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A Technique for Estimating Space Power System Costs

OCTOBER 1967

Prepared by J. G. FISH
System Planning Division
El Segundo Technical Operations
AEROSPACE CORPORATION

Prepared for SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

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Los Angeles Air Force Station
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FOREWORD

This report is published by the Aerospace Corporation, El Segundo, California under Air Force Contract No. F04695-67-C-0158. The report was authored by J. G. Fish of the System Planning Division at El Segundo Technical Operations.

This report, which documents research carried out from 4 January 1966 through 4 September 1967, was submitted on 3 November 1967 to Lieutenant Joseph A. Soulia, SMASD, for review and approval.

Approved

S. Scesa

S. Scesa
Associate Group Director
General Planning Directorate
System Planning Division

Joseph A. Soulia, Lieutenant
Strategic Systems Division
Space and Missile Systems Organization
Air Force Systems Command

ABSTRACT

A technique is presented for estimating development and procurement costs for space power subsystems. The data employed in deriving the costing relationships stem primarily from the 1966 DOD Space Power Study and the Aerospace Corporation's experience and data sources. These sources represent the most current and extensive survey of both costs and technologies of the space power field that exist today.

Energy sources and power conversion schemes are analyzed separately and jointly in feasible combinations of power systems applicable to future space missions. Cost-scaling factors are provided for integrating each type of power subsystem into a payload. Estimated projections of space power subsystem costs for fifteen years into the future are also provided.

Due to the vast uncertainty involved in estimating future system costs, all pertinent details of the estimating procedure are given so that the technique can be readily altered by replacing any of the parameters that appear questionable.

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I. INTRODUCTION

Space power subsystems are normally considered to be one of the major hardware groupings that make up a total spacecraft system. The current space missions plans of the Air Force, NASA, and industry include systems requiring relatively high electrical power requirements. Future missions, including manned space stations and laser experiments, will undoubtedly include some of the more sophisticated, complex space power subsystems such as the nuclear reactor/dynamic conversion power plant. The costs of these subsystems, as well as other subsystems, are becoming more critical as our space program faces cost reductions.

This report presents a technique for estimating the procurement and development costs of current and future space power subsystems. This technique provides a quick and simple method of economic evaluation of space power alternatives. The technique was initially developed and used at Aerospace Corporation for evaluating all candidate space power subsystems considered for missions in the 1966 DOD Space Power Study.

Two industrial contractors participated in the Space Power Study. Each contractor developed space power cost estimating relationships (CER's) for the study based on data acquired from his experience, surveys of the literature, and contact with numerous other space power subsystem and component contractors. The technique presented in this report relies on the study contractors' cost data and the cost data available at Aerospace from previous space power studies.

The technique involves a short series of computational steps for estimating both the first unit procurement and development costs for a wide range of space power subsystems. A few performance and physical characteristics are required to define a candidate system, usually one each such as average power and array area for a solar cell subsystem. These parameters are employed to derive the procurement cost of the energy source and power conversion scheme from individually provided CER's. Additional subsystem elements (e.g., batteries and power conditioning equipment) are estimated at a constant dollar per pound basis. A factor which varies with the type of power subsystem is applied to the subtotal cost to yield the subsystem first unit procurement cost.

The development cost portion of the technique uses an estimating relationship of engineering man-hours required based on the type, power, and design life of a candidate system. Both the procurement and development costs are estimated with respect to year of operational capability (i.e., the CER's are time-phased).

The space power subsystem, as used in this report, is defined as the total package required to produce the desired electrical output at 110 vac and 28 v regulated dc for a given mission. It does not include any portion of the payload power conditioning equipment necessary to properly condition the power for a specific payload subsystem.

An energy source and a power conversion scheme are the two major items of the space power subsystem. Various types of energy sources and power conversion schemes may be combined to form space power subsystems. Cost estimates for any of these combinations may be determined by this technique.

Hardware and system cost elements are handled separately in both the procurement and development estimates. The technique is designed to readily facilitate substitutions of individual cost elements of a given subsystem in order to meet specialized requirements or substitutions of better data as they become available.

II. PROCUREMENT COSTS

The space power subsystem procurement costs, as defined in this report, include manufacturing labor, material, planning, recurring tooling, quality control, and subcontracting. Functionally, they include fabrication, subassembly, checkout, acceptance test, and integration of the subsystem. Specific cost-quantity relationships are neglected; but, in general, the CER's employed in Ref. 1 assumed a 90 percent log-linear cumulative average curve with respect to time of operational use and the projected state of the art.

A. HARDWARE AND SYSTEM COST ELEMENTS

The following five cost elements constitute the major cost categories recommended to estimate total space power subsystem procurement costs.

1. ENERGY SOURCE SUBSYSTEM

Cost estimating relationships are provided for numerous energy sources as a function of time for intended operational employment. These costs include the total procurement cost of acquiring the energy source for a specific mission.

2. POWER CONVERSION SUBSYSTEM

The space power subsystems that require a conversion subsystem are costed similarly to the energy source subsystems.

3. STORAGE BATTERIES

The storage battery costs are an insignificant portion of the total space power subsystem cost and for simplicity they are evaluated at a constant rate of \$100/lb irrespective of battery type or time of employment. Reference 2 is representative of the data available for acquiring detailed storage battery costs.

4. POWER CONDITIONING EQUIPMENT

Costs of power conditioning equipment are assumed to be $1000/lb; this figure has been substantiated