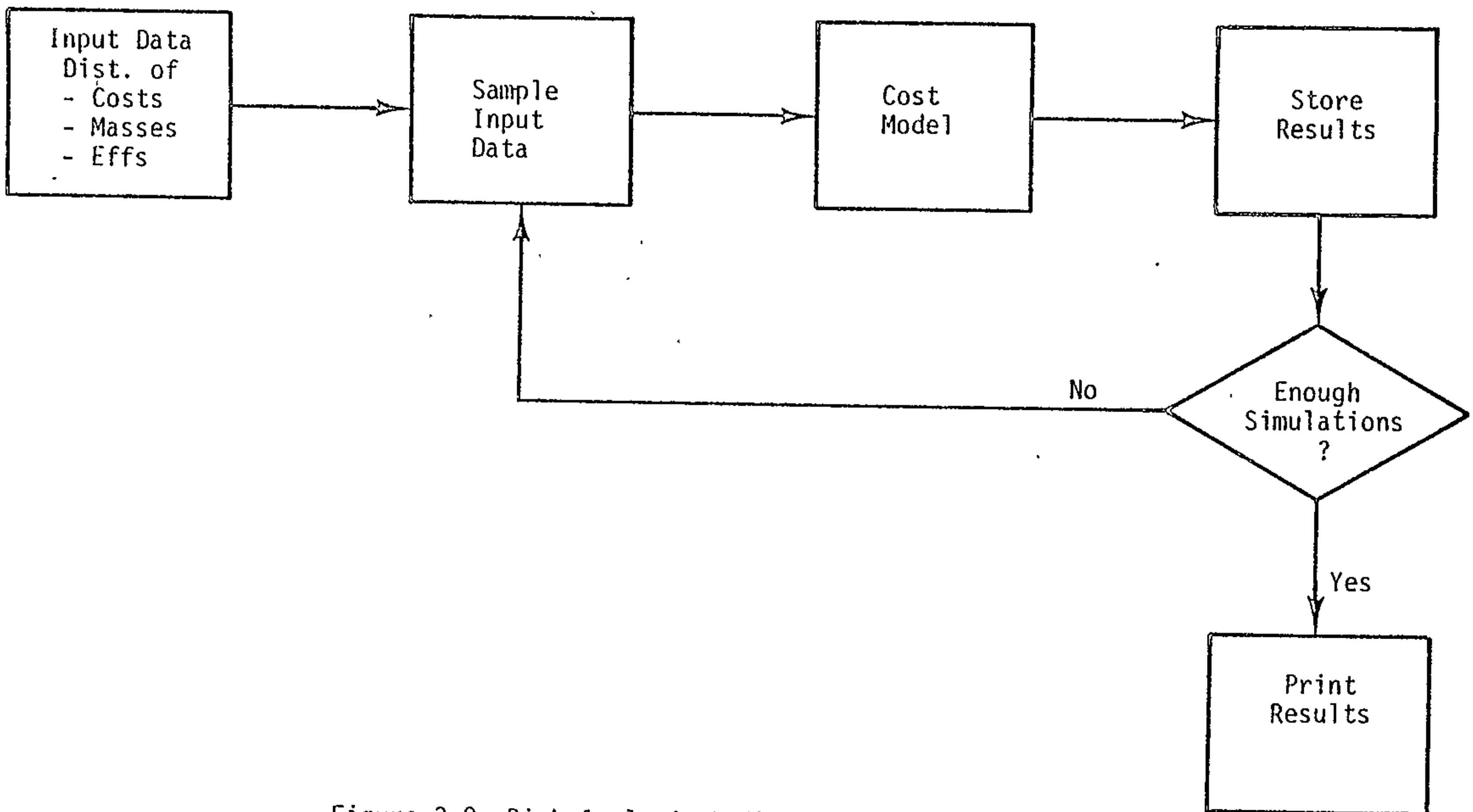


Figure 3.8 Risk Analysis Methodology for Unit Production and Operation and Maintenance Costs

reliabilities, etc., are input as probability distributions--states-of-knowledge. These variables are then sampled by the use of a sequence of random numbers. The sampled inputs are entered as deterministic numbers into the cost model and the results stored in a table. The process is then repeated several times (perhaps 250 to 1000 times) and the stored results thus generated are used to produce statistics and probability distributions that describe the risk associated with a specific alternative. In rare cases, with sufficiently simple problems, it is possible to perform a risk analysis without resorting to computer simulation techniques. The case of SSPS is far from this simple.

3.2.1 Cost Modeling

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

The cost models developed for the risk analysis of SSPS are described in Section 4 and Appendices B and C of this volume.

3.2.2 Uncertainties

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

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

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

3.2.3 Effect of Reliability

The effect of reliability in various operations and components is to introduce risk into a system even if all costs, masses, efficiences, etc., are known precisely. The fact that there is a chance for failures to occur implies that there is a chance that costs will be incurred to remedy the failure. Since failures cannot generally be predicted (precisely), there exists an inherent variability in the cost of constructing or maintaining any system in which failures can occur.

The maintenance of an SSPS requires dealing with failures. To the extent that such failures can influence operation and maintenance costs, there is variability in these costs that must be accounted for in the risk analysis. While failures of various sorts, for example, launch vehicle failures, can occur in the production phase of an SSPS unit these have been neglected in the risk model described herein. The cost and risks associated with component failures in the operation and maintenance of an SSPS unit are included in the operation and maintenance cost-risk model. The procedure for their computation is described in Section 4.3.

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

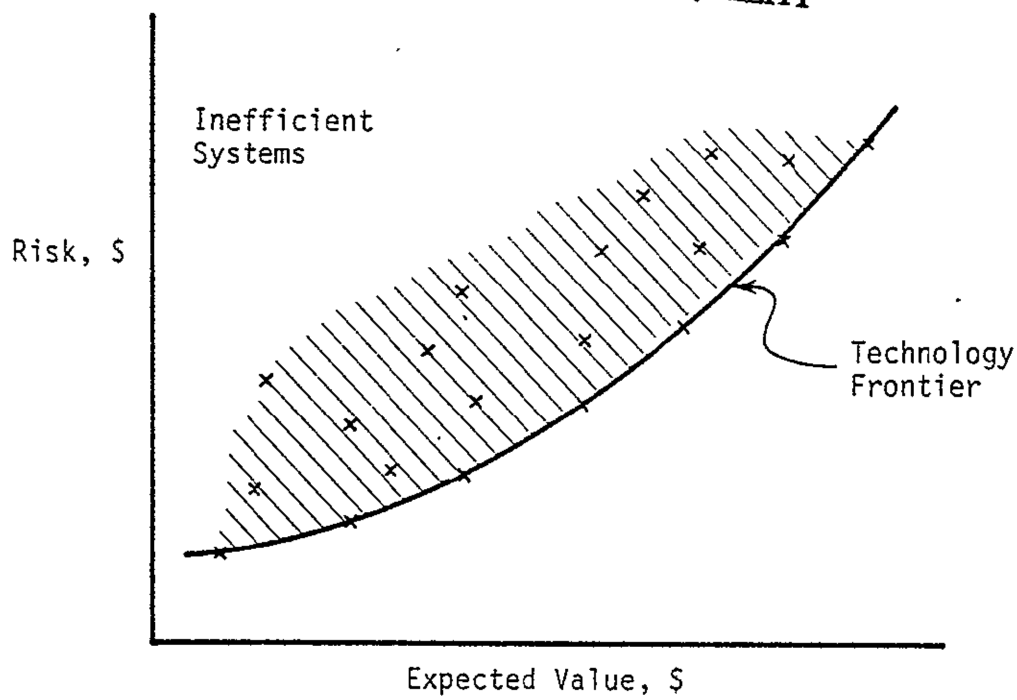

Figure 3.9 Development of the Technology Frontier

3.3 Comparison of Alternatives

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

The risk profile of many alternatives approaches a normal or Gaussian distribution* to a sufficient extent that is suffices to describe these alternatives in terms of their expected value and risk (standard deviation). Now, consider the range of alternatives contained within the set of systems labeled SSPS, expressed in terms of their expected value and risk (Figure 3.9). Certainly there exist many ways of implementing

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

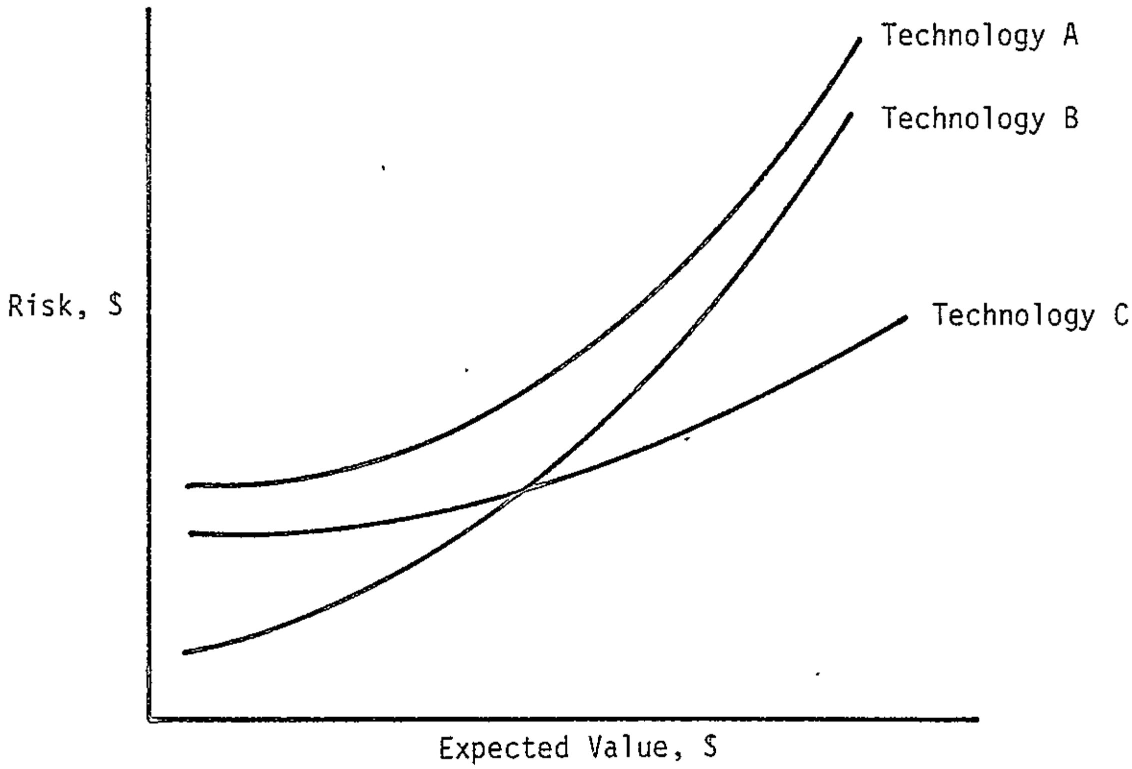

Figure 3.10 Comparison of Technology Alternatives

a technology to produce an SSPS. Each way results in a unique expected value and risk as shown by the points plotted in Figure 3.9. It should be the objective of the program manager to determine the "best" technology implementations. These are those implementations which simultaneously maximize the expected value and minimize the risk. Given any technology base to work from, there is a limit to the extent to which these mutually competitive goals can be simultaneously met. This limit is known as the technology frontier and it represents the focus of best achievable combinations of expected value and risk commensurate with the specified technology base. The selection of the "best" alternative from the technology frontier requires a statement of the decision maker's risk preferences. It cannot be made by economic principles alone.

Thus, in terms of the selection of alternatives within a program, the purpose of a risk analysis is to define the technology frontier. The selection of alternatives between competing programs is accomplished by comparing the technology frontiers (Figure 3.10). As shown, Technology B might be SSPS, Technology C, terrestrial nuclear and Technology A, terrestrial fossil fuel--the curves are arbitrarily drawn here for illustrative purposes only. As shown, Technologies B and C always dominate A. Thus, A would never logically be chosen on economic grounds. On the other hand, the selection between Technologies B and C depends on the risk preferences of the decision maker. A highly risk-averse decision maker would forego the potential to obtain a high value in order to obtain reduced risk by choosing to implement Technology B in the region of expected value that produces low risk. A less risk-averse decision maker might choose Technology C, seeking the opportunity to capture a higher value.

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

3.4 The Relationship Between Engineering and Economics

It should be recognized that, while systems engineering is a vital element of a technical and economic assessment of a space power system concept, the systems that are engineered for such assessments are not the systems that might be built 20 years from now. Indeed, based upon the present state-of-knowledge, it is neither possible nor desirable to focus present engineering efforts on the detail design of a "flightworthy" system. Rather, the engineering efforts are properly addressed to the development of a more detailed technical understanding of the general concept of space power systems and to providing a basis for both the technical and economic assessment of such a concept. Two basic approaches could be taken to the engineering effort. The first would seek to examine all the potential system configurations and types with the objective of identifying their characteristics. The second approach would focus on one or a few potential configurations and examine them in depth. It might be said that, given a limited budget to perform a study, the first approach succeeds in determining essentially nothing about everything while the second approach provides a good understanding of (probably) the wrong thing. Ultimately, some combination of both approaches must be taken. However, this study took the second approach. The reason is that one purpose of this study is to provide an economic assessment of the space power system concept and, in order to do this, it is necessary to study each assessed concept in some detail. As a result, this study does not cover the range of ideas and configurations that may have been dealt with, but it does provide economic analysis results that would have been impossible to provide if the first approach had been taken.

It is important here to make one other point as well. The purpose of this economic analysis is to provide information to a decision making process. Relevant to a space power system, however, it is not necessary, nor is it desirable, to decide upon the developing of a particular system configuration at this time. Rather, it is only necessary to decide upon the funding of a supporting research and technology (SR&T) program that will improve upon the present state-of-knowledge in various critical technology areas so that, in the future, a decision can be made either to proceed with the development of a particular space power system configuration or, if at that time the concept proves not to be economically (or otherwise) viable, to terminate the program. Thus, if the system configuration studied in depth justifies proceeding with an SR&T program, it has appropriately served its purpose and there is no need, for the purpose of economic justification, to seek better configurations. The only remaining issue is one of identifying the critical technology items that should be addressed in the SR&T program. But, to a substantial extent, these are independent of the system configuration and, thus, useful insights are gained as the result of an in-depth study on one configuration as conducted herein.

Now, if it is accepted that the purpose of the engineering work performed in this study is in support of a technical and economic evaluation of space power, then the objective of that work should be to provide optimal designs against economic criteria. This does not mean that the system should be designed to minimize cost. Rather, both cost and cost-risk should be taken into account. This principle is illustrated by the following example. Suppose, for the photovoltaic configuration SSPS studied, it is desired to find the optimal concentration ratio and, for this example, assume that the only area of cost uncertainty is the cost per unit area of the solar array blanket. Then, as shown in Figure 3.11, the (expected value of) cost would be minimized by proper choice of the concentration ratio, C_R*. However, going to higher concentration ratios continues to decrease cost-risk since increasing concentration ratio reduces the solar array blanket area. Thus, looking at a plot of cost-risk versus cost for varying concentration ratios indicates clearly that it would be undesirable to design the system to minimum cost since, by moving to slightly higher concentration ratios, it is possible to significantly reduce the cost-risk with only an infinitesimal increase in cost. The space power system risk analysis model developed as a result of this study is an existing tool for use in the analysis of engineering tradeoffs of this sort.

At this point in time, the best configuration is that one which provides the strongest justification for a development program.

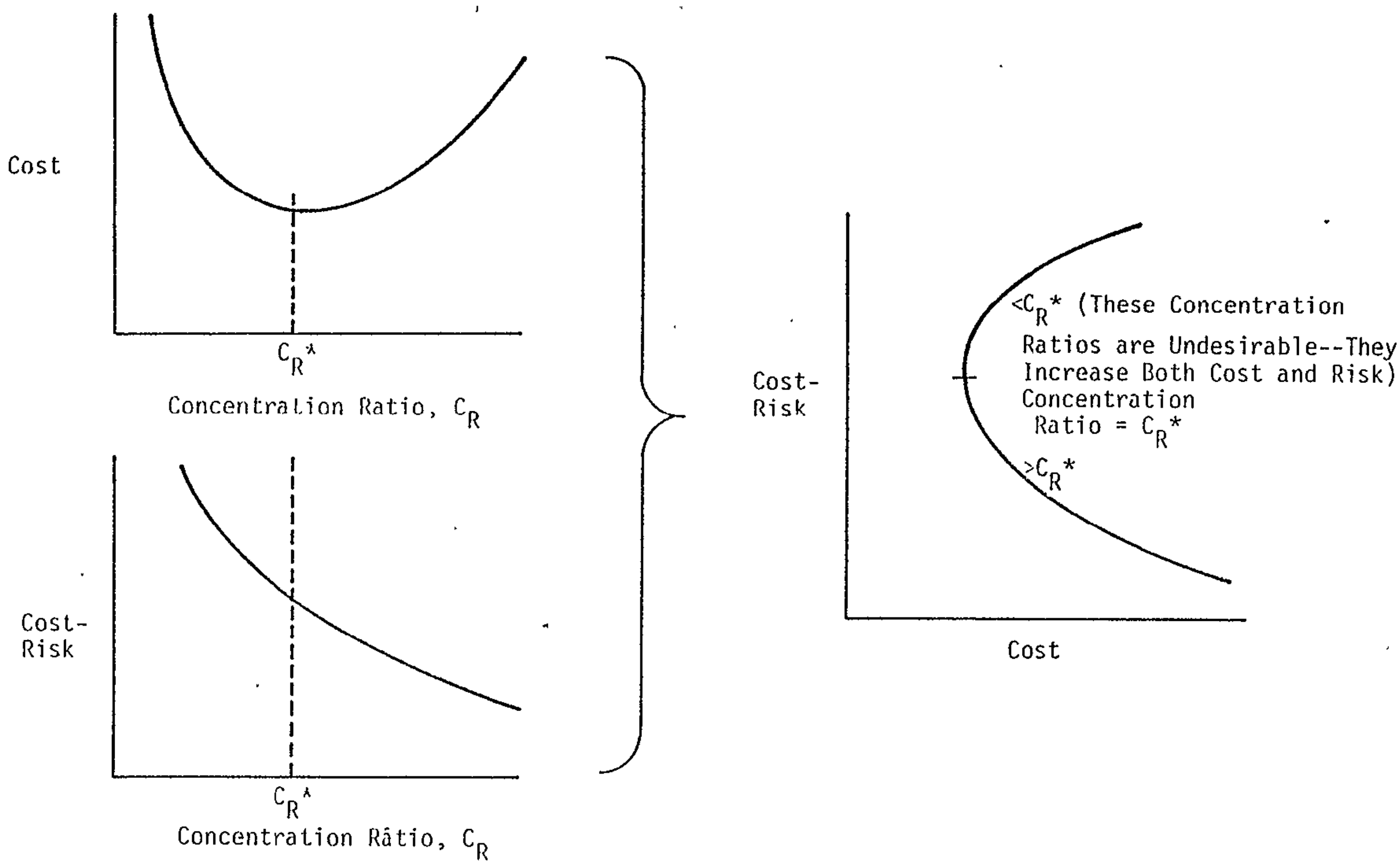

Figure 3.11: A Typical Cost Versus Risk Tradeoff

4. COST MODELING OF SPACE-BASED SOLAR POWER SYSTEMS

The SSPS program is divided into three major cost categories: development, unit production, and operation and maintenance, as shown in Figure 4.1. The development includes all activities that occur through initial operation of the first full-scale unit, and the unit production cost model includes all recurring costs for producing the "nth" (typically second) SSPS unit--satellite and ground equipment. The reason for this division of costs is the variety of methods by which the first unit could be built, for example, by growth from a 500 MW pilot satellite, whereby the costs of the first unit would not relate in any direct way to the costs of, say, the second unit.

Although all cost components of an SSPS program are dealt with, the emphasis in this study has been on the development of recurring cost models (both unit production and operation and maintenance) for an SSPS unit to serve as the basis for a risk analysis model. Descriptions of, first, the development costs (Section 4.1), and then of the unit production cost and the operation and maintenance cost models follow (Sections 4.2 and 4.3, respectively).

4.1 Development Program Costs

The estimates of development program costs were developed by Grumman Aerospace Corp. and the Raytheon Company. The costs are connected with specific programs whose rationales were established by Grumman. Development costs are not modeled functionally as are the recurring (unit production, O&M) costs, and they are described only briefly here, being dealt with in more detail in Volume II.

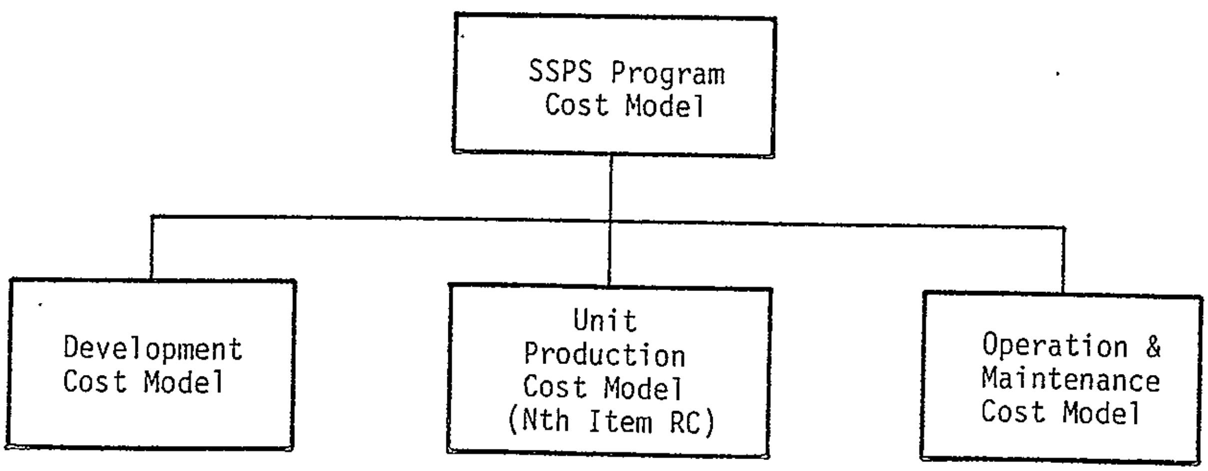

Figure 4.1 SSPS Program Cost Model

A number of different development programs have been formulated and analyzed as a part of this study. These are discussed in detail in Section 7 of this volume and Volume II of this report. During the first study phase, a development program including a 15 MW LEO and a 1,000 MW GEO test satellite was costed. In the second study phase, two additional programs were examined, one with no major test satellites and one making use of a 500 MW GEO test satellite. In the third study phase, two new development programs were formulated and analyzed. Both of these programs made use of a 150 kW and a 2 MW test satellite but with different test objectives. The discussion below pertains mainly to the development programs formulated for the third study phase. The actual cost numbers for all of the development programs are given in Section 7 of this volume.

4.1.1 Supporting Research and Technology Program Costs

The three major areas of the supporting technology program include solar energy conversion technology, microwave transmission system technology, and large structure fabrication. Physical characteristics of the solar array blanket, such as solar cell conversion efficiency, specific mass, and thermal and radiation resistance, will be addressed as well as techniques for economic large-scale production. Microwave transmission technology development will be directed at the efficiencies of dc to rf conversion and phase front control as well as to the fabrication and assembly of waveguides and antenna and power transfer structures. Further, studies of the effect of microwave transmission on the ionosphere will be conducted using the Areceibo antenna. Finally, different structural materials will be examined consistent with the thermal environment, applied loads, and the requirements for on-orbit manufacturing and assembly. Also examined will be the equipment required for such space-based operations.

4.1.2 150 kW Test Satellite Program Costs

This test satellite is primarily intended to test solar array technology, involving the deployment of a large array by Shuttle sortie. Different deployment techniques may be tested. This test satellite may be used to test portions of the microwave transmission systems if it is transported to geosynchronous orbit.

The costs include design, procurement and assembly, and operation of the test satellite.

4.1.3 Geosynchronous Orbit Test Satellite Program Cost

Although this geosynchronous orbit test satellite is smaller (2 MW power output level) than those examined in previous study phases, it is large enough to allow testing of the performance of major system elements as well as microwave transmissiom from geosynchronous altitude.

The costs include design, procurement and assembly, and operation of the geosynchronous test satellite.

4.1.4 DDT&E Costs

The costs connected with the design, development, testing and evaluation underlying the construction of the first full-scale prototype have been separated from the actual costs of procuring the first unit. This separation allows for an intermediate determination of the state-of-knowledge and likely economic viability of the system, before committing to the procurement of the first unit.

4.1.5 First Unit Production Costs

The costs of procuring and assembling the first unit are dealt with independently from the costs of producing subsequent units, as the first unit may be constructed in a manner entirely different (for instance, by expanding a test satellite, or by using space stations instead of the projected factory-in-space from that used for subsequent "production run" satellites). Furthermore, there exists the possibility that production could be terminated after the first full-scale unit.

4.2 Unit Production Cost Model

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

The central feature of an SSPS performance evaluation is a chain of power conversion and transmission efficiencies. This efficiency chain forms the backbone of the unit production cost model as seen in Figure 4.2, which shows the correspondence of system components to elements in the SSPS efficiency chain.

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

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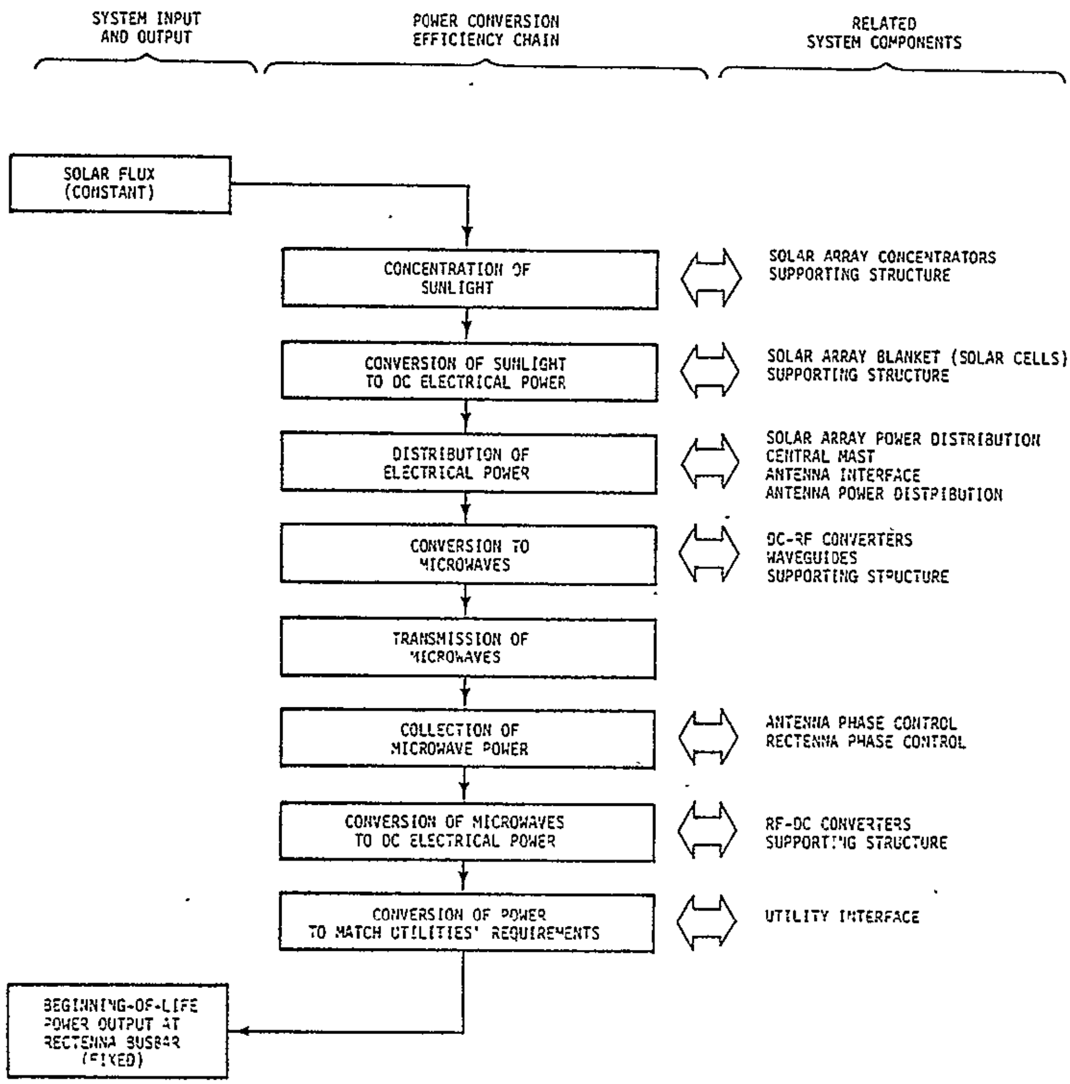

Figure 4.2 Relationship of SSPS Components to the System Efficiency Chain

The unit production cost model has five Level 3 components, as shown in Figure 4.3: ground station, LEO (low earth orbit) launch, construction base, LEO-GEO (geosynchronous earth orbit) transportation, and satellite procurement. Each of these cost components is dealt with in detail below; an overview of the model's structure is provided in Figure 4.4. The model has been kept as general as possible, that is, insofar as possible, design and performance parameters have been treated as variables. Certain assumptions, however, are implicit in the model. Wherever such limitations occur in the model, they have been called out in the discussion that follows. In future developments of the model, greater generality will be developed, allowing examination of the effects of a wider range of design tradeoffs.

4.2.1 Ground Station Cost Model

This cost model consists of the cost of land and site preparation for both the receiving antenna structure and a safety zone around the receiving antenna, rf-dc converters, phase control equipment and utility interface. The size of the rectenna was set in the Raytheon MPTS study [13], based upon 20 mW/cm^2 being an acceptable maximum power density level and 2.45 GHz being the optimum frequency for transmission and is then scaled by the elevation angle of the beam. The model does not allow tradeoffs* among receiving antenna area, cost, and power density; costs are determined on the basis of power level.

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

4.2.2 LEO Launch Cost Model

This model includes the cost of procuring and operating fleets of heavy lift launch vehicles (HLLVs) and Space Shuttles to launch to LEO the materials and personnel necessary for the construction placement and final check-out of an SSPS satellite. The HLLVs are used to launch equipment and supplies and the Shuttles are used to rotate on-orbit personnel. The upper and lower stages of the HLLV are dealt with separately in the model, as they have different expected design lives. The model allows consideration of payload masses, load factor, unit costs, launch operations costs per flight and vehicle design life. The costs for both vehicles are determined on a "per launch" basis by dividing the unit cost over the expected life of the vehicle and adding the launch operations and refurbishment costs per flight. The number of HLLV flights is calculated by dividing the total mass of the satellite and required assembly equipment by the payload of the HLLV and its load factor. Similarly, the number of shuttle flights is determined by the number of personnel needed on orbit, the number of personnel carried per shuttle flight and the rate of personnel rotation.

One limitation of the model in its present form is that it does not consider such operations factors as vehicle refurbishment (turnaround) time.

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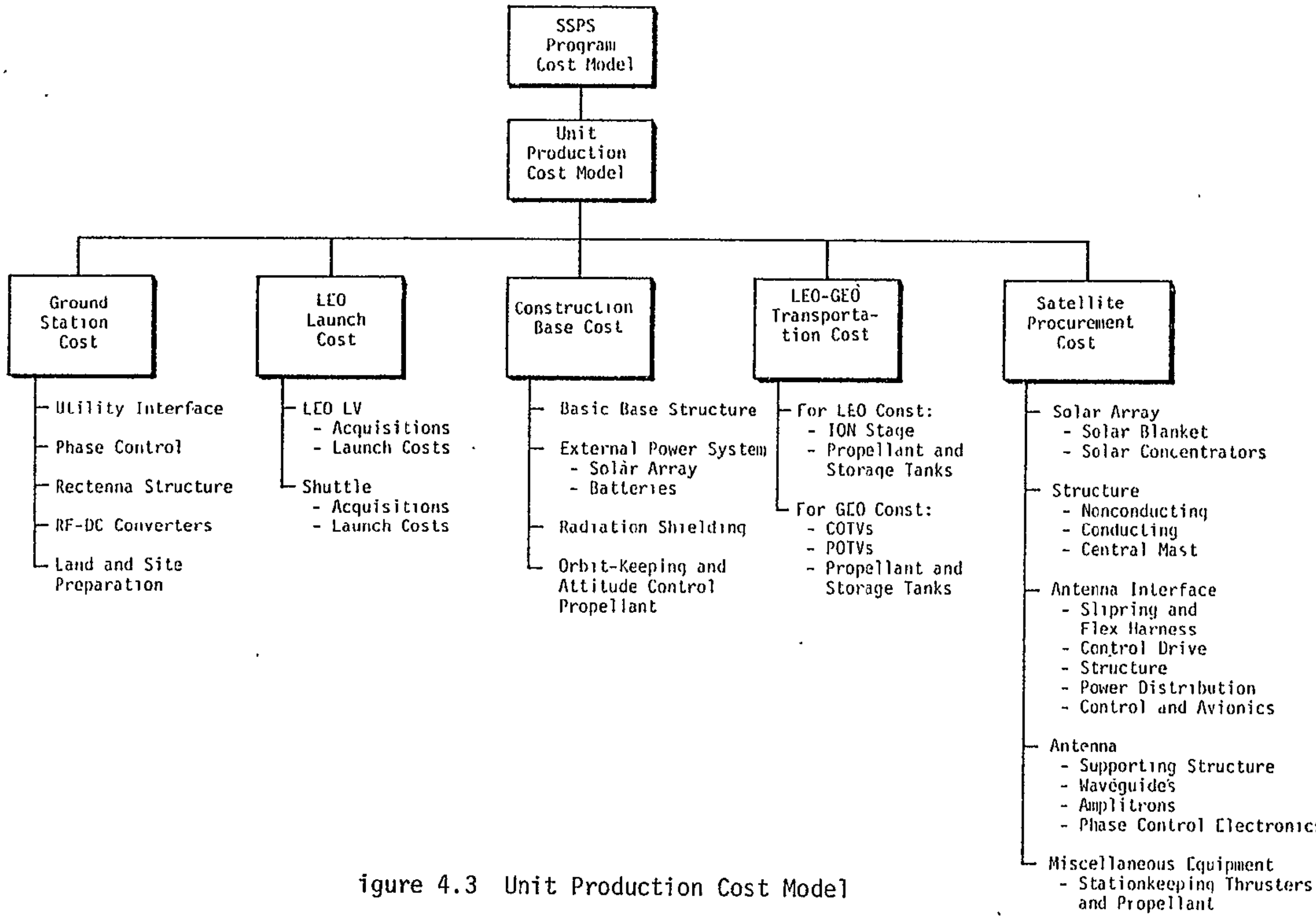
*These tradeoffs were analyzed by appropriate cost and design inputs to the model and the results are set forth in Section 5.4.



igure 4.3 Unit Production Cost Model

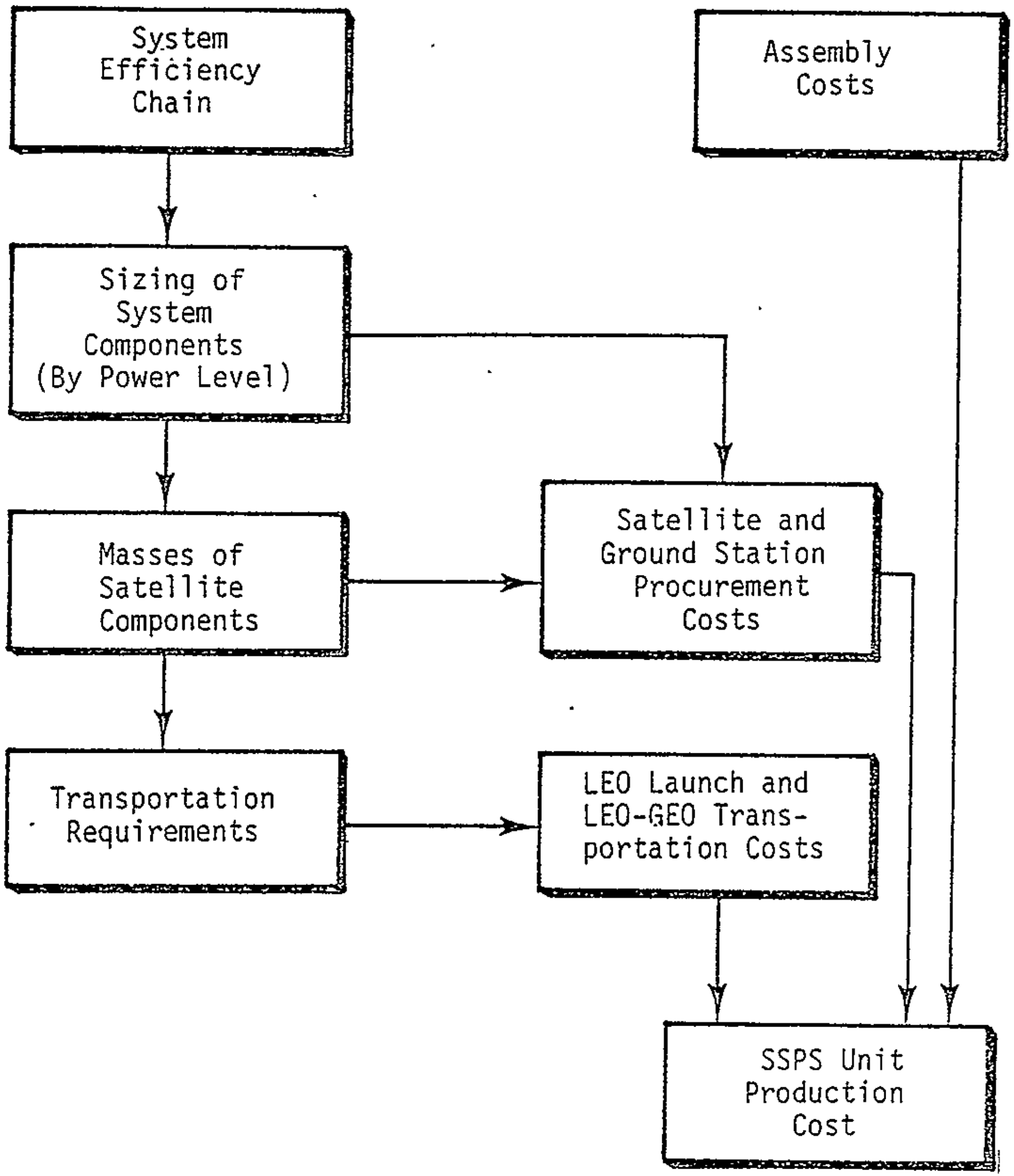


Figure 4.4 General Logic Flow of the SSPS Unit Production Cost Model

Such scheduling factors will have to be considered as the model is refined because the rate of launch may be expected to be nonuniform for the construction of a single SSPS satellite, although the overall launch facility activity level could be expected to become more uniform (allowing more efficient use of resources) as more SSPS satellites are constructed simultaneously given proper planning to accomplish this. In addition to more detailed consideration of launch operations, explicit consideration of launch vehicle reliability should be included in future model development.

4.2.3 Factory-in-Space Cost Model

This model represents the costs of a factory-in-space, the preliminary design of which was developed by Grumman Aerospace in the final phase of this study. A single base is intended to construct the entire fleet of satellites.

In order to examine the cost differences of construction in LEO and GEO, the costs and masses of characteristics of the base which were principally affected by orbital location (orbit-keeping and attitude control propellant requirements, external power system (EPS) requirements, and radiation shielding) were included as separate variables in addition to the basic mass and cost of the base. Analysis of two different factory sizes (reflecting two different rates of construction), as well as the two orbital assembly sizes, was conducted by appropriate design and cost inputs.

The costs of the factory-in-space are attributed uniformly to each satellite built; that is, they are calculated on a "per satellite built" basis, where the total number of satellites built is a variable.

The major limitation of the factory-in-space cost model is the lack of detail possible because of the preliminary state of development of the design itself. Whereas it is possible to examine the relative cost-effectiveness of construction in LEO versus GEO for two specific base configurations, it is not possible to examine the configurations themselves to determine the most important cost- and risk-driving elements to help guide further studies.

4.2.4 LEO-GEO Transportation Cost Model

Two different LEO-GEO transportation scenarios are possible with this model. One reflects the costs of transporting a fully assembled satellite from LEO using an advanced ion stage. This scenario is used when analyzing LEO construction and includes the costs of the ion stage and its propellants, along with propellant storage tanks.

The other scenario reflects the costs of transporting the materials necessary for construction of the satellites to GEO using chemical cargo orbit transfer vehicles (COTV) and for using chemical personnel orbit transfer vehicles (POTV) for personnel (to and from the construction base). This scenario is used when analyzing GEO construction and includes the costs of the COTVs and POTVs (taking into account the design lives of each), the propellant necessary for the required number of trips (depending upon total satellite mass, crew size and crew rotation rate), and propellant storage tanks.

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

4.2.5 Satellite Procurement Cost Model

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

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

4.3 Operation and Maintenance Cost Model

The second element of SSPS unit recurring costs which was modeled in this study phase was the cost of operation and maintenance (O&M). The model contains four Level 3 components, as shown in Figure 4.5: launch facility O&M, ground station O&M, space station and support O&M and satellite O&M; these are developed separately below.

4.3.1 Launch Facility O&M Cost Model

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

4.3.2 Ground Station O&M Cost Model

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

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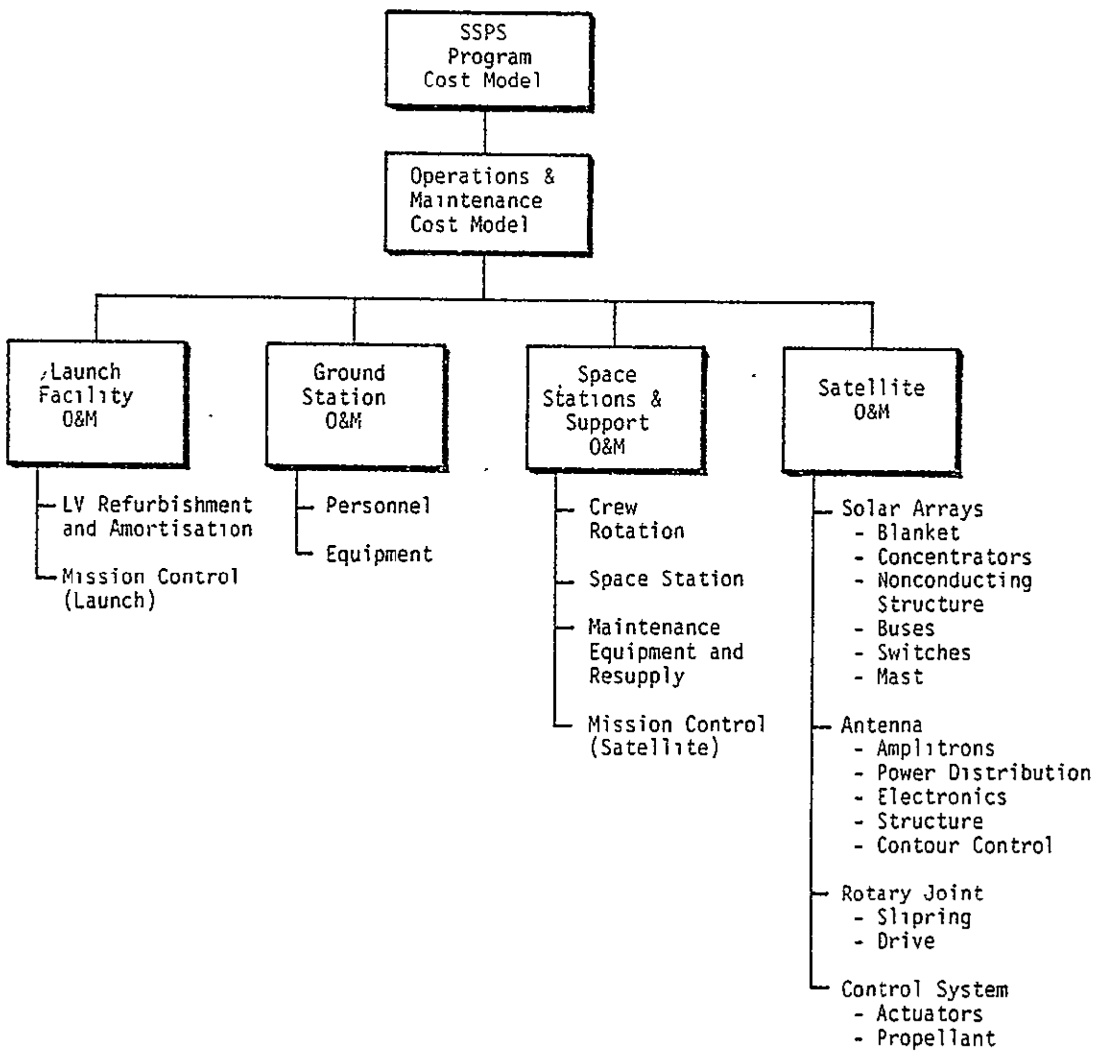

Figure 4.5 Operation and Maintenance Cost Model

4.3.3 Space Station and Support O&M Cost Model

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

4.3.4 Satellite O&M Cost Model

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

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

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

The failure rates of smallest replaceable components are sampled in a Monte Carlo simulation to calculate a probability distribution for annual O&M costs. The rate of replacements of units of a given satellite component is a random variable that depends on the mean time between failures for that component. That is to say, the nature of failures is such as to produce uncertainty in the annual O&M cost despite potentially perfect knowledge of all costs. In the Monte Carlo simulation, the rate of replacement is obtained as a probability distribution over integer numbers of replaced units. The computer algorithm for computing the distribution of component replacements is shown in Figure 4.6. Each component is interrogated to determine if it fails during the period of consideration. If it does, it is replaced and the replacement part is interrogated to determine if it fails in the remaining time. The process is continued until the time period considered ends. Then, replaced units and replacement costs are accounted for.

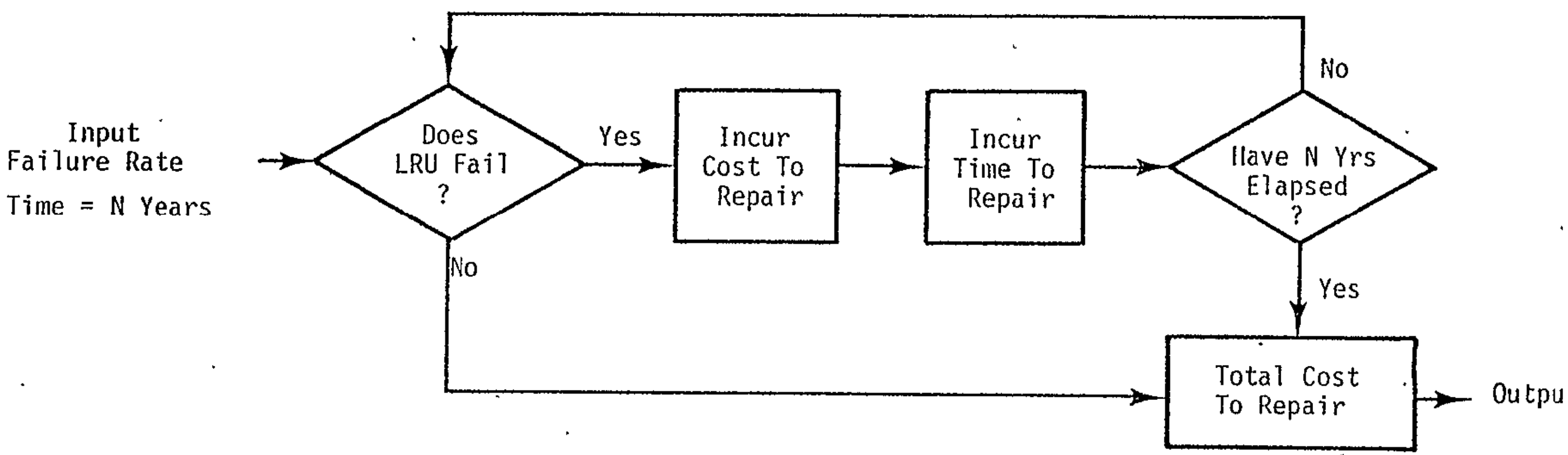

Figure 4.6 Computer Algorithm for Computing Cost of Replacing Failed Components

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

5.1 Current State-of-Knowledge

The cost and risk analysis discussed in this section is based upon the current configuration SSPS, illustrated in Figure 5.1, which is sized to generate 5375 MW* of rectified power at the output bus of the receiving antenna at the beginning of life of the system. This power level was chosen to provide economies of scale while keeping the peak microwave power density in the center of the rectenna to about 20 mW/cm^2, a level that is expected to meet anticipated environmental standards. The 20 mW/cm^2 value approaches the anticipated threshold level for affecting changes in the ionosphere. It is noted, however, that the effects of these anticipated changes are unknown.

The satellite's mass in orbit is deterministically estimated to be 27.2 million kg, using the most likely values described below. An operating frequency of 2.45 GHz was selected based on considerations of power transmission efficiency, low susceptability to brownouts in rain, and minimal potential problems with radio frequency interference. The transmitting antenna is an active planar phased array which uses amplitrons for dc-to-rf power conversion. The photovoltaic power source nominally generates 9267 MW of power using an advanced 50-micron thick silicon blanket that has an initial nominal efficiency of 9.2 percent at a solar concentration ratio of two. The overall efficiency from solar blanket busbar to ground station busbar is nominally estimated to be 58 percent.

The nominal design concept has two large solar cell arrays, each approximately 8.4 km x 5 km, interconnected by a carry-through structure of dielectric material. A 1.026 km diameter microwave antenna is located on the centerline between the two arrays and is supported by the central power

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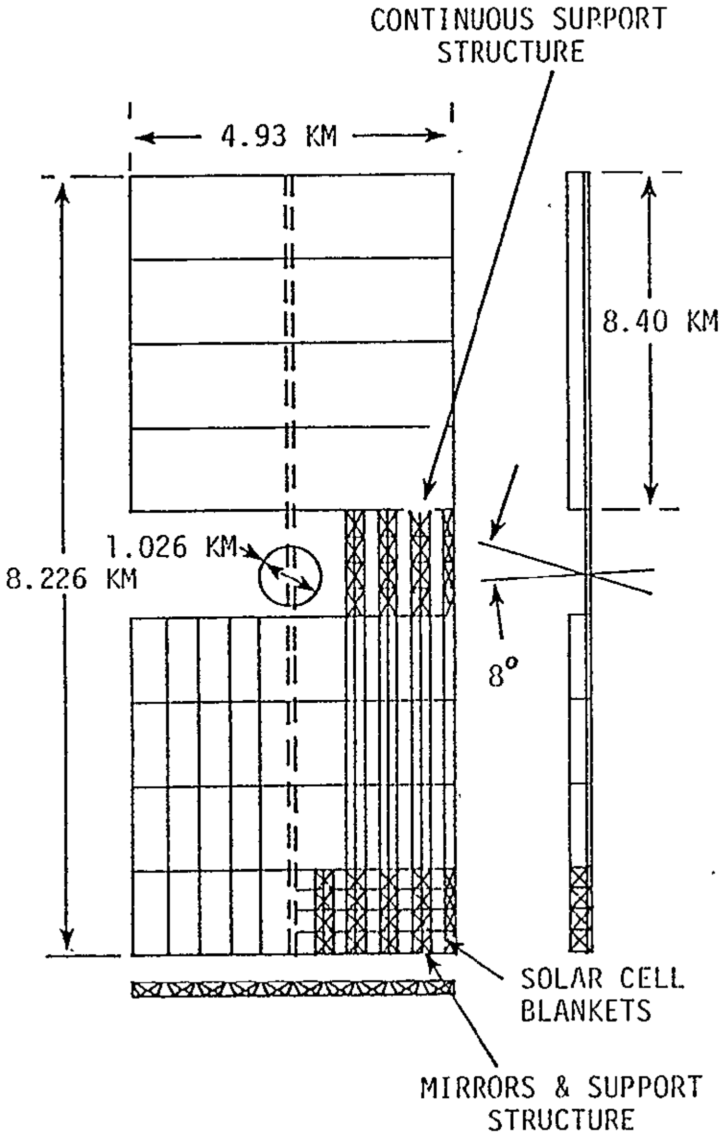
*The 5000 MW power level commonly used in earlier phases of this study refers to the power output at the beginning of the sixth year of operation, although the satellite was designed to handle the higher beginning-of-life power level. (Degradation in the power level occurs throughout the life of the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



- Concept Description

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

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

- Power	5375 MW (BOL)
- Mass	27.2×10^6 kg
- Size	18.226 x 4.13 km
- Orbit	Geosynchronous
- Life	30 Years
- Operating Frequency	2.45 GHz
- dc-to-dc Efficiency	58%
- Solar Cell Efficiency	9.2% (BOL)
- Solar Cell Material	Single Crystal Silicon
- Initial Operation Date	1995 (prototype)

Figure 5.1 Current Configuration of an SSPS Satellite

transmission bus (mast) structure that extends the full length of the power station. The antenna is attached to the mast structure by a joint system which rotates 360 degrees in azimuth (east-west) and $\pm$ 8 degrees in elevation (north-south). The solar cell blankets are laid out between channel concentrators stretched over a supporting frame. In the analysis conducted here, in addition to single crystal silicon solar cells (Si), two other materials are also analyzed. These are gallium-arsenide (GaAs) and cadmium-sulfide (CdS). In all cases, a concentration ratio of 2 was used. It is recognized that this concentration ratio is not optimum for either of the last two materials; however, the conclusions thus obtained strengthen the notion that economically attractive solar cell material alternatives to Si do exist and should be given consideration.

In addition to the consideration given to different solar cell materials, four different construction methods were analyzed. All involve the factory-in-space concept developed by the Grumman Aerospace Corporation. The methods analyzed include total assembly in low earth orbit (LEO) with subsequent ion stage transportation to geosynchronous earth orbit (GEO) and total assembly in GEO and, for each assembly location, assembly using a small factory, capable of producing nominally four satellites per year; and a large factory, capable of producing nominally six satellites per year.

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

In order to represent in the SSPS program cost model (described in Section 4) the state-of-knowledge that exists for the design factors relating to SSPS, ranges were established with maximum and minimum values, and a most likely value was assigned. The rule observed in setting the maximum (worst) and minimum (best) values was that there is essentially zero probability of the outcome exceeding the assigned maximum or being less than the assigned minimum. Most likely values were estimated based on available information and engineering judgment.

It was beyond the scope of this study to develop probability density functions in the manner described in Appendix E. However, distributions were assigned as shown in Figure 5.2 that might be representative of design factors, the states-of-knowledge of which are not well developed; that is,

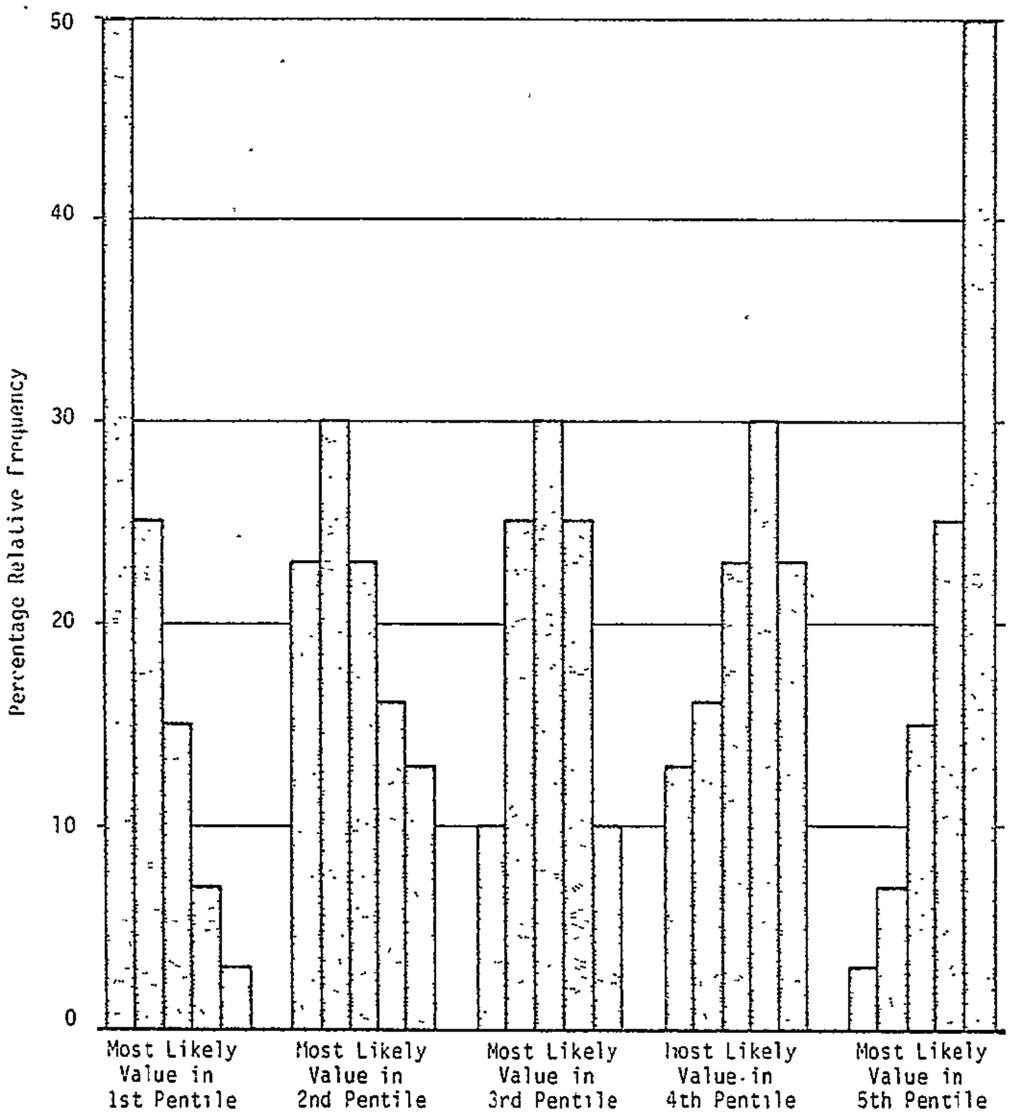


Figure 5.2 Uncertainty Profiles

the distributions are not sharply peaked, however, neither are they particularly broad. For each variable, the particular distribution was selected based on the location of the most likely value between the minimum and maximum values. It is expected that this process would be refined, for example, according to Appendix E, in future work.

The range of values and the most likely value for each design factor may be found in Appendix D. It should be noted that these data are specific to the current configuration SSPS and are intended to represent the state-of-knowledge with respect to this particular configuration at this point in time. Also shown in Appendix D are the data that were used for the analysis of cost and risk in the previous study phase. The data and results presented in this section are based on the satellite configuration and assembly techniques as they have been developed in their final (most advanced) form by this study.

Some adjustments have occurred during this phase of the study in the assignment of ranges and most likely values for a number of design factors. These adjustments have come as the result of more detailed analysis both in this study and in related studies (such as the space station studies being conducted by Grumman Aerospace Corporation). The adjustments having the greatest impact on system size and cost involve the solar array blanket: the values for specific cost, specific mass and solar cell efficiency, which had previously been treated as target values, are now viewed as the most optimistic values. Also, the efficiency of Si solar cells is taken to be 9.2 percent in this phase of the study. This is the result of the analysis conducted by A. D. Little, Inc. The lower efficiency cell corresponds to one which is more likely to be developed as a result of ERDA efforts. It does not incorporate band-pass filters to maintain a high efficiency under concentration ratios greater than one as did the previously assumed cell.

5.2 Risk Assessment of the Current Configuration

Based upon the assessment of the state-of-knowledge discussed in Section 5.1 and Appendix D, a risk assessment of the current configuration SSPS was conducted. The assessment provides probability distributions of unit production costs (2nd unit)* and operation and maintenance costs; see Figures 5.3 and 5.4. These figures show the cumulative distribution functions, referred to as risk profiles, for costs for the Si solar cell configuration SSPS assembled in LEO using a small factory. The probability value shown on the ordinate represents the probability (or confidence) that the current configuration SSPS could be produced (Figure 5.3) or operated and maintained

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

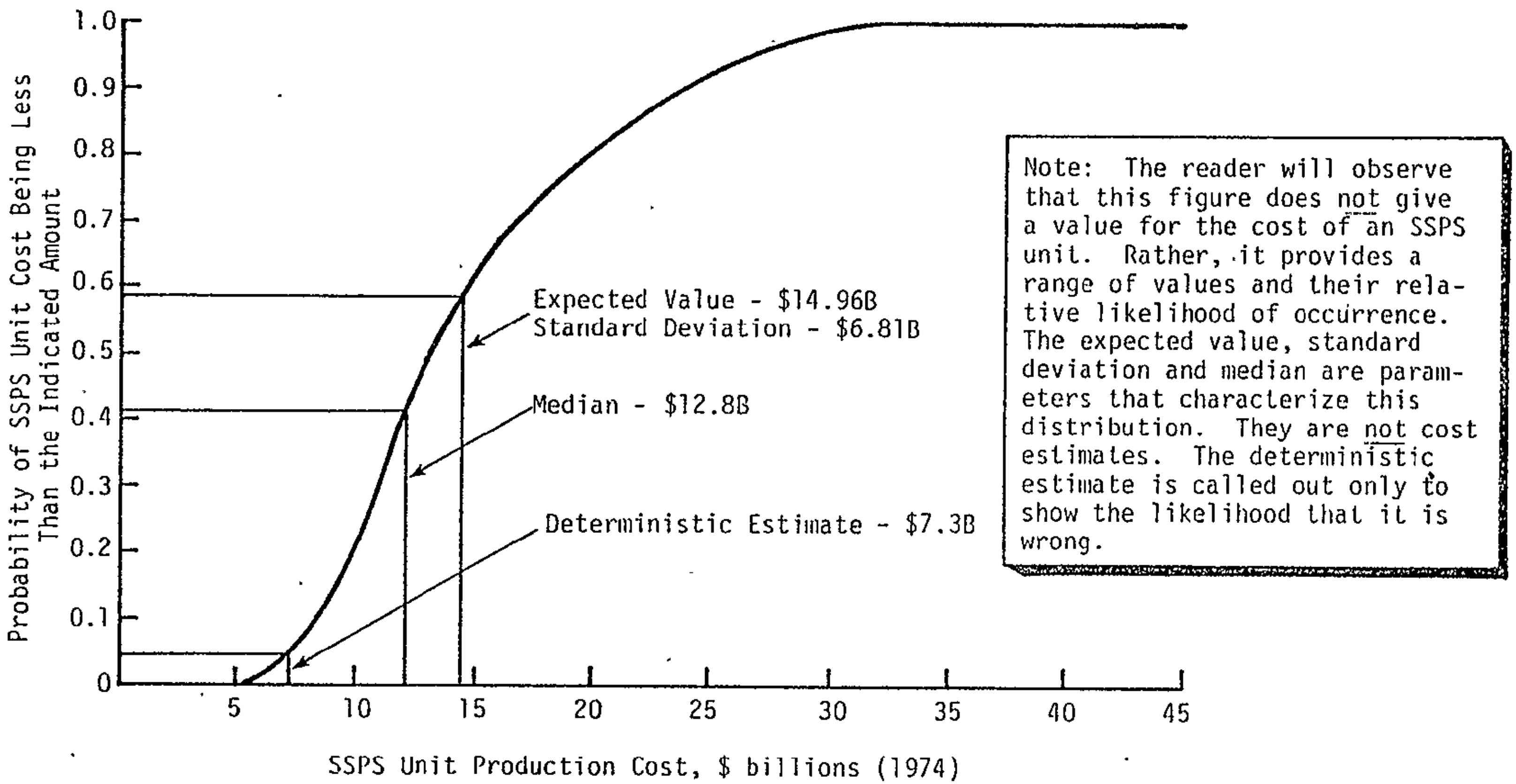

Figure 5.3 Cumulative Distribution Function of SSPS Unit Cost for the Si Solar Cell Configuration Assembled in LEO Using a Small Factory

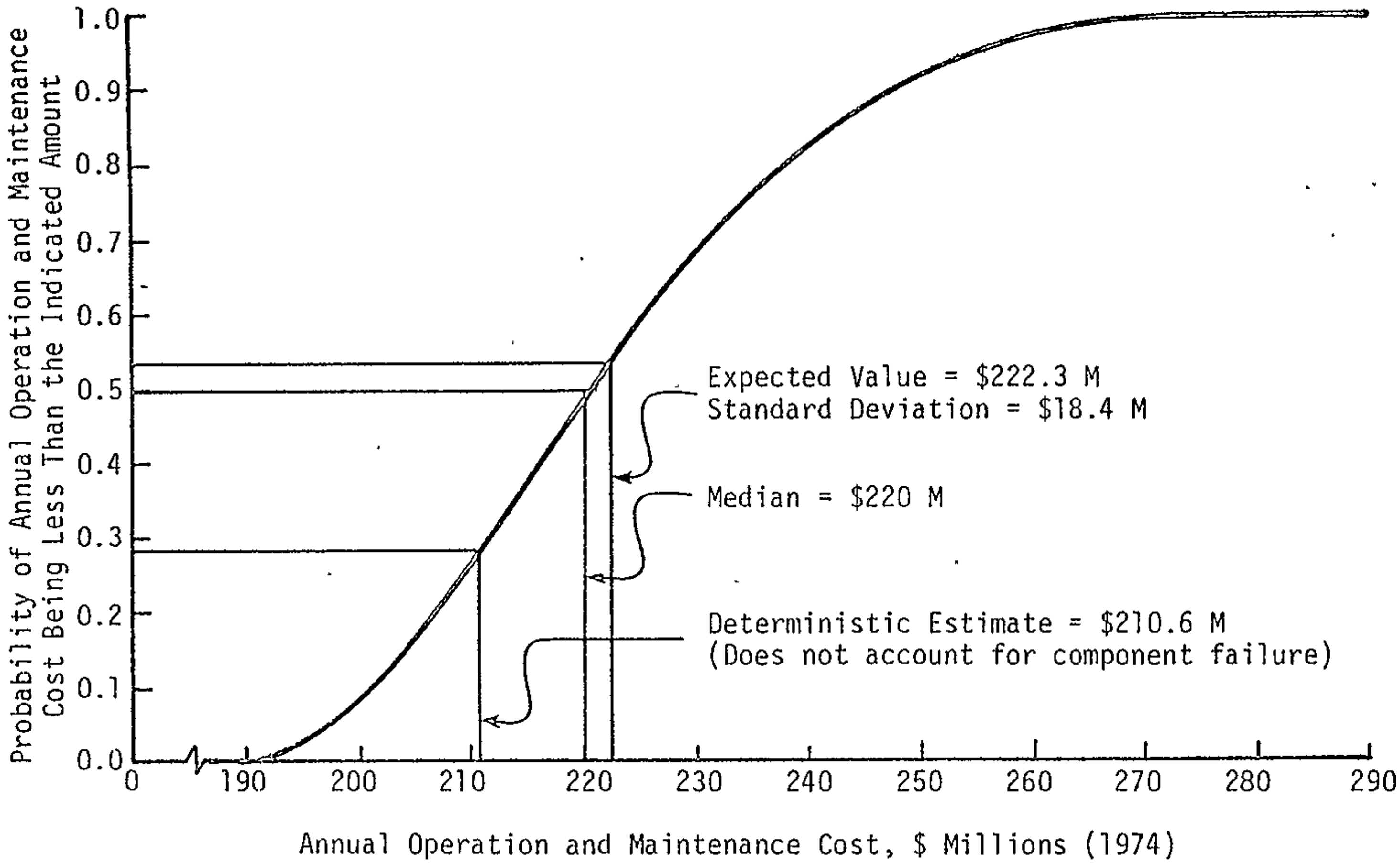

Figure 5.4 Cumulative Distribution Function of SSPS Operation and Maintenance Cost for the Si Solar Cell Configuration Assembled Using a Small Base in LEO

(Figure 5.4) for a value shown on the abcissa, or less, under the current state-of-knowledge. Thus, for example, there is a 50 percent chance that the second unit SSPS could be constructed for $12.1 billion (1974 dollars) or less. Alternatively, if one wished to commit to the construction of the second unit today and, furthermore, if one wished a 90 percent confidence of successfully completing that unit, one would have to commit about $23.4 billion (1974 dollars) to the project (for that unit--that is, in excess of the DDT&E program).

Of course, one could argue over the accuracy of the curves shown in Figures 5.3 and 5.4. These curves are preliminary and do not include all of the uncertainties inherent in the current configuration SSPS. Thus, if anything, the high end of the unit production risk profile is probably optimistic. However, arguments over the high end of the risk profile do not necessarily apply to the low end and, thus, have only a limited effect on the decision process. Furthermore, one would probably never choose to commit $23.4 billion to the production of a single SSPS unit since it is unlikely that the price that could be obtained for power at the rectenna busbar would be sufficiently high to pay back this capital cost.

What knowledge about the desirability of pursuing an SSPS development program can be legitimately gleaned from Figure 5.3 and 5.4? First, consider the process of obtaining cost estimates. Figure 5.3 shows that a cost estimate for the current configuration SSPS based upon deterministic estimates of all parameters in the cost model (most likely values) yields $7.34 billion (1974 dollars).* Note that there is only about a 5 percent chance of the unit production cost being this low, and note that more appropriate estimates, the median cost, the expected cost and the 90 percent confidence costs, are substantially higher. The discrepancy between the deterministic estimate and the expected cost, some $7.7 billion or 104 percent, is strictly the result of the system costing phenomenon illustrated in Figure 3.3. To obtain any more information from these distributions, it is necessary to combine them with additional data and assumptions in order to examine the probability distribution of net present value of an SSPS unit. Accordingly, the following assumptions are made:

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

2. The power output of the Si solar cell SSPS unit decreases with time due to degradation of various components, mainly the solar cells.**

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

**See Volume IV of this report for data on solar cell degradation.

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

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

5. In the initial year of operation, the price of power at the rectenna busbar is taken at two values, 20 mills/kWh and 30 mills/kWh (1974 dollars).

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

7. No charge is made for taxes and insurance.

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

With the above assumptions, the cumulative distribution function of net present value (revenues minus costs) of an SSPS unit referenced to the initial operation date is as shown in Figure 5.5.* The proper interpretation of this curve is that there is about a 35 percent chance that, under the conditions of the above assumptions and at a price of 30 mills/kWh for power on the initial operation date of the system, the second SSPS unit will be economically viable. Also, the expected value and the median of the net present value distribution occur at substantially negative values. The clear implication of this is that not enough is known at present about the technologies required for the production of an SSPS unit to commit to a program to produce such a unit at this time.

The most critical assumption inherent in Figure 5.5 is the price of power at the rectenna busbar at the initial operation date. This assumption is treated parametrically in Figure 5.6 with the remaining assumptions held unchanged. Clearly, increases in the price of power at the rectenna busbar significantly increase the probability of an SSPS unit being economically viable.

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

1. There is a finite chance that the current configuration SSPS could be economically viable. The magnitude of this chance is dependent primarily on the price of power at the rectenna busbar during the period of operation of the SSPS unit. Subject to the assumptions outlined above and a price of 30 mills/kWh for power at the rectenna busbar at the initial operation date, there is about a 35

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*Note that Figure 5.5 cannot be derived directly from Figures 5.3 and 5.4 and the stated assumptions because there is some degree of correlation between the unit production costs and the operation and maintenance costs that must be accounted for. Thus, the curve of Figure 5.5 is computed as an independent output of the risk assessment.

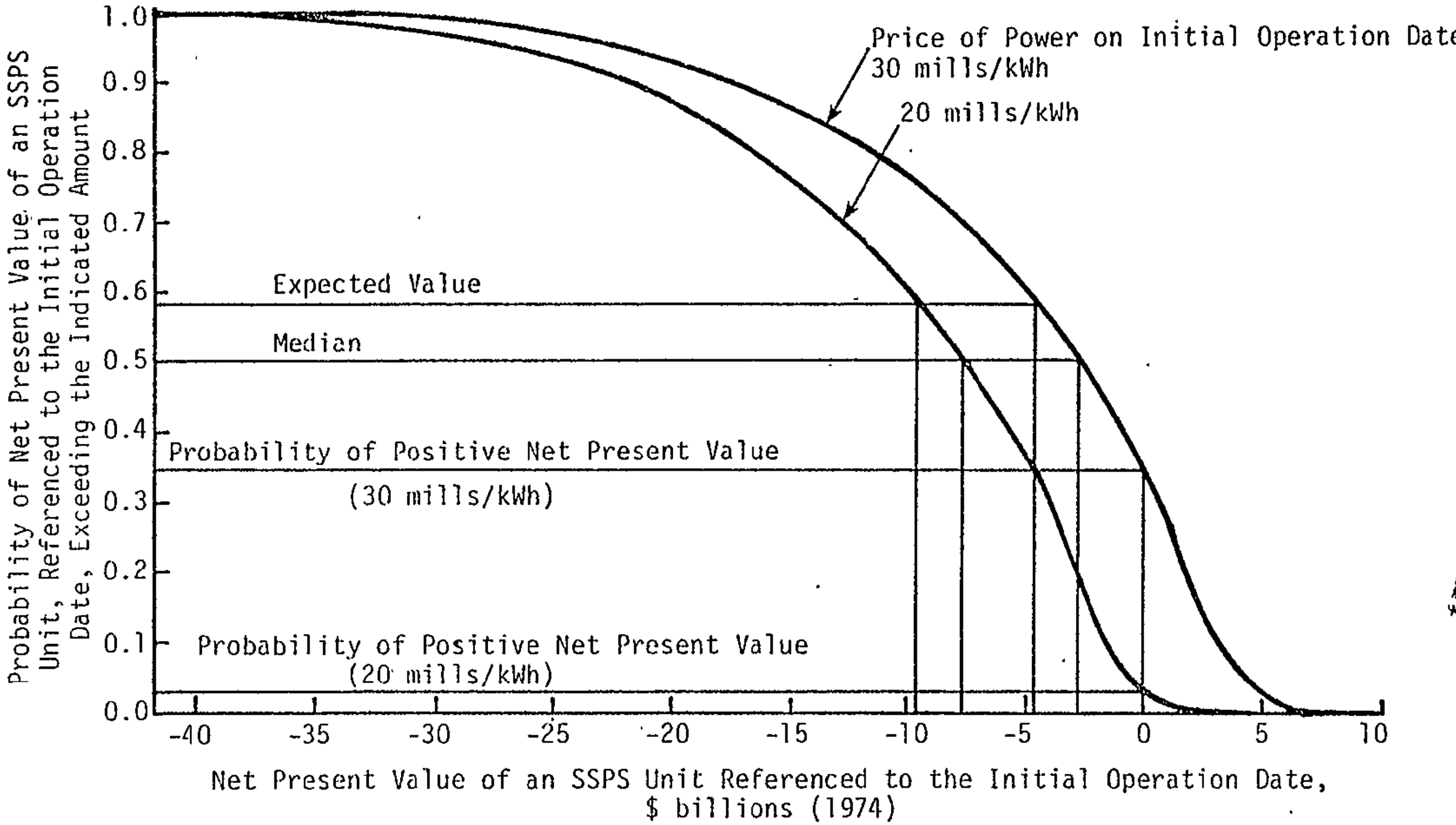

Figure 5.5 Cumulative Density Function of the Net Present Value of an SSPS Unit Referenced to the Initial Operation Date

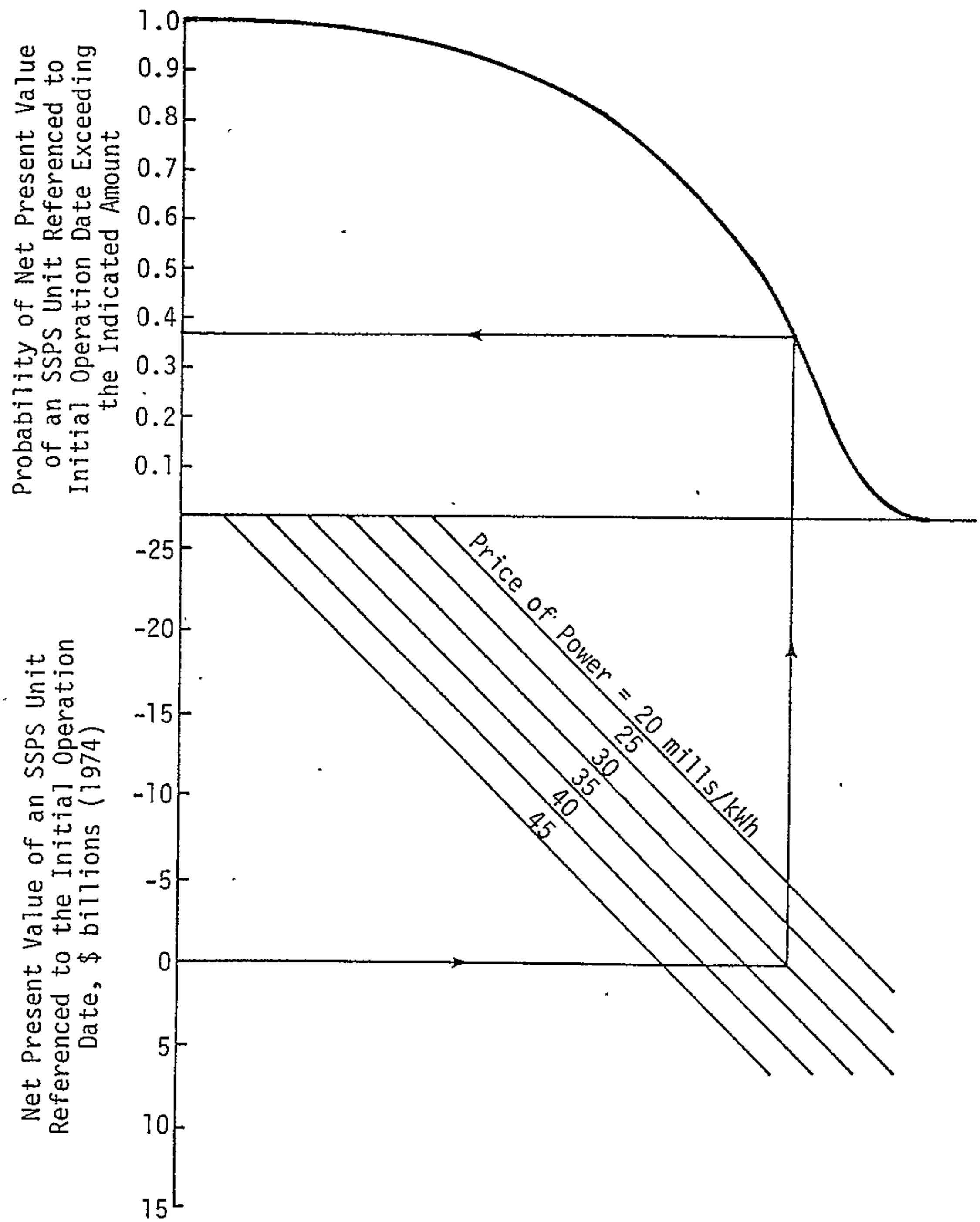

Figure 5.6 Cumulative Distribution Function of Net Present Value of an SSPS Unit at the Initial Operation Date as a Function of Price of Power

percent chance that the second SSPS unit would be economically viable. This decreases to about 3 percent if the price of power is 20 mills/kWh on the initial operation date.

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

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

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

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

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

5.3 A Cost-Risk Comparison of SSPS Alternatives

Twelve SSPS alternatives were analyzed, as noted above. These include three different solar cell materials, two different assembly locations, and two different construction facilities. The solar cell materials analyzed include Si, GaAs and CdS. The assembly locations include total assembly at LEO with subsequent ion stage transportation to GEO, and total assembly at GEO. (Construction of subassemblies in LEO and final assembly in GEO, which may offer advantages, was not examined.) The construction facilities assumed for SSPS construction are detailed in Volume II of this report.

The comparisons presented here are based on total life cycle costs for each alternative. The total life cycle costs are derived as the sum of the unit production cost and the annual operation and maintenance cost for the first 30 years of operation of a unit, all discounted back to the initial operation date of the unit. A typical probability distribution of total life cycle costs of the second SSPS unit for the Si solar cell configuration assembled in LEO by a small factory is given in Figure 5.7. Called out on this figure are four parameters which, together, provide a description of the probability distribution: the 10 percent confidence cost, the most likely cost, the expected value of the cost, and the 90 percent confidence cost. Since no single parameter can be adequately used to describe a probability distribution, the comparison is conveniently depicted here in terms of these four parameters, as shown in Figure 5.8. This figure shows remarkably similar costs for the different solar cell materials and different construction facilities, however, a significant difference according to the assembly location. The proper interpretation of this figure is that it is very likely that the costs for SSPS assembly in GEO would be greater than

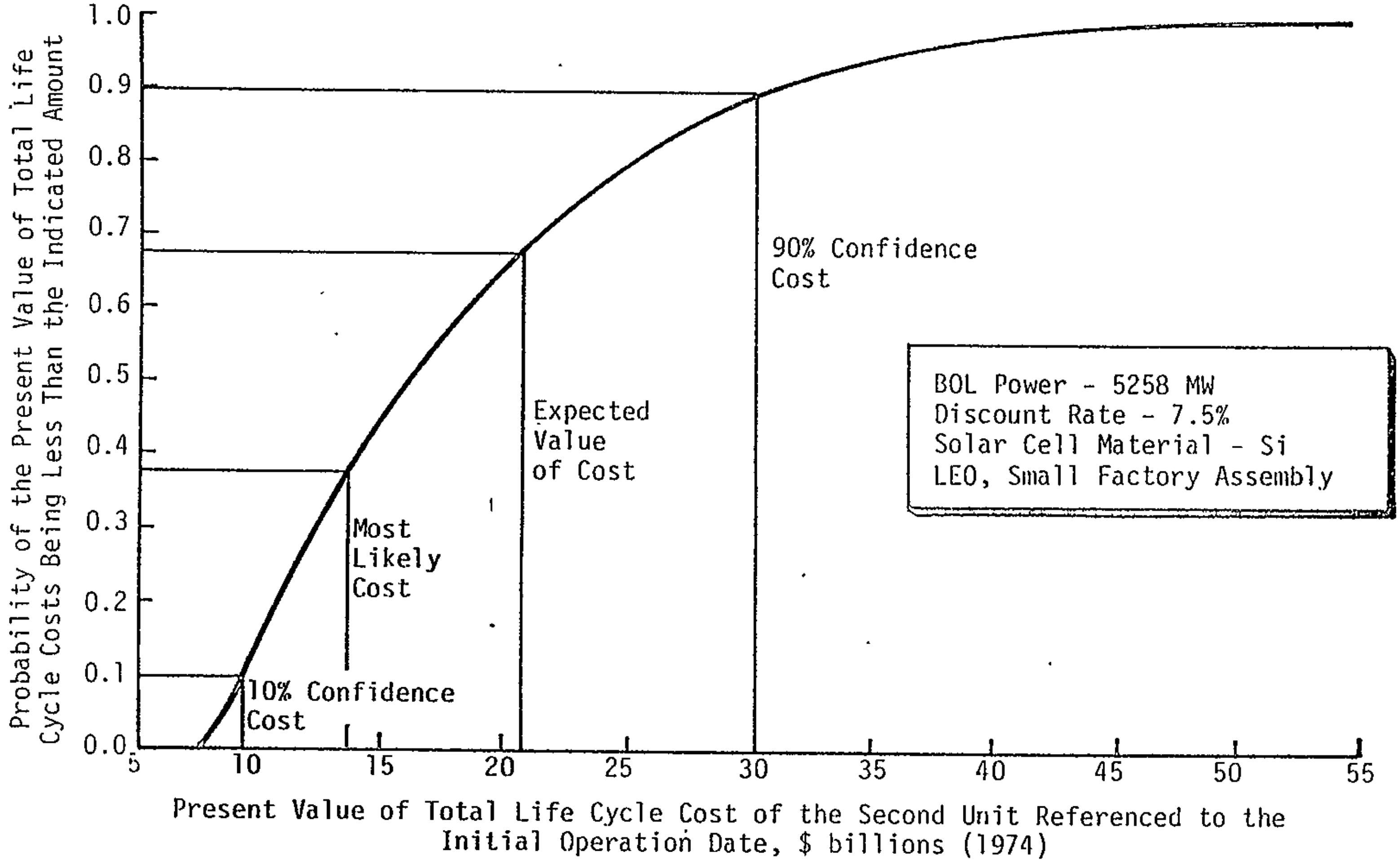

Figure 5.7 Total Life Cycle Cost of the Second SSPS Unit

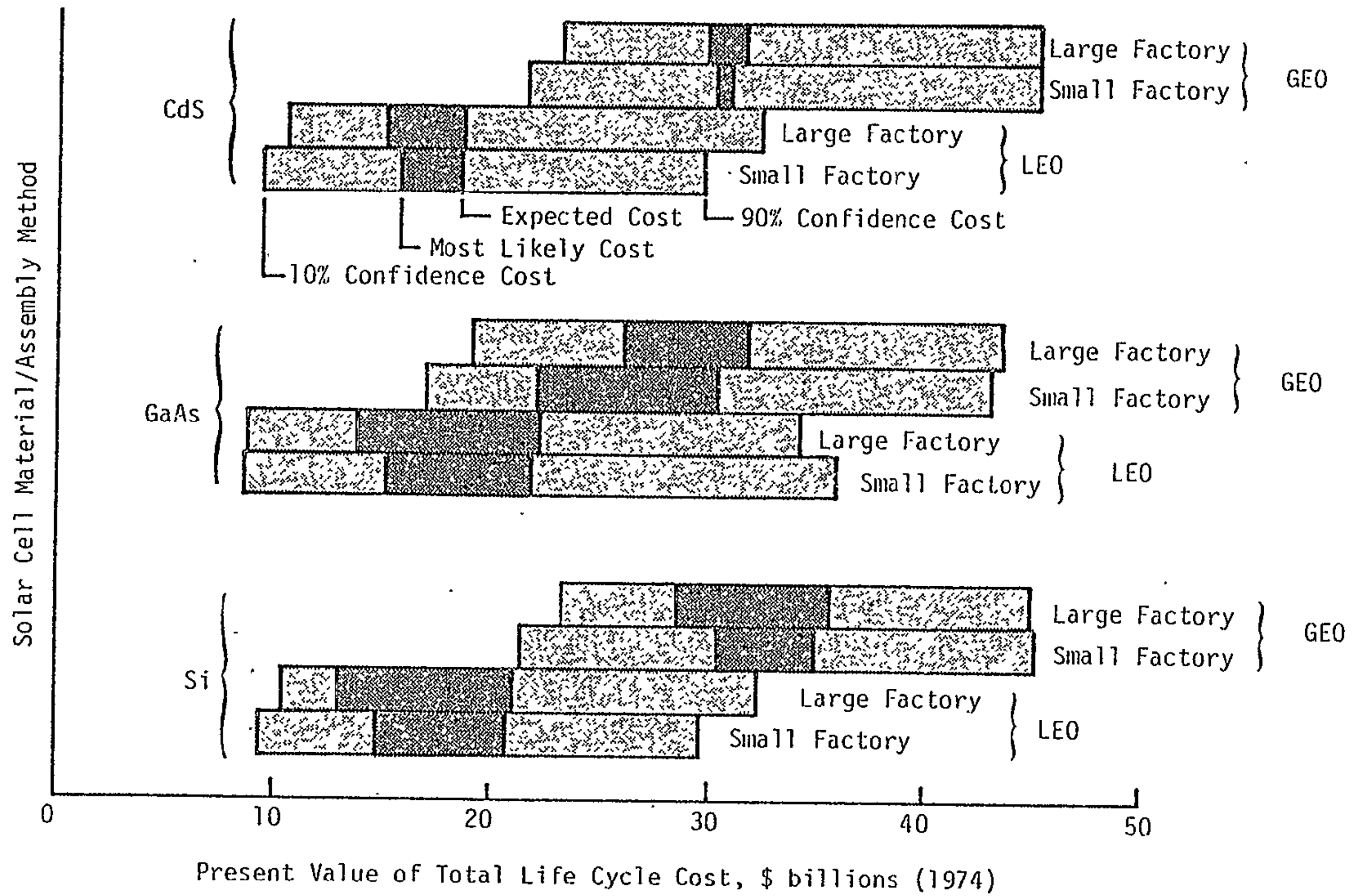

Figure 5.8 A Comparison of Total Life Cycle Costs for SSPS Alternatives

the costs for assembly in LEO with subsequent transportation to GEO. One should be careful to avoid the interpretation that GEO assembly will cost more than LEO assembly, or that some combination of the two locations is not economically desirable. It should also be emphasized that this result is configuration dependent.

Total life cycle cost, however, is only one side of the picture in comparing SSPS alternatives. The other side is the revenues generated by each alternative. Here, too, it must be pointed out that differences exist between the solar cell materials in terms of their respective rates of degradation due to radiation damage. Whereas Si solar cells degrade substantially with time, GaAs and CdS solar cells exhibit much lower rates of degradation. A full discussion of these effects is provided in Volume IV of this report. Consequently, an SSPS using these materials produces significantly more revenues over a 30-year satellite operational lifetime than does an SSPS that uses Si solar cells. The effect of solar cell degradation on revenues generated by an SSPS with a beginning-of-life power of 5258 MW is shown in Figure 5.9 as a function of the price of power on the initial operation date. The advantages offered by GaAs and CdS are evident.

It is interesting to place the cost and revenue data shown above into the context of an SSPS fleet. Assuming that 120 units total (including the prototype) will be produced at the rate of four per year beginning with the second unit coming on line January 1, 1998, Figure 5.10 shows the expected value of the net present value of the fleet (referenced to January 1, 1977) and the standard deviation of this estimate (reflecting the present inability to estimate the total life cycle cost for each alternative). It is interesting that only the CdS solar cell configurations have a positive net expected value for the entire fleet. Thus, a commitment to an entire SSPS development program based upon the use of either Si or GaAs solar cells is clearly not justified today.

The data presented above can be shown to the decision maker in one other interesting way. In Figure 5.11 the probability that the second unit will pay off, that is, that the net present value of the second unit will be zero or more, is plotted as a function of the price of power at the rectenna busbar on the initial operation date of the unit, for units constructed using each of the three solar cell materials considered. This figure clearly shows the advantages offered by the alternative solar cell materials. The conclusion which one could properly draw from this figure is that there exist alternative solar cell materials to single crystal silicon and that these materials offer potential economic advantages. It may, therefore, be inferred that these alternative materials warrant some consideration in future studies.

5.4 Power Beam Ionospheric and Biological Effects

A major area of technical uncertainty impacting SSPS design is the effect of the microwave power beam on the ionosphere and on biological materials. These effects are likely to result in a constraint on the maximum power density somewhere in the range of 10 mW/cm^2 to 100 mW/cm^2. The technical

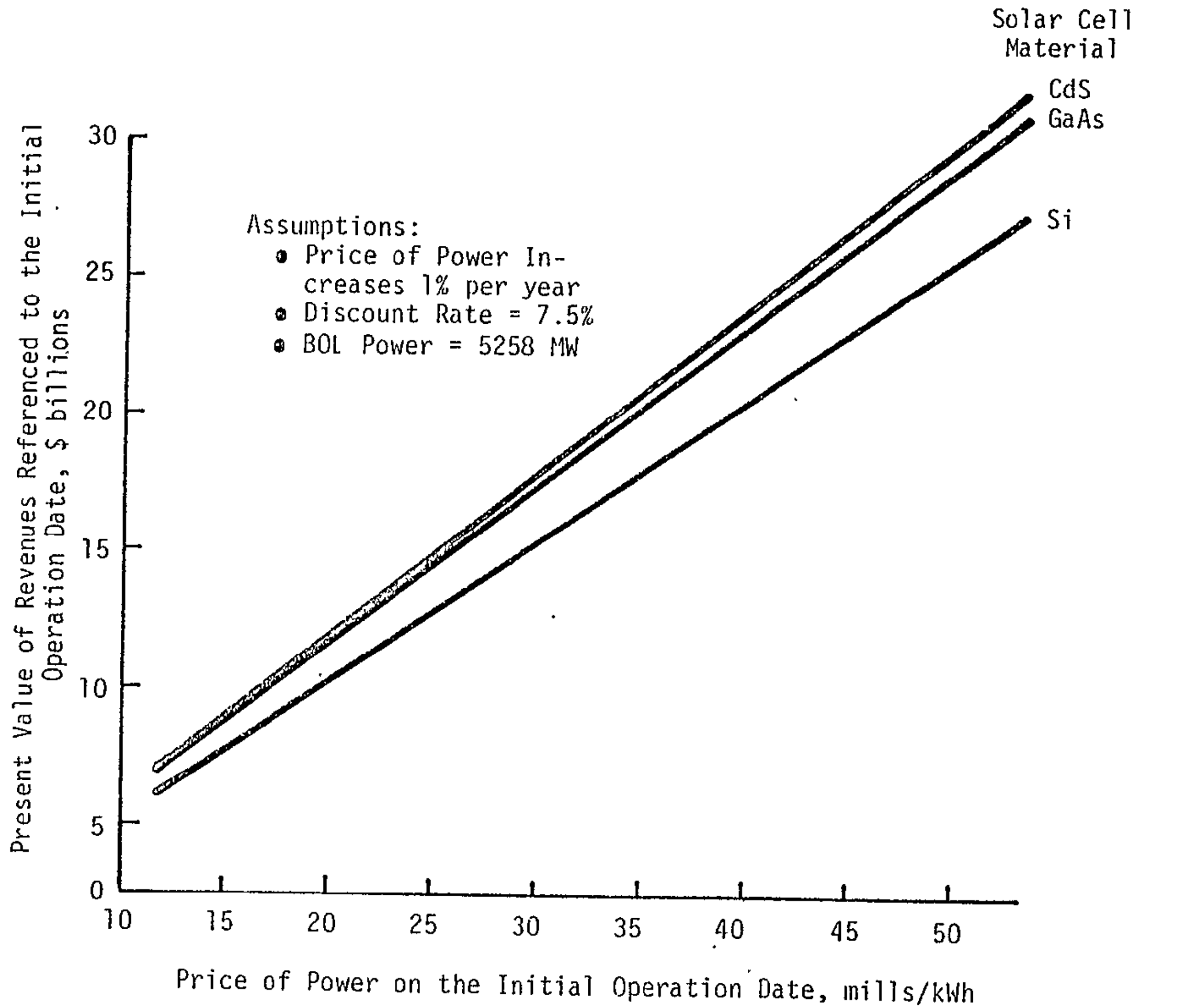

Figure 5.9 Comparison of Revenues Generated by Alternative SSPS Solar Cell Materials

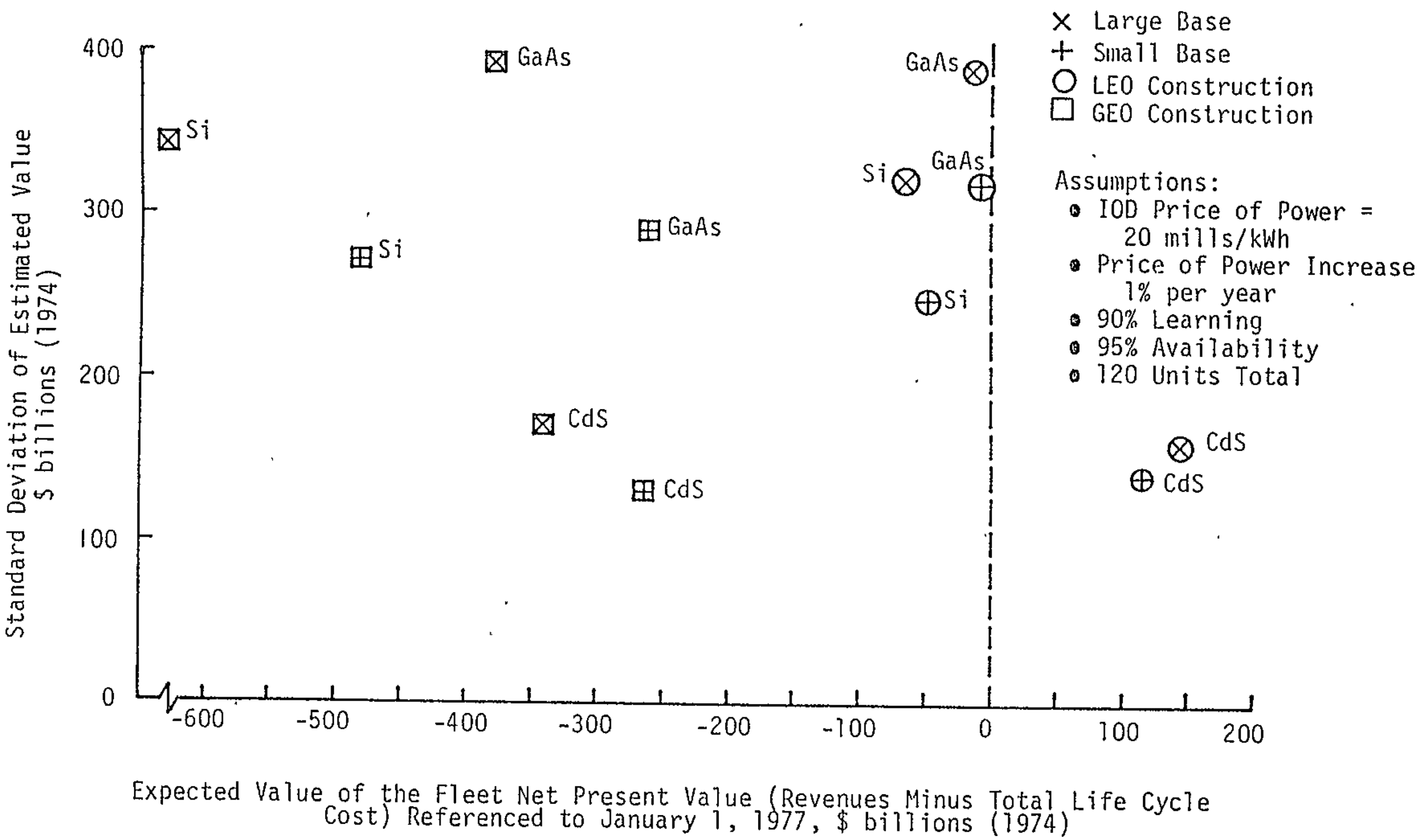

Figure 5.10 Net Present Value of an SSPS Fleet for Different Combinations of Assembly Scenario and Solar Cell Material

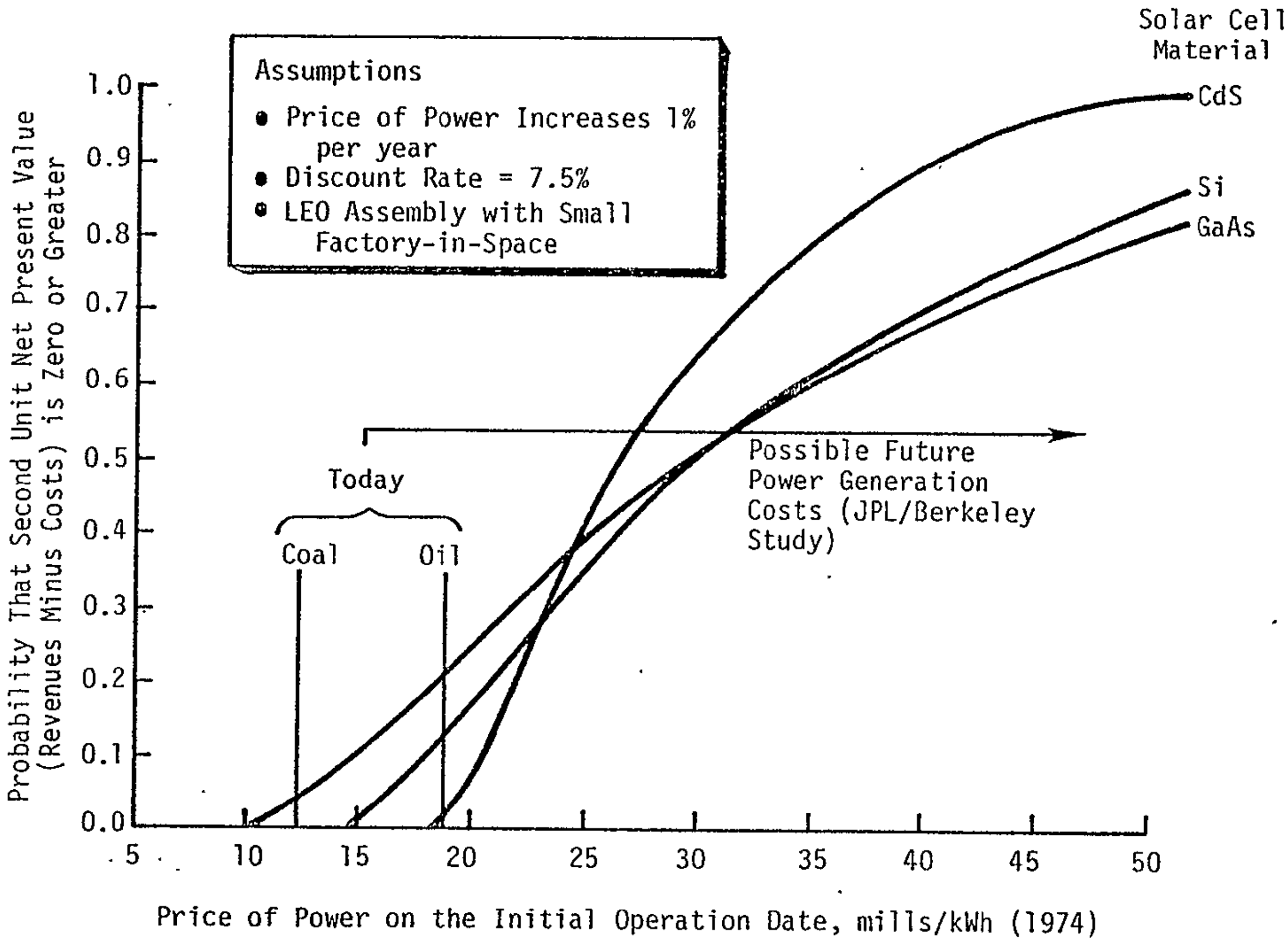

Figure 5.11 Chance That the Second Unit Will Pay Off

aspects of this issue are discussed in Volume III of this report. As a part of this study, the economic impact of this constraint on the second and subsequent units was investigated. The results are summarized in Figure 5.12 for a CdS solar cell configuration SSPS. On the left side of this figure, a probability distribution (heavy line) is given that indicates the likelihood of being constrained to operate at or below a given maximum microwave power density. This joint distribution is decomposed into its two constituent parts, the likelihood of encountering a constraint due to ionospheric effects and the likelihood of encountering a constraint due to biological effects. The maximum microwave power density is then assumed to determine the beginning-of-life power and this in turn determines the expected value of the total life cycle cost for each unit. The revenues that each unit generates depend on the price of power at the rectenna busbar. They are shown accordingly on the right side of the figure. A point to the right of the break-even line indicates that the revenues are larger than the costs. The shaded region drawn about the 30 mills/kWh line indicates the present 1σ uncertainty in the total life cycle cost estimate. It should be read vertically as indicated. The conclusions of this study can be summarized as follows:

1. The SSPS is likely to be constrained to operate at a maximum microwave power density below 100 mW/cm².

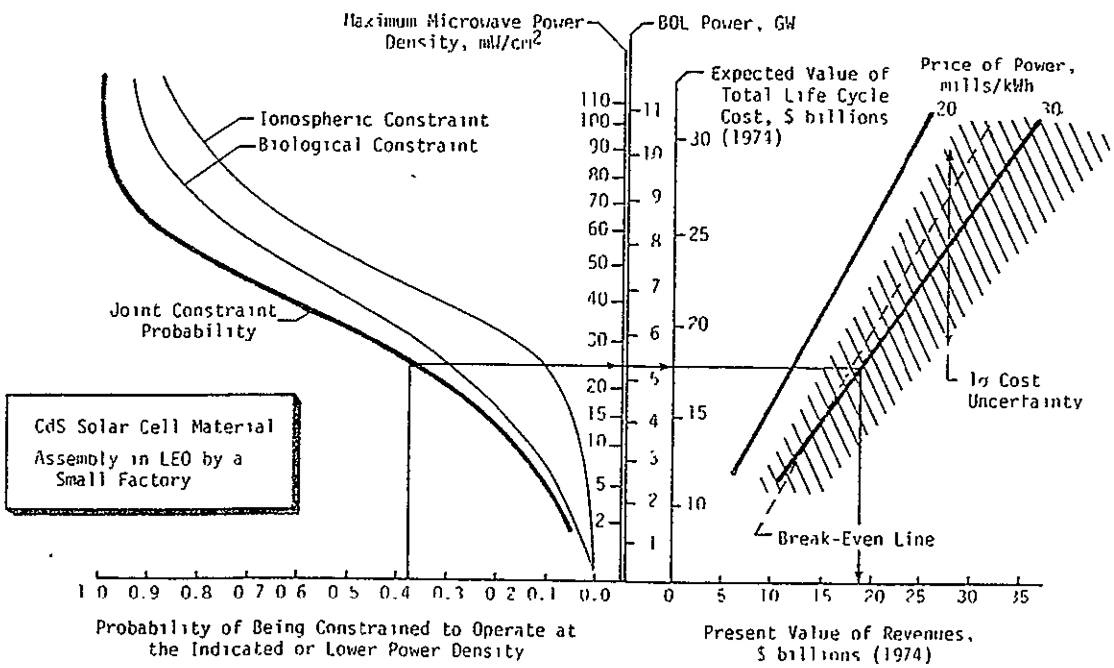

Figure 5.12 The Effect of Constraints on Maximum Microwave Power Density

2. The magnitude of the maximum microwave power density constraint will impose a design condition on the satellite, either determining power level as shown in Figure 5.12 or forcing other methods of limiting the power beam power density, for example, defocusing the beam or employing multiple beams.

3. The economics of the second and subsequent units is not strongly affected by the magnitude of the constraint. Over the full range upon which the constraint is likely to be imposed, the break-even price of power varies only about 4 mills/kWh.

Although the magnitude of the constraint is not an important economic parameter, it is nonetheless necessary to determine its value relatively early in the program to allow for the systems impacts and provide for the necessary program planning.

6. IDENTIFICATION OF CRITICAL TECHNOLOGIES AND ISSUES

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

6.1 Critical Issues

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

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

All of the areas of social and environmental impact associated with an SSPS that have been identified to date [14, 15] are summarized in Table 6.1. This table lists the major areas of impact by the three main system elements: launch complex and operations, orbital system, and rectenna and power interface systems. These impacts were then organized in the manner suggested by Figure 6.1: first, according to those impacts which are critical, that is, those which might have substantial detrimental local or even global impacts (for example, interaction of the microwave beam with the ionosphere) which would render an SSPS socially unacceptable or which cause substantial economic uncertainty (for example, acceptable microwave densities affecting rectenna size) and those impacts which clearly could not; next, according to those impacts which could be tested (such as effects of exposure to microwave energy) and those which could not (such as shifts in demographic patterns resulting from the location of terrestrial facilities). At this time, there appear to be no impacts with which there are associated large uncertainties and that are thought to be critical, but which are not amenable to testing to reduce uncertainty or simply to a logical decision process. The impacts considered to be both testable and critical represent the areas of social and environmental risk associated with an SSPS which must be dealt with in the development of a test/validation/documentation program. These risks are summarized in Table 6.2. More complete descriptions of each impact that has been identified to date follow.

6.1.1 Launch Complex and Operations

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

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

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

Environmental Modification. Two major environmental impacts that have been identified with the launch complex are the noise from the launch vehicles and the pollutants injected into the atmosphere by propellant combustion. Noise levels must be taken into account in siting and designing the launch facilities (testable, noncritical) and the effect of different

Table 6.1 SSPS-Related Social and Environmental Impacts Identified to Date

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

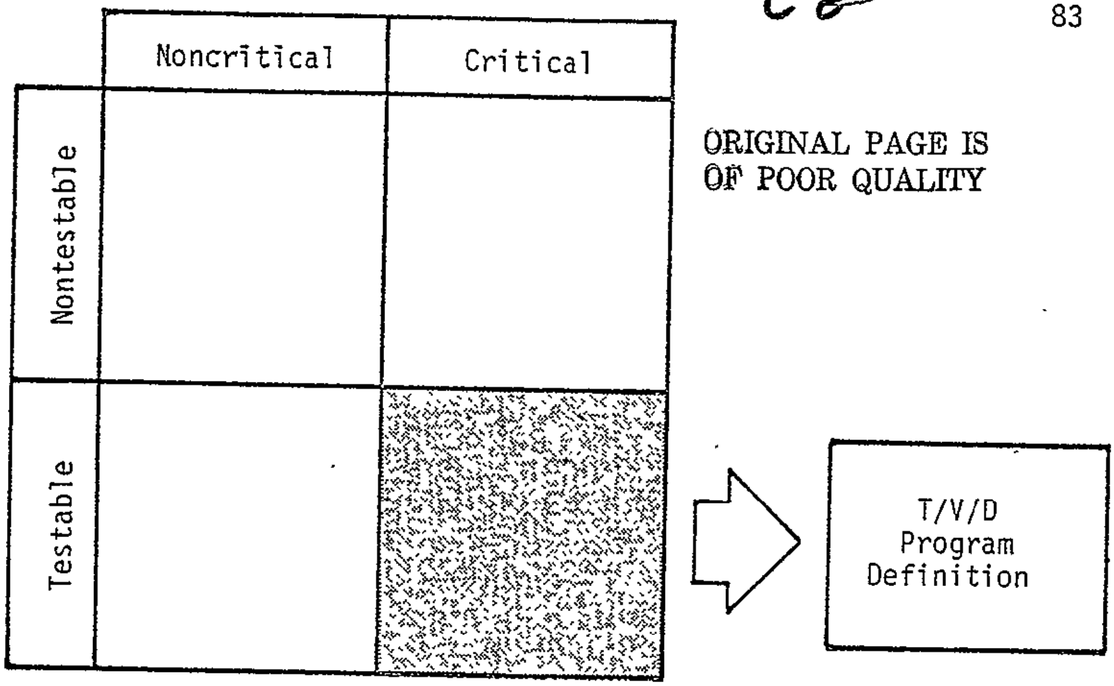

Figure 6.1 Social and Environmental Impact Matrix

Table 6.2 Critical and Testable SSPS Social and Environmental Risks

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

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

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

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

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

6.1.2 Orbital System

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

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

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

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

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

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

6.1.3 Rectenna and Power Interface Systems

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

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

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

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

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

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

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

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

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

6.2 Critical Technologies

In this section, the technologies critical to the economically successful production of a current configuration SSPS are identified. Two separate efforts are reported. The first deals with the full spectrum of technologies needed to produce an SSPS, and the second focuses on solar cell technology. The first effort was performed during the second study phase and the results derive from the cost model and state-of-knowledge as identified during that study phase. This study suggested the importance of solar cell technology as a critical technology area. In the third study phase, considerable emphasis was placed on an analysis of alternative solar cell materials and was performed using the cost model and state-of-knowledge as updated during the third study phase. The critical technologies are identified in terms of their contribution to the cost and risk of SSPS unit production as follows. First, the risk profile of the current configuration SSPS was established as is described in Section 5. Then, from the lists of inputs to the risk analysis model (for the second study phase), 56 potentially significant technology items were identified. As identified in Section 5, each of these variables has associated with it a state-of-knowledge that is described by a probability density function ranging from a minimum value to a maximum value. (Based on today's knowledge, there is probability zero that a parameter will lie outside the range so described. Furthermore, the probability density function has its maximum value at the most likely value of a parameter.) The assessment of critical technologies focuses on the minimum, maximum and most likely values of each significant input variable. The effect of removing uncertainty in each of these variables is then investigated by setting the range over which each variable may vary to zero, one-by-one, first to the minimum value, then the most likely value, and then the maximum value. That is, the effect of removing uncertainty in each variable is investigated over the full range of values which, by today's state-of-knowledge, each variable may take on. For example, to determine the contribution to cost and risk of the cost of the solar array blanket per unit area, that cost is input to the risk model as a deterministic value, first at its minimum value, then at its most likely value and, last, at its maximum value, holding all other inputs as they are described in Section 5. The results of this exercise are given in Table 6.3, with the variables listed in three groups. The top group in the table presents the results for the critical technology areas. These are the technologies that drive the cost and risk. They include:

- Solar cell efficiency
- Specific mass of the solar blanket
- Fraction of satellite assembled by man
- Rate of manned assembly
- Rate of remote assembly
- LEO space station unit cost
- Solar array blanket specific cost.

It is interesting to note that these critical technologies encompass only two general areas: uncertainties associated with the solar arrays, that is, solar array costs, mass and performance, and uncertainties associated with the assembly of large systems in space. These seven elements of risk are plotted in Figure 6.2, which visually shows the potential for control of cost and risk by technology development in each area.* This figure clearly shows the driving technology to be the rate of manned assembly--that is, productivity in space is the major cost and risk driver for the current configuration SSPS. Since this conclusion could substantially affect future SSPS development programs, it is recommended that it be subjected to a careful review before being fully accepted. It must be emphasized again that these results derive from subjective assessments of the state-of-knowledge relative to the current configuration SSPS and are subject to variability upon review. However, there is little doubt that this is an area of uncertainty that needs to be dealt with sooner rather than later.

The second group of variables in Table 6.3 are variables that are only moderately important cost and risk drivers. These are variables which should probably receive attention as components of major study areas but, at this time, do not deserve specific studies for their resolution.

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

Table 6.3 The Effect on Cost and Cost Risk* of Changes in the State-of-Knowledge

	Item	Range of Values ($Billions, 1974)					
		Best		Most Likely		Worst	
		Mean Cost	Cost Risk	Mean Cost	Cost Risk	Mean Cost	Cost Risk
	Nominal**	3.76	--	14.92	3.86	144.83	--
Major Cost- and Risk-Driving Factors	Rate of Manned Assembly	11.56	1.90	15.57	2.87	21.91	5.16
	Fraction of Satellite Assembled by Man	13.05	2.43	14.53	3.05	17.56	4.56
	Rate of Remote Assembly	13.93	3.42	14.96	3.61	16.65	3.67
	Solar Cell Efficiency	13.74	3.26	14.27	3.59	17.04	4.13
	Specific Mass of the Solar Blanket	13.34	2.87	14.67	3.24	15.92	4.13
	LEO Space Station Unit Cost	12.99	2.83	14.34	3.07	17.74	4.77
	Solar Array Blanket Specific Cost	13.33	3.49	13.84	3.42	17.27	3.48
Factors Having Noticeable Cost- and Risk-Driving Effects	EVA Equipment Unit Cost	14.49	3.17	14.56	3.59	15.16	3.88
	DC-RF Converter Specific Cost	14.45	3.21	14.95	3.82	15.00	3.49
	Nonconducting Structure Specific Cost	14.57	3.49	14.82	4.09	15.22	3.67
	Central Mast Specific Cost	14.57	3.52	14.71	3.69	15.14	3.68
	Rectenna Structure Specific Cost	14.66	3.65	14.75	3.79	15.13	3.85
	Crew Rotation Period	14.00	3.13	14.99	3.84	15.77	3.95
	HLLV Average Load Factor	14.40	3.61	14.83	4.06	15.61	3.57
	Number of Personnel per Shuttle Flight	14.34	3.34	14.70	3.60	15.90	4.08
	Launch Cost per Shuttle Flight	14.22	3.73	14.15	3.27	15.35	3.85
	HLLV Unit Cost	14.52	3.60	14.87	3.63	15.18	3.93
	Launch Cost per Shuttle Flight	14.59	3.52	14.70	3.65	15.28	4.14
	Teleoperator Unit Cost	14.49	3.48	14.46	3.61	15.51	3.65
	DC-RF Converter Efficiency	14.27	3.61	14.79	3.58	15.25	4.07
	RF-DC Converter Efficiency	14.17	3.26	14.62	3.17	15.00	3.54
	Specific Mass of the Solar Concentrators	14.24	3.15	14.97	3.82	15.17	3.59
	Specific Mass of Waveguides	14.40	3.48	14.55	3.63	15.74	3.91
	Miscellaneous Mass	14.73	3.64	14.80	3.77	14.92	3.83
	Personnel Productivity Factor	14.04	3.30	14.56	3.56	15.64	3.66
	Fabrication Rate of Modules	14.61	3.59	14.73	3.57	14.39	3.96

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Table 6.3 The Effect on Cost and Cost Risk* of Changes in the State-of-Knowledge (continued)

Factors Having No Noticeable Cost- and Risk-Driving Effects

Item	Range of Values ($Billions, 1974)					
	Best		Most Likely		Worst	
	Mean Cost	Cost Risk	Mean Cost	Cost Risk	Mean Cost	Cost Risk
Beam Collection Efficiency	14.61	3.69	15.17	3.72	14.89	3.22
Ratio: Conducting Structure Mass to Array Area	15.00	3.66	14.60	3.67	14.94	3.56
Ratio: Nonconducting Structure Mass to Array Area	14.71	3.41	14.69	3.64	14.97	3.54
Specific Mass of Central Mast	14.78	3.45	14.84	3.78	14.55	3.55
Specific Mass of DC-RF Converters	14.68	3.40	14.86	4.08	15.30	3.82
Specific Mass of Antenna Interface	14.89	3.84	14.60	3.41	15.06	3.74
Specific Mass of Phase Control Electronics	14.65	3.58	14.89	3.64	14.85	3.91
Teleoperator Availability Factor	14.53	3.42	14.95	3.74	14.85	3.89
Teleoperator Work Factor	14.75	3.82	14.61	3.30	15.18	3.93
Fabrication Module Availability Factor	14.98	3.90	14.56	3.78	14.85	3.70
Manipulator Availability Factor	14.89	3.77	15.18	3.72	14.63	3.18
Fabrication Module Unit Mass	14.54	3.41	14.62	3.15	14.59	3.37
Manipulator Unit Mass	14.55	3.73	14.75	3.37	14.70	3.37
LEO Space Station Unit Mass	14.47	3.21	14.98	3.83	14.93	3.50
Crew Module Unit Mass	15.02	3.66	14.60	3.60	14.93	3.56
GEO Space Station Unit Mass	14.84	3.50	14.69	3.64	14.83	3.45
Fabrication Module Unit Cost	14.74	3.60	14.72	3.60	14.57	3.54
Shuttle Unit Cost	14.74	3.50	14.78	3.51	14.67	3.58
Manipulator Unit Cost	14.73	3.85	14.92	3.72	14.75	3.49
GEO Space Station Unit Cost	14.79	3.70	14.56	3.78	15.03	3.90
AIS Unit Cost	14.83	3.96	14.69	3.57	14.75	3.69
Antenna Power Distribution Specific Cost	14.52	3.15	15.16	3.72	15.03	3.80
Phase Control Specific Cost	14.50	3.41	14.60	3.15	14.69	3.37
Waveguide Specific Cost	14.68	3.37	14.73	3.37	14.60	3.73
Solar Array Concentrator Specific Cost	14.79	3.45	14.68	3.64	14.97	3.50

Table 6.3 The Effect on Cost and Cost Risk* of Changes in the State-of-Knowledge (continued)

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

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

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

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

As a note of caution in the interpretation of values in Table 6.3, it should be recognized that these values derive from a Monte Carlo simulation, that is, they are obtained by sampling probability distributions. They are not the result of precise computation. Thus, these data contain some amount of noise. For example, determination of expected costs is accurate to about $200 million one sigma or about ± 1 percent. Determination of risk is also accurate to about the same absolute amount, or about ± 5 percent. This amount of noise accounts for the apparent inconsistencies in some of the results presented in Table 6.3, particularly with respect to the Group 3 variables.

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

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

2. Solar cell blanket mass, cost and efficiency.

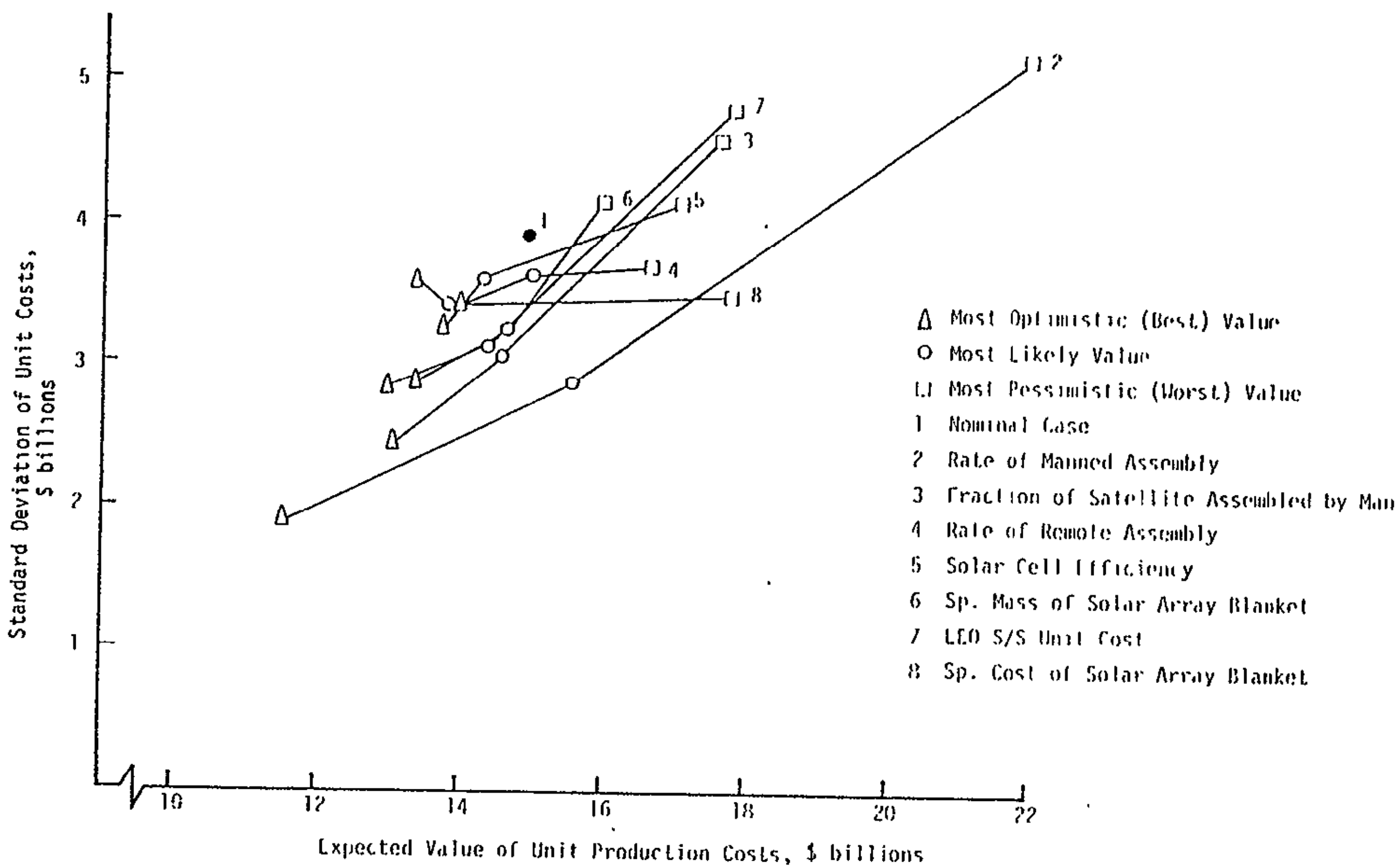

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Figure 6.2 Effect of Removing Uncertainty on Cost Components--
Major Cost- and Risk-Driving Factors

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

- These conclusions be reviewed by a "panel of experts," and
- Assuming that their validity is confirmed, these technology areas should be addressed by detailed study early in the continuing program.

6.2.1 Analysis of Alternative Solar Cell Materials

Three solar cell materials were studied as candidates for the energy conversion subsystem of the SSPS: single crystal silicon (Si), gallium-arsinide (GaAs) and cadmium-sulfide (CdS). The present state-of-knowledge regarding these different materials is substantially different. Si cells have a long history of use in space, whereas cells made of the other materials are presently laboratory curiosities. Nonetheless, GaAs and CdS materials offer the possibility of being lower cost alternatives. The problem is that very little is known about these materials and, therefore, data with respect to them must be considered highly speculative. (To some extent, this is also true of very thin, low cost Si cells, despite the present background of knowledge regarding Si solar cells in general.) This section deals with what is not known about alternative solar cell materials. From the work documented in Section 5 of this volume, it is concluded that materials other than Si deserve consideration. The efforts devoted to studying alternative materials should be focused to provide the best possible selection with the minimum investment in resources.

Three areas of uncertainty in solar cell materials technology were examined. These include solar cell efficiency, blanket mass and blanket cost. An analysis of the effect of learning about these three parameters was conducted using the same methodology that is described above for the identification of critical technologies. The results of this analysis are shown in Figure 6.3. The conclusion is that the driving area of uncertainty for all solar cell materials is the cost of the solar array blanket. It must be recognized that the cost that will actually apply in the 1990s, when an SSPS might be built, cannot be known before the date when the system is built. What can be known today, however, is the upper limit of the solar array blanket cost. Thus, a major focus of solar cell research over the next several years should be the establishment of an acceptable upper bound on this cost. By so doing, a major area of risk in the SSPS program is effectively controlled. It is also recommended that the solar cell material to be used in the final satellite solar power system not be chosen now or, for that matter, in the near future. Rather, the proper approach is to perform research on a number of alternative materials at this time, and to remain flexible in the selection of the material that will ultimately be used. This will permit the decision to be made when the state-of-knowledge on alternative solar cell materials is substantially improved.

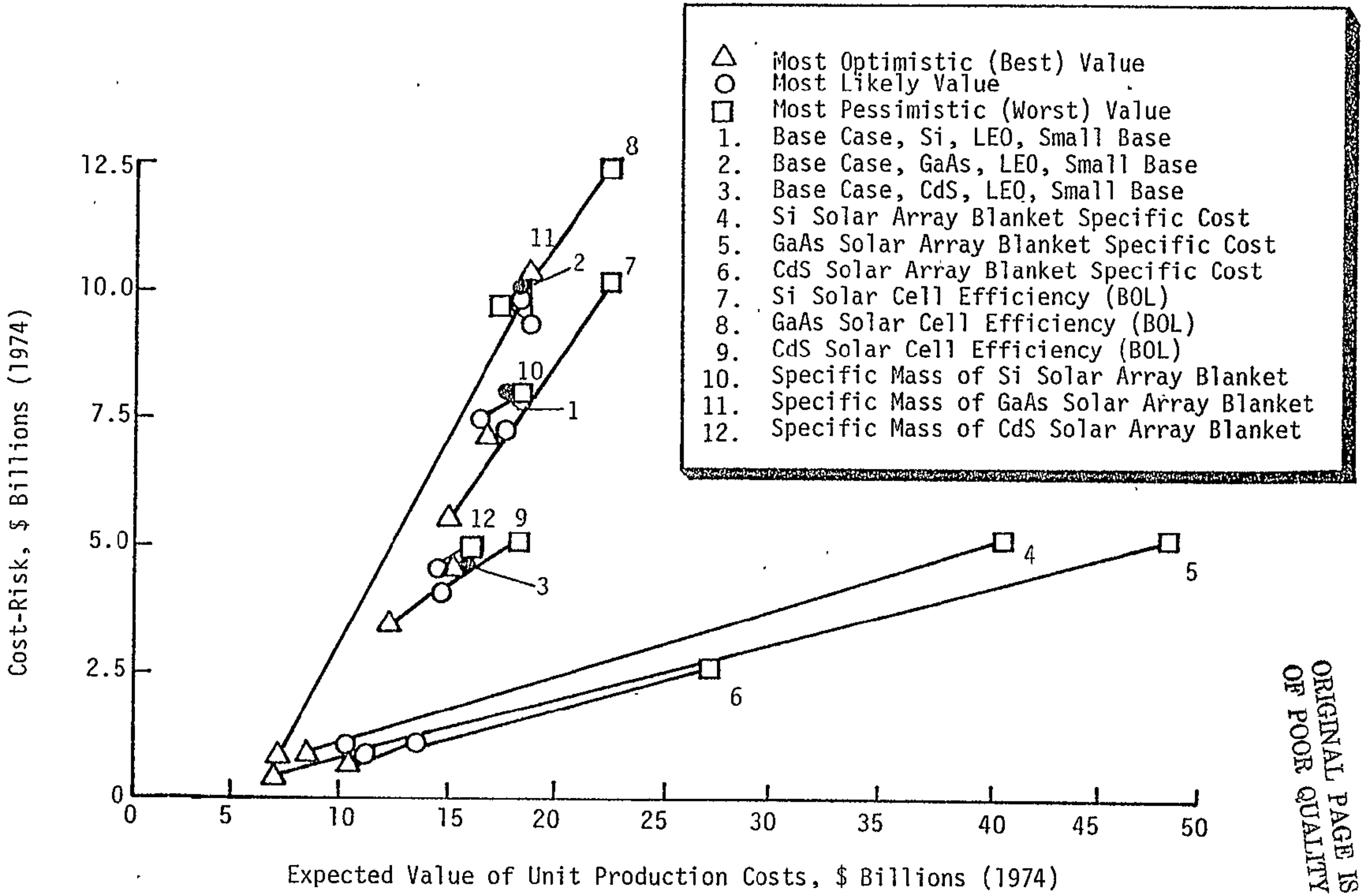

Figure 6.3 The Effect of Removing Uncertainty in Components of Solar Cell Technology for Alternative Solar Cell Materials

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6.2.2 Analysis of the Effect of Construction Time

A brief analysis was conducted to determine the economic effect of the time required for SSPS construction and transportation to station in GEO. The analyses documented in this volume all assume that the capital expenditure for an SSPS unit is made as a lump-sum payment two years prior to the initial operation date of the system. A discount rate of 7.5 percent is then used to determine the present value of the capital cost referenced to the initial operation date. The period of time between the lump-sum payment and the initial operation date of the system is referred to as the cost-equivalent construction time. It is defined such that the present value of the lump-sum payment and the present value of the actual construction cost stream, referenced to the initial operation date of the system, are equal. Increasing the cost-equivalent construction time increases the present value of the total life cycle cost of the system, as shown in Figure 6.4. This figure clearly shows the need for maintaining a short cost-equivalent construction time. This means, among other things, procurement of hardware items on a schedule that is closely keyed to the satellite construction schedule. The magnitude of the economic impact of construction time on overall SSPS economics suggests that added attention should be given to the development of production schedules for candidate satellite configurations.

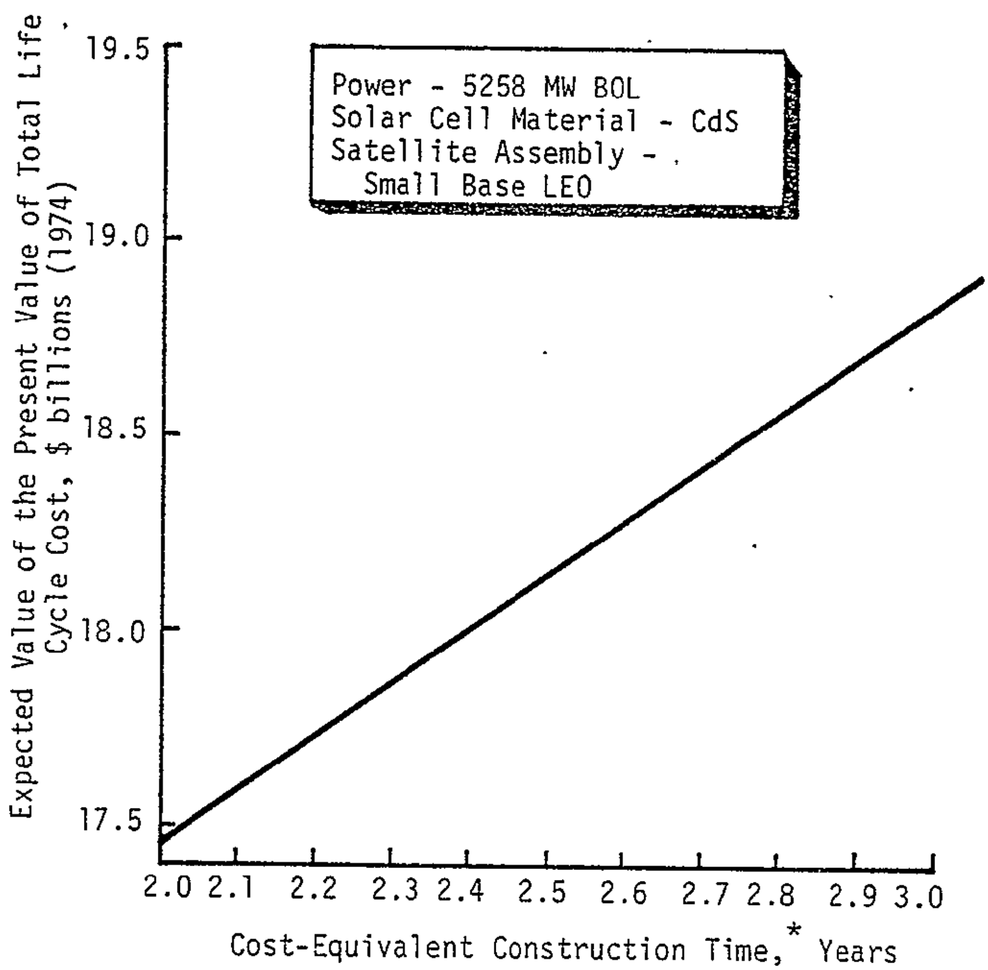

Figure 6.4 The Effect of the Time Required to Construct and Transport One SSPS to GEO on the Present Value of Total Life Cycle Cost

*This is the time increment between the time that a present value-equivalent lump sum payment would be made and the initial operation date of the system. The present value-equivalent payment is a payment of magnitude equal to the undiscounted unit production cost made at a point in time when the present value of both the lump sum payment and the actual cost stream, discounted to the initial operation date, are equal.

7. ANALYSIS OF ALTERNATIVE PROGRAM PLANS

Previous sections of this volume have been directed at the development and use of a risk analysis model for the assessment of cost-risks associated with the production of an SSPS unit (satellite and ground station). This section makes use of the results of the risk analysis to assess a number of alternative SSPS development program plans and to gain insights necessary for improving the proposed plans. The programmatic analysis documented in this section was conducted in two steps during the second and third study phases. First, during the second study phase, three development programs, Programs I, II and III, were formulated and evaluated. The results are based on the cost model and input data developed during that phase of the study. Then, based on the insights developed from the analysis of the first three development programs, two new development programs, Programs IV and V, were formulated and evaluated. As a part of this effort, alternative solar cell materials were evaluated in the context of the overall development program. The results reported for Programs IV and V are based on the cost model and input data as updated during the third study phase.

The discussion below treats Development Programs I, II and III first in their entirety. Then Programs IV and V are discussed separately in Section 7.5.

7.1 Direct Development Program

The Program I, Direct Development, schedule is shown in Figure 7.1. The program begins with a supporting research and technology (SR&T) program in 1977 and proceeds into the design, development, test and evaluation (DDT&E) phase in 1984. The decision to produce the first unit is made in 1987 and the initial operation date of the first unit is December 31, 1991. The final social and environmental (FS&E) impact statement is required on December 31, 1983; the technology is set as of December 31, 1986; and the heavy lift launch vehicle (HLLV) is required on January 1, 1989.

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

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

7.2 GEO Test Satellite to Full-Scale Program

The Program II, GEO Test Satellite to Full-Scale, schedule is shown in Figure 7.2. The program begins with an SR&T phase in 1977. A preliminary

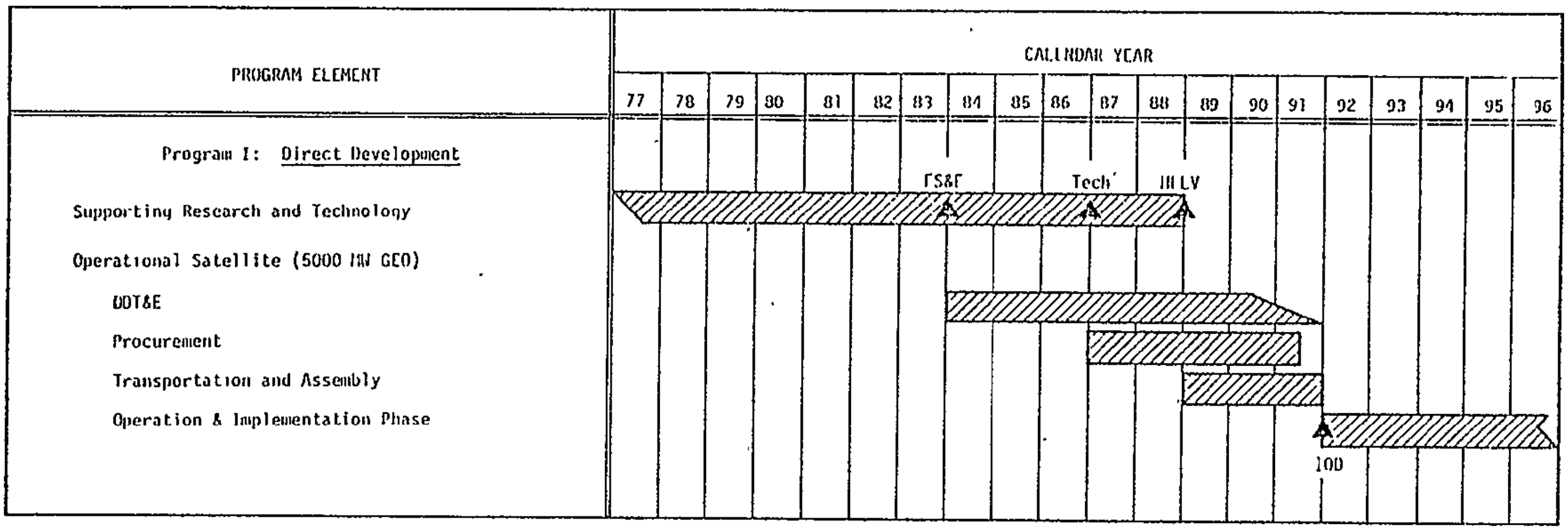

Figure 7.1 Program I Schedule

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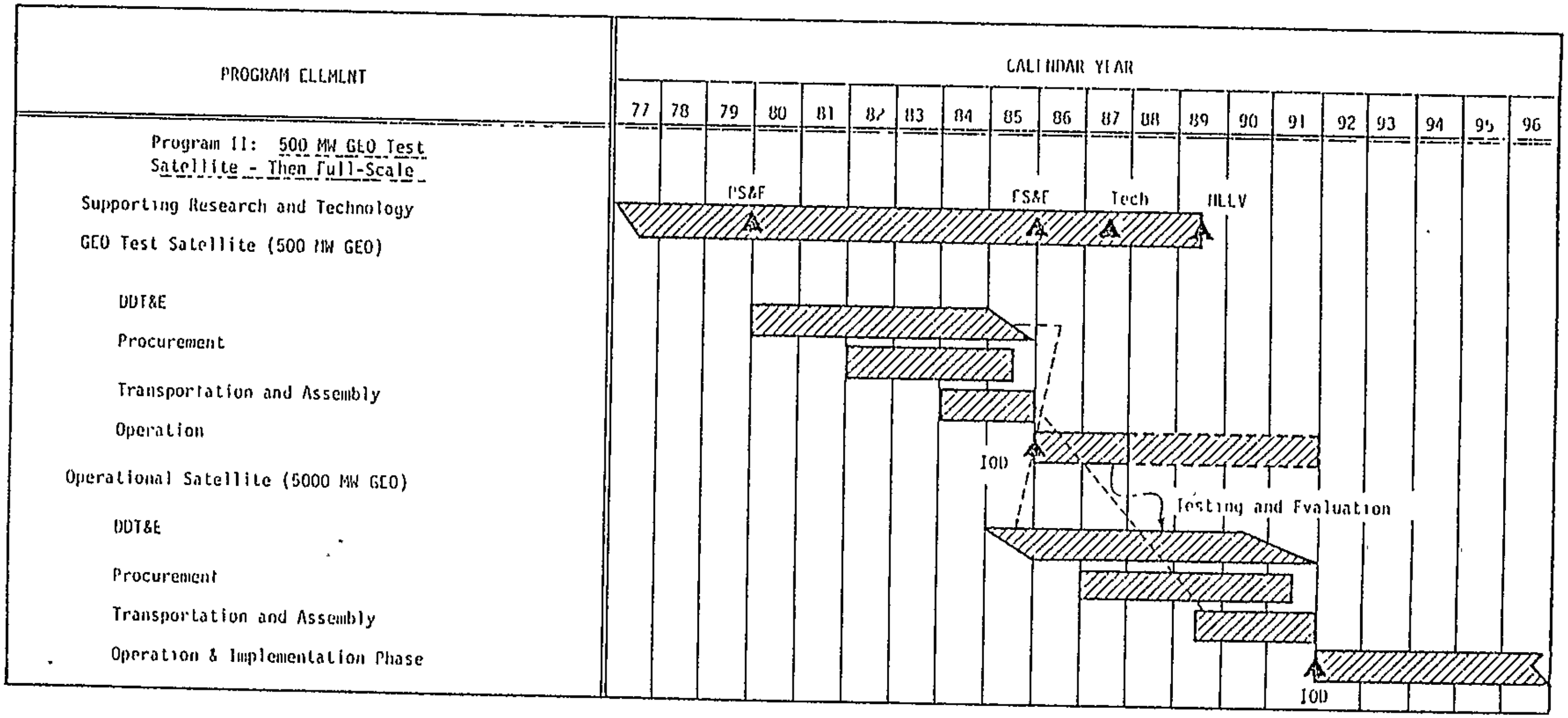


Figure 7.2 Program II Schedule

social and environmental impact statement is required on December 31, 1979, and on January 1, 1980 the decision to develop a 500 MW GEO test satellite is made. The IOD of the GEO test satellite is December 31, 1985. Commitment to the DDT&E of the full-scale satellite is made on January 1, 1985. In reality, this decision would probably be reviewed after the IOD of the GEO test satellite; however, this degree of freedom is not considered here. A commitment to produce the first satellite is made on January 1, 1987, and the satellite IOD is December 31, 1991. The decision to proceed with the implementation of subsequent units is made on January 1, 1992.

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

7.3 LEO and GEO Test Satellites to Full-Scale Program

The Program III, LEO and GEO Test Satellites to Full-Scale, schedule is shown in Figure 7.3. The program begins with an SR&T phase in 1977. Commitment to a LEO test satellite is made in 1980 and the IOD of the satellite is December 31, 1985. Commitment to a GEO test satellite is made on January 1, 1985, and the IOD of the GEO satellite is December 31, 1990. Commitment to the DDT&E of the full-scale satellite is made January 1, 1992. The IOD of the first full-scale unit is December 31, 1995. The decision to implement units 2 through 109 is made on January 1, 1996.

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

It should be noted that these three programs are approximate and not yet well-developed. Assumptions had to be made to perform the following analysis.

7.4 Decision Tree Analysis of Alternative Program Plans

The analysis of alternative program plans begins with an assessment of the current state-of-knowledge relative to the present configuration SSPS. This is assessed in Section 5 and results in the probability distribution of second unit costs shown in Figures 7.4 and 7.5, which provide both the cumulative distribution and probability density functions, respectively, of the present value of the total (life cycle, that is, capital investment plus operation and maintenance) unit costs referenced to the initial operation

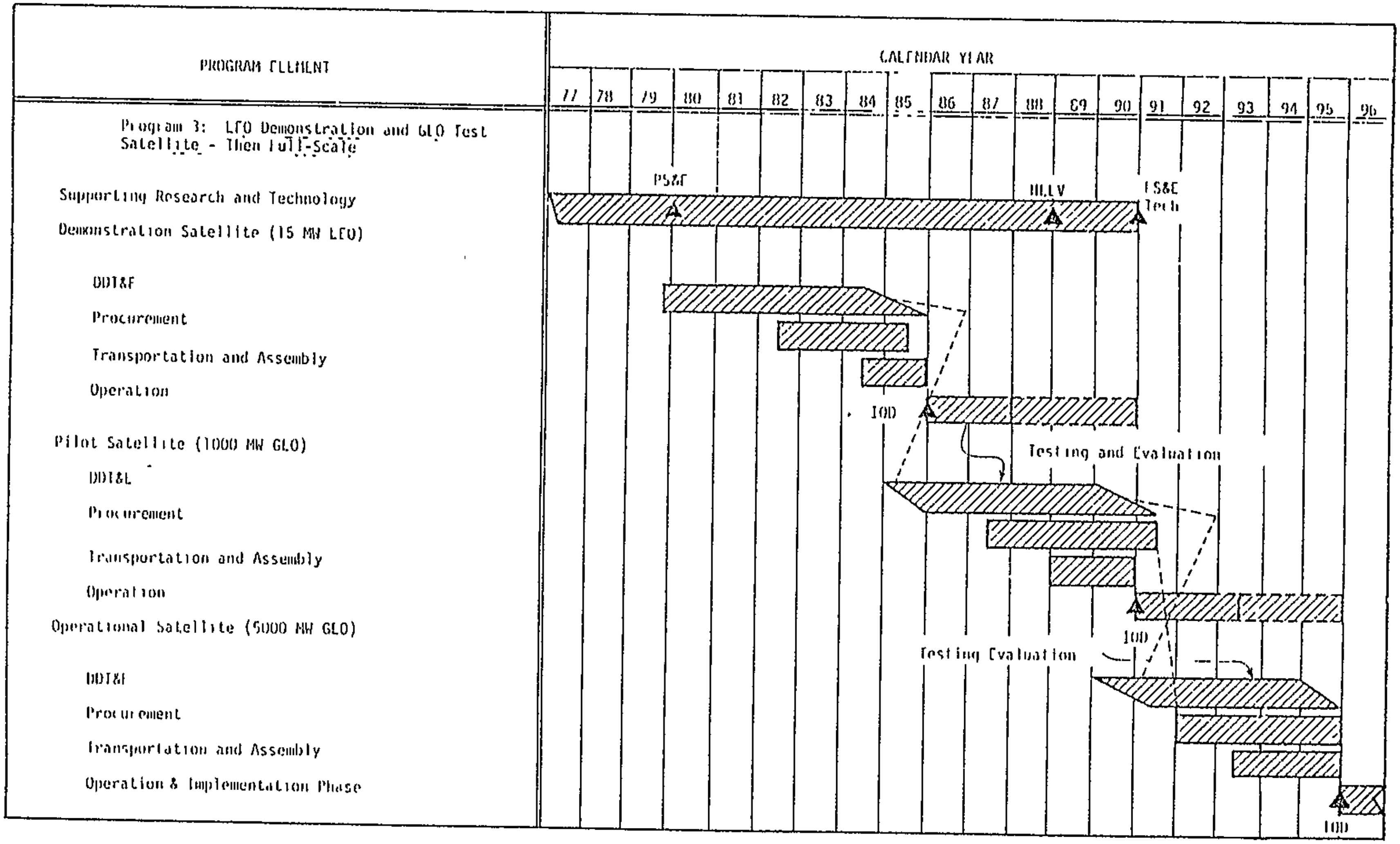


Figure 7.3 Program III Schedule

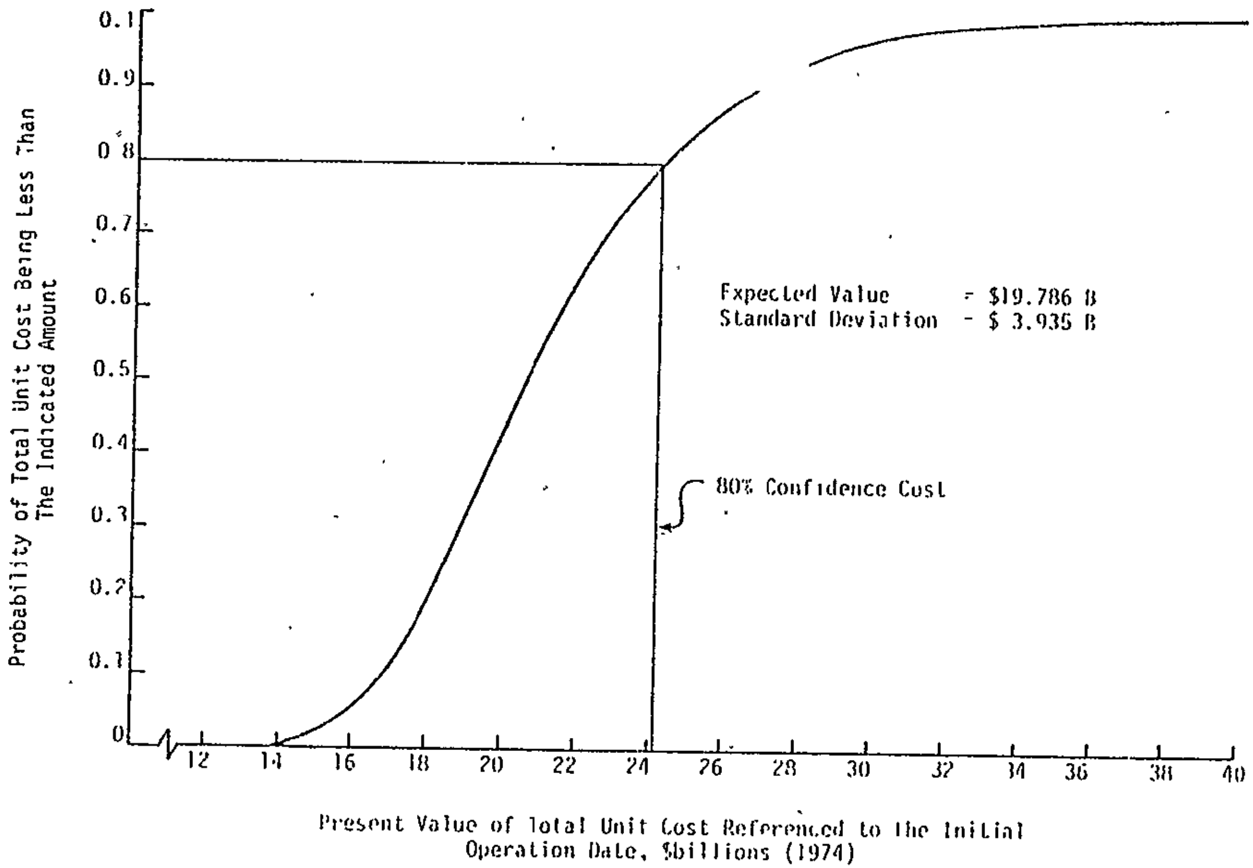


Figure 7.4 Cumulative Distribution Function Of Total (Life Cycle) Second Unit Costs

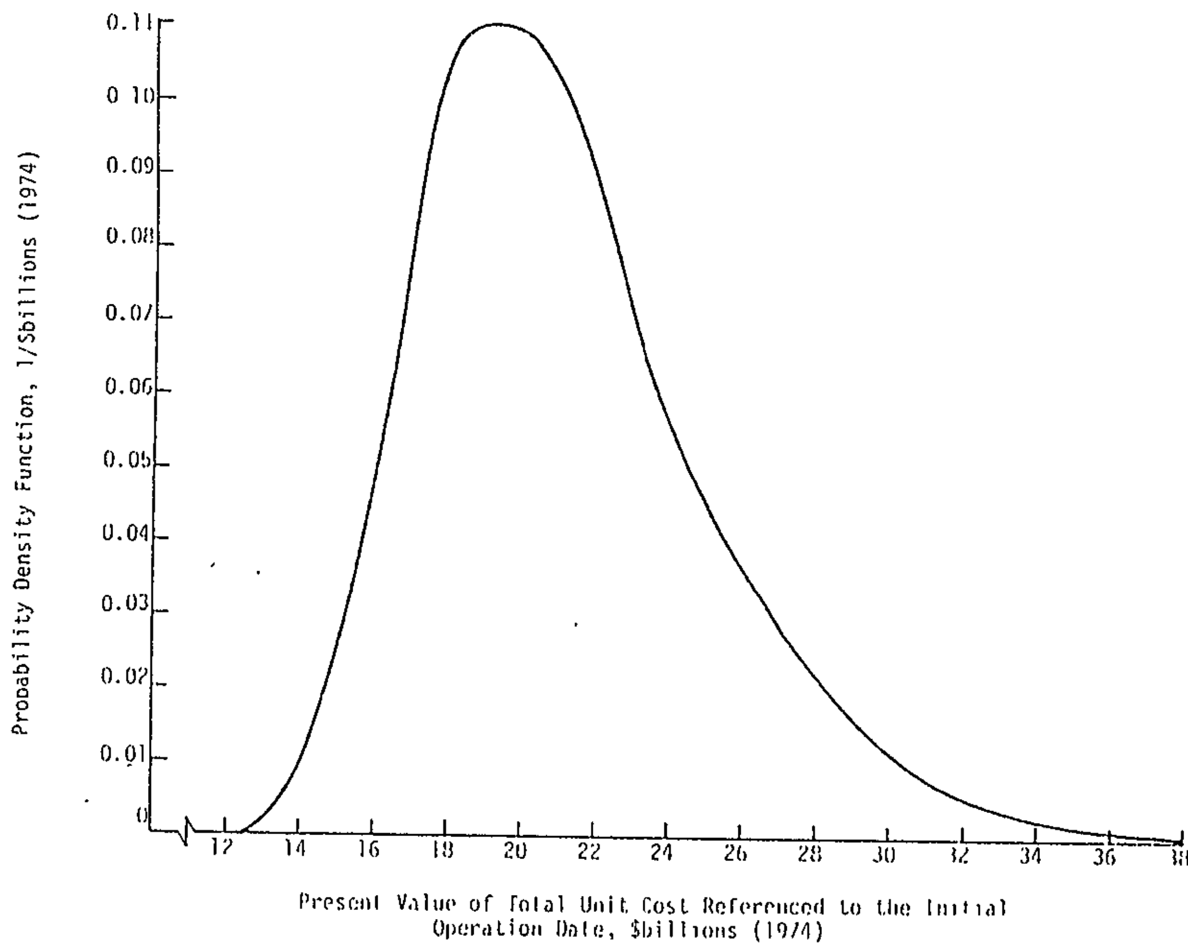


Figure 7.5 Probability Density Function Of Total (Life Cycle) Second Unit Costs

date of that unit. Throughout the analysis which follows, this cost is the key decision variable. Note that the first unit cost is not important here, insofar as the first unit is essentially a prototype and its costs do not necessarily relate to the second and subsequent unit costs. In the computation of the unit costs shown, it is assumed that the capital investment for the SSPS unit is made in a lump sum payment two years prior to the initial operation date of the unit, and a discount rate of 7.5 percent is used. In addition, the following assumptions are made:

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

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

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

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

5. Implementation of second and subsequent satellites is described in Sections 7.1, 7.2 and 7.3. That is, the initial operation date of the second unit is as follows:

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

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

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

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

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

It is assumed that a decision to select one of the three alternative programs will be made on January 1, 1977, thus all following data are referenced to that date. Under the conditions of the above assumptions, the present value of gross revenues of each program is given as a function of the price of power at the rectenna busbar on January 1, 1992, in Figure 7.6. Likewise, the present values of total life cycle costs for units 2 through 109 are given as a function of the present value of the second unit total cost referenced to the initial operation date of that unit in Figure 7.7. From these figures and from the present values of costs of each program (including operation and maintenance costs of the first unit), the net present value of each program

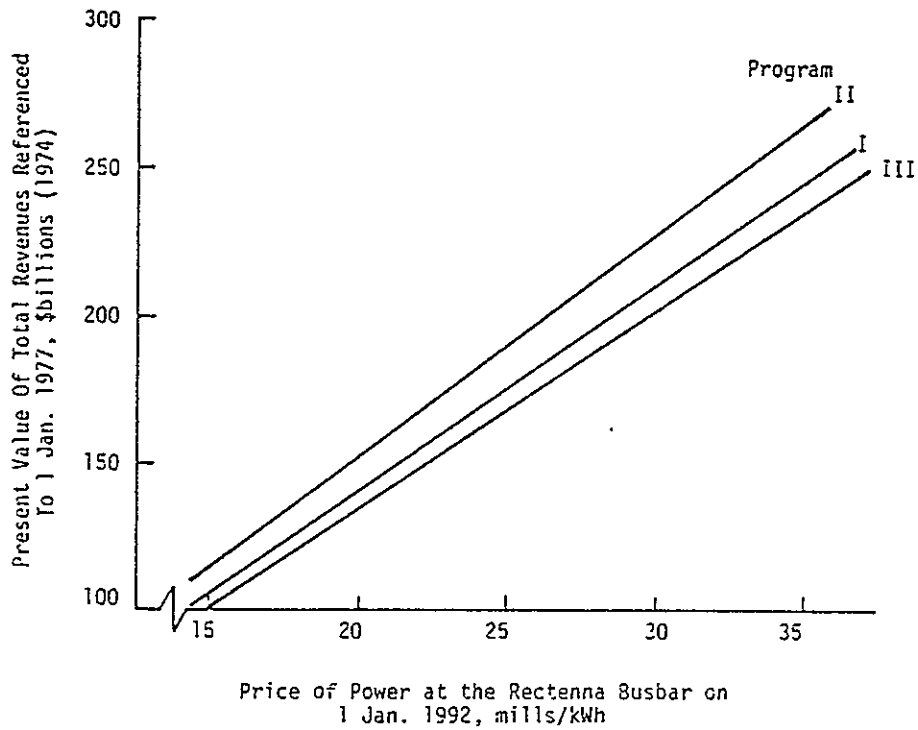


Figure 7.6 Present Value of Gross Revenues Generated by Each Program

is determined as a function of the second unit cost and the price of power on January 1, 1992, as shown in Figure 7.8. The price of power in this figure does not include an allowance for taxes and insurance. Thus, if taxes and insurance are 8.6 mills/kWh as previously estimated, the curves labeled 20 mills/kWh would actually represent a total price of 28.6 mills/kWh at the rectenna busbar on January 1, 1992. In the analysis that follows, it is assumed that the price of power at the rectenna busbar on January 1, 1992 is 20 mills/kWh (or 28.6 mills/kWh including 8.6 mills/kWh allowance for taxes and insurance).

The alternative program plans are now analyzed to determine their expected values. As outlined in Section 3, a go-ahead decision on a specific program plan should be predicated on the basis that that plan has a positive expected value and that risks associated with the plan are adequately controlled. Selection of the best program plan would normally be to choose that plan that yields the highest expected value at the desired decision-making confidence level. The confidence level for decision making chosen for this analysis is 80 percent. While this is a moderately high confidence level, it is not so high as to arouse disputes over the accuracy of the tail (high end) of the distribution shown in Figure 7.4.

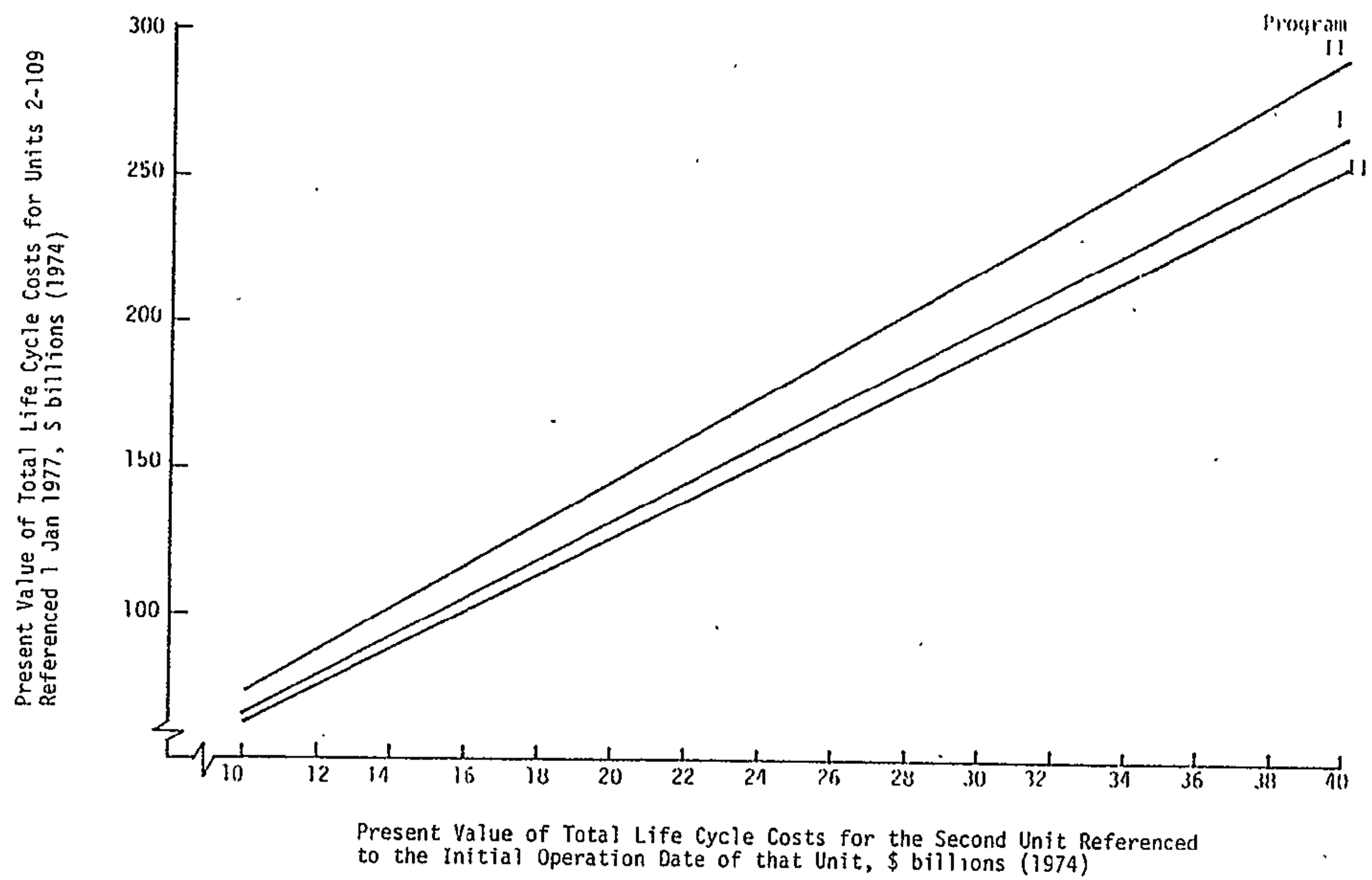


Figure 7.7 Present Value of Total Life Cycle Costs for Units 2 Through 109

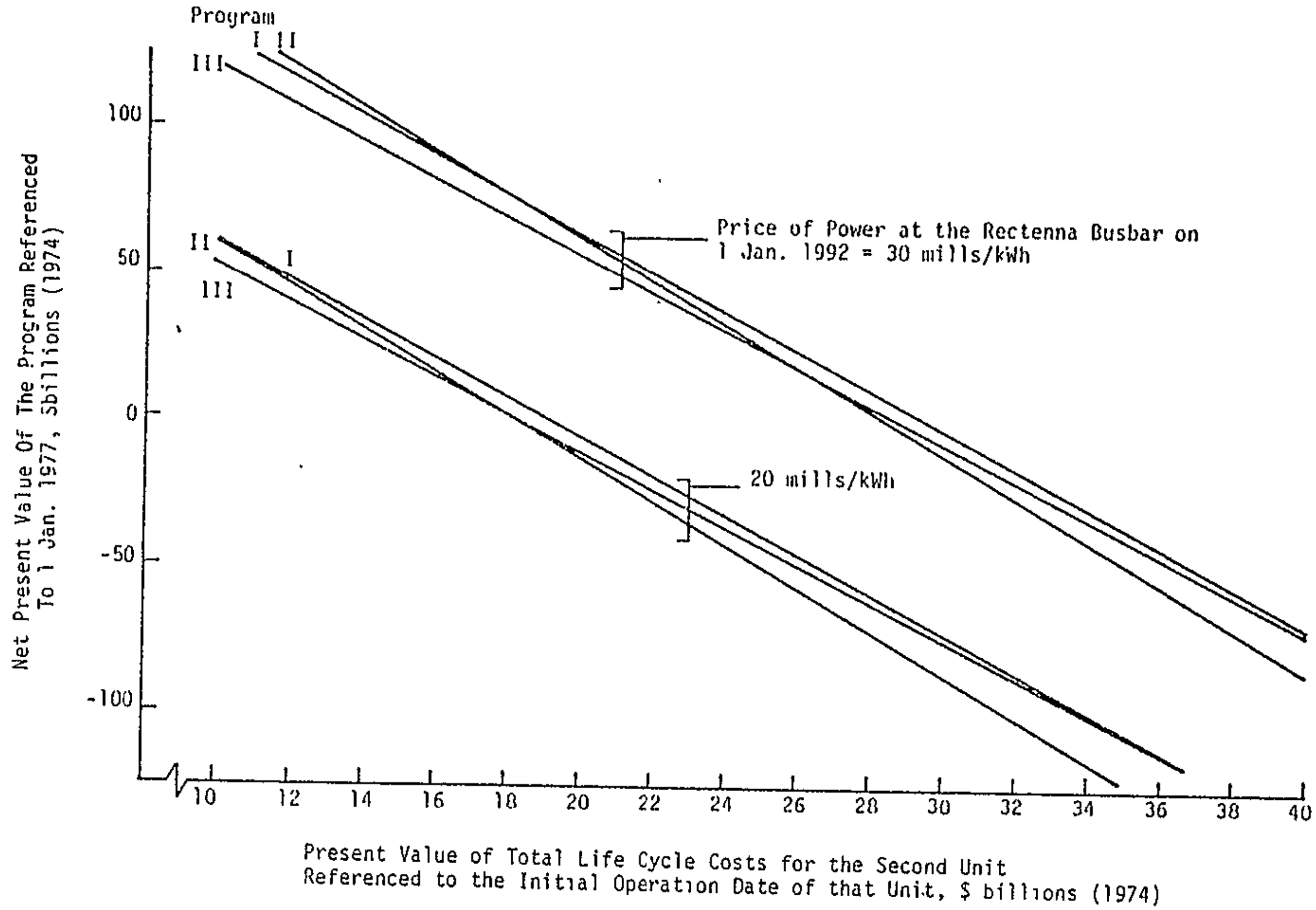


Figure 7.8 The Net Present Value of the Alternative Programs

To proceed with the analysis, the program plans outlined above are expressed in the form of decision trees as shown in Figures 7.9, 7.10 and 7.1 At each decision point in these decision trees, there is a specific criteri based upon which the decision will be made to continue or to terminate the program. These criteria are derived as shown in Figures 7.12, 7.13 and 7.1 First, the state-of-knowledge as of January 1, 1977 is assessed, as shown i Figure 7.4. Then, the 80 percent confidence state-of-knowledge is established--with 80 percent confidence, the second SSPS unit can be produced at a cost of $24.1 billion (1974) or less. This state is plotted as a point i each of Figures 7.12, 7.13 and 7.14. Next, the "break even" cost of the second unit is computed for each program plan. This is the cost of the second unit for which there is exactly zero net present value for the entir program (present value of costs equals present value of revenues). This cost, for each program plan, is taken as the technology target and is also plotted. This shows the cost that the second unit must come in at or below for a "successful" program. Thus, in Program I a successful program is defined as one which proves that the second unit costs are equal to or less than $18.9 billion (1974) by January 1, 1992--the initial operation date of the first unit and the completion date of the development program. At that date, a decision will be made to implement the second and subsequent units or to discontinue the program with the operation of the first unit. For simplicity, the decision rule is then taken as a linear improvement in the 80 percent confidence bound of the technology during the development progran These curves are shown as the 80 percent confidence technology requirements for each program. If the technology development is such that the 80 percent confidence technology bound remains under the 80 percent confidence technology requirement throughout the development program, then the development program will be a success.

Many other decision rules could be formulated. In fact, the one discussed here is probably not the best. For example, the target technology could be based on breaking even only with respect to unsunk (that is, uncommitted) funds. This would improve the chance of success of the program, but would not assure payback of the development costs. In addition, there is nc reason that the technology requirement must improve linearly with time, although this rule does seem to lead to quite logical technology requirements.

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

In the computation of expected value for each program plan, it is neces sary to assess the prior probabilities (that is, the probabilities based on today's state-of-knowledge, before the test takes place) that each test will be passed or failed. To do this, each branch of the decision tree is though of as a process of buying information on the cost of the second unit. As such, the work performed on these branches does not change the cost of the

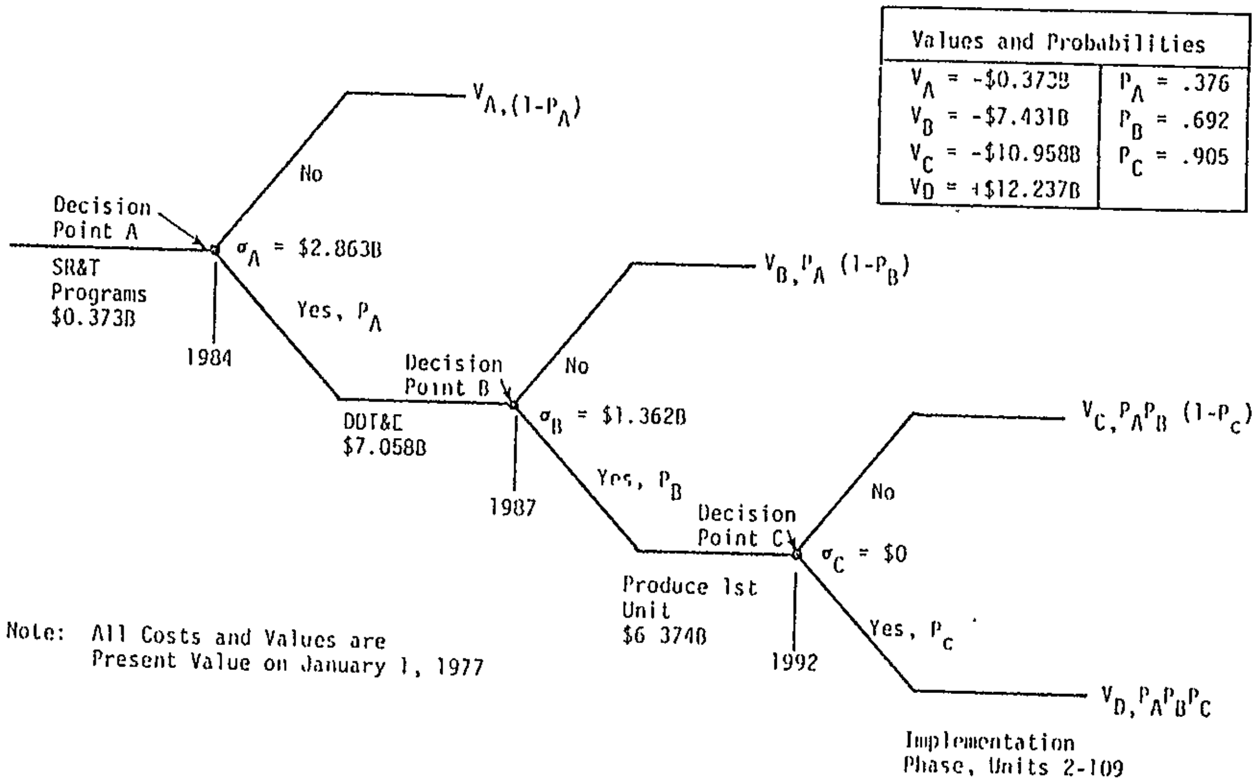
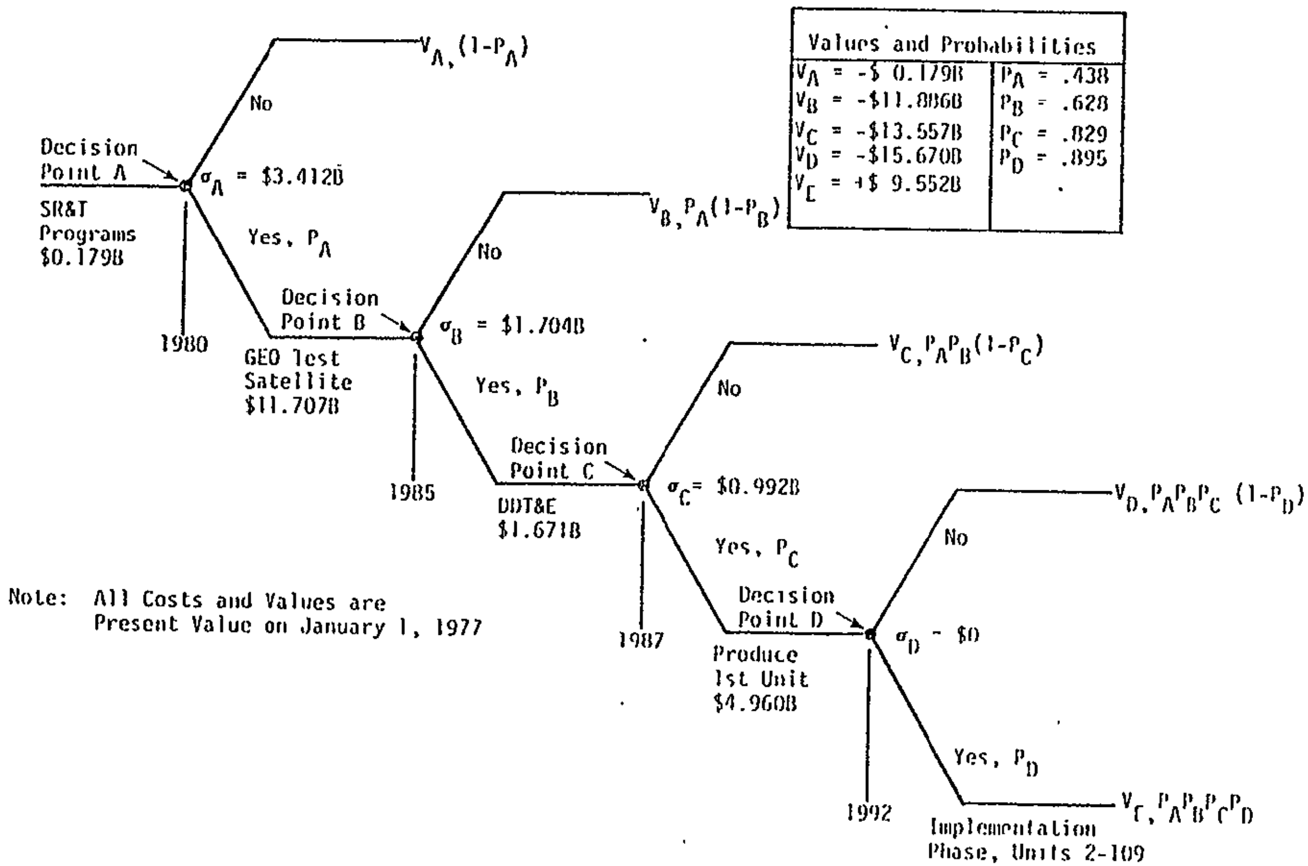


Figure 7.9 Decision Tree Representation of Program I



Note: All Costs and Values are Present Value on January 1, 1977

Figure 7.10 Decision Tree Representation of Program II

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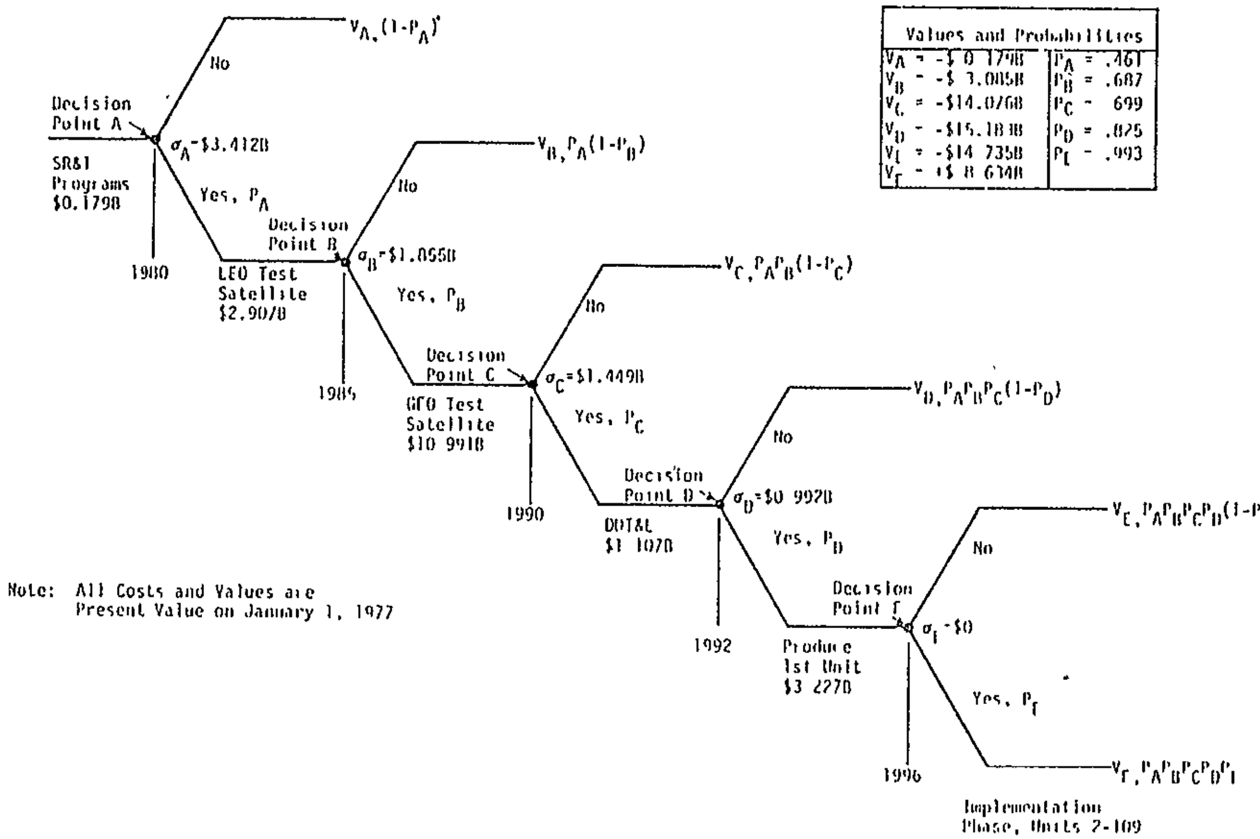

Figure 7.11 Decision Tree Representation of Program III

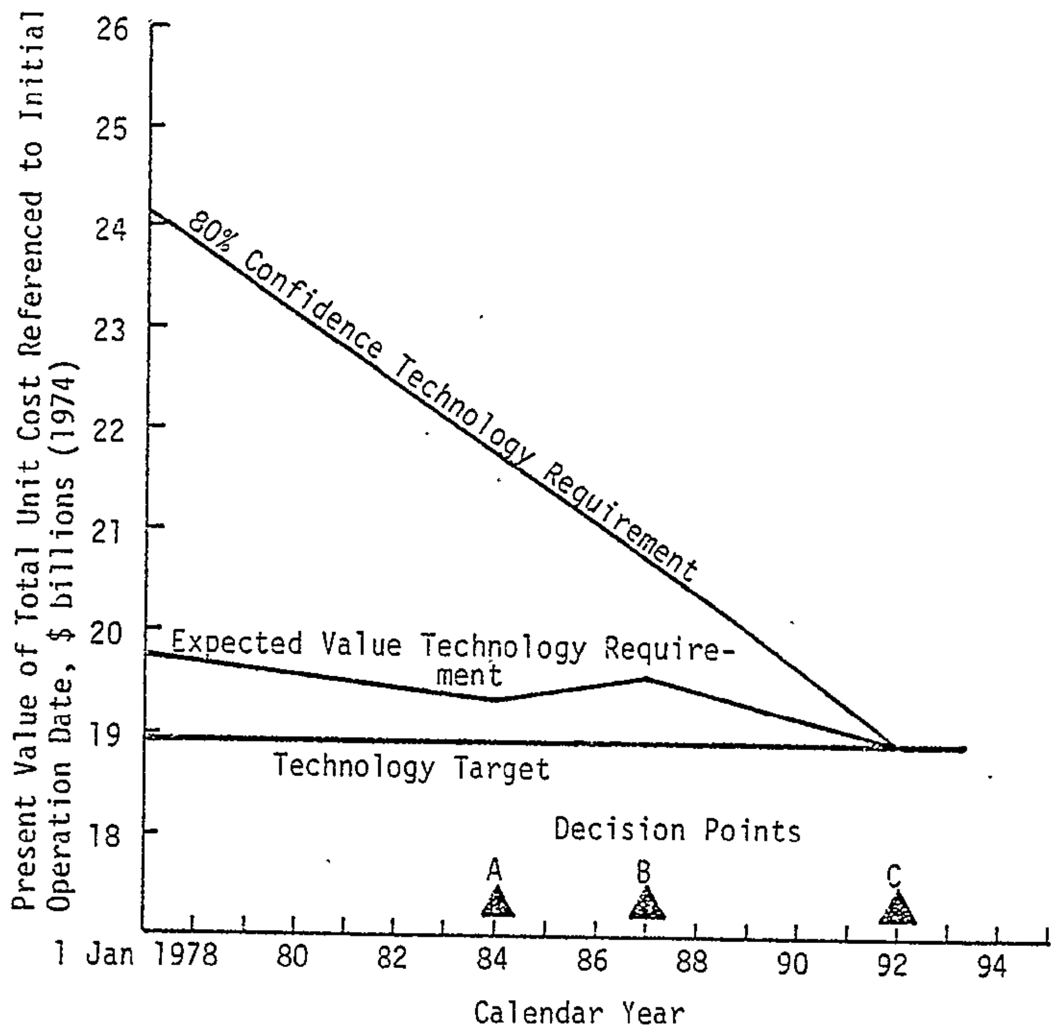

Figure 7.12 Decision Rule For Program I

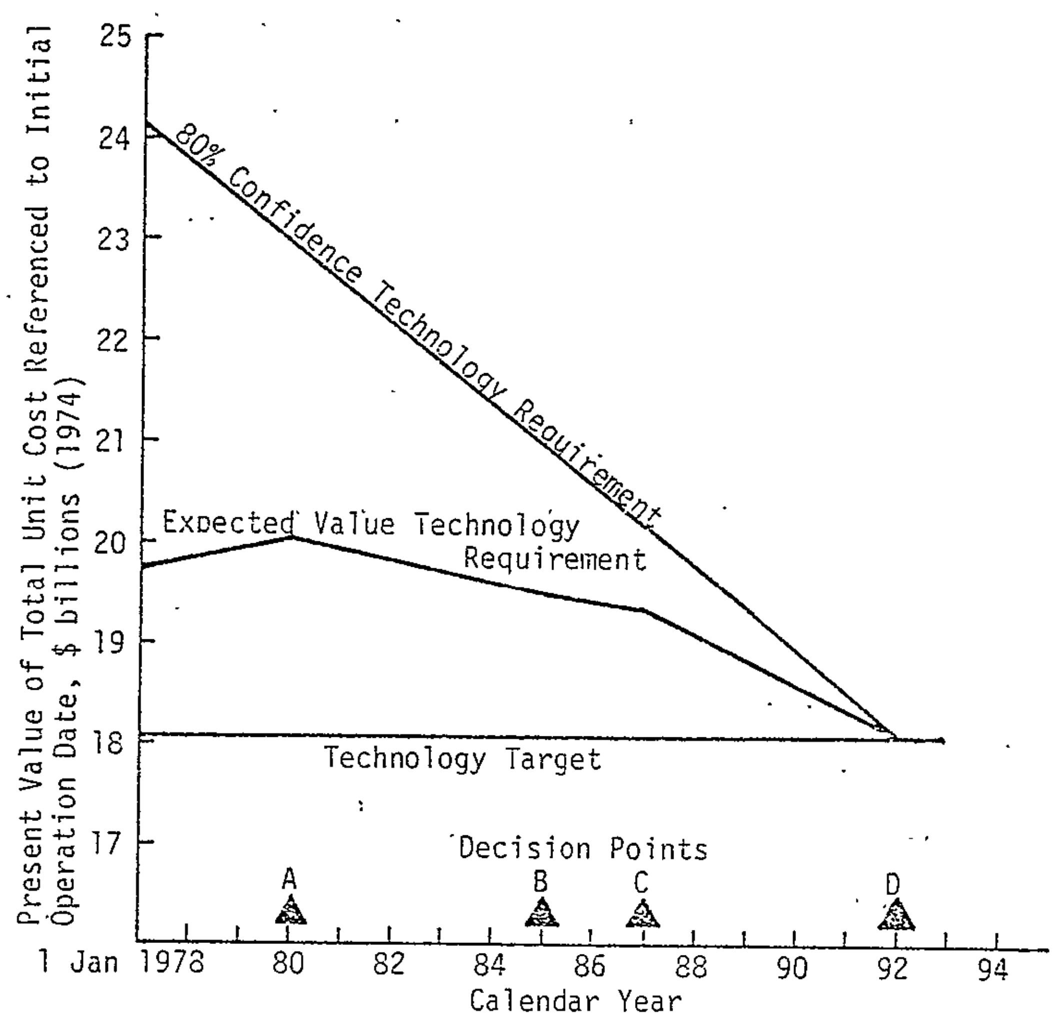

Figure 7.13 Decision Rule For Program II

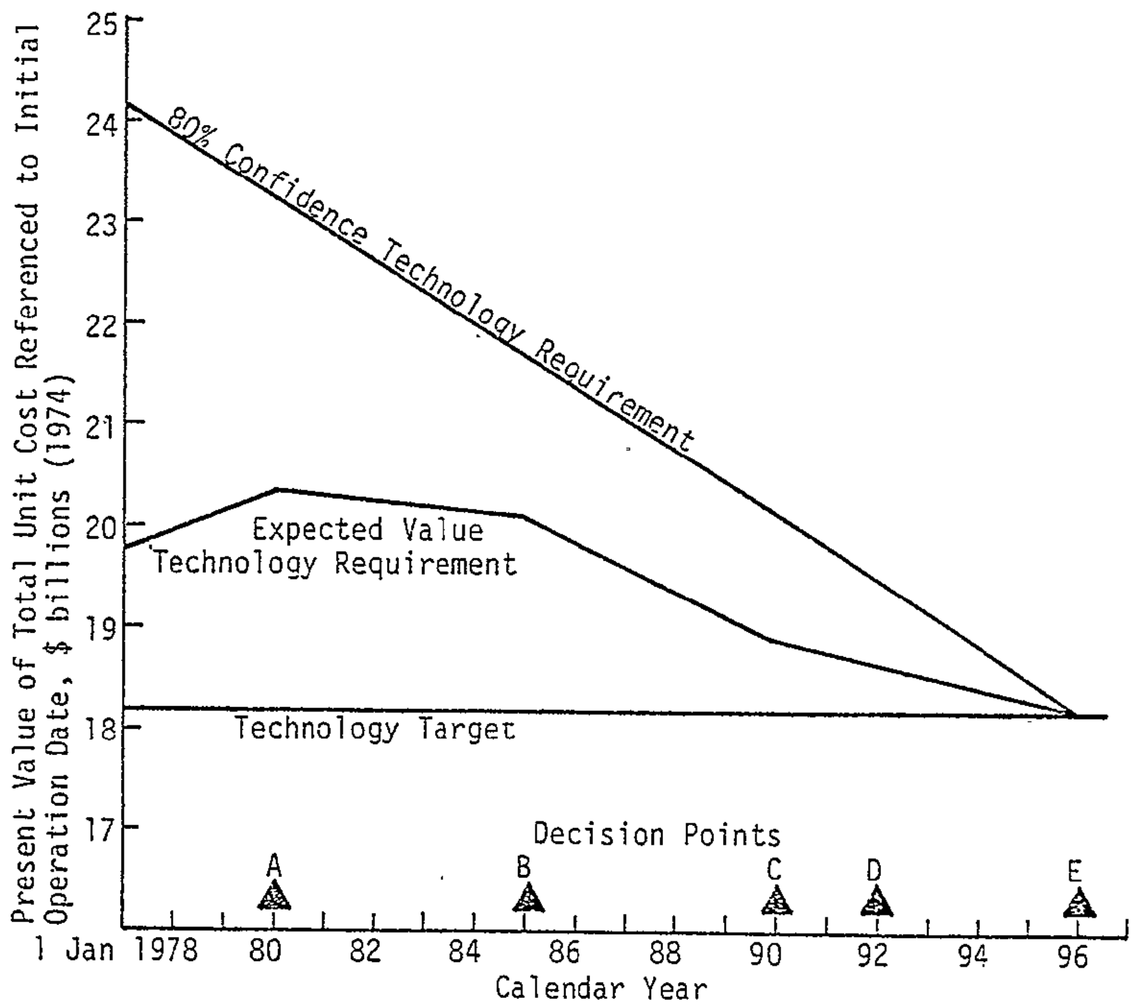

Figure 7.14 Decision Rule For Program III

second unit,* rather it determines with increasing accuracy what that cost is. Thus, a key part of this analysis is an assessment of the accuracy with which the second unit cost will be known at future points in time. To perform this assessment, the improvements in the states-of-knowledge of each variable of the cost model resulting from work performed on each branch of each decision tree have been subjectively estimated. These estimates are shown in Appendix F. Then, the risk analysis model was run to establish the magnitudes of the cost-risks associated with each decision point. The values of the resulting standard deviations of cost estimates, σ_A, σ_B, etc., at each decision point are shown in Figures 7.9, 7.10 and 7.11.

Now, given the 80 percent technology requirement and given the states-of-knowledge at each decision point, it is possible to compute the prior probabilities that each branch of each decision tree will result. It is first necessary to establish the expected value technologies at each decision point. This is done by assuming that the form of the probability distribution of second unit cost is Guassian (or normal) and that the 80 percent cumulative probability point occurs, for each decision point, on the 80 percent confidence technology requirement line. Thus, the required state-of-knowledge at Decision Point A of Program I is expressed as a Gaussian distribution with a standard deviation of \$2.863 billion (1974) and an 80 percent cumulative distribution point of about \$21.7 billion (1974). The expected value technology requirement can be derived as the mean of this distribution. Thus, the expected value technology requirement lines shown on Figures 7.12, 7.13 and 7.14 represent the required expected values of cost estimates made at the time of the corresponding decision points. The methodology for computing the prior probabilities of taking each branch on a decision tree is given in Appendix G.

The resulting values are shown in Figures 7.9, 7.10 and 7.11. Finally, the expected value of each program is computed as the sum of the outcomes for each path through the corresponding decision tree weighted by the probability of occurrence of the path. The expected values for the three program plans considered are as follows:

Program I: +\$1.51 billion (1974)
Program II: -\$1.10 billion (1974)
Program III: -\$0.92 billion (1974).

Under the specific set of assumptions chosen for this analysis, only Program I has a net positive expected value. Thus, of the three specific program options examined during the second study phase, one could only economically justify undertaking Program I. However, recall that this analysis is subject to many assumptions and preliminary cost estimates. For example, decision making is conducted at the 80 percent confidence level. At a lower

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

confidence level, or at a higher price for power at the busbar, Programs II or III or a variant of these programs may become the desired alternative. The appropriate confidence level for decision making might not be 80 percent; this needs to be examined in further studies and the uncertainty relative to the price of power at the busbar should be incorporated into future analyses. Changes in other parameters could also alter the above result.

The reason that the test satellites proposed have negative net value becomes apparent from an examination of the program decision trees. The proposed test satellite subprograms cost more than the economic value they provide; thus, they add negative value to the overall program. However, this conclusion pertains only to the test satellite subprograms proposed in Programs II and III. It is inferred here that other test satellite subprograms might be developed with a net positive value. These programs could make use of smaller test satellites to "buy" essentially the same information at a substantially reduced cost. This logic forms the rationale for the formulation of Programs IV and V, which are discussed in the next section.

7.5 Analysis of Programs IV and V

As a result of the insights gained from the analysis of Programs I, II and III as discussed above, two new programs were formulated and analyzed during the third study phase. These two programs are very similar to each other and are, thus, both described together in this section. The program plans corresponding to Programs IV and V are shown in Figure 7.15. A technology development program begins with research and studies in 1977 and proceeds through about 1985. This program involves ground and orbital tests, including a number of shuttle flight tests on such things as solar cell materials, structures and construction techniques, and microwave power transmission. In 1980, as a part of the overall technology development program, a 150 kW test satellite subprogram is initiated. In 1983, also as a part of the overall technology development program, a 2 MW test satellite subprogram is initiated. The decision to design, develop, test and evaluate (DDT&E) the first full-scale prototype is made January 1, 1987 and the decision to produce the full-scale prototype is made January 1, 1992. The first full-scale satellite becomes operational on December 31, 1995, and the decision to proceed with the implementation phase is made on January 1, 1996. In the implementation phase, it is assumed that four new satellites become operational each year, beginning on January 1, 1998 with the second unit, until a total of 120 satellites have become operational.

The differences between Programs IV and V are detailed in Table 7.1 and lie entirely in the test satellite subprograms. In Program IV, the 150 kW test satellite is built and remains in LEO. It produces 150 kW of power continuously (330 kW peak power with storage) and is used to power a space station. In Program V, this test satellite is sized to produce 150 kW of power (peak) and is built in LEO and transported to GEO, where it is used to conduct a number of experiments, including tests on plasma effects with large solar arrays in GEO, solar concentration, and microwave phase front control in the presence of a ground-heated ionosphere. The satellite will have a 100-meter-long linear array transmitting antenna. The 2 MW test satellite in both

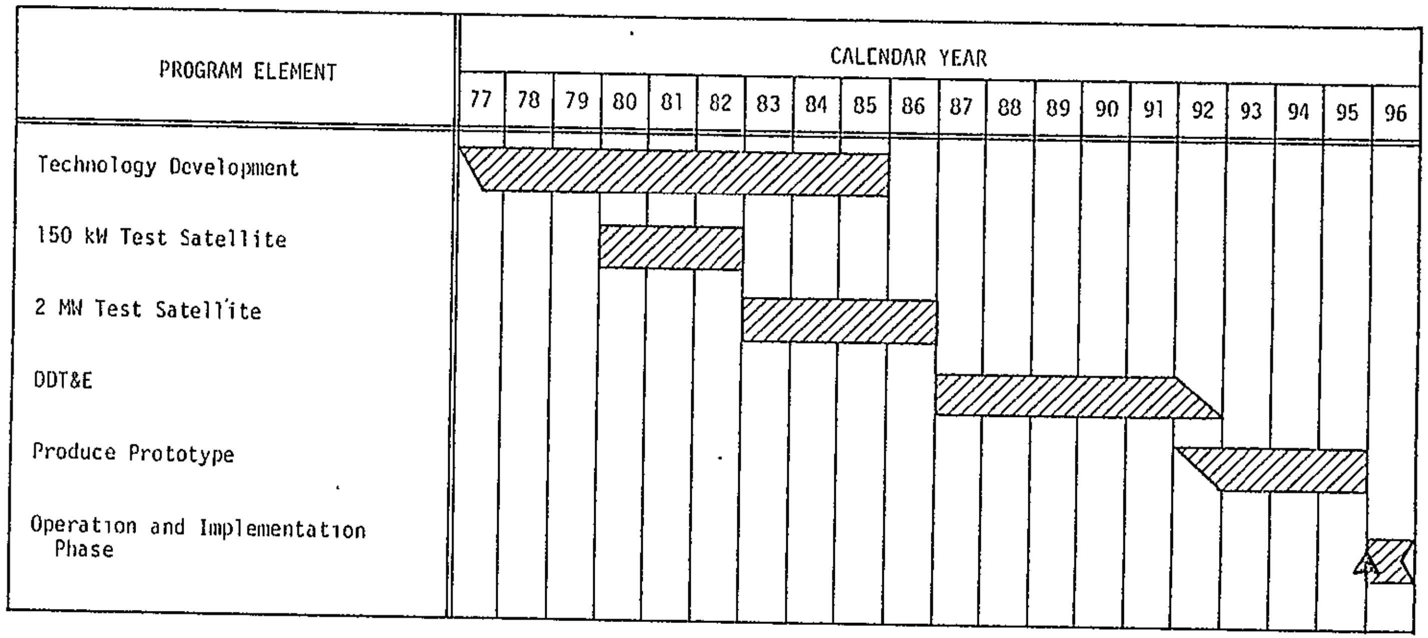

Figure 7.15 Programs IV and V Schedule

Table 7.1 Test Satellite Subprograms

Parameter	Program IV	Program V
150 kW Test Satellite		
Power Level	150 kW Cont. (330 kW Peak)	150 kW
Mass	13,000-21,000 kg	8,000-10,000 kg
Antenna	None	105 m Linear Array
Conc. Ratio	1	1.7 Design/1.5 Effective
Use	Power Space Station	Conduct Tests--Solar conc., plasma effects, microwave trans., ground heat ionosphere
Remarks	Stays in LEO	Built in LEO, trans. to GEO
2 MW Test Satellite		
Power Level	2 MW	2 MW
Mass	20,000 kg	35,000-45,000 kg
Antenna	20 m x 20 m Subarray	20 m x 20 m Subarray and 1000 m Linear Array
Remarks		Conduct ionospheric and phase control tests

Programs IV and V will be placed in GEO and used for microwave tests. However, in Program IV, the test will be performed using a 20 m x 20 m antenna subarray whereas, in Program V, the satellite will have both a 20 m x 20 m subarray and a 1000-meter linear array antenna.

The costs of Programs IV and V are summarized in Table 7.2 and a decision tree for these programs is shown in Figure 7.16. The programmatic analysis was conducted for Programs IV and V for an SSPS configuration making use of each of the three candidate solar cell materials examined, Si, GaAs and CdS. The assumptions made on the size, power production, availability, and costs for the program are the same as those made for Programs I, II and III in Section 7.4, except that the power degradation in time is taken to be a function of the solar cell material as described in Section 5.3. The analysis then proceeds precisely as described above for Programs I, II and III.

The results of the programmatic analysis are summarized in Table 7.3. All of the programmatic alternatives examined in Programs IV and V are substantially better than those examined in Programs I, II and III. The results

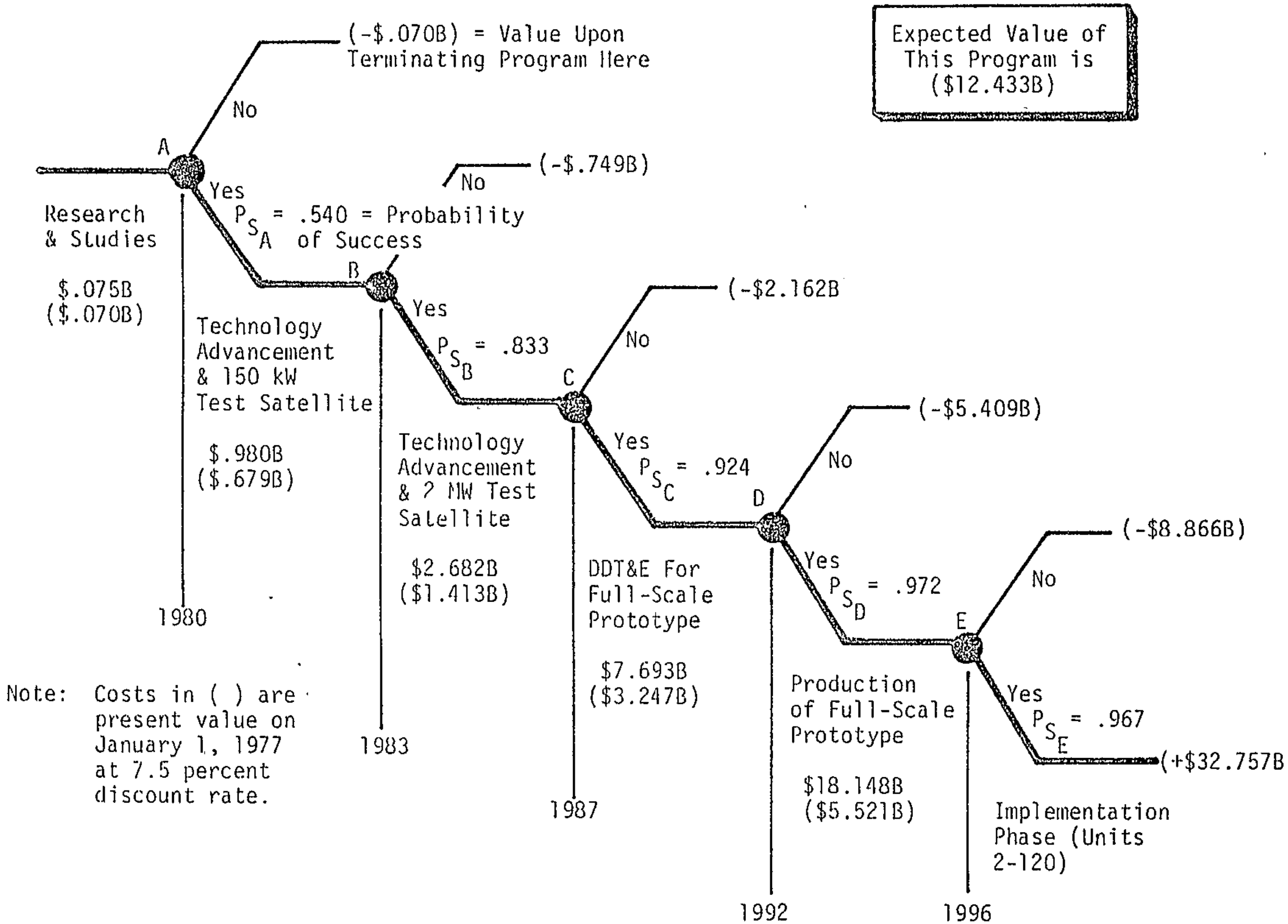

Figure 7.16 Development Program Decision Tree for Programs IV and V--Data Shown for Program V, Si Solar Cell Configuration SSPS

Table 7.2 Programs IV and V Costs

	Decision Date	P.V. of Cost,* $B
Program IV		
Research and Studies	1977	0.070
LEO Test Satellite (150 kW)	1980	0.578
GEO Test Satellite (2 MW)	1983	1.216
DDT&E	1987	3.257
Production of Prototype (First Unit)	1992	5.513
Implementation (Total 120 Satellites)	1996	
Program V		
Research and Studies	1977	0.070
LEO Test Satellite (150 kW)	1980	0.679
GEO Test Satellite (2 MW)	1983	1.413
DDT&E	1987	3.247
Production of Prototype (First Unit)	1992	5.521
Implementation (Total 120 Satellites)	1996	

*Present value of cost referenced to January 1, 1977 at a discount rate of 7.5 percent.

for Programs IV and V indicate a significant advantage for CdS solar cells and with GaAs solar cells being the second favored option. However, too little is really known about these materials at this time to simply accept one or the other of these materials as the appropriate material for the SSPS in lieu of Si. But the results strongly suggest that the development program should not limit itself to the consideration of Si solar cell material alone. More work is necessary to define a solar cell material development program that, in its early phases, examines a broad range of potential materials and focuses on one or two materials only after much more is known about the full range of possibilities.

A second major area of interest in the comparison of Programs IV and V to Programs I, II and III is in the probability of success of the entire program that is estimated for each program alternative. Here it is seen that Programs IV and V both have about twice the chance of succeeding that Programs I, II and III have. This is due to two major effects. The first is that the risk analysis performed for the SSPS configurations examined in

Table 7.3 Results of Programmatic Analysis

Program	Solar Cell Material	Probability of Success	Expected Value,* $B
I	Si	.236	1.51
II	Si	.204	-1.10
III	Si	.181	-0.92
IV**	Si	.380	12.29
	CdS	.560	25.60
	GaAs	.371	18.78
V**	Si	.389	12.43
	CdS	.570	25.86
	GaAs	.379	19.00

*Present value on January 1, 1977 at a discount rate of 7.5 percent.

**For LEO assembly using the small factory-in-space.

Programs IV and V shows more cost-risk than the analysis performed for Programs I, II and III; however, the expected value of the costs was about equal for all the alternatives analyzed. Thus, not only is there a higher chance of a higher cost resulting for these alternatives, but there is also a higher chance of a lower cost resulting. In the context of a program plan that adequately controls high-side risk, this added risk is beneficial because it affords, at the same time, an increased chance for a more economical SSPS. That is to say that, in the early phases of a research and development program, it can be economically beneficial (and justifiable) to take risks in order to seek out potentially beneficial opportunities. The second effect deals with the fact that Programs IV and V appear to "buy information" in a more effective manner than do Programs I, II and III. As discussed in Section 8, this results in a lower probability that a successful development effort will be mistaken for an unsuccessful one and the program terminated. It also means that there will be a lower probability of continuing a program that should be terminated.

The results of the above analysis clearly show that Programs IV and V are better than Programs I, II and III. They do not show, nor are they meant to imply, that Program IV or V is the best program, or even the "right" program, to pursue. But they are economic and they are effective programs; and pursuit of one of them could probably be economically justified, even after a substantially more in-depth analysis and review. However, it is recommended that neither of these programs be pursued; but rather, that an effort should be devoted, first, to the formulation of even better programs. The direction to pursue at this point would be one of finding parallel development paths, such as in the area of solar cell materials, in order to increase the overall probability of success for the program.

As a final warning, the results of the above analysis depend upon the assumptions made. Changes in the assumptions may change the conclusions. Thus, while the insights gained may be valuable, decisions should be based on this analysis <u>only after a thorough review of the cost model, the cost model (state-of-knowledge) data and the assumptions made for the analysis</u>.

8. PROGRAMMATIC RISK ANALYSIS

Given the results of Section 7, a brief programmatic risk assessment is possible. This discussion will focus on Programs I, IV and V and draw comparisons between them. Program I is the only program, of the specific alternatives analyzed in the second study phase, that has a positive expected value. This development program consists of three major subprograms: an SR&T subprogram, a DDT&E subprogram and a first unit production subprogram. Success in each of these subprograms can be defined as achieving a state from which a decision to continue the program can be justified. Then, from Figure 7.9, it is seen that the probability of a successful SR&T subprogram is 0.376, the probability of a successful DDT&E subprogram is 0.692 given that the SR&T subprogram is successful and the probability of a successful first unit production subprogram is 0.905 given that the DDT&E subprogram is successful.

The probability of success of the program is the product of the probabilities of success of each subprogram. Thus, there is a probability of 0.235 that Program I will be successfully completed. This compares with a probability of about 0.32 (from Figure 7.4) that the current configuration could be economically viable given Program I. Thus, the program as presently planned yields about a 27 percent chance of rejecting a viable outcome. That is, given that the current configuration is economically viable, there is about a 27 percent chance that it will be classified as not viable, resulting in a program failure. This is the result of inaccuracies in the measurements of projected second unit costs at Decision Points A and B. This loss could be reduced if more accurate measurements could be obtained at about the same cost.

Program V consists of five development phases: a research and studies subprogram, a 150 kW test satellite subprogram, a 2 MW test satellite subprogram, a DDT&E subprogram and a first unit production subprogram. The probabilities of success for the silicon solar cell configuration are respectively: 0.539, 0.832, 0.924, 0.973, and 0.967. This yields a total probability of success for Program V of 0.389 for this configuration. One difference between Programs I and V that results in Program V having a higher probability of success lies in the cost model. While the cost model used to evaluate system costs for Program V incorporates additional areas of uncertainty compared to the cost model used in Program I, these additional areas of uncertainty result in a higher level of cost-risk which subsequently yields both a higher probability of a lower cost and a higher probability of a higher cost. It is the higher probability of a lower cost that is played upon in Program V to increase the probability of success of this program. Use of the factory-in-space concept for construction of the satellite also has a beneficial effect on program economics.

Comparing the probability of success of Program V, 0.389, to the theoretical maximum probability of success for that program as obtained from Figure 7.16, 0.505, it is seen that there is about a 23 percent chance of rejecting a viable outcome. This is a 15 percent reduction over Program I. That is to say, the economic analysis above indicates that one significant reason that Program V is more likely to be successful than Program I is that it is less likely that an incorrect economic assessment of the program at some future decision date will result in its termination. Properly structuring a development program to buy information for future decisions so as to insure that these decisions are made under the best possible state-of-knowledge is key in obtaining a high probability of success in a program.

It is also of interest to compare Programs IV and V for, say, the silicon solar cell configuration. These two programs are similar in most respects, differing only in the 150 kW and 2 MW test satellite subprograms. Program V is more costly than Program IV, yet Program V has a higher probability of success. Surprisingly, it does this while requiring the second unit total life cycle cost to be lower than is necessary for break-even in Program IV. The reason that this occurs is simply that Program V buys information to proceed through the program in a more efficient way than does Program IV. This example serves to indicate that there is an optimum funding level for an SSPS development program and that it is not necessarily true that the minimum cost program is either the best from an engineering point of view or from an economic point of view. In fact, the analysis described in this report embeds the engineering factors in the economic analysis.

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

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

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

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

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

9. UTILITY INTERFACE ANALYSIS

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

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

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

9.1 Effects of Reliability

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

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

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

There are a number of factors which affect utility system reliability which ought to be included in such a model. The size of a new unit will create a disproportionate increase in the reserve requirement if it is very large with respect to the other units in the system or large with respect to the total system capacity. This effect will decrease as other large units are added and/or as the total system capacity increases. An example of the trend toward larger unit sizes is provided in Figure 9.1, which shows the distribution of sizes of units to be added this decade and next decade in the Eastern Central Area (ECAR), shown in Figure 9.2. The total capacity in this area is expected to increase from 55 GW in 1970, to 116 GW in 1990. The effect of SSPS unit size is discussed later.

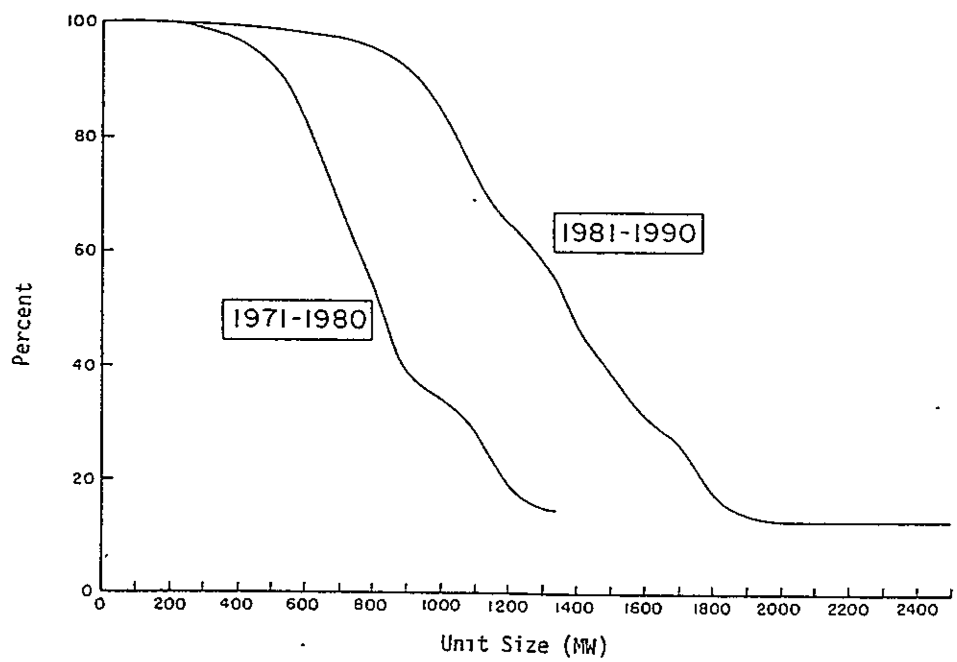

Figure 9.1 Cumulative Distribution of Steam Generating Units Added Between Years (Percent of Installed on Generating Units Sizes Equal or Greater Than Abscissa) For the East Central Region (Source: Federal Power Commission, The 1970 National Power Survey - Part II)

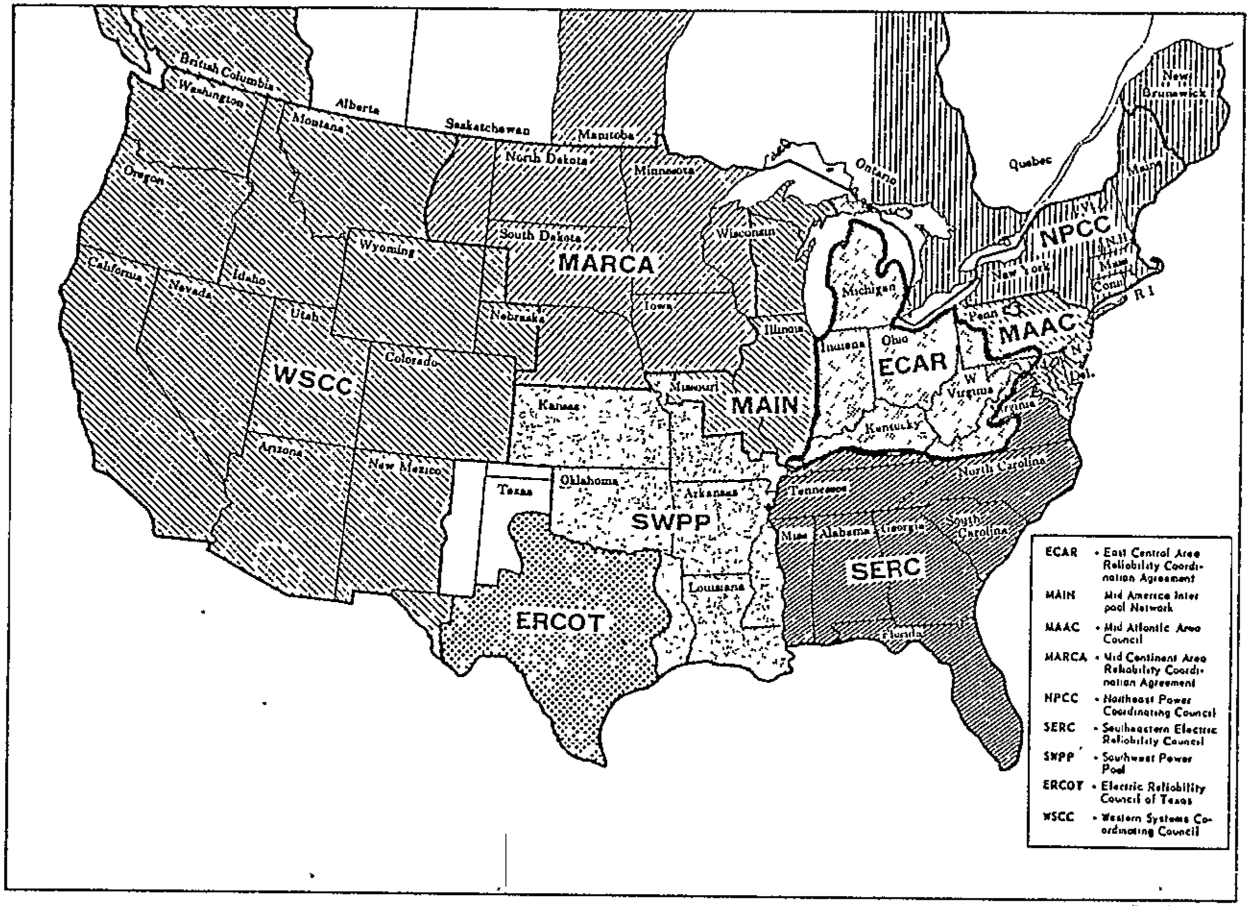

Figure 9.2 Geographic Area of the Eastern Central Area Reliability Coordination Agreement (Source: Federal Power Commission, Annual Report 1973)

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

Increasing the number of generating units in a system and increasing the number of interconnections with other systems through power pooling both have the effect of reducing required reserve margins. The seasonal distribution of peak loads can also have an effect on reserve margin; if there is wide variation between seasonal peaks, then planned outages can be scheduled for lower demand seasons without requiring reserve capacity. If, however, the load is fairly balanced from season to season, then it may be necessary to install reserve capacity to allow planned outages, such as those necessary for maintenance.

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

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

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

Availability rates are used in calculating the cost of power from baseload generation plants, because availability rates account for the time that a plant is not able to produce power due to maintenance or other scheduled outages. The effect of availability on the cost of power can be significant, especially for capital-intensive generation methods such as nuclear reactors or SSPS. Based on cost data provided by Arthur D. Little, Inc.,* the total busbar energy cost has been calculated as a function of unit availability,** for three different generation systems: light water reactor, liquid metal fast breeder reactor and direct coal-fired plant. These relationships between energy costs and generating unit availability are displayed in Figure 9.3. Given that SSPS availability is expected to be about 95 percent, it is clear from Figure 9.3 that SSPS could tolerate a somewhat higher life cycle cost per kilowatt and still produce power at the same energy cost. Light water reactors currently are designed for 80 percent availability; and SSPS operating at 95 percent availability (Case A) could cost approximately $70/kW more than the light water reactor and produce power at the same capital equipment cost. The industry-wide experience for light water reactors at the moment is closer to 65 percent***; if this value remains unchanged, an SSPS costing $200/kW more than the nuclear plant (Case B) could produce power at the same capital equipment cost. Thus, the level of reliability projected for SSPS could be an important economic factor.

In addition to reliability, SSPS size in both absolute and relative terms is an important consideration in calculating the system reserve requirements and accompanying costs resulting from the introduction of an SSPS. A simulation which would estimate the cost effect of the addition of SSPS's to realistic representations of utility systems projected for 1995 could not be conducted within the scope of this study. However, an examination was made of the effect on reserve margin requirements of adding an SSPS to several systems, each containing units of uniform size and reliability, over a range of system sizes that might be typical in the future (30-50 GW). The results are presented in Figure 9.4. The unit sizes used were 1 GW and 2.5

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

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

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

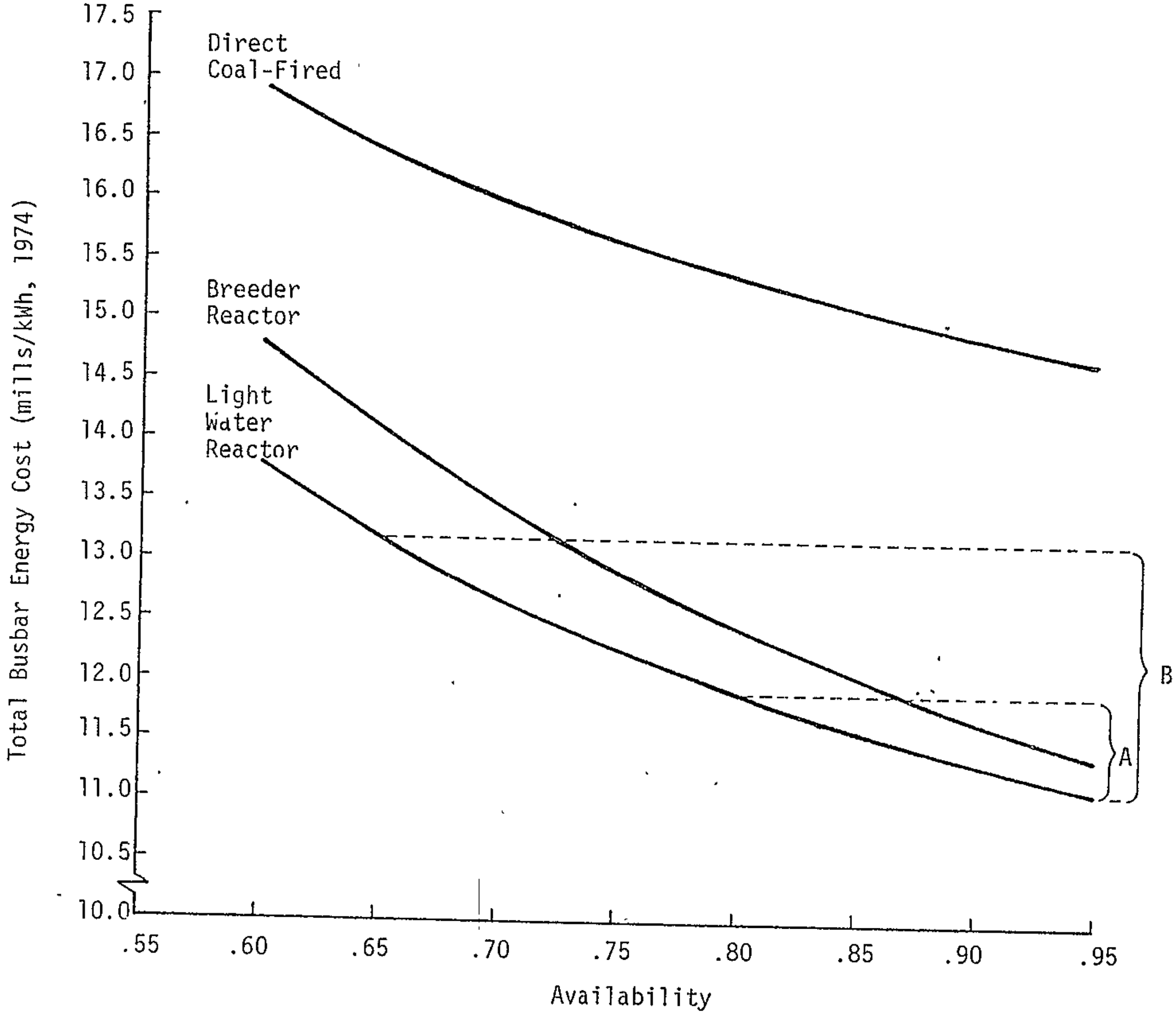

Figure 9.3 Relationship of Generating Unit Availability to Total Energy Cost

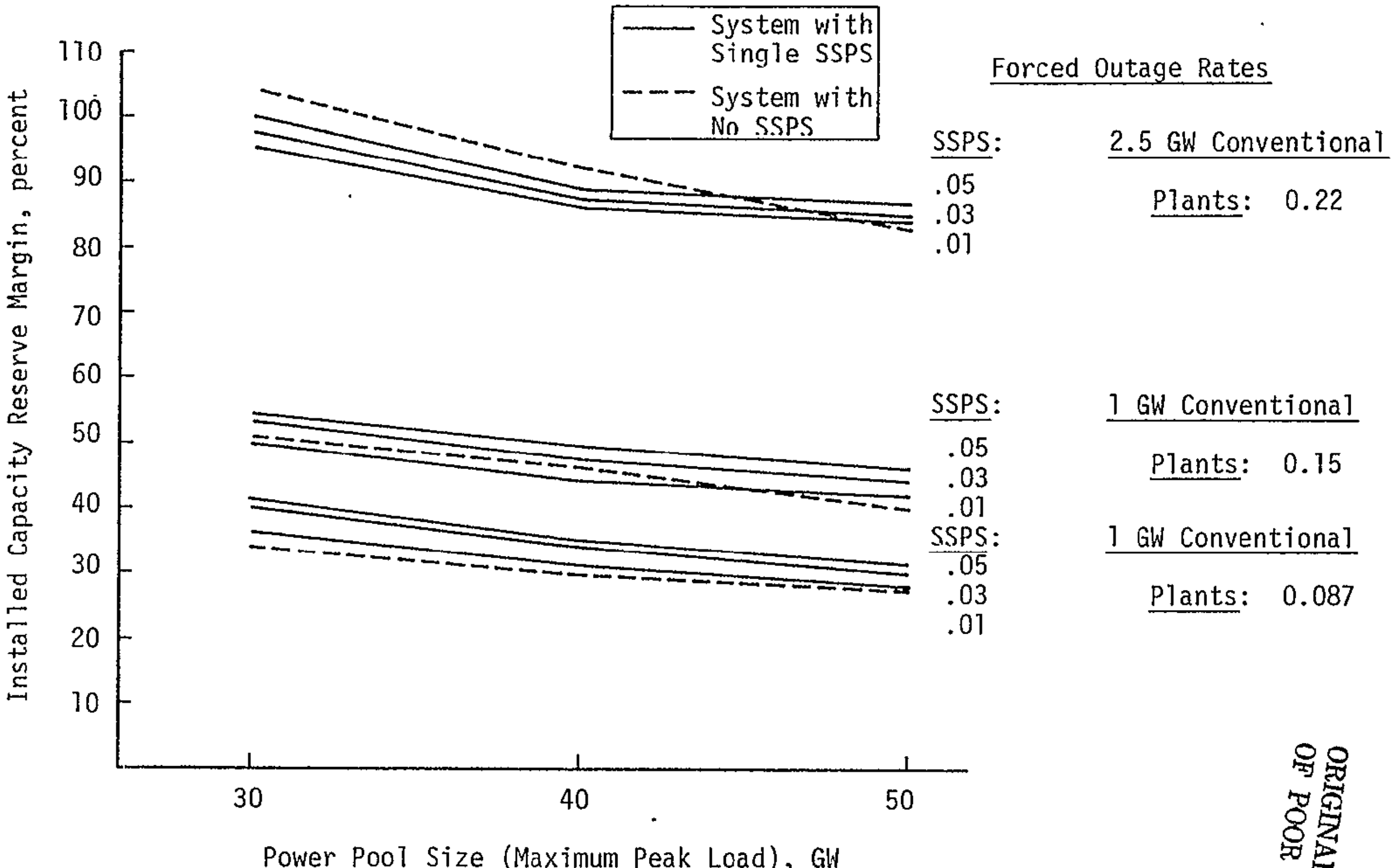

Figure 9.4 Installed Capacity Reserve Requirements as a Function of Utility System Size and SSPS Reliability Level for a One-Day-in-Ten-Years Loss-of-Load Probability

GW, and the forced outage rates used were 8.7 percent* and 15 percent** the 1 GW plants and 22 percent*** for the 2.5 GW plants.

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

The above analysis assumes that the load is constant at the rated system capacity. In reality, however, the load equals (or exceeds) the rated system capacity for only a fraction of the time. Thus, the actual reserve margins required to achieve the stated loss-of-load probability are less than those indicated in Figure 9.4. Subsequently, the above analysis was performed also for a loss-of-load probability of one day in one year. The results of this exercise are shown in Figure 9.5. Comparison of Figures 9.4 and 9.5 indicate that the reserve margins required for a system with an SSPS should be reduced more than those required for a system without an SSPS as the loss-of-load probability requirements are relaxed. However, the effect of loss-of-load probability on the differential reserve margin requirements between systems with and without an SSPS is not substantial.

In summary, it can be noted that the inclusion of an SSPS is sometimes advantageous (that is, it reduces the required reserve margin) and sometimes disadvantageous, depending upon the system size and the reliability of the constituent units with an advantage for SSPS in systems comprised of larger conventional power plants. Whether or not the SSPS is advantageous also depends on the reliability of the SSPS.

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

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

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

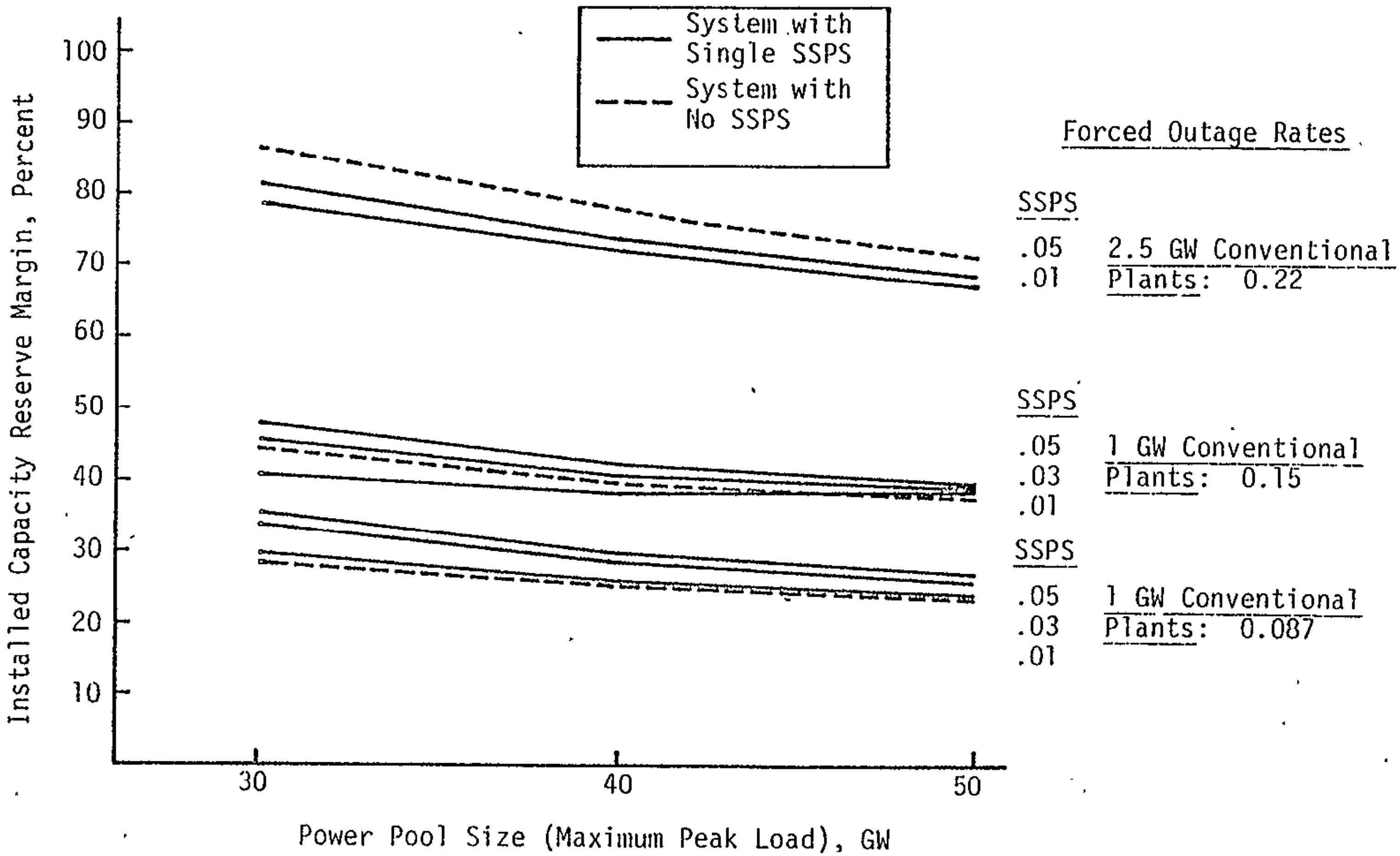

Figure 9.5 Installed Capacity Reserve Requirements as a Function of Utility System Size and SSPS Reliability Level for a One-Day-in-One-Year Loss-of-Load Probability

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The purpose of this examination was to determine whether or not the installed reserve requirement posed by SSPS might be critical. From this analysis, reserve requirements do not appear to represent a critical economic issue. In fact, under certain circumstances, an SSPS may reduce the necessary reserve margin.

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

9.2 Effects of Solar Eclipses

An SSPS satellite in geosynchroneous orbit will experience eclipses around midnight of varying durations in the periods surrounding the two equinoxes, as shown in Figure 9.6. These eclipse periods occur during times that are daily and seasonal "valleys" in demand for nearly all utilities. Representative daily and seasonal load cycles are shown in Figures 9.7 and 9.8, respectively.

Given that the eclipses occur during off-peak periods and that they are predictable, so long as sufficient alternate generating capacity

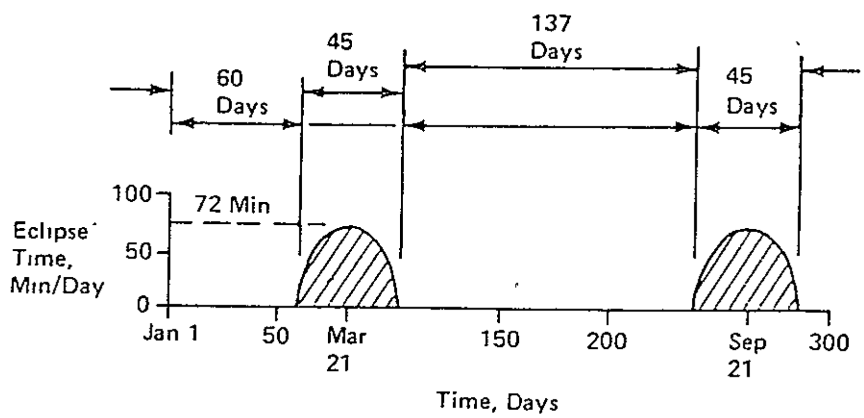
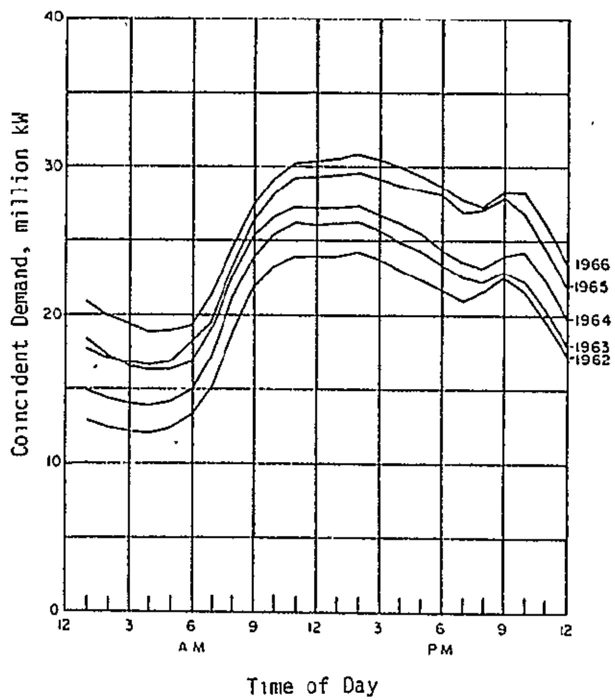


Figure 9.6 Duration of SSPS Eclipses at Synchronous Equatorial Orbit

*Arthur D. Little, Inc. is presently under contract to the Jet Propulsion Laboratory to study this problem.



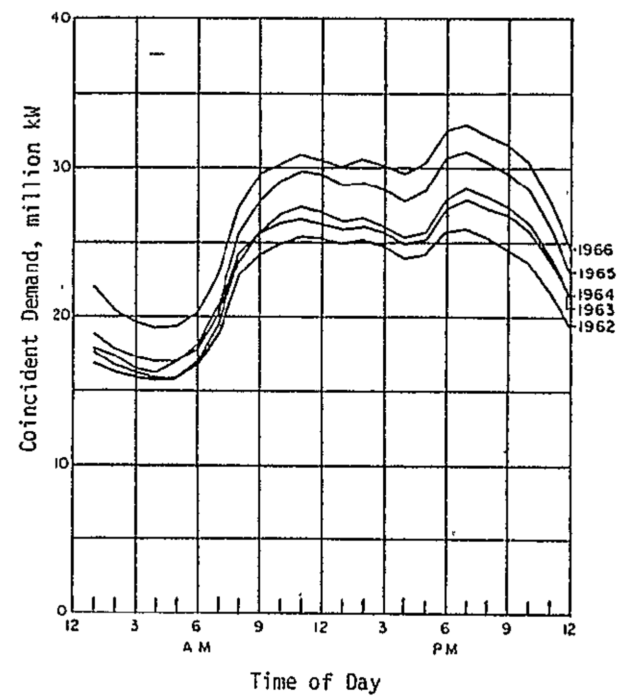


Figure 9.7 Daily Load Cycles for Summer Peak (Left) and Winter Peak (Right) Days Among ECAR Systems for 1962-66. (Source: Federal Power Commission. The 1970 National Power Survey - Part II.)

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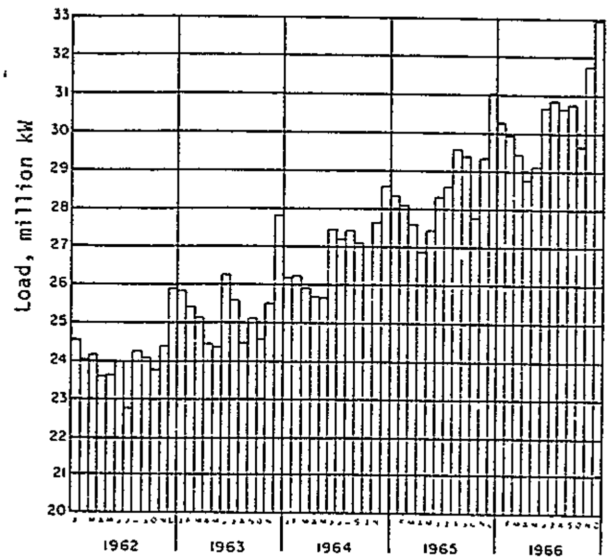

Figure 9.8 Seasonal Variation of Monthly Peak Loads Among ECAR Systems (Source: The 1970 Power Survey - Part II.)

is available, an SSPS eclipse may be treated as a planned outage not requiring installed reserve capacity. The costs then associated with an eclipse are the marginal costs of whatever alternate capacity is used to generate power during the eclipse period. The costs of alternate generation means have been assessed parametrically, and the results are presented in Table 9.1. The costs associated with an eclipse do not appear to be critical because in the worst case examined here (having to use peaking capacity during the duration of the eclipses) the average annual generating cost of power produced by an SSPS baseload system would only be increased by 0.5 mills/kWh.

The scope of this study did not allow examination of the assumption of alternate capacity being available, as power during an SSPS eclipse would probably be provided by power pooling or other interconnections between utility systems. The size of power pools and the number of interconnections is growing. (An example of this expansion is provided in Figure 9.9.) It was noted in the example in Section 9.1, that the Eastern Central Area Reliability Coordination Agreement will oversee an installed capacity of over 100 GW in 1990. The effect of this pooling would be to reduce the cost of providing power during an SSPS eclipse. However, with SSPS satellites displaced by 2400 km in synchronous orbit, during maximum eclipse periods, seven satellites

Table 9.1 Annual Generation Costs of Alternate Sources to Cover SSPS Unit Eclipse Time

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

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

would be occulted at any point in time; hence, a given power pool area might be faced with replacing the capacity of several SSPS's during an eclipse period. The interaction of the effects of pooling and multiple occlusions is a complicated one requiring further study. An additional concern for further study should be the extent and effect of occultations of one satellite by another.

9.3 Effect of Power Fluctuations

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

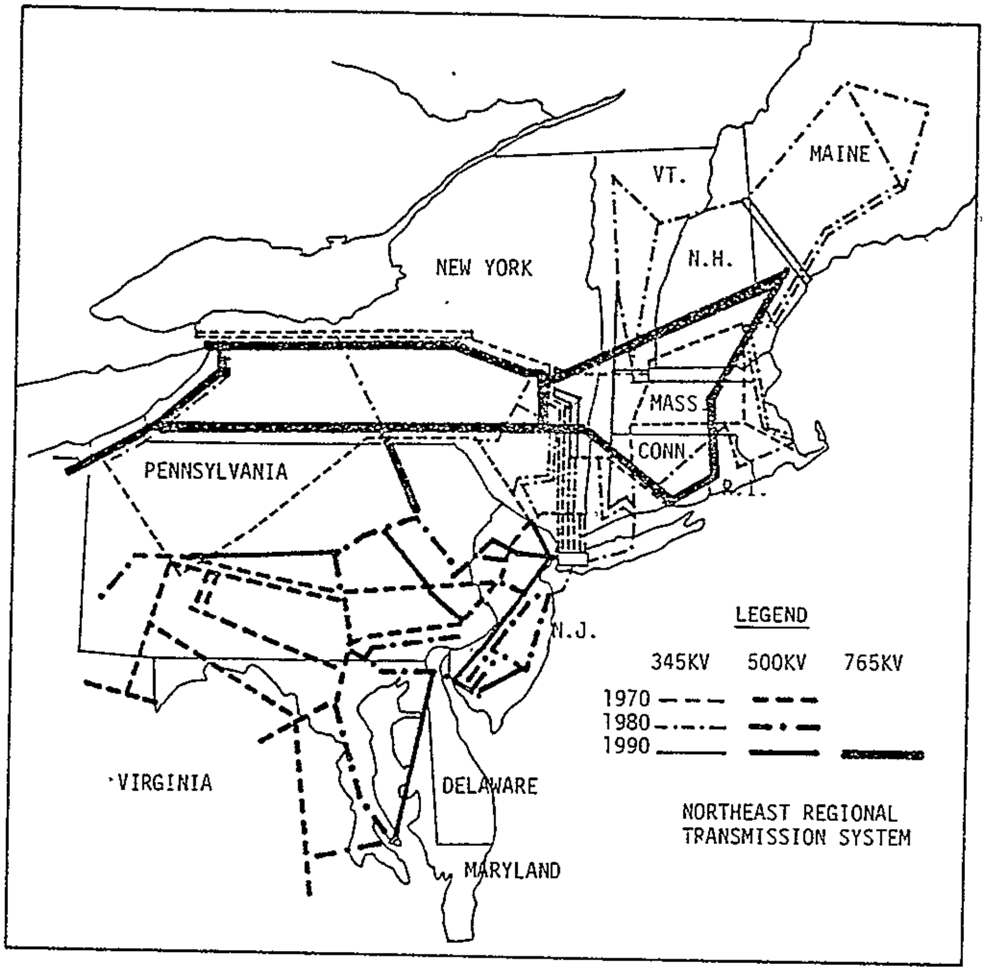

Figure 9.9 Projected Expansion Of The Northeast Regional Transmission System From 1970 Through 1990 (Source: Federal Power Commission, The 1970 National Power Survey - Part II.)

If the fluctuations in SSPS transmitted power are sufficiently rapid, then the effect will be a derating (reduction in the rated capacity) of SSPS. The effect on the cost of power produced by SSPS of various levels of power fluctuation is presented in Figure 9.10, with the effect of the expected variation of 1 percent to be an increase of about 0.2 mills/kWh in SSPS cost of capital,* hence an equivalent increase in the user charge of SSPS-produced power.

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

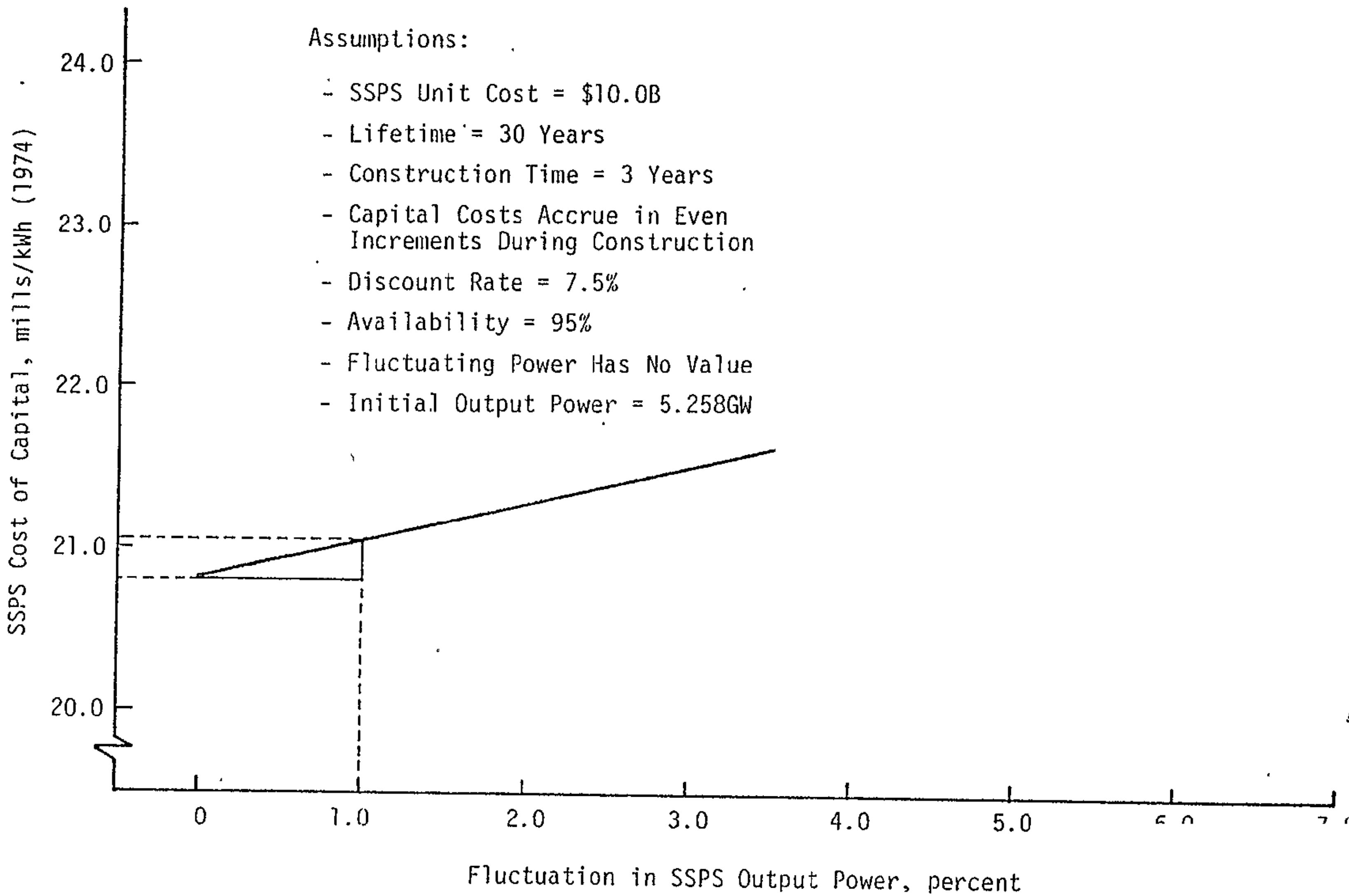

Figure 9.10 Effect on the Cost of SSPS-Produced Power of Fluctuations in Power Transmission

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

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GLOSSARY OF TECHNICAL UNITS AND ABBREVIATIONS

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

APPENDIX A

ECONOMIC METHODOLOGY

The purpose of this appendix is to present a detailed review of the economic concepts and analytical constructions used in this report. The objective is twofold:

- To provide the reader with the means to verify the study's results and substitute alternative input data and assumptions if desired, and

- To provide a reconciliation of the approaches used in this study with those of other energy-economics studies.

The basis for the first objective is clear. Regarding the second objective, it is all too often that due to the lack of complete information and inconsistency of approaches among energy-economics studies, comparisons are impossible. In this appendix, the minimum information required to make interstudy comparisons is established.

The following topics are addressed:

- Methodology for Comparative Economic Analysis of Electric Generation Systems (A.1)

- Computation of the Present Value of Capital and the Equivalent Annuity (A.2)

- Reconciliation of Alternative Approaches for Computing the Present Value of Capital and Equivalent Annuity (A.3)

- Computation of Economically Justifiable SSPS Unit Cost (A.4)

- DDT&E Payback Analysis (A.5).

A.1 Methodology for Comparative Economic Analysis of Electric Generation Systems

Figure A.1 illustrates the cash flow profile of a representative, 1 GW electric power generation system. The cash flows required for the construction of the system are represented by the values, $110 million per year ($C_t$) over the period 1991 to 1995. The capital payback (A_t) is represented by the values, $41.7 million per year over the 30-year operational life of the system.

In the example shown, the constant dollar cost of the plant is $440 per kilowatt and these costs are distributed equally over the

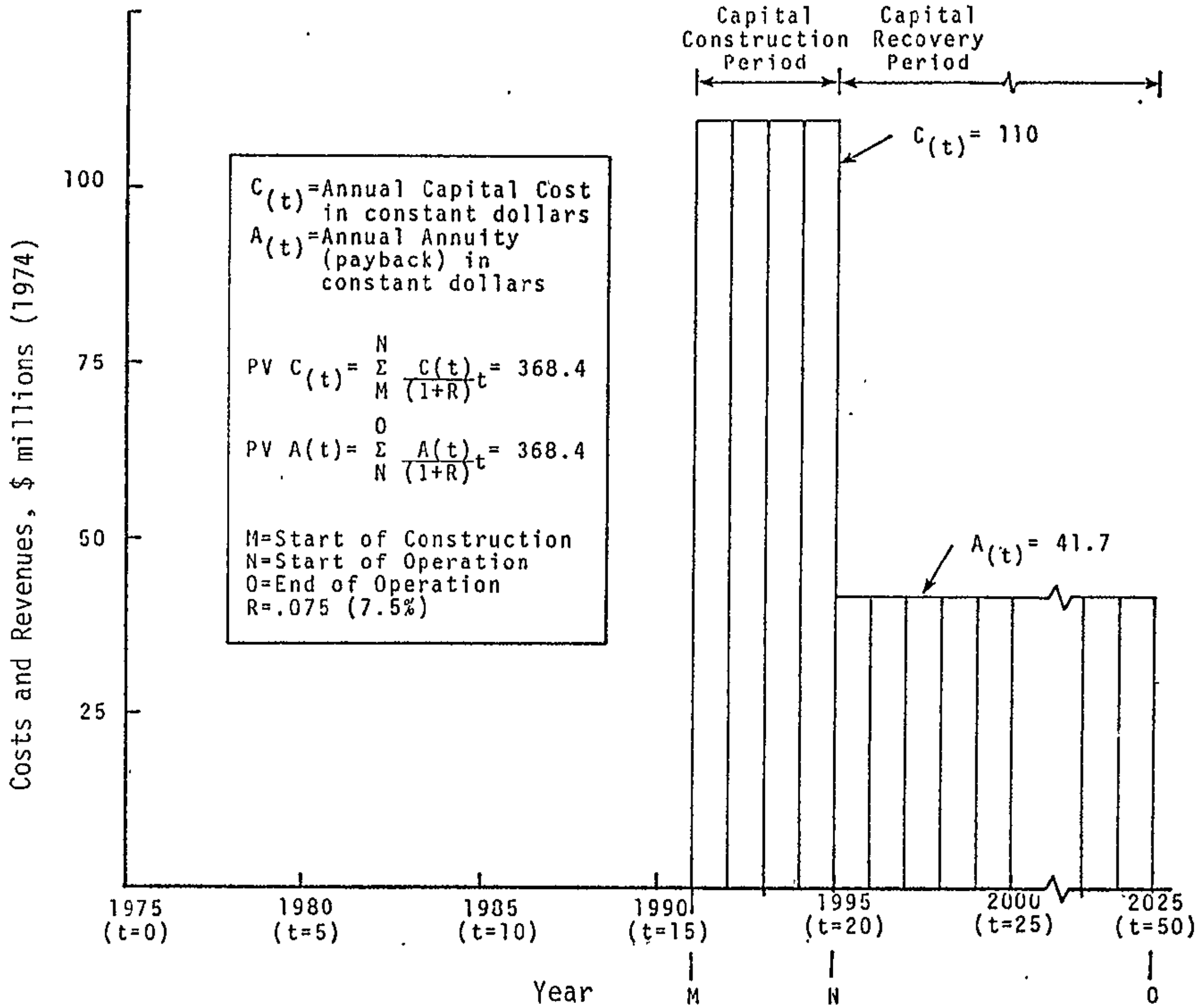

Figure A.1 Electric Generation System Cash Flow Profile

4-year construction period.* According to the formula provided for computation of present value, the (1975) present value of the cost of capital is $368.40 per kilowatt. The capital recovery payment (annuity over the 30-year operational period of the plant) is a value such that its (1975) present value equals that of the present value of the capital. Thus, at the stipulated discount rate, 7.5 percent, the annuity (A_t) is a cash flow received by the providers of capital to the utilities (lenders and equity owners) such that they (in 1975) are indifferent to holding $368.40 or receiving an annuity of $41.70 per year over the period 1995 through 2025. This present value concept is expanded below with the use of Figure A.2 which provides an additional example.

Assume that a particular technology substeem of the SSPS were estimated to cost $380 million and that the costs of development would be expended--evenly--over the period 1985 through 1990. All expenditures would be paid out at the beginning of each year, that is, $76 million would be expended at the beginning of each year for five years. Using the formula provided in Figure A.1, the present value of this expenditure is computed to be $161 million. This is the value which is economically equivalent in 1975 to $360 million expended in the way assumed, that is, five equal payments. That is, a "rational" economic being would be economically indifferent between having a bank balance of $161 million (in 1975) and receiving $76 million per year for five years starting at the beginning of 1985.

As illustrated in Figure A.2, a $380 million DDT&E expenditure could be financed with an initial bank balance of $161 million starting in 1975. The present value, $161 million, is a function of (1) the discount rate, (2) the year that the expenditure begins, and (3) the expenditure pattern. Higher interest rates and/or an earlier expenditure start would reduce the present value, and vice versa.

As shown in Figure A.2, $161 million put in the "bank" would compound at an annual rate of 7.5 percent to $325 million at the beginning of 1985 when the first "withdrawal" of $76 million is made. This would reduce the "bank balance" which would, in turn, increase by the interest received over the year; and then another $76 million payment would be made, and so on. After the last $76 million payment, the balance would be reduced to zero.

The computed value of A, the economically equivalent annuity, is a function of the parameters shown, that is, M, the date of the beginning of construction, N the date of the beginning of operation, O the end of operation and R, the discount rate. The most sensitive parameter is R--

*The assumption of equal distribution of costs over the construction period is only for purposes of example. Certainly, the present value of capital may be computed under any distribution of outlays.

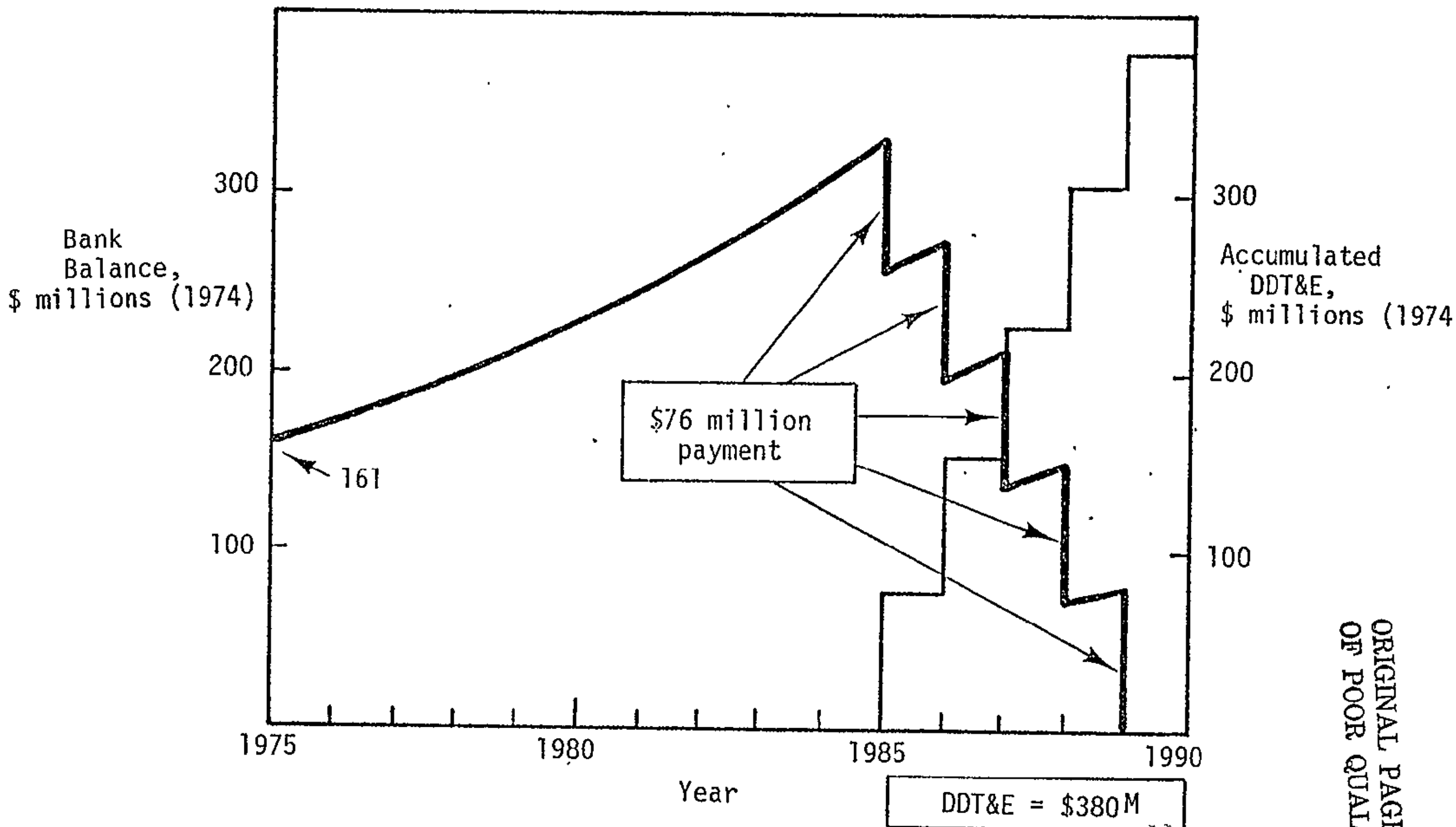

Figure A.2 Present Value Rationale, R = 7.5%

the higher the value of R the greater the annuity must be to yield an equivalent economic value, and vice versa.

To the value of A must then be added the "recurring" costs of the electrical generation system, that is, values for taxes and insurance, operations and maintenance and, in the case of the terrestrial systems, fuels.

A major point to be emphasized is that "constant dollars" not "current dollars" measure the economic cost of a project. Unless it can be shown that there will be differential inflation among the cost components of a plant, the correct approach is to use constant dollars.

While the recent experience has, indeed, evidenced a higher rate of inflation for fuels than other generating systems' cost components, the historical data show that over the long-run, relative price changes in these categories have been essentially equal. It is assumed, therefore, that the recent dramatic (differential) inflation in fuels will be a short-run phenomenon, and by the time period in which the SSPS or terrestria systems would be constructed (around 1995) the relative prices will have readjusted themselves to their long-run historical relationships. The issue is that we do not know what the rate of differential inflation may be over the next 20 years, and it is deemed preferable to make the neutral assumption--which, again, is in line with the historical trend--that over the long run the relative rate of inflation among the cost components will be approximately equal. On the other hand, to the extent that it is believed that differential changes in the real economic cost may be expected, that is, relative prices of fuels, etc., these should be introduced into the analysis.

The discount rate chosen for this study, 7.5 percent, is economically conservative with respect to the SSPS. This rate has the effect of placing a relative cost burden on the SSPS, since it is the most capital intensive of the systems being compared. Other studies* have indicated a required real average rate of return (between equity and debt capital) for the future funding of electric utilities to be about 5 percent. We have elected to use a higher discount rate for two reasons: one, to introduce a risk factor for uncertainties in the development and operations in the SSPS system and two, to reflect the

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*U.S. Federal Energy Administration, Project Independence Blueprint Final Task Force Report - Finance, November 1974.

The Aerospace Corporation, Power Plant Economic Model, Program Description/User's Guide (ATR-74[7417-16]-1, June 1974.

Hass, J.E., E.J. Mitchell and B.K. Stone, Financing the Energy Industry, Cambridge: Ballinger Publishing Company, 1974.

idea that SSPS--at least in its earliest stages--may be a mixed public/private enterprise. Currently, a discount rate of 10 percent is being used to evaluate public projects. The 7.5 percent used would represent, therefore, an averaging between the real rate of return that is required by a commercial venture (5 percent) and that which is expected to accrue to purely public ventures (10 percent).

A.2 Computation of the Present Value of Capital and the Equivalent Annuity

Figure A.3 contains a summary of the methodology used for computing the present value of capital and the (economically) equivalent annuity. The numbers in parenthesis represent the step-numbers identified in the figure.

The "constant-dollar cost" measured in units of dollars per kilowatt (1) is divided by the "mature plant availability factor" (2). This equals the "adjusted constant dollar cost" measured in dollars per kilowatt (3). This value, divided by the "length of the construction period" measured in years (4) equals the "adjusted constant dollar cost" of capital per year measured in dollars per kilowatt (5). This value and others (the discount rate [R] and the number of compounding periods per year [N]) as given in (6) are inputted to an equation (7) to compute the "present value of capital" at t=0 (8). This result and the other parameters in (9) may be inputted into an equation (10) which computes a value for the annuity that must be adjusted to account for the waiting (construction) period. This adjustment is done with the value generated in (11). This yields the equivalent annuity (PMT*), the dimensions of which are dollars per kilowatt per year. This value if received annually over the payback period would yield a present value equal to the present value of the capital. If a result in units of "mills per kilowatt-hour" is desirable, the next step is to divide the result in (12) by the constant, 8.76, given in (13). This equals (14) the annuity value in mills per kilowatt-hour.

As indicated in Figure A.3, the parameter PMT is the value obtained in (5), Y is equal to the construction period in years given in (4), N is equal to one (the number of compoundings per year) and R is the discount rate. In (9) the parameter, PV, is the result obtained from (8), X is equal to the payback period (assumed to be 30 years), N is equal to one and R is equal to 7.5 percent. The value, 8.76, given in (13) is the well-known conversion factor used to adjust dollars per kilowatt-year into mills per kilowatt-hour.

A.3 Reconciliation of Alternative Approaches for Computing the Present Value of Capital and Equivalent Annuity

Figure A.4 illustrates a reconciliation between various approaches that are used for determining the present value of capital and the equivalent annuity. As will be shown, they yield the same economic results.

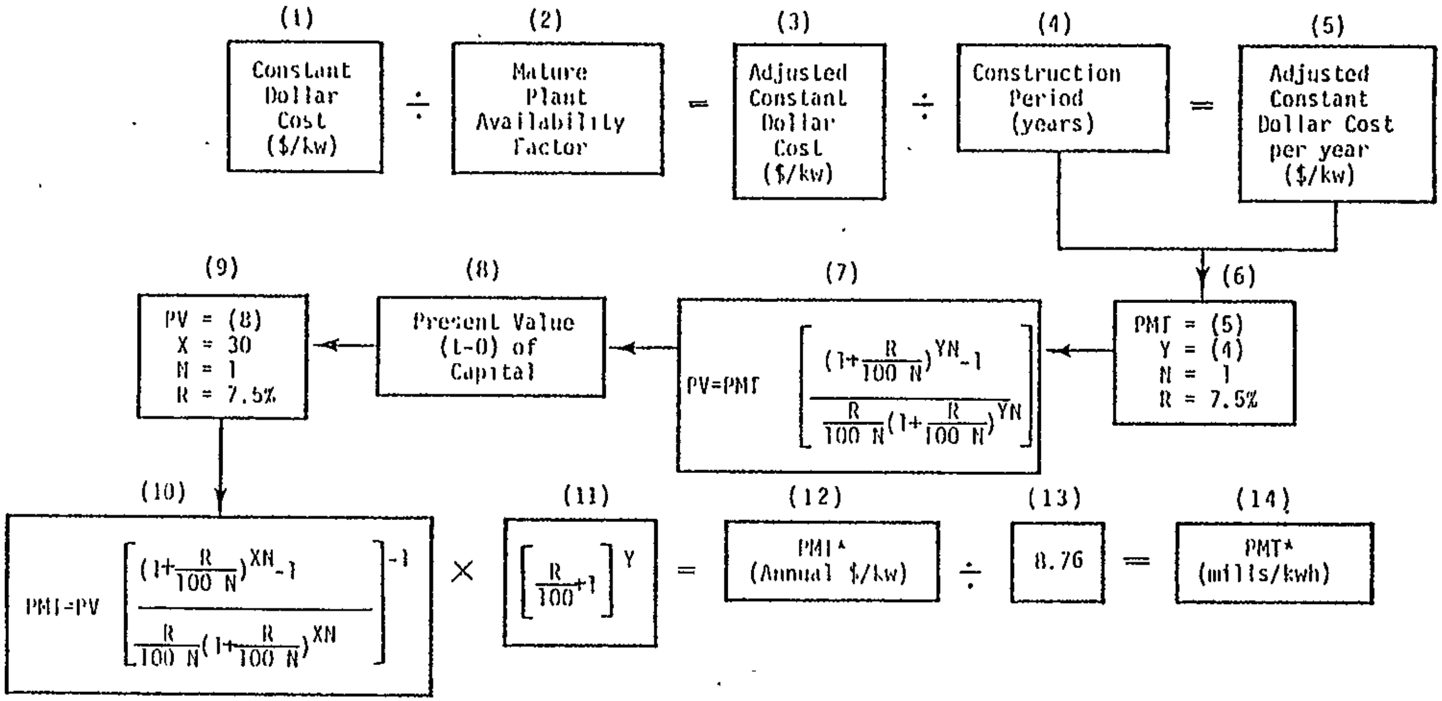
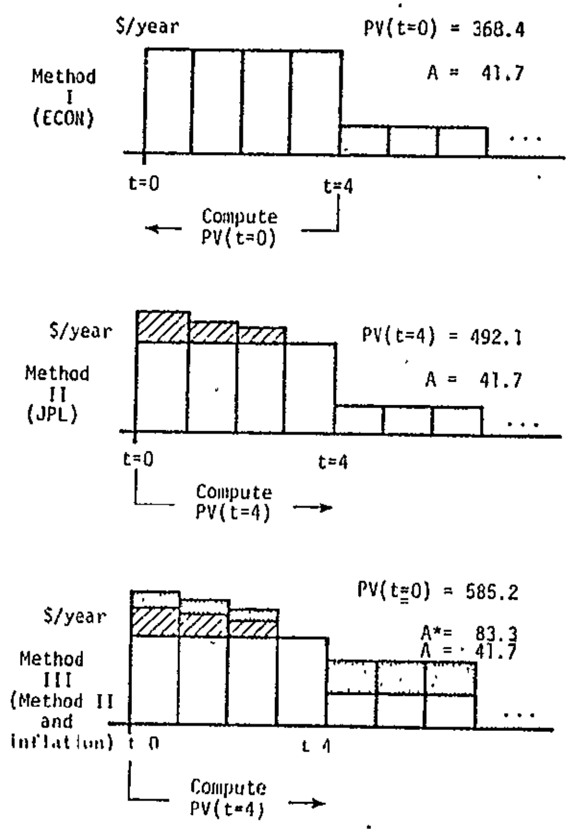


Figure A.3 Methodology for Determining the Present Value of Capital and Equivalent Annuity



PV(t) Present Value of Capital, time equals t
A*= Equivalent Annuity with Inflation Component
A = Equivalent Annuity in Constant Dollars

CAPITAL COST CONSTANT $	ESCALATION (6%) DURING CONSTRUCTION	INTEREST (7.5%) DURING CONSTRUCTION	TOTAL CONSTRUCTION COST
440.0	-	-	440.0
440.0	-	92.1	492.1
440.0	41.2	104.0	585.2

Figure A.4 Reconciliation of Alternative Approaches
(Costs in Units of $/kW)

Method I is the approach used throughout this study. The example given is for a direct coal-fired plant operating at a (mature) plant availability factor of .75. As provided in the previous section, the adjusted capital costs for an environmentally controlled system, is $440 per kilowatt. As illustrated in Figure A.4, the capital costs are assumed to be distributed equally over the construction period, that is, $110 per kilowatt, per year. The costs are then discounted back to the start of the construction period, t=0. The present value at t=0 given a 7.5 percent discount rate equals $368.40 per kilowatt. The equivalent annuity over the operational period equals $41.7 per year or 4.8 mills/kwh.

According to Method II (which is the approach that JPL has chosen*), the present value calculations are evaluated at t=4, the end of the construction period. According to this approach, the present value of the capital would be $492.1 per kilowatt. The numerical difference in present value between Method II and Method I is represented by the shaded area in the illustration for Method II, and this is usually referred to as "interest incurred during construction." The equivalent annuity evaluated at t=4 is $41.7 per year, the same as Method I, and hence, the approaches used by ECON and JPL yield identical results.

The reason that the numerical results for the equivalent annuity are equal in approaches I and II is explained as follows: In Method I the present value of capital outlays is calculated at t=0 and revenues do not accrue until after t=4. Thus, there is a period of waiting (varying for each dose of capital outlay) before revenues accrue to pay back the capital expenditure. In Method II there is no waiting period, revenues are received in the period immediately following t=4, the reference date for which the present value of capital outlays has been computed.

Method III is Method II plus a factor provided for inflation during the construction period. As seen, the capital cost in constant dollars is the same. There is, additionally, an escalation factor--assumed for the example to be 6 percent per year--that would raise the total capital costs by $41.2 per kilowatt. Added to this is the interest accrued during construction, and considering inflation, this would be $104.0 per kilowatt. Total capital cost evaluated at t=4 is $585.2 per kilowatt. In order to compute the equivalent annuity, the "nominal interest rate" of 13.9 percent is used. This is the product of the real interest rate, 7.5 percent and the inflation rate, 6 percent (1.075 x 1.06 = 1.1395). Thus, under this approach with a 6 percent per year inflation assumed to be sustained throughout the 30-year payback period, it requires $83.3 per year (9.5 mills/kwh) to generate revenues with a present value equal to that of the capital, and provide for a real rate of return of 7.5 percent or $41.7 per year in constant dollars.

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*Doane, J.W. and R.P. O'Toole, "Baseline Economic Analysis for Solar and Conventional Central Power Plants," Jet Propulsion Laboratory Engineering Memorandum, September 3, 1975.

Each of these methods are economically equivalent. Although the numerical results may differ, each evaluates the systems to cost the same amount in terms of economic resources.

A.4 Computation of Economically Justifiable SSPS Unit Cost

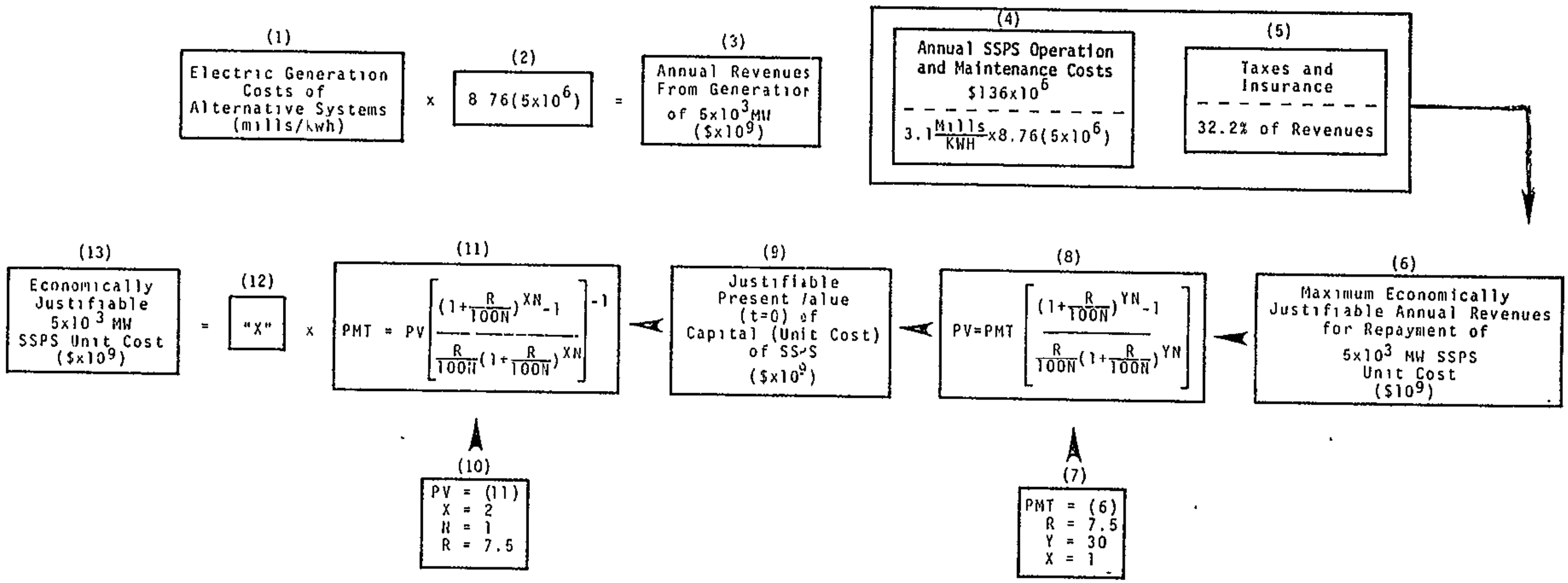
Figure A.5 provides the methodology used for computing the "economically justifiable" unit cost of a 5,000 MW SSPS.

The first input in Figure A.5 is a value for electric generation costs (in mills per kilowatt hour) of an alternative (competing) system, item (1). This value must then be scaled up to the annual revenues at a level of 5,000 MW. The scaling factor is given in (2). This equals the annual revenues from the generation of 5,000 MW per year, and it is this revenue which serves as the basis for the computation of the SSPS allowable unit cost.

Before the capital can be repaid, the SSPS has to pay its annual operation and maintenance costs, taken here to be \$136 million per year and taxes and insurance which are taken to be 32.2 percent of the revenues. The use of this latter constant requires an explanation.

It is a working assumption that annual taxes and insurance are equal to 5 percent of capital. This is in line with a "rule-of-thumb" currently used for terrestrial plants. One cannot, however, use the 5 percent constant in this exercise, since it is the capital itself that is to be estimated. To eliminate this problem, a "trick" has been devised. This is to assume that the cost for taxes and insurance would be incurred in the same proportion to revenues as computed with the original SSPS unit cost estimate. Hence, if the capital costs of SSPS are taken to be \$7.6 billion, using the 5 percent constant, the value for taxes and insurance is estimated to be \$377 million per year. Summing the annual cost of capital (\$657 million per year for the capital cost assumed), the value for maintenance (\$136 million per year assumed), and \$377 million per year, the total annual SSPS cost is \$1170 million per year. The proportion of annual costs for taxes and insurance is 32.2 percent of the total.

Subtracting the value for taxes and insurance and operations and maintenance from the annual revenues, a value may be obtained for the maximum economically justifiable annual revenues for repayment of the SSPS unit cost. This value is designated as the parameter, "PMT", and with the other parameters shown in (7) are inputted into the equation (8) to obtain the economically justifiable present value (at t=0) of the unit cost (9). In order to convert the present values into undiscounted dollars, the result in (9) is inputted along with the parameters given in (10) into the equation shown in (11). This provides a value for the economically justifiable annual construction cost of the SSPS. To obtain the total economically justifiable unit cost, this result is multiplied by the value of the parameter "X" given in (10) which is the length of the construction period--in years. The product of the result in (11) and (12) is the economically justifiable (5,000 MW) SSPS unit cost given in (13).



$$PV = PMT\left[\frac{\left(1+\frac{R}{100N}\right)^{YN}-1}{\frac{R}{100N}\left(1+\frac{R}{100N}\right)^{YN}}\right]$$

$$PMT = PV\left[\frac{\left(1+\frac{R}{100N}\right)^{XN}-1}{\frac{R}{100N}\left(1+\frac{R}{100N}\right)^{XN}}\right]^{-1}$$

Figure A.5 Methodology for Computing the Economically Justifiable Unit Cost of a 5,000 MW SSPS

A.5 DDT&E Payback Analysis

A methodology for performing SSPS DDT&E Payback Analysis is illustrated in Figure A.6. Inputs to the analysis are the SSPS buildup profile (1) and the present value of the SSPS DDT&E (2). Although the exact date to which the DDT&E is discounted is arbitrary, it is, in this example, 1975.

An assumed SSPS buildup profile is given in Figure A.7. As indicated, with an initial operational date (IOD) of (end of) 1995, by the (end of) 1996 there would have been one SSPS revenue-year. According to the build-up profile there would be a build-up rate of two SSPS per year until 2000, and after that, four per year through 2025. The cumulative number of 5 GW operational units at the end of a given year, t, would be as indicated in Figure A.7.

The second input to the analysis is the present value of the SSPS DDT&E (2). Here, this value in undiscounted dollars is assumed to be $44 billion.

The next step (3) is to solve for "delta revenues" (R*) per SSPS such that the (1975) present value of R* equals the (1975) present value of the DDT&E. Examples of the calculations of R* for 1996, 1997 and 1998 are provided in Table A.1.

Table A.1 contains examples of the method for computing the SSPS DDT&E Payback Function.

By (end of) 1996, t--which for purposes of discounting back to 1975--is valued at "21." There is one SSPS operating for one year. To solve for R*, the present value of R* is set equal to the present value of the SSPS DDT&E. The computed value is, of course, a relatively large value, and one would not expect that a single operational SSPS could ever repay the DDT&E. In 1997 (t+1) there would have been one SSPS operating for two years and three SSPSs operating for one year (the original SSPS would be operating for two years and the two additional SSPSs with a 1996 IOD would have been operating for one year). The method would be to solve for an R* such that its present value would be equal to the present value of the DDT&E. In 1998 (t+2) there would be one SSPS operating for three years, three SSPSs operating for two years and five SSPSs operating for one year, and so on.

As indicated in Figure A.7, the values of the DDT&E Payback Function do not begin to fall into a reasonable "range" until about 2005 when 29 SSPSs will have been operating for at least one year, leading to a value of R* of about 20 mills per kilowatt hour.

As stated in the report, the DDT&E Payback Function becomes asymptotic to the x-axis as the alternative electric generation costs approach 27 mills per kilowatt hour. This is explained by the discounting phenomenon which reduces the present value of future revenues.

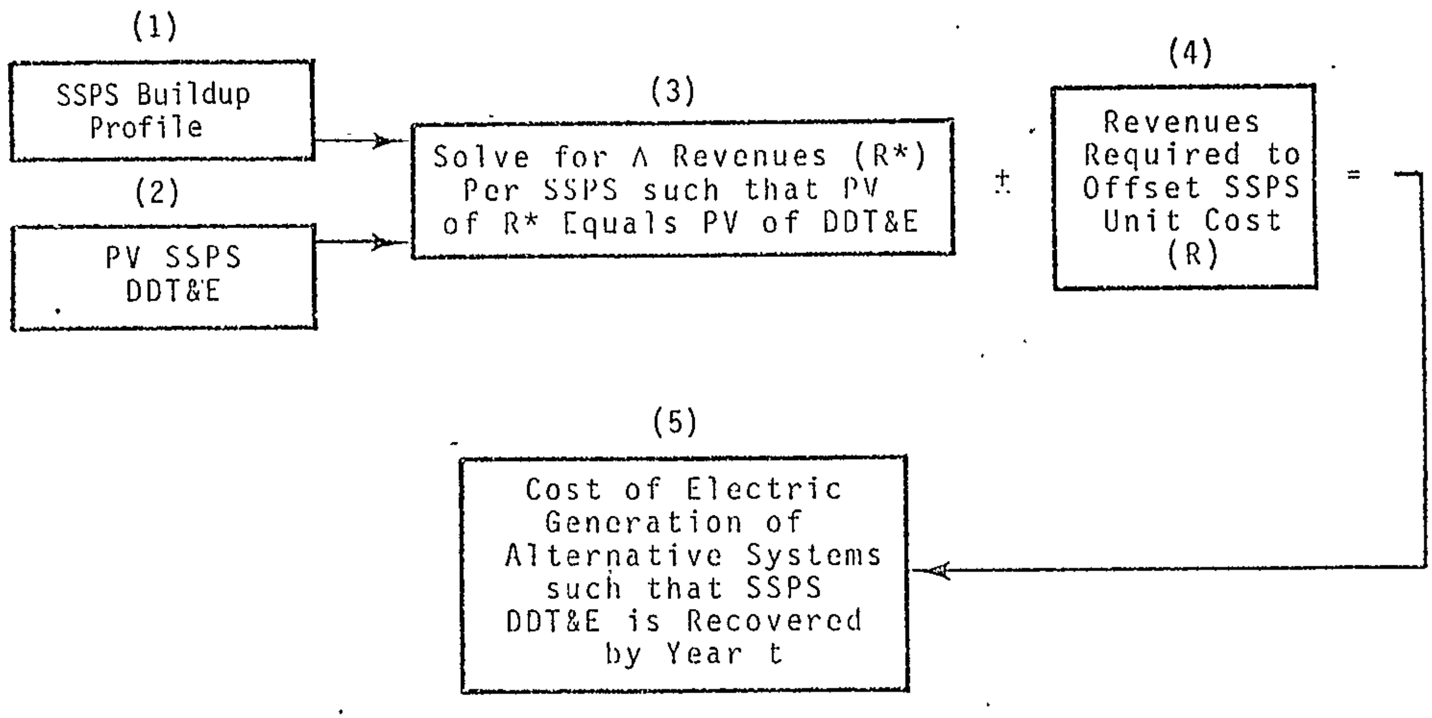


Figure A.6 Methodology for SSPS DDT&E Payback Analysis

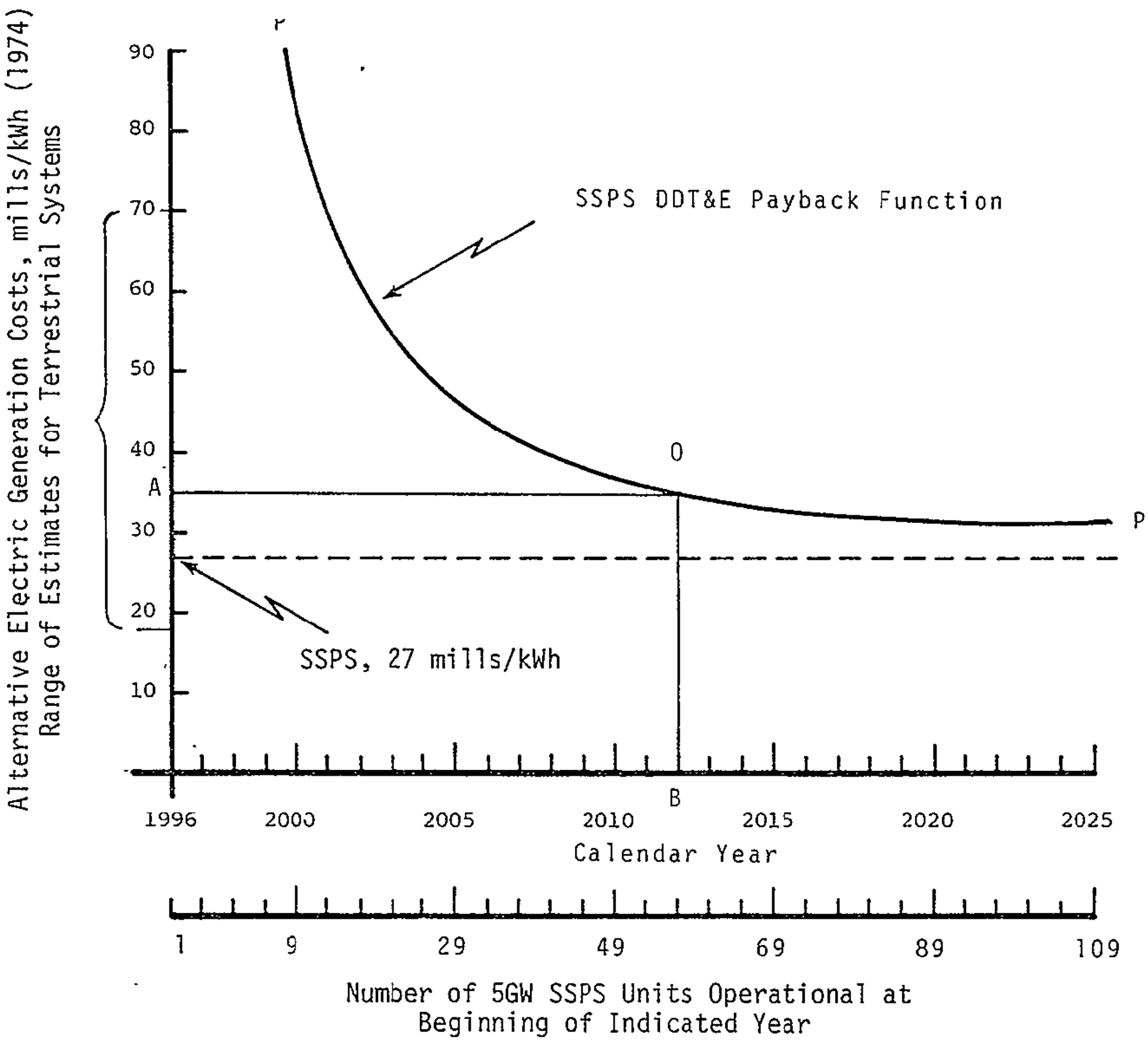


Figure A.7 Payback Analysis of SSPS Development Programs (r=7.5%)

Table A.1 Method for Estimating the SSPS DDT&E Payback Function

(END OF) YEAR	SSPS BUILD-UP SCENARIO	SOLUTION FOR (R*)[1]: ANNUAL REVENUES PER OPERATIONAL $5x10^3$ MW SSPS[2]
1996(t)	1 SSPS operating for 1 year	$(1975)PV= \$16.5x10^9 = \frac{R^*}{(1+r)^t}$.
1997(t+1)	1 SSPS operating for 2 years 3 SSPS operating for 1 year	$(1975)PV= \$16.5x10^9 = \frac{R^*}{(1+r)^t} + \frac{3R^*}{(1+r)^{t+1}}$.
1998(t+2)	1 SSPS operating for 3 years 3 SSPS operating for 2 years 5 SSPS operating for 1 year	$(1975)PV= \$16.5x10^9 = \frac{R^*}{(1+r)^t} + \frac{3R^*}{(1+r)^{t+1}} + \frac{5R^*}{(1+r)^{t+2}}$.
...	...	...
2025(t+29)	1 SSPS operating for 30 years 3 SSPS operating for 29 years ... 109 SSPS operating for 1 year	$(1975)PV= \$16.5x10^9 = \frac{R^*}{(1+r)^t} + \frac{3R^*}{(1+r)^{t+1}} + \ldots + \frac{109R^*}{(1+r)^{t+29}}$

1. R*=Required annual revenues per SSPS in year t+N for DDT&E recovery.
   To convert to mills per kilowatt-hour, divide result by: $8.76(5.10^6)$.
2. $r = .075$ (7.5%), $t=21$

To the value of R* is added the unit SSPS costs shown in (4) as (R) and is estimated (under the above assumptions) to be 26.7 mills per kilowatt hour. R*--which is a unique, interest rate-dependent value--is added to the value, R, which is constant, and the result is given in Figure A.6 as (5), the cost of electric generation of alternative system such that the SSPS DDT&E is recovered by year t. This is the ordinate of Figure A.7. The reason that the ordinate and the result in (5) is given as the cost of alternative generation systems, is that we assume that SSPS would not be used if there were alternative systems available that would provide equal generation capabilities and electric power at lower cost.

APPENDIX B

UNIT PRODUCTION COST MODEL

The following is a listing of the equations incorporated in the Unit Production Cost Model. (A description of the cost model is found in Section 4.2.) 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. The model is documented first in its final form as it was used to evaluate unit production costs for Programs IV and V. In an earlier form, the model was used to evaluate unit production costs for Programs I, II and III. The cost model in this earlier form is also documented separately in this appendix. The model in its present form is described below.

B.1 The Present Unit Production Cost Model

Satellite Mass

$$A_B = \frac{P_{IN}}{P_F \; F \; n_{EFF}}$$

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

$$A_C = \frac{(n_{EFF} - 1) \; A_B}{n_{CONC}}$$

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

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

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

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

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

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

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

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

$$M_{ANT-INT} = m_{ANT-INT}\, P_{ANT-INT}$$

$$M_{PCE} = m_{PCE}\, P_{PCE}$$

$$M_{ANT} = M_{ANTS} + M_{DC-RF} + M_{WG} + M_{ANT-INT} + M_{PCE} + M_{ANT\ PD}$$

$$M_{TOT\ SAT} = M_{SAB} + M_{SAC} + M_{STC} + M_{STNC} + M_{STCM} + M_{ANT} + M_{MISC}$$

Construction Base Mass

$$M_{CB} = (m_{CB} + m_{P1}\, P_{EPSREQ} + m_{P2}\, P_{EPSREQ} + m_{RDS})\, a_{CB} + m_{OP} + m_{AP}$$

Masses Related to Interorbit Transportation

$$N_{POTV} = \left(\frac{N_{CREW}}{f_{POTV}}\right)^{*} \frac{f_{CROT}}{R_{CONST}}$$

$$M_{POTVPRP} = N_{POTV}\, f_{POTVPRP}$$

$$M_{PPT} = \left[\left(\frac{M_{POTVPRP}}{f_T}\right)^{*} m_T\right] a_T$$

$$N_{COTV} = \left(M_{TOT\ SAT} + M_{CB} + (1/3)M_{POTVPRP} + (1/3)M_{PPT}\right) \frac{1}{f_{COTV}}$$

$$M_{COTV} = \left(\frac{N_{COTV}}{f_{COTV\ LIFE}}\right) m_{COTV}$$

---

*Integer rounded up.

$$M_{POTV} = \left(\frac{N_{POTV}}{f_{POTV\ LIFE}}\right) m_{POTV}$$

$$M_{COTVPRP} = N_{COTV}\, f_{CPRP}$$

$$M_{CPT} = \left[\left(\frac{2\, M_{P/L}}{f_T}\right)^* m_T\right] a.$$

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

$$M_{AIS\ PROP} = (M_{TOT\ SAT}) \frac{\lambda_{AIS}\,(\sqrt{\alpha_{AIS}} - 1)}{\lambda_{AIS} - (\alpha_{AIS} - 1)(1 - \lambda_{AIS})}$$

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

$$M_{PROP\ DEPOT} = \left(\frac{M_{AIS\ PROP}}{f_{IT}}\right)^* m_{IT}\, a_{IT} + M_{PPT} + M_{CPT}$$

Total Mass to LEO

$$M_{IOVP} = M_{POTVPRP} + M_{COTVPRP} + M_{POTV} + M_{COTV} + M_{AIS\ PROP} + M_{AIS} + M_{PROP\ DEPOT}$$

$$M_{LEO} = M_{CB} + M_{IOVP} + M_{TOT\ SAT}$$

LEO Launch Cost

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

$$N_{HUS} = \frac{N_{HLLV}}{f_{HUS\ LIFE}}$$

*Integer rounded up.

$$N_{HLS} = \frac{N_{HLLV}}{f_{HLS\ LIFE}}$$

$$N_{SHUTTLE} = \frac{N_{CREW} \dfrac{f_{CROT}}{R_{CONST}}}{f_{SHUTTLE}}$$

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

$$C_{HLLV} = c_{HLLV}\ N_{HLLV} + N_{HUS}\ c_{HUS} + N_{HLS}\ c_{HLS}$$

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

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

Construction Base Cost

$$C_{CB} = a_{CB}(c_{CB} + c_{P1}\ P_{EPSREQ} + c_{P2}\ P_{EPSREQ} + c_{RDS}) + c_{AP}\ m_{AP} + c_{OP}\ m_{OP}$$

LEO-GEO Transportation Cost

$$C_{LEO\text{-}GEO} = \left(\frac{N_{COTV}}{f_{COTV\ LIFE}}\right) c_{COTV} + \left(\frac{N_{POTV}}{f_{POTV\ LIFE}}\right) c_{POTV} + c_{PRP}(M_{POTVPRP} + M_{COTVPRP}) + a_{AIS}\ C_{AIS} + c_{AIS\ PROP}\ M_{AIS\ PROP} + c_T\ a_T \left(\frac{M_{POTVPRP} + M_{COTVPRP}}{f_T}\right)^{*} + a_{IT}\ c_{IT} \left(\frac{M_{AIS\ PROP}}{f_{IT}}\right)^{*}$$

*Integer rounded up.

Satellite Procurement Cost

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

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

Ground Station Cost

$$A_{RECT} = \left(\frac{\pi}{4}\right)\left(\frac{5}{P_{5YR}}\right)\left(\frac{10^4}{\sin E}\right) \times 10^6$$

$$C_{GRD\ STAT} = C_{RECT} A_{RECT} + c_{INTERF} P_{INTERF} + C_{PC}$$

Total Unit Production Cost

$$C_{UPC} = C_{LLC} + C_{LEO\text{-}GEO} + C_{CB} + C_{SAT} + C_{GRD\ STAT}$$

Definitions of Unit Production Cost Model Variables

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

A_B = area of solar blanket (km^2)

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

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

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

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

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

where:

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

η_{SAPD} = solar array power distribution efficiency

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

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

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

η_{PC} = phase control efficiency

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

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

η_{BC} = beam collection efficiency

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

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

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

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

η_{EFF} = effective concentration ratio

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

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

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

η_{CONC} = efficiency of the concentrator

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$M_{ANT\ PD}$ = total mass of the antenna power distribution system (kg)

$m_{ANT\ PD}$ = specific mass of the antenna power distribution system (kg/kW)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

M_{CB} = total mass of the construction base attributed to each satellite for the purposes of estimating LEO launch cost per satellite built (kg)

m_{CB} = basic mass of construction base (excluding external power system (EPS) and radiation shielding masses) (kg) [Note: this mass varies with construction base size]

m_{P1} = specific mass of the construction base EPS solar array (kg/kW)

P_{EPSREQ} = construction base EPS power requirements (kW) [Note: this power requirement varies with construction base size and orbital assembly site]

m_{P2} = specific mass of the construction base EPS batteries (kg/kW)

m_{RDS} = mass of the construction base radiation shielding (kg) [Note: this mass varies with construction base size and orbital assembly site]

a_{CB} = factor which attributes a uniform fraction of the construction base to the mass launched for each satellite built ($a_{CB} = 1/N_{SAT}$, where N_{SAT} = total number of satellites built)

m_{OP} = mass of the orbit-keeping propellant required by the construction base during the construction of one satellite (kg) [Note: this mass varies with the construction base size and orbital assembly site]

m_{AP} = mass of the attribute control propellant required by construction base during the construction of one satellite (kg) [Note: this mass varies with the construction base size and orbital assembly site]

N_{POTV} = total number of personnel orbit transfer vehicle (POTV) flights required to rotate construction base crew members during the construction of one satellite [Note: the POTV is used only in the case of GEO construction]

N_{CREW} = total number of construction base crew members (including support personnel)
[Note: this number varies with construction base size]

f_{POTV} = number of personnel that can be carried per personnel orbit transfer vehicle (POTV) flight

f_{CROT} = rate of crew rotations (number of rotations/year)

R_{CONST} = rate of satellite construction (number of satellites/year)

$M_{POTVPRP}$ = total mass of POTV propellant consumed during the construction of one satellite (kg)

$f_{POTVPRP}$ = mass of propellant consumed per POTV (round-trip) flight (kg)

M_{PPT} = total mass of POTV propellant storage tanks (kg)

f_T = capacity of single propellant storage tank (kg)

m_T = unit mass of propellant storage tank (kg)

a_T = amortization factor which specifies what fractional amount of each propellant tank's design life is "consumed" for each satellite built (a_T = 1/design life/R_{CONST}, where design life is measured in years)

N_{COTV} = total number of cargo orbit transfer vehicle (COTV) flights required to transport the mass necessary for the construction of one satellite
[Note: the COTV is used only in the case of GEO construction]

f_{COTV} = payload capability of each COTV, from LEO to GEO (kg)

M_{COTV} = total mass of COTV's "consumed" during the construction of one satellite (kg)

$f_{COTV\ LIFE}$ = design life of a COTV (number of flights)

m_{COTV} = unit mass of a COTV (kg)

M_{POTV} = total mass of POTV's "consumed" during the construction of one satellite (kg)

$f_{POTV\ LIFE}$ = design life of a POTV (number of flights)

m_{POTV} = unit mass of a POTV (kg)

$M_{COTVPRP}$ = total mass of COTV propellant consumed during the construction of one satellite (kg)

f_{CPRP} = mass of propellant consumed per COTV (round-trip) flight (kg)

M_{CPT} = total mass of COTV propellant storage tanks (kg)

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

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

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

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

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

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

$M_{PROP\ DEPOT}$ = total mass of the tanks used as propellant depots (kg)

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

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

a_{IT}' = amortization factor for the ion propellant storage tank

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

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

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

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

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

N_{HUS} = total number of HLLV upper stages "consumed" during the construction of one satellite (this may be a fractional amount)

$f_{HUS\ LIFE}$ = design life of an HLLV upper stage (number of flights)

N_{HLS} = total number of HLLV lower stages "consumed" during the construction of one satellite (this may be a fractional amount)

$f_{HLS\ LIFE}$ = design life of an HLLV lower stage (number of flights)

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

$f_{S\ LIFE}$ = design life of a shuttle (number of flights)

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

$N_{S\ UNITS}$ = total number of shuttles "consumed"

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

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

c_{HUS} = unit cost of an HLLV upper stage ($)

c_{HLS} = unit cost of an HLLV lower stage ($)

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

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

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

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

C_{CB} = total cost of the construction base attributed to each satellite for the purpose of estimating the assembly cost per satellite built ($)

c_{CB} = basic unit cost of construction base excluding cost of EPS, radiation shielding and RCS propellants ($) [Note: since one construction base is assumed to build the entire fleet of satellites, the cost of the construction base 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 7.5 percent per year equals the present value of the cost of the construction base at the IOD of the first production unit--this value is the one shown in the input data table in Appendix D. This cost varies with construction base size and orbital assembly site.]

c_{P1} = specific cost of the construction base EPS solar array ($/kW)

c_{P2} = specific cost of the construction base EPS batteries ($/kW)

c_{RDS} = cost of the radiation shielding ($)
[Note: this value varies with construction base size and orbital assembly site]

c_{AP} = specific cost of attitude control propellant ($/kg)

c_{OP} = specific cost of orbit-keeping propellant ($/kg)

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

c_{COTV} = unit cost of a COTV ($)

c_{POTV} = unit cost of a POTV ($)

c_{PRP} = specific cost of OTV propellants ($/kg)

C_{AIS} = unit cost of the advanced ion stage ($)

a_{AIS} = amortization factor of the ion stage

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

c_T = unit cost of an OTV propellant storage tank ($)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

A_{RECT} = total area of the rectenna site (m^2)

P_{5YR} = power output level of system after five years, where

$$P_{5YR} = P_{OUT}\left(\frac{5}{5.258}\right)$$

E = elevation angle of the power transmission beam (°)

c_{RECT} = specific cost of the rectenna (\$/m^2)

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

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

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

C_{PC} = cost of the rectenna phase control electronics (\$)

B.2 The Unit Production Cost Model Used to Evaluate Programs I, II and III

Satellite Mass

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

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

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

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

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

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

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

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

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

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

$$M_{ANT-INT} = m_{ANT-INT}\ P_{ANT-INT}$$

$$M_{PCE} = m_{PCE}\ P_{PCE}$$

$$M_{ANT} = M_{ANTS} + M_{DC-RF} + M_{WG} + M_{ANT-INT} + M_{PCE}$$

$$M_{TOT\ SAT} = M_{SAB} + M_{SAC} + M_{STC} + M_{STNC} + M_{STCM} + M_{ANT} + M_{MISC}$$

Assembly Equipment Mass

$$M_{MANNED} = \beta\ M_{TOT\ SAT}$$

$$M_{REMOTE} = (1 - \beta)\ M_{TOT\ SAT}$$

$$T_{MANNED} = \frac{M_{MANNED}}{R_{MANNED}}$$

$$T_{REMOTE} = \frac{M_{REMOTE}}{R_{REMOTE}}$$

$$N_{LEO} = \frac{T_{MANNED}\ f_S}{T_{CONST\ LEO}\ f_M}$$

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

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

$$N_{MANIP} = \frac{\gamma\ N_{LEO}}{f_S\ f_{MANIP}}$$

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

$$M_{FAB} = m_{FAB}\ N_{FAB}\ a_{FAB}$$

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

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

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

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

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

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

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

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

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

<u>Masses Related to Interorbit Transportation</u>

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

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

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

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

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

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

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

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

Total Mass to LEO

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

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

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

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

LEO Launch Cost

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

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

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

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

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

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

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

Space Station and Assembly Cost

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

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

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

LEO-GEO Transportation Cost

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

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

Satellite Procurement Cost

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

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

Ground Station Cost

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

Total Unit Production Cost

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

Definitions of Unit Production Cost Model Variables

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

A_B = area of solar blanket (km^2)

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

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

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

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

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

where:

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

η_{SAPD} = solar array power distribution efficiency

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

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

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

η_{PC} = phase control efficiency

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

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

η_{BC} = beam collection efficiency

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

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

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

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

η_{eff} = effective concentration ratio

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

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

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

η_{CONC} = efficiency of the concentrator

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

N_{LEO} = number on-orbit personnel*

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

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

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

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

f_S = number of shifts per day

N_{TELE} = number of on-orbit teleoperators

N_{FAB} = total number of fabrication modules

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

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

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

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

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

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

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

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

a_{TELE} = amortization factor for teleoperators

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

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

a_{TUG} = amortization factor for LEO support tugs

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

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

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

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

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

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

a_{MANIP} = amortization factor for manned manipulators

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

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

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

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

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

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

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

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

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

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

a_{CREW} = amortization factor of crew module

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

f_{GRD} = number of shifts of ground operators

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

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

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

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

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

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

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

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

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

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

a_{LCT} = amortization factor of cryo tug

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

a_{AIS} = amortization factor of the ion stage

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX C

OPERATION AND MAINTENANCE COST MODEL

The following is a listing of the equations incorporated in the Operation and Maintenance Cost Model. (A description of the cost model is found in Section 4.3).

Launch Facility O&M

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

Ground Station O&M

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

Space Station and Support O&M

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

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

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

$$C_{S/S\ MC} = f_{S/S\ MC}\ P_{OUT}$$

Satellite O&M

$$C_{SAT\ O\&M} = \sum_{i=1}^{n} c_{SAT\ COMP_i}$$

Definitions of O&M Cost Model Variables

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

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

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

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

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

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

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

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

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

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

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

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

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

P_{OUT} = power output at the rectenna busbar (beginning of life) (kW)

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

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

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

$f_{SAT\ COMP_i}$ = the rate of replacement of units of satellite component i (1/yr)

$\mu_{SAT\ COMP_i}$ = the mass of the lowest replaceable unit of satellite component i (kg)

$c_{COMP\ PROC_i}$ = the procurement cost of the lowest replaceable unit of satellite component i ($/kg)

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

$c_{O\&M\ ASSY_i}$ = specific cost of assembly for a unit of satellite component i ($/kg)

APPENDIX D

THE CURRENT STATE-OF-KNOWLEDGE

The current state-of-knowledge relative to the current configuration SSPS is reflected by the ranges of input variables to the risk analysis model. These ranges have been subjectively assessed and are given in Table D.1 for the unit production costs for Programs I, II and III, and in Table D.2 for the unit production costs for Programs IV and V. Tables D.3 and D.4 give the input variables for the operation and maintenance costs which are the same for all five programs.

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

In addition, several meetings with Rudy Adornato and C. Allan Nathan of Grumman Aerospace were conducted to review and update these data, and Owen Maynard of Raytheon Co. was consulted on several occasions concerning the microwave portions of the systems. Data on solar cell materials was supplied by Arthur D. Little, Inc. as a part of this study. Their work in preparing these data is reported in Volume IV of this report,

Table D.1 UNIT PRODUCTION COST MODEL INPUT VALUES

INPUT ELEMENT	UNITS	VARIABLE NAME	RANGE OF VALUES		
			BEST	MOST LIKELY	WORST
Power Output at the Busbar (bol)	kW	P	*	5.258×10^5	*
Packing Factor of the Solar Blanket	Fraction	P_F	0.99	0.95	0.91
Effective Concentration Ratio	Fraction	η_{eff}	2.0	2.0	2.0
Solar Cell Efficiency (bol)	Fraction	η_{SC}	0.1440	0.1293	0.1019
Solar Array Power Distribution Efficiency	Fraction	η_{SAPD}	0.95	0.93	0.92
Antenna Interface Efficiency	Fraction	$\eta_{ANT-INT}$	0.99	0.98	0.97
Antenna Power Distribution Efficiency	Fraction	$\eta_{ANT\ PD}$	0.97	0.96	0.96
DC-RF Converter Efficiency	Fraction	η_{DC-RF}	0.90	0.87	0.85
Phase Control Efficiency	Fraction	η_{PC}	0.97	0.96	0.95
Ionospheric Propagation Efficiency	Fraction	$\eta_{ION\ PROP}$	1.00	1.00	1.00
Atmospheric Propagation Efficiency	Fraction	$\eta_{ATM\ PROP}$	0.99	0.99	0.99
Beam Collection Efficiency	Fraction	η_{BC}	0.95	0.925	0.90
RF-DC Converter Efficiency	Fraction	η_{RF-DC}	0.90	0.87	0.84
Rectenna Power Distribution Efficiency	Fraction	$\eta_{RECT\ PD}$	0.95	0.94	0.93
Specific Mass of the Solar Blanket	kg/km^2	m_{SAB}	282×10^3	400×10^3	525×10^3
Efficiency of the Solar Concentrator	Fraction	η_{CONC}	0.90	0.85	0.80
Specific Mass of the Solar Concentrator	kg/km^2	m_{SAC}	39820	59340	79120
Ratio: Conducting Struct. Mass to Array Area	kg/km^2	m_{STC}	4140	4600	5060
Ratio: Noncond. Struct. Mass to Array Area	kg/km^2	m_{STNC}	34200	38000	41800
Specific Mass of Central Mast	kg/km	m_{STCM}	43970	48850	53740
Aspect Ratio of Solar Array	Fraction	r_A	*	1.2	*
Antenna Clearance	Fraction	r_L	*	1.5	*
Diameter of Transmitting Antenna	km	D_{ANT}	*	0.33	*
Specific Mass of Antenna Structure	kg/kW	m_{ANTS}	.0802	0.0891	0.0980
Specific Mass of DC-RF Converters	kg/kW	m_{DC-RF}	0.2495	0.2772	0.4544
Specific Mass of Waveguides	kg/kW	m_{WG}	0.2473	0.2748	0.5496
Specific Mass of Antenna Interface	kg/kW	$m_{ANT-INT}$	0.0171	0.0190	0.0380
Specific Mass of Phase Control Electronics	kg/kW	m_{PCE}	0.0160	0.0178	0.0356
Miscellaneous Mass	kg	M_{MISC}	70×10^3	100×10^3	360×10^3
Percentage of Satellite Assembled by Man	Fraction	β	0.20	0.20	0.50
Rate of Manned Assembly	kg/Day	R_{MANNED}	254	100	50
Rate of Remote Assembly	kg/Day	R_{REMOTE}	500	100	48
Total Construction Time	Days	T_{CONST}	*	730	*
Shift Factor	#/Day	f_S	*	3.0	*
Personnel Productivity Factor	Fraction	f_M	0.70	0.60	0.50
Teleoperator Availability Factor	Fraction	$f_{TELE\ AV}$	0.95	0.90	0.85
Teleoperator Work Factor	Fraction	f_T	0.50	0.30	0.20
Fabrication Rate of Modules	kg/Day	R_{FAB}	4560	3000	2250
Fabrication Module Availability Factor	Fraction	f_{FAB}	0.30	0.20	0.10
Percentage of Personnel Using Manipulators	Fraction	r	*	0.10	*
Manipulator Availability Factor	Fraction	f_{MANIP}	0.50	0.30	0.20

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

INPUT ELEMENT	UNITS	VARIABLE NAME	RANGE OF VALUES		
			BEST	MOST LIKELY	WORST
Number of Personnel Per LEO Space Station	Number	$f_{LEO\ S/S}$	•	12	•
Fabrication Module Unit Mass	kg	m_{FAB}	1500	4540	9000
Teleoperator Unit Mass	kg	m_{TELE}	50	180	250
LEO Support Tug Unit Mass	kg	m_{TUG}	500	1364	3000
EVA Equipment Unit Mass	kg	m_{EVA}	68	90	135
EVA Unit Use Factor	Fraction	f_{EVA}	0.40	0.30	0.20
Manipulator Unit Mass	kg	m_{MANIP}	900	1940	3600
LEO Space Station Unit Mass	kg	$m_{LEO\ S/S}$	80×10^3	102×10^3	150×10^3
Assembly Equip. Propellant Estimation Factor	Fraction	$f_{AE\ PROP}$	0.01	0.02	0.05
Space Station Resupply Estimation Factor	Kg/man/day	$f_{S/S\ RES}$	•	10	•
Crew Module Unit Mass	kg	m_{CREW}	12×10^3	13×10^3	15×10^3
GEO Space Station Unit Mass	kg	$m_{GEO\ S/S}$	40×10^3	50×10^3	76×10^3
LCT Total LEO-GEO Mission ΔV	m/sec	ΔV_{LCT}	•	8534	•
LCT Rocket Exhaust Jet Velocity	m/sec	$V_{J_{LCT}}$	•	4564	•
LCT Propellant Mass-Fraction	Fraction	λ_{LCT}	•	0.90	•
Crew Rotation Period	Days	T_{ROT}	180	90	60
AIS Total LEO-GEO Mission ΔV	m/sec	ΔV_{AIS}	•	9754	•
AIS Exhaust Jet Velocity	m/sec	$V_{J_{AIS}}$	•	47316	•
AIS Propellant Mass-Fraction	Fraction	λ_{AIS}	•	0.335	•
Liquid Hydrogen Storage Tank Unit Mass	kg	m_{HT}	•	39105	•
Liquid Hydrogen Storage Tank Capacity	kg	C_{HT}	•	720900	•
Liquid Oxygen Storage Tank Unit Mass	kg	m_{LOXT}	•	39105	•
Liquid Oxygen Storage Tank Capacity	kg	C_{LOXT}	•	720900	•
Ion Propellant Storage Tank Mass	kg	m_{IT}	•	39105	•
Ion Propellant Storage Tank Capacity	kg	C_{IT}	•	720900	•
HLLV Payload to LEO	kg	$M_{P/L}$	•	181×10^3	•
HLLV Average Load Factor	Fraction	f_{LOAD}	1.00	0.90	0.70
HLLV Turnaround Time	Days	$T_{H\ TURN}$	•	14	•
Number of Personnel Per Shuttle Flight	Number	$f_{SHUTTLE}$	60	40	20
Shuttle Turnaround Time	Days	$T_{S\ TURN}$	•	14	•
Launch Cost Per HLLV Flight	$	C_{HLLV}	8×10^5	9×10^5	20×10^5
HLLV Unit Cost	$	$C_{H\ UNIT}$	350×10^6	400×10^6	600×10^6
Launch Cost Per Shuttle Flight	$	$C_{SHUTTLE}$	11×10^6	12×10^6	20×10^6
Shuttle Unit Cost	$	$C_{S\ UNIT}$	190×10^6	200×10^6	250×10^6
Fabrication Module Unit Cost	$	C_{FAB}	10×10^5	12×10^5	20×10^6
Fabrication Module Amortisation Factor	Fraction	a_{FAB}	•	0.2	•
Teleoperator Unit Cost	$	C_{TELE}	2.0×10^5	2.5×10^5	10.0×10^5
Teleoperator Amortisation Factor	Fraction	a_{TELE}	•	0.2	•
Assembly Equipment Propellant Specific Cost	$/kg	$C_{AE\ PROP}$	•	0.33	•
LEO Support Tug Unit Cost	$	C_{TUG}	2.0×10^5	2.5×10^5	10.0×10^5
LEO Support Tug Amortisation Factor	Fraction	a_{TUG}	•	0.2	•

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

INPUT ELEMENT	UNITS	VARIABLE NAME	RANGE OF VALUES		
			BEST	MOST LIKELY	WORST
Number of Shifts for Ground Operators	Number	f_{GRO}	*	4	*
EVA Equipment Unit Cost	$	c_{EVA}	1.5×10^5	2.0×10^5	5.0×10^5
Manipulator Unit Cost	$	c_{MANIP}	8.0×10^6	11.0×10^6	30.0×10^6
Manipulator Amortisation Factor	Fraction	a_{MANIP}	*	0.2	*
LEO Space Station Unit Cost	$	$c_{LEO\ S/S}$	190×10^6	360×10^6	720×10^6
LEO Space Station Amortisation Factor	Fraction	$a_{LEO\ S/S}$	*	0.2	*
GEO Space Station Unit Cost	$	$c_{GEO\ S/S}$	96×10^6	180×10^6	360×10^6
GEO Space Station Amortisation Factor	Fraction	$a_{GEO\ S/S}$	*	0.2	*
Space Station Resupply Specific Cost	$	$c_{S/S\ RES}$	5.0	10.0	20.0
LCT Unit Cost	$	c_{LCT}	12×10^6	15×10^6	25×10^6
LCT Amortisation Factor	Fraction	a_{LCT}	*	0.2	*
AIS Unit Cost	$	c_{AIS}	150×10^5	190×10^5	1000×10^5
AIS Amortisation Factor	Fraction	a_{AIS}	*	0.2	*
Cryo Tug Propellant Specific Cost	$/kg	$c_{LCT\ PROP}$	*	0.55	*
Ion Propellant Specific Cost	$/kg	$c_{AIS\ PROP}$	*	0.33	*
Crew Module Unit Cost	$	c_{CREW}	18×10^5	23×10^5	40×10^5
Crew Module Amortization Factor	Fraction	a_{CREW}	*	0.04	*
Liquid Hydrogen Storage Tank Unit Cost	$	c_{LHT}	12×10^5	15×10^5	20×10^5
Liquid Oxygen Storage Tank Unit Cost	$	c_{LOXT}	12×10^5	16×10^5	20×10^5
Ion Propellant Storage Tank Unit Cost	$	c_{IT}	12×10^5	16×10^5	20×10^5
Liquid Hydrogen Tank Amortisation Factor	Fraction	a_{LHT}	0.67	1.0	1.5
Liquid Oxygen Tank Amortisation Factor	Fraction	a_{LOXT}	0.67	1.0	1.5
Ion Propellant Tank Amortisation Factor	Fraction	a_{IT}	0.67	1.0	1.5
Antenna Power Distribution Specific Cost	$/kW	c_{PD}	9.72	10.80	21.60
Phase Control Specific Cost	$/kW	c_{PC}	16.83	18.70	37.40
Waveguide Specific Cost	$/kW	c_{WG}	7.92	8.80	17.60
DC-RF Converter Specific Cost	$/kW	c_{DC-RF}	14.67	16.30	32.60
Antenna Structure Specific Cost	$/kW	c_{ST}	8.10	9.00	18.00
Solar Array Blanket Specific Cost	$/km^2	c_{SAB}	27.5×10^5	55.0×10^5	165.0×10^5
Solar Array Concentrator Specific Cost	$/km^2	c_{SAC}	1.04×10^5	2.07×10^5	6.22×10^5
Conducting Structure Specific Cost	$/kg	c_{STC}	20.0	81.0	300.0
Non-Conducting Structure Specific Cost	$/kg	c_{STNC}	20.0	81.0	300.0
Central Mast Specific Cost	$/kg	c_{STCM}	20.0	81.0	300.0
Miscellaneous Equipment Specific Cost	$/kg	c_{MISC}	219	437	760
Rectenna Site Specific Cost	$/kW	c_{RE}	19.89	22.10	44.20
Rectenna Structure Specific Cost	$/kW	c_{STRUCT}	83.88	93.20	186.40
RF-DC Convertor Specific Cost	$/kW	c_{RF-DC}	56.00	62.20	124.40
Power Interface Specific Cost	$/kW	c_{INTERF}	39.80	44.20	88.40
Phase Control Specific Cost	$/kW	c_{PC}	3.33	3.70	7.40
Solar Flux Constant	kW	F	*	1.353×10^3	*

Table D.2 Unit Production Cost Model Input Values

Input Element	Units	Variable Name	Range of Values		
			Best	Most Likely	Worst
Power Output at Rectenna Busbar (B.O.L.)	kW	P_{OUT}	--	5.258×10^6	--
Solar Cell Efficiency (B.O.L.) CdS	Fraction	η_{SC}	.065	.054	.043
Solar Cell Efficiency (B.O.L.) Si	Fraction	η_{SC}	.118	.092	.067
Solar Cell Efficiency (B.O.L.) GaAs	Fraction	η_{SC}	.184	.149	.116
Solar Array Power Distribution Efficiency	Fraction	η_{SAPD}	0.95	0.93	0.92
Antenna Interface Efficiency	Fraction	$\eta_{ANT\ INT}$	0.99	0.98	0.97
Antenna Power Distribution Efficiency	Fraction	$\eta_{ANT\ PD}$	0.99	0.98	0.97
DC-RF Converter Efficiency	Fraction	η_{DC-RF}	0.90	0.87	0.85
Phase Control Efficiency	Fraction	η_{PC}	0.96	0.95	0.94
Ionospheric Propagation Efficiency	Fraction	$\eta_{ION\ PROP}$	1.0	1.0	1.0
Atmospheric Propagation Efficiency	Fraction	$\eta_{ATM\ PROP}$	0.99	0.99	0.99
Beam Collection Efficiency	Fraction	η_{BC}	0.97	0.95	0.93
RF-DC Converter Efficiency	Fraction	η_{RF-DC}	0.91	0.88	0.85
Rectenna Power Distribution Efficiency	Fraction	$\eta_{RECT\ PD}$	0.96	0.95	0.94
Packing Factor of Solar Blanket	Fraction	P_F	0.99	0.95	0.91
Solar Flux Constant	kW/km^2	F	--	1.35×10^6	--

Table D.2 Unit Production Cost Model Input Values (continued)

Input Element	Units	Variable Name	Range of Values: Best	Most Likely	Worst
Effective Concentration Ratios	Fraction	η_{EFF}	2.0	2.0	1.8
Specific Mass of Solar Blanket: CdS	kg/km^2	m_{SAB}	1.15×10^5	1.49×10^5	1.94×10^5
Specific Mass of Solar Blanket: Si	kg/km^2	m_{SAB}	8.05×10^5	11.5×10^5	14.95×10^5
Specific Mass of Solar Blanket: GaAs	kg/km^2	m_{SAB}	3.32×10^5	4.32×10^5	5.26×10^5
Efficiency of Solar Concentrator	Fraction	η_{CONC}	0.90	0.86	0.82
Specific Mass of Solar Concentrator	kg/km^2	m_{SAC}	39820	59340	79120
Ratio: Conducting Structure Mass to Solar Array Area	kg/km^2	m_{STC}	4140	4625	5060
Ratio: Nonconducting Structure Mass to Solar Array Area	kg/km^2	m_{STNC}	35900	39900	43890
Specific Mass of Central Mast	kg/km	m_{STCM}	100×10^3	120×10^3	200×10^3
Aspect Ratio of Solar Array	Fraction	r_A	--	1.2	--
Antenna Clearance	Fraction	r_L	--	1.5	--
Diameter of Transmitting Antenna	km	D_{ANT}	--	1.027	--
Specific Mass of Antenna Structure	kg/kW	m_{ANT}	.0262	.0291	.0320
Specific Mass of DC-RF Converters	kg/kW	$m_{DC\text{-}RF}$	.2495	.2772	.4544
Specific Mass of Antenna Power Distribution System	kg/kW	$m_{ANT\ PD}$	0.047	0.052	0.104

Table D.2 Unit Production Cost Model Input Values (continued)

Input Element	Units	Variable Name	Range of Values		
			Best	Most Likely	Worst
Specific Mass of Waveguides	kg/kW	m_{WG}	0.3786	0.4207	0.8415
Specific Mass of Antenna Interface	kg/kW	$m_{ANT\ INT}$	0.0171	0.0190	0.0380
Specific Mass of Phase Control Electronics	kg/kW	m_{PCE}	0.0160	0.0178	0.0356
Miscellaneous Satellite Mass	kg	M_{MISC}	70×10^3	100×10^3	360×10^3
Basic Unit Mass of Construction, Small	kg	m_{CB}	2.475×10^6	2.75×10^6	3.025×10^6
Basic Unit Mass of Construction, Large	kg	m_{CB}	4.95×10^6	5.5×10^6	6.05×10^6
Specific Mass of EPS Solar Array	kg/kW	m_{P1}	1.5	2	5
EPS Power Requirements, Small Base LEO	kW	$P_{EPS\ REQ}$	2376	2640	2904
EPS Power Requirements, Large Base LEO	kW	$P_{EPS\ REQ}$	6466	7185	7903
EPS Power Requirements, Large Base GEO	kW	$P_{EPS\ REQ}$	2628	2920	3212
EPS Power Requirements, Small Base GEO	kW	$P_{EPS\ REQ}$	945	1050	1155
Special Mass of EPS Batteries	kg/kW	m_{P2}	25	27	40

Table D.2 Unit Production Cost Model Input Values (continued)

Input Element	Units	Variable Name	Range of Values		
			Best	Most Likely	Worst
Orbit Keeping Propellant Mass, Small Base LEO	kg	m_{OP}	9000	10000	14000
Orbit Keeping Propellant Mass, Large Base LEO	kg	m_{OP}	9000	10000	14000
Orbit Keeping Propellant Mass, Small Base GEO	kg	m_{OP}	0	0	0
Orbit Keeping Propellant Mass, Large Base GEO	kg	m_{OP}	0	0	0
Attitude Control Propellant Mass, Small Base LEO	kg	m_{AP}	2.52×10^{6}	2.8×10^{6}	3.08×10^{6}
Attitude Control Propellant Mass, Large Base LEO	kg	m_{AP}	1.35×10^{6}	1.5×10^{6}	1.65×10^{6}
Attitude Control Propellant Mass, Small Base GEO	kg	m_{AP}	2.52×10^{3}	2.8×10^{3}	3.08×10^{3}
Attitude Control Propellant Mass, Large Base GEO	kg	mAP	58.5×10^{3}	65×10^{3}	71×10^{3}
Total Satellite Fleet Size	Number	N_{SAT}	--	120	--
Total Crew Size, Small Base	Number	N_{crew}	600	682	750
Total Crew Size, Large Base	Number	N_{crew}	1600	1875	2060

Table D.2 Unit Production Cost Model Input Values (continued)

Input Element	Units	Variable Name	Range of Values		
			Best	Most Likely	Worst
Number of Personnel Carried per POTV Flight	#/Flight	f_{POTV}	80	75	70
Number of Crew Rotations Per Year	#/Year	f_{CROT}	3	4	6
Rate of Satellite Construction	#/Year	R_{const}	8 Large/ 6 Small	6 Large/ 4 Small	5 Large/ 3 Small
Propellant Consumption per POTV Flight (RT)	kg	$f_{POTV\ PRP}$	$156x10^3$	$159x10^3$	$162x10^3$
Capacity of Propellant Storage Tank	kg	f_T	--	$106x10^3$	--
Unit Mass of Propellant Storage Tank	kg	m_T	--	$3.18x10^3$	--
Payload of COTV	kg	f_{COTV}	--	$250x10^3$	--
Unit Mass of COTV (Dry)	kg	m_{COTV}	--	$35x10^3$	--
Design Life of POTV	# Flights	$f_{POTV\ Life}$	--	30	--
Unit Mass of POTV (Dry)	kg	m_{COTV}	--	$17x10^3$	--
Propellant Consumption per COTV Flight	kg	$f_{COTV\ PRP}$	--	$475x10^3$	--
HLLV Payload to LEO	kg	$M_{P/L}$	--	$265x10^3$	--
AIS Propellant Mass-Fraction	Fraction	λ_{AIS}	--	0.7289	--
AIS Total LEO-GEO Mission ΔV	$^m/_{sec}$	ΔV_{AIS}	--	5975	--

Table D.2 Unit Production Cost Model Input Values (continued)

Input Element	Units	Variable Name	Range of Values: Best	Most Likely	Worst
AIS Exhaust Jet Velocity	m/sec	$V_{J_{AIS}}$	--	50,000	--
Ion Propellant Storage Tank Capacity	kg	F_{IT}	--	2.33×10^6	--
Ion Propellant Storage Tank Unit Mass (Dry)	kg	m_{IT}	--	163×10^3	--
HLLV Average Load Factor	Fraction	f_{LOAD}	1.0	0.9	0.8
Design Life of HLLV Upper Stage	# Flights	$f_{HUS\ LIFE}$	500	500	400
Design Life of HLLV Lower Stage	# Flights	$f_{HLS\ LIFE}$	300	300	200
Number of Personnel per Shuttle Flight	Number	$f_{SHUTTLE}$	--	75	--
Design Life of Shuttle	# Flights	f_{SLIFE}	--	100	--
HLLV Upper Stage Unit Cost	$	c_{HUS}	175×10^6	192×10^6	250×10^6
HLLV Lower Stage Unit Cost	$	c_{HLS}	175×10^6	191×10^6	250×10^6
Launch Operations Cost per HLLV Flight	$	c_{HLLV}	6.5×10^6	6.9×10^6	9.0×10^6
Launch Operations Cost per Shuttle Flight	$	$c_{SHUTTLE}$	12×10^6	13×10^6	20×10^6
Shuttle Unit Cost	$	c_{SUNIT}	190×10^6	200×10^6	250×10^6

Table D.2 Unit Production Cost Model Input Values (continued)

Input Element	Units	Variable Name	Range of Values		
			Best	Most Likely	Worst
Basic Unit of Construction Base (Small)	$	c_{CB}	1.128×10^9	2.165×10^9	3.631×10^9
Basic Unit Cost of Construction Base (Large)	$	c_{CB}	2.447×10^9	3.612×10^9	5.23×10^9
Specific Cost of EPS Solar Array	$/kW	c_{P1}	100	200	600
Specific Cost of EPS Batteries	$/kW	c_{P2}	4000	5000	20000
Cost of Radiation Shielding, Small Base LEO	$	c_{RDS}	5×10^6	10×10^6	30×10^6
Cost of Radiation Shielding, Large Base LEO	$	c_{RDS}	15×10^6	30×10^6	100×10^6
Cost of Radiation Shielding, Small Base GEO	$	c_{RDS}	15×10^6	30×10^6	100×10^6
Cost of Radiation Shielding, Large Base GEO	$	c_{RDS}	30×10^6	90×10^6	200×10^6
Specific Cost of Altitude Control Propellant	$/kg	c_{AP}	--	.33	--
Specific Cost of Orbit-Keeping Propellant	$/kg	c_{OP}	--	.33	--
COTV Unit Cost	$	c_{COTV}	12×10^6	15×10^6	25×10^6
POTV Unit Cost	$	c_{POTV}	18×10^6	23×10^6	40×10^6

Table D.2 Unit Production Cost Model Input Values (continued)

Input Element	Units	Variable Name	Range of Values: Best	Most Likely	Worst
Specific Cost of OTV Propellant	\$/kg	c_{PRP}	--	.55	--
AIS Unit Cost	\$	C_{AIS}	150×10^6	400×10^6	500×10^6
Specific Cost of Ion Propellant	\$/kg	$c_{AIS\ PROP}$	--	.33	--
CTV Propellant Storage Tank Unit Cost	\$	C_T	12×10^6	16×10^6	20×10^6
Ion Propellant Storage Tank Unit Cost	\$	C_{IT}	12×10^6	16×10^6	20×10^6
Antenna Power Distribution Specific Cost	\$/kW	c_{PD}	6.00	6.59	12.52
Phase Control Electronics Specific Cost	\$/kW	c_{PCE}	25.77	28.63	56.80
Wave Guide Specific Cost	\$/kW	c_{WG}	12.13	13.47	26.95
DC-RF Converter Specific Cost	\$/kW	$c_{DC\text{-}RF}$	14.67	16.3	32.6
Antenna Structure Specific Cost	\$/kW	c_{ST}	12.40	13.78	27.56
Solar Array Blanket Specific Cost: CdS	\$/km²	c_{SAB}	4.87×10^7	8.66×10^7	27.06×10^7
Solar Array Blanket Specific Cost: Si	\$/km²	c_{SAB}	4.87×10^7	8.66×10^7	73.06×10^7
Solar Array Blanket Specific Cost: GaAs	\$/km²	c_{SAB}	4.87×10^7	20.3×10^7	148.8×10^7
Solar Array Concentrator Specific Cost	\$/km²	c_{SAC}	1.04×10^6	2.07×10^6	6.22×10^6
Conducting Structure Specific Cost	\$/kg	c_{STC}	20	81	300
Nonconducting Structure Specific Cost	\$/kg	c_{STNC}	20	81	300

Table D.2 Unit Production Cost Model Input Values (continued)					
Input Element	Units	Variable Name	Range of Values		
			Best	Most Likely	Worst
Central Mast Specific Cost	\$/kg	c_{STCM}	20	81	300
Miscellaneous Equipment Specific Cost	\$/kg	c_{MISC}	219	437	750
Rectenna Specific Cost	\$/km²	c_{RECT}	7.37	10.98	16.06
Beam Elevation Angle	Radians	E	--	50	--
Power Interface Specific Cost	\$/kw	c_{INTERF}	39.8	44.2	88.4
Phase Control Specific Cost	\$/kw	c_{PC}	20.29×10^6	23.79×10^6	49.81×10^6

Table D.3 LAUNCH FACILITY GROUND STATION, AND SPACE STATION O&M INPUT VALUES

INPUT ELEMENT	UNITS	VARIABLE NAME	RANGE OF VALUES		
			MINIMUM	MOST LIKELY	MAXIMUM
Number of O&M Resupply Flights Per Year	Number	$N_{O\&M\ FLTS}$	1	1	1
Cost Per HLLV Flight	\$	C_{HLLV}	8×10^6	9×10^5	20×10^5
Amortisation Factor for the HLLV	Fraction	a_{HLLV}	.01	.01	.01
Unit Cost of HLLV	\$	$C_{H\ UNIT}$	350×10^6	400×10^6	600×10^6
Cost Per AIS Flight	\$	$C_{AIS\ FLT}$	1×10^5	1×10^6	1×10^5
Unit Cost of AIS for O&M Flights	\$	C_{AIS2}	23×10^5	23×10^6	23×10^6
Amortisation Factor for the AIS	Fraction	a_{AIS}	0.20	0.20	0.20
Total Number of Launch Mission Control Personnel	Number	N_{LFP}	320	320	320
Cost Per Person - Launch Mission Control	\$/yr	f_{LFP}	43,750	43,750	43,750
Percentage Rate of Ground Equipment Replacement	Fraction	$f_{GRD\ EQUIP}$	.01	.01	.01
Procurement Cost of Ground Station -	\$	$C_{GRD\ STAT}$	[Input From Unit Production Cost Model]		
Total Number of Ground Station O&M Personnel	Number	$N_{GST\ P}$	60	60	60
Cost Per Person - Ground Station O&M	\$/yr	$C_{GST\ P}$	60×10^3	60×10^3	60×10^3
Crew Rotation Rate	#/Year	f_{CROT}	4	4	4
Cost Per Shuttle Flight	\$	$C_{SHUTTLE}$	11×10^6	12×10^6	20×10^6
Amortisation Factor for Shuttle	Fraction	$a_{SHUTTLE}$	0.01	0.01	0.01
Unit Cost of Shuttle	\$	$C_{S\ UNIT}$	190×10^6	190×10^5	190×10^5
Cost Per Tug Flight	\$	$C_{TUG\ OPS}$	1×10^5	1×10^5	1×10^5
Unit Cost of Tug	\$	C_{TUG}	12×10^6	15×10^5	25×10^6
Amortisation Factor for Tug	Fraction	a_{TUG}	0.05	0.05	0.05
Cost of Crew Module Refurbishment	\$	$C_{CREW\ REF}$	1×10^5	1×10^6	1×10^5
Unit Cost of Crew Module	\$	C_{CREW}	18×10^5	23×10^5	40×10^5
Amortisation Factor of Crew Module	Fraction	a_{CREW}	0.01	0.01	0.01
Amortisation Factor of O&M Space Station	Fraction	$a_{S/S\ O\&M}$	0.10	0.10	0.10
Mass of GEO Space Station	kg	$M_{GEO\ S/S}$	76×10^3	76×10^3	76×10^3
Specific Cost of Transportation to GEO	\$/kg	$C_{GEO\ TRANSP}$	106	106	106
Amortisation Factor for Manipulators	Fraction	$a_{S/S\ EQUIP}$	0.10	0.10	0.10
Total Number of O&M Manipulators	Number	$N_{O\&M\ MANIP}$	50	50	50
Mass of O&M Manipulator	kg	M_{MANIP}	.82	182	182
Unit Cost of O&M Manipulator	\$	$C_{O\&M\ MANIP}$	8×10^5	3×10^5	8×10^6
Specific Cost of Mission Control Facility	\$/kW	$f_{S/S\ MC}$	4	4	4
Power Output at Rectenna Busbar (B O L)	kW	P	*	[illegible]	*

Table 0.4 Satellite O&M Input Values

MAINTENANCE ELEMENT	FAILURE RATE, λ (1/MTBF,yr^{-1})	LRU * MASS (kg)	LRU PRO-CUREMENT COST ($/kg)	GEO TRANSP SPECIFIC COST ($/kg)	ASSEMBLY SPECIFIC COST ($/kg)
Solar Blanket	$2.6x10^{-4}$	97,900	190	106	132
Solar Concentrator	$<2.6x10^{-4}$	7,687	55	106	132
Nonconducting Structure	-	-	-	-	-
Busses	10^{-9}	26,000	81	106	191
Switches	10^{-7}	97,484	190	106	132
Mast	$3x10^{-2}$	85,000	81	106	191
Microwave Tube	$1.14x10^{-6}$	3,017	236	106	132
Power Distribution	$3x10^{-2}$	3,017	236	106	132
Command Electronics	[0.1%/Year]	467	43,788	106	132
Antenna (Excluding Tubes)	$3x10^{-2}$	3,107	236	106	132
Antenna Structure	-	-	-	-	-
Contour Control	$1.25x10^{-6}$	22	11	106	132
Rotary Joint Slip Ring:					
- Brush	10^{-1}	10	96	106	132
- Slip Ring	10^{-1}	63	106	106	132
Rotary Joint Drive:					
- Motor/Gears	10^{-1}	1,367	98	106	132
- Limb	-	1,086	-	-	-
Control System:					
- Actuators	$3.8x10^{-3}$	203	7,500	106	132
- Propellant (Annual Consumption)	-	24,000	0.33	106	-

* LRU = Lowest Replaceable Unit

APPENDIX E

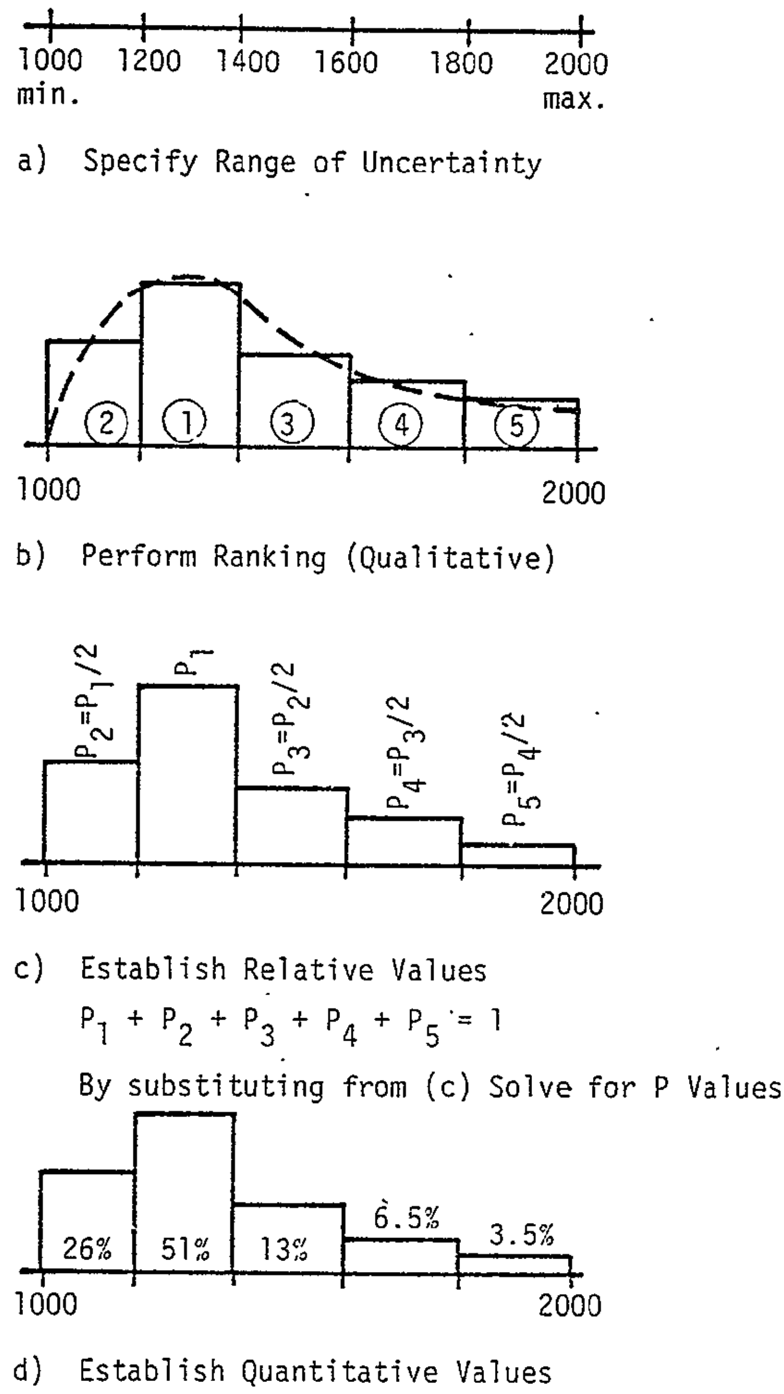
ESTABLISHING UNCERTAINTY PROFILES

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

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

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

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



gure E.1 Methodology for Establishing Shape of Cost Uncertainty Profile (pdf)

APPENDIX F

STATES-OF-KNOWLEDGE AT DECISION POINTS

The states-of-knowledge at the decision points of each alternative program plan have been subjectively assessed and are shown here in Tables F.1 to F.5. The numbers shown represent the percent reduction in uncertainty (that is, the range) in each variable over the state-of-knowledge today (that is, January 1, 1977). These improvements in the states-of-knowledge derive from work that is scheduled during each branch of the respective decision trees. The variables for which a dash is indicated have been treated as deterministic in the analysis conducted to date. It has also been assumed in this analysis that the state-of-knowledge relative to operation and maintenance costs does not change from the present state-of-knowledge until the IOD of the first unit at which time all uncertainty disappears.

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

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

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

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

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

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE-OF-KNOWLEDGE OVER TODAY, %	
			D.P. A	D.P. B
Number of Shifts for Ground Operators	Number	f_{GRD}	--	--
EVA Equipment Unit Cost	\$	c_{EVA}	0	100
Manipulator Unit Cost	\$	c_{MANIP}	0	100
Manipulator Amortisation Factor	Fraction	a_{MANIP}	--	--
LEO Space Station Unit Cost	\$	$c_{LEO\ S/S}$	0	100
LEO Space Station Amortisation Factor	Fraction	$a_{LEO\ S/S}$	--	--
GEO Space Station Unit Cost	\$	$c_{GEO\ S/S}$	0	90
GEO Space Station Amortisation Factor	Fraction	$a_{GEO\ S/S}$	--	--
Space Station Resupply Specific Cost	\$	$c_{S/S\ RES}$	0	100
LCT Unit Cost	\$	c_{LCT}	0	90
LCT Amortisation Factor	Fraction	a_{LCT}	--	--
AIS Unit Cost	\$	c_{AIS}	0	90
AIS Amortisation Factor	Fraction	a_{AIS}	--	--
Cryo Tug Propellant Specific Cost	\$/kg	$c_{LCT\ PROP}$	--	--
Ion Propellant Specific Cost	\$/kg	$c_{AIS\ PROP}$	--	--
Crew Module Amortisation Factor	Fraction	a_{CREW}	--	--
Liquid Hydrogen Storage Tank Unit Cost	\$	c_{LHT}	0	100
Liquid Hydrogen Storage Tank Unit Cost	\$	c_{LHT}	0	100
Liquid Oxygen Storage Tank Unit Cost	\$	c_{LOXT}	0	100
Ion Propellant Storage Tank Unit Cost	\$	c_{IT}	0	100
Liquid Hydrogen Tank Amortisation Factor	Fraction	a_{LHT}	0	100
Liquid Oxygen Tank Amortisation Factor	Fraction	a_{LOXT}	0	100
Ion Propellant Tank Amortisation Factor	Fraction	a_{IT}	0	100
Antenna Power Distribution Specific Cost	\$/kW	c_{PD}	25	70
Phase Control Specific Cost	\$/kW	c_{PC}	25	70
Waveguide Specific Cost	\$/kW	c_{WG}	25	70
DC-RF Converter Specific Cost	\$/kW	c_{DC-RF}	25	70
Antenna Structure Specific Cost	\$/kW	c_{ST}	25	30
Solar Array Blanket Specific Cost	\$/km^2	c_{SAB}	25	30
Solar Array Concentrator Specific Cost	\$/km^2	c_{SAC}	25	30
Conducting Structure Specific Cost	\$/kg	c_{STC}	0	30
Non-Conducting Structure Specific Cost	\$/kg	c_{STNC}	0	30
Central Mast Specific Cost	\$/kg	c_{STCM}	0	30
Miscellaneous Equipment Specific Cost	\$/kg	c_{MISC}	25	30
Rectenna Site Specific Cost	\$/kW	c_{RS}	25	100
Rectenna Structure Specific Cost	\$/kW	c_{STRUCT}	25	100
RF-DC Convertor Specific Cost	\$/kW	c_{RF-DC}	25	100
Power Interface Specific Cost	\$/kW	c_{INTERF}	25	100
Phase Control Specific Cost	\$/kW	c_{PC}	25	100
Solar Flux Constant	[illegible]	F	--	--

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

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

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

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

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

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

TABLE F.3. STATE-OF-KNOWLEDGE AT DECISION POINTS - PROGRAM III

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

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

INPUT ELEMENT	UNITS	VARIABLE NAME	IMPROVEMENT IN THE STATE - OF KNOWLEDGE OVER TODAY, %		
			D.P.B	D.P.C	A & D
Number of Personnel Per LEO Space Station	Number	$f_{LEO\ S/S}$	-	-	
Fabrication Module Unit Mass	kg	m_{FAB}	50	100	
Teleoperator Unit Mass	kg	m_{TELE}	50	100	
LEO Support Tug Unit Mass	kg	m_{TUG}	50	100	
EVA Equipment Unit Mass	kg	m_{EVA}	100	100	
EVA Unit Use Factor	Fraction	f_{EVA}	100	100	
Manipulator Unit Mass	kg	m_{MANIP}	50	90	
LEO Space Station Unit Mass	kg	$m_{LEO\ S/S}$	100	100	
Assembly Equip. Propellant Estimation Factor	Fraction	$f_{AE\ PROP}$	50	100	
Space Station Resupply Estimation Factor	Fraction	$f_{S/S\ RES}$	-	-	
Crew Module Unit Mass	kg	m_{CREW}	100	100	
GEO Space Station Unit Mass	kg	$m_{GEO\ S/S}$	75	100	
LCT Total LEO-GEO Mission ΔV	m/sec	ΔV_{LCT}	-	-	
LCT Rocket Exhaust Jet Velocity	m/sec	$V_{J_{LCT}}$	-	-	
LCT Propellant Mass-Fraction	Fraction	λ_{LCT}	-	-	
Crew Rotation Period	Days	T_{ROT}	0	100	SAME AS PROGRAM II, D.P.A&C
AIS Total LEO-GEO Mission ΔV	m/sec	ΔV_{AIS}	-	-	
AIS Exhaust Jet Velocity	m/sec	$V_{J_{AIS}}$	-	-	
AIS Propellant Mass-Fraction	Fraction	λ_{AIS}	-	-	
Liquid Hydrogen Storage Tank Unit Mass	kg	m_{HT}	-	-	
Liquid Hydrogen Storage Tank Capacity	kg	C_{HT}	-	-	
Liquid Oxygen Storage Tank Unit Mass	kg	m_{LOXT}	-	-	
Liquid Oxygen Storage Tank Capacity	kg	C_{LOXT}	-	-	
Ion Propellant Storage Tank Mass	kg	m_{IT}	-	-	
Ion Propellant Storage Tank Capacity	kg	C_{IT}	-	-	
HLLV Payload to LEO	kg	$M_{P/L}$	-	-	
HLLV Average Load Factor	Fraction	f_{LOAD}	70	30.	
HLLV Turnaround Time	Days	$T_{H\ TURN}$	-	-	
Number of Personnel Per Shuttle Flight	Number	$f_{SHUTTLE}$	100	100	
Shuttle Turnaround Time	Days	$T_{S\ TURN}$	-	-	
Launch Cost Per HLLV Flight	\$	C_{HLLV}	50	100	
HLLV Unit Cost	\$	$C_{H\ UNIT}$	50	100	
Launch Cost Per Shuttle Flight	\$	$C_{SHUTTLE}$	100	100	
Shuttle Unit Cost	\$	$C_{S\ UNIT}$	100	100	
Fabrication Module Unit Cost	\$	C_{FAB}	100	30	
Fabrication Module Amortization Factor	Fraction	a_{FAB}	-	-	
Teleoperator Unit Cost	\$	C_{TELE}	30	30	
Teleoperator Amortization Factor	Fraction	a_{TELE}	-	-	
Assembly Equipment Propellant Specific Cost	\$	$C_{AE\ PROP}$	-	-	
LEO Support Tug Unit Cost	\$	C_{TUG}	100	100	
LEO Support Tug Amortization Factor	Fraction	a_{TUG}	-	-	

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

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

Table F.4 State-of-Knowledge at Decision Points - Program IV

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Power Output at Rectenna Busbar (B.O.L.)	kW	P_{OUT}	-	-	-	-	-
Solar Cell Efficiency (B.O.L.)	Fraction	η_{SC}	40	60	80	90	100
Solar Array Power Distribution Efficiency	Fraction	η_{SAPD}	40	50	80	90	100
Antenna Interface Efficiency	Fraction	$\eta_{ANT\ INT}$	20	30	60	90	100
Antenna Power Distribution Efficiency	Fraction	$\eta_{ANT\ PD}$	-	-	-	-	-
DC-RF Converter Efficiency	Fraction	η_{DC-RF}	-	-	-	-	-
Phase Control Efficiency	Fraction	η_{PC}	-	-	-	-	-
Ionospheric Propagation Efficiency	Fraction	$\eta_{ION\ PROP}$	-	-	-	-	-
Atmospheric Propagation Efficiency	Fraction	$\eta_{ATM\ PROP}$	-	-	-	-	-
Beam Collection Efficiency	Fraction	η_{BC}	-	-	-	-	-
RF-DC Converter Efficiency	Fraction	η_{RF-DC}	-	-	-	-	-
Rectenna Power Distribution Efficiency	Fraction	$\eta_{RECT\ PD}$	-	-	-	-	-
Packing Factor of Solar Blanket	Fraction	P_F	20	80	90	100	100
Solar Flux Constant	kW/km^2	F	-	-	-	-	-

Table F.4 State-of-Knowledge at Decision Points - Program IV (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Effective Concentration Ratios	Fraction	η_{EFF}	20	40	80	100	100
Specific Mass of Solar Blanket	kg/km^2	m_{SAB}	20	50	70	100	100
Efficiency of Solar Concentrator	Fraction	η_{CONC}	20	40	90	100	100
Specific Mass of Solar Concentrator	kg/km^2	m_{SAC}	10	20	80	100	100
Ratio: Conducting Structure Mass to Solar Array Area	kg/km^2	m_{STC}	20	50	90	100	100
Ratio: Nonconducting Structure Mass to Solar Array Area	kg/km^2	m_{STNC}	20	50	90	100	100
Specific Mass of Central Mast	kg/km	m_{STCM}	20	50	90	100	100
Aspect Ratio of Solar Array	Fraction	r_A	-	-	-	-	-
Antenna Clearance	Fraction	r_L	-	-	-	-	-
Diameter of Transmitting Antenna	km	D_{ANT}	-	-	-	-	-
Specific Mass of Antenna Structure	kg/kW	m_{ANT}	20	30	70	100	100
Specific Mass of DC-RF Converters	kg/kW	m_{DC-RF}	-	-	-	-	-
Specific Mass of Antenna Power Distribution System	kg/kW	$m_{ANT\ PD}$	-	-	-	-	-
Specific Mass of Waveguides	kg/kW	m_{WG}	-	-	-	-	-

Table F.4 State-of-Knowledge at Decision Points - Program IV (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Specific Mass of Antenna Interface	kg/kW	$m_{ANT\ INT}$	-	-	-	-	-
Specific Mass of Phase Control Electronics	kg/kW	m_{PCE}	-	-	-	-	-
Miscellaneous Satellite Mass	kg	M_{MISC}	20	30	80	90	100
Basic Unit Mass of Construction, Small	kg	m_{CB}	20	40	80	90	100
Basic Unit Mass of Construction, Large	kg	m_{CB}	20	40	80	90	100
Specific Mass of EPS Solar Array	kg/kW	m_{P1}	20	40	80	90	100
EPS Power Requirements; Small Base LEO	kW	$P_{EPS\ REQ}$	20	40	80	90	100
EPS Power Requirements, Large Base LEO	kW	$P_{EPS\ REQ}$	20	40	80	90	100
EPS Power Requirements, Large Base GEO	kW	$P_{EPS\ REQ}$	20	40	80	90	100
EPS Power Requirements, Small Base GEO	kW	$P_{EPS\ REQ}$	20	40	80	90	100
Specific Mass of EPS Batteries	kg/kW	m_{P2}	30	50	70	100	100
Orbit Keeping Propellant Mass, Small Base LEO	kg	m_{OP}	20	70	90	100	100

Table F.4 State-of-Knowledge at Decision Points - Program IV (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Orbit Keeping Propellant Mass, Large Base LEO	kg	m_{OP}	20	70	90	100	100
Orbit Keeping Propellant Mass, Small Base GEO	kg	m_{OP}	-	-	-	-	-
Orbit Keeping Propellant Mass, Large Base GEO	kg	m_{OP}	-	-	-	-	-
Attitude Control Propellant Mass, Small Base LEO	kg	m_{AP}	20	60	90	100	100
Attitude Control Propellant Mass, Large Base LEO	kg	m_{AP}	20	60	90	100	100
Attitude Control Propellant Mass, Small Base GEO	kg	m_{AP}	20	40	70	90	100
Attitude Control Propellant Mass, Large Base GEO	kg	m_{AP}	20	40	70	90	100
Total Satellite Fleet Size	Number	N_{SAT}	-	-	-	-	100
Total Crew Size, Small Base	Number	N_{crew}	20	40	70	90	100
Total Crew Size, Large Base	Number	N_{crew}	20	40	70	90	100
Number of Personnel Carried per POTV Flight	#/Flight	f_{POTV}	30	50	90	100	100
Number of Crew Rotations Per Year	#/Year	f_{CROT}	30	70	90	100	100

Table F.4 State-of-Knowledge at Decision Points - Program IV (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Rate of Satellite Construction	#/Year	R_{const}	20	50	90	100	100
Propellant Consumption per POTV Flight (RT)	kg	$f_{POTV\ PRP}$	20	70	90	100	100
Capacity of Propellant Storage Tank	kg	f_T	-	-	-	-	-
Unit Mass of Propellant Storage Tank	kg	m_T	-	-	-	-	-
Payload of COTV	kg	f_{COTV}	-	-	-	-	-
Unit Mass of COTV (Dry)	kg	m_{COTV}	-	-	-	-	-
Design Life of POTV	# Flights	$f_{POTV\ Life}$	-	-	-	-	-
Unit Mass of POTV (Dry)	kg	m_{COTV}	-	-	-	-	-
Propellant Consumption per COTV Flight	kg	$f_{COTV\ PRP}$	-	-	-	-	-
HLLV Payload to LEO	kg	$M_{P/L}$	-	-	-	-	-
AIS Propellant Mass-Fraction	Fraction	λ_{AIS}	-	-	-	-	-
AIS Total LEO-GEO Mission ΔV	m/sec	ΔV_{AIS}	-	-	-	-	-
AIS Exhaust Jet Velocity	m/sec	$V_{J_{AIS}}$	-	-	-	-	-
Ion Propellant Storage Tank Capacity	kg	F_{IT}	-	-	-	-	-

Table F.4 State-of-Knowledge at Decision Points - Program IV (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Ion Propellant Storage Tank Unit Mass (Dry)	kg	m_{IT}	-	-	-	-	-
HLLV Average Load Factor	Fraction	f_{LOAD}	20	50	70	100	100
Design Life of HLLV Upper Stage	# Flights	$f_{HUS\ LIFE}$	30	70	90	100	100
Design Life of HLLV Lower Stage	# Flights	$f_{HLS\ LIFE}$	30	70	90	100	100
Number of Personnel per Shuttle Flight	Number	$f_{SHUTTLE}$	-	-	-	-	-
Design Life of Shuttle	# Flights	f_{SLIFE}	-	-	-	-	-
HLLV Upper Stage Unit Cost	$	c_{HUS}	30	70	90	100	100
HLLV Lower Stage Unit Cost	$	c_{HLS}	30	70	90	100	100
Launch Operations Cost per HLLV Flight	$	c_{HLLV}	30	70	90	100	100
Launch Operations Cost per Shuttle Flight	$	$c_{SHUTTLE}$	100	-	-	-	-
Shuttle Unit Cost	$	c_{SUNIT}	100	-	-	-	-
Basic Unit Cost of Construction Base (Small)	$	c_{CB}	20	50	70	90	100
Basic Unit Cost of Construction Base (Large)	$	c_{CB}	20	50	70	90	100

Table F.4 State-of-Knowledge at Decision Points - Program IV (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Specific Cost of EPS Solar Array	\$/kV	c_{P1}	20	50	70	90	100
Specific Cost of EPS Batteries	\$/kV	c_{P2}	20	70	100	-	-
Cost of Radiation Shielding, Small Base LEO	\$	c_{RDS}	20	50	70	90	100
Cost of Radiation Shielding, Large Base LEO	\$	c_{RDS}	20	50	70	90	100
Cost of Radiation Shielding, Small Base GEO	\$	c_{RDS}	20	50	70	90	100
Cost of Radiation Shielding, Large Base GEO	\$	c_{RDS}	20	50	70	90	100
Specific Cost of Altitude Control Propellant	\$/kg	c_{AP}	-	-	-	-	-
Specific Cost of Orbit-Keeping Propellant	\$/kg	c_{OP}	-	-	-	-	-
COTV Unit Cost	\$	c_{COTV}	20	50	90	100	100
POTV Unit Cost	\$	c_{POTV}	20	50	90	100	100
Specific Cost of OTV Propellant	\$/kg	c_{PRP}	-	-	-	-	-
AIS Unit Cost	\$	C_{AIS}	20	50	90	100	100
Specific Cost of Ion Propellant	\$/kg	$c_{AIS\ PROP}$	-	-	-	-	-

Table F.4 State-of-Knowledge at Decision Points - Program IV (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
CTV Propellant Storage Tank Unit Cost	$	C_T	20	50	90	100	100
Ion Propellant Storage Tank Unit Cost	$	C_{IT}	20	50	90	100	100
Antenna Power Distribution Specific Cost	$/kW	c_{PD}	-	-	-	-	-
Phase Control Electronics Specific Cost	$/kW	c_{PCE}	-	-	-	-	-
Wave Guide Specific Cost	$/kW	c_{WG}	-	-	-	-	-
DC-RF Converter Specific Cost	$/kW	c_{DC-RF}	-	-	-	-	-
Antenna Structure Specific Cost	$/kW	c_{ST}	20	50	70	100	100
Solar Array Blanket Specific Cost	$/km^2	c_{SAB}	20	50	70	100	100
Solar Array Concentrator Specific Cost	$/km^2	c_{SAC}	10	40	80	100	100
Conducting Structure Specific Cost	$/kg	c_{STC}	10	50	90	100	100
Nonconducting Structure Specific Cost	$/kg	c_{STNC}	10	50	90	100	100
Central Mast Specific Cost	$/kg	c_{STCM}	10	50	90	100	100
Miscellaneous Equipment Specific Cost	$/kg	c_{MISC}	10	40	70	100	100
Rectenna Specific Cost	$/km^2	c_{RECT}	-	-	-	-	-

Table F.4 State-of-Knowledge at Decision Points - Program IV (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Beam Elevation Angle	Radians	E	-	-	-	-	-
Power Interface Specific Cost	$/kw	c_{INTERF}	-	-	-	-	-
Phase Control Specific Cost	$/kw	c_{PC}	-	-	-	-	-

Table F.5 State-of-Knowledge at Decision Points - Program V

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Power Output at Rectenna Busbar (B.O.L.)	kW	P_{OUT}	-	-	-	-	-
Solar Cell Efficiency (B.O.L.)	Fraction	η_{SC}	40	70	85	90	100
Solar Array Power Distribution Efficiency	Fraction	η_{SAPD}	40	60	85	90	100
Antenna Interface Efficiency	Fraction	$\eta_{ANT\ INT}$	20	60	75	90	100
Antenna Power Distribution Efficiency	Fraction	$\eta_{ANT\ PD}$	-	-	-	-	-
DC-RF Converter Efficiency	Fraction	η_{DC-RF}	-	-	-	-	-
Phase Control Efficiency	Fraction	η_{PC}	-	-	-	-	-
Ionospheric Propagation Efficiency	Fraction	$\eta_{ION\ PROP}$	-	-	-	-	-
Atmospheric Propagation Efficiency	Fraction	$\eta_{ATM\ PROP}$	-	-	-	-	-
Beam Collection Efficiency	Fraction	η_{BC}	-	-	-	-	-
RF-DC Converter Efficiency	Fraction	η_{RF-DC}	-	-	-	-	-
Rectenna Power Distribution Efficiency	Fraction	$\eta_{RECT\ PD}$	-	-	-	-	-
Packing Factor of Solar Blanket	Fraction	P_F	20	80	90	100	-
Solar Flux Constant	kW/km^2	F	-	-	-	-	-

Table F.5 State-of-Knowledge at Decision Points - Program V (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Effective Concentration Ratios	Fraction	η_{EFF}	20	70	90	100	-
Specific Mass of Solar Blanket	kg/km^2	m_{SAB}	-	-	-	-	-
Efficiency of Solar Concentrator	Fraction	η_{CONC}	20	90	100	-	-
Specific Mass of Solar Concentrator	kg/km^2	m_{SAC}	10	40	90	100	-
Ratio: Conducting Structure Mass to Solar Array Area	kg/km^2	m_{STC}	20	50	90	100	-
Ratio: Nonconducting Structure Mass to Solar Array Area	kg/km^2	m_{STNC}	20	50	90	100	-
Specific Mass of Central Mast	kg/km	m_{STCM}	20	50	90	100	-
Aspect Ratio of Solar Array	Fraction	r_A	-	-	-	-	-
Antenna Clearance	Fraction	r_L	-	-	-	-	-
Diameter of Transmitting Antenna	km	D_{ANT}	-	-	-	-	-
Specific Mass of Antenna Structure	kg/kW	m_{ANT}	30	60	90	100	-
Specific Mass of DC-RF Converters	kg/kW	m_{DC-RF}	-	-	-	-	-
Specific Mass of Antenna Power Distribution System	kg/kW	$m_{ANT\ PD}$	-	-	-	-	-
Specific Mass of Waveguides	kg/kW	m_{WG}	-	-	-	-	-

Table F.5 State-of-Knowledge at Decision Points - Program V (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Specific Mass of Antenna Interface	kg/kW	$m_{ANT\ INT}$	-	-	-	-	-
Specific Mass of Phase Control Electronics	kg/kW	m_{PCE}	-	-	-	-	-
Miscellaneous Satellite Mass	kg	M_{MISC}	30	50	90	100	-
Basic Unit Mass of Construction, Small	kg	m_{CB}	20	40	80	90	100
Basic Unit Mass of Construction, Large	kg	m_{CB}	20	40	80	90	100
Specific Mass of EPS Solar Array	kg/kW	m_{P1}	20	40	80	90	100
EPS Power Requirements, Small Base LEO	kW	$P_{EPS\ REQ}$	20	40	80	90	100
EPS Power Requirements, Large Base LEO	kW	$P_{EPS\ REQ}$	20	40	80	90	100
EPS Power Requirements, Large Base GEO	kW	$P_{EPS\ REQ}$	20	40	80	90	100
EPS Power Requirements, Small Base GEO	kW	$P_{EPS\ REQ}$	20	40	80	90	100
Specific Mass of EPS Batteries	kg/kW	m_{P2}	30	50	70	100	-
Orbit Keeping Propellant Mass, Small Base LEO	kg	m_{OP}	20	70	100	-	-

Table F.5 State-of-Knowledge at Decision Points - Program V (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Orbit Keeping Propellant Mass, Large Base LEO	kg	m_{OP}	20	70	100	-	-
Orbit Keeping Propellant Mass, Small Base GEO	kg	m_{OP}	20	60	90	100	-
Orbit Keeping Propellant Mass, Large Base GEO	kg	m_{OP}	20	60	90	100	-
Attitude Control Propellant Mass, Small Base LEO	kg	m_{AP}	20	70	90	100	-
Attitude Control Propellant Mass, Large Base LEO	kg	m_{AP}	20	70	90	100	-
Attitude Control Propellant Mass, Small Base GEO	kg	m_{AP}	20	40	70	90	100
Attitude Control Propellant Mass, Large Base GEO	kg	m_{AP}	20	40	70	90	100
Total Satellite Fleet Size	Number	N_{SAT}	-	-	-	-	-
Total Crew Size, Small Base	Number	N_{crew}	20	50	80	90	100
Total Crew Size, Large Base	Number	N_{crew}	20	50	80	90	100
Number of Personnel Carried per POTV Flight	#/Flight	f_{POTV}	30	50	90	100	-
Number of Crew Rotations Per Year	#/Year	f_{CROT}	30	70	90	100	-

Table F.5 State-of-Knowledge at Decision Points - Program V (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Rate of Satellite Construction	#/Year	R_{const}	20	50	90	100	-
Propellant Consumption per POTV Flight (RT)	kg	$f_{POTV\ PRP}$	20	70	90	100	-
Capacity of Propellant Storage Tank	kg	f_T	-	-	-	-	-
Unit Mass of Propellant Storage Tank	kg	m_T	-	-	-	-	-
Payload of COTV	kg	f_{COTV}	-	-	-	-	-
Unit Mass of COTV (Dry)	kg	m_{COTV}	-	-	-	-	-
Design Life of POTV	# Flights	$f_{POTV\ Life}$	-	-	-	-	-
Unit Mass of POTV (Dry)	kg	m_{COTV}	-	-	-	-	-
Propellant Consumption per COTV Flight	kg	$f_{COTV\ PRP}$	-	-	-	-	-
HLLV Payload to LEO	kg	$M_{P/L}$	-	-	-	-	-
AIS Propellant Mass-Fraction	Fraction	λ_{AIS}	-	-	-	-	-
AIS Total LEO-GEO Mission ΔV	m/sec	ΔV_{AIS}	-	-	-	-	-
AIS Exhaust Jet Velocity	m/sec	$V_{J_{AIS}}$	-	-	-	-	-
Ion Propellant Storage Tank Capacity	kg	F_{IT}	-	-	-	-	-

Table F.5 State-of-Knowledge at Decision Points - Program V (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Ion Propellant Storage Tank Unit Mass (Dry)	kg	m_{IT}	-	-	-	-	-
HLLV Average Load Factor	Fraction	f_{LOAD}	20	50	70	100	-
Design Life of HLLV Upper Stage	# Flights	$f_{HUS\ LIFE}$	30	70	90	100	-
Design Life of HLLV Lower Stage	# Flights	$f_{HLS\ LIFE}$	30	70	90	100	-
Number of Personnel per Shuttle Flight	Number	$f_{SHUTTLE}$	-	-	-	-	-
Design Life of Shuttle	# Flights	f_{SLIFE}	-	-	-	-	-
HLLV Upper Stage Unit Cost	$	c_{HUS}	30	70	90	100	-
HLLV Lower Stage Unit Cost	$	c_{HLS}	30	70	90	100	-
Launch Operations Cost per HLLV Flight	$	c_{HLLV}	30	70	90	100	-
Launch Operations Cost per Shuttle Flight	$	$c_{SHUTTLE}$	100	-	-	-	-
Shuttle Unit Cost	$	c_{SUNIT}	100	-	-	-	-
Basic Unit Cost of Construction Base (Small)	$	c_{CB}	20	50	70	90	100
Basic Unit Cost of Construction Base (Large)	$	c_{CB}	20	50	70	90	100

Table F.5 State-of-Knowledge at Decision Points - Program V (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Specific Cost of EPS Solar Array	$/kV	c_{P1}	20	50	70	90	100
Specific Cost of EPS Batteries	$/kV	c_{P2}	20	50	90	100	-
Cost of Radiation Shielding, Small Base LEO	$	c_{RDS}	20	50	70	90	100
Cost of Radiation Shielding, Large Base LEO	$	c_{RDS}	20	50	70	90	100
Cost of Radiation Shielding, Small Base GEO	$	c_{RDS}	20	50	70	90	100
Cost of Radiation Shielding, Large Base GEO	$	c_{RDS}	20	50	70	90	100
Specific Cost of Altitude Control Propellant	$/kg	c_{AP}	-	-	-	-	-
Specific Cost of Orbit-Keeping Propellant	$/kg	c_{OP}	-	-	-	-	-
COTV Unit Cost	$	c_{COTV}	20	50	90	100	-
POTV Unit Cost	$	c_{POTV}	20	50	90	100	-
Specific Cost of OTV Propellant	$/kg	c_{PRP}	-	-	-	-	-
AIS Unit Cost	$	c_{AIS}	20	50	90	100	-
Specific Cost of Ion Propellant	$/kg	$c_{AIS\ PROP}$	-	-	-	-	-

Table F.5 State-of-Knowledge at Decision Points - Program V (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
CTV Propellant Storage Tank Unit Cost	$	C_T	20	70	90	100	-
Ion Propellant Storage Tank Unit Cost	$	C_{IT}	20	50	90	100	-
Antenna Power Distribution Specific Cost	$/kW	c_{PD}	-	-	-	-	-
Phase Control Electronics Specific Cost	$/kW	c_{PCE}	-	-	-	-	-
Wave Guide Specific Cost	$/kW	c_{WG}	-	-	-	-	-
DC-RF Converter Specific Cost	$/kW	c_{DC-RF}	-	-	-	-	-
Antenna Structure Specific Cost	$/kW	c_{ST}	20	70	90	100	-
Solar Array Blanket Specific Cost	$/km^2$	c_{SAB}	20	50	70	100	-
Solar Array Concentrator Specific Cost	$/km^2$	c_{SAC}	10	60	90	100	-
Conducting Structure Specific Cost	$/kg	c_{STC}	10	60	90	100	-
Nonconducting Structure Specific Cost	$/kg	c_{STNC}	10	50	90	100	-
Central Mast Specific Cost	$/kg	c_{STCM}	10	50	90	100	-
Miscellaneous Equipment Specific Cost	$/kg	c_{MISC}	10	50	80	100	-
Rectenna Specific Cost	$/km^2$	c_{RECT}	-	-	-	-	-

Table F.5 State-of-Knowledge at Decision Points - Program V (continued)

Input Element	Units	Variable Name	Improvement in State-of-Knowledge, %				
			DPA	DPB	DPC	DPD	DPE
Beam Elevation Angle	Radians	E	-	-	-	-	-
Power Interface Specific Cost	\$/kw	c_{INTERF}	-	-	-	-	-
Phase Control Specific Cost	\$/kw	c_{PC}	-	-	-	-	-

APPENDIX G

COMPUTATION OF CONDITIONAL PROBABILITIES

This appendix details the computational procedure for determining the probabilities necessary for analyzing the decision trees presented in Section 7. It is to be noted that the probabilities are conditioned upon getting to the decision node in question. Figure G.1 shows the effects of the decision rules acting on the probability density function of the current state-of-knowledge for Program I. The population or density function after Decision Point A is obtained by taking the product of the initial probability density function with one minus the cumulative distribution representing decision rule A. Thus:

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

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

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

and

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

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

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

and

$$P_C = \frac{\text{Area under curve } f_C}{\text{Area under curve } f_B} = \frac{\text{Area under curve } f}{P_A \; P_B}$$

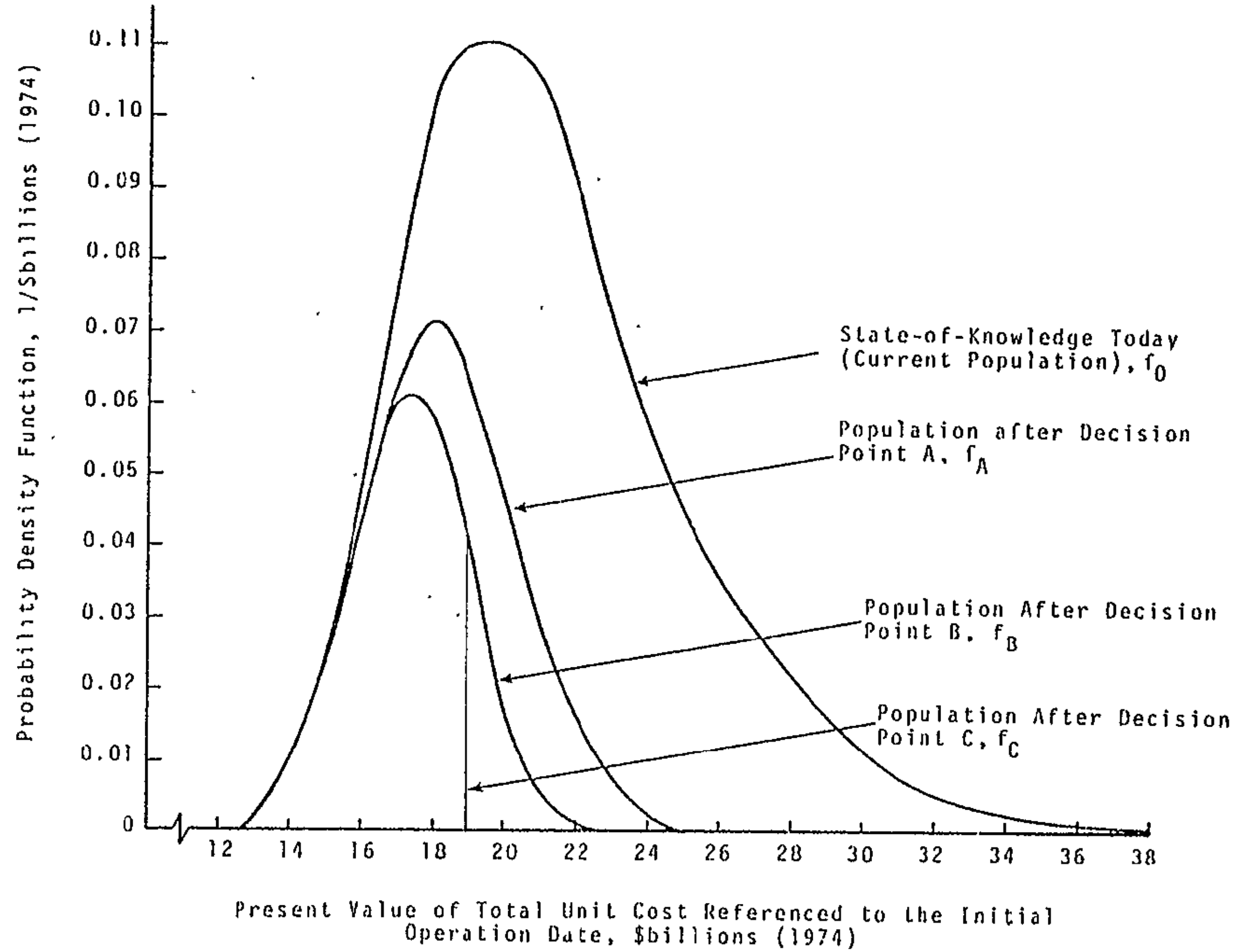

Figure G.1 Analysis of Conditional Branching Probabilities

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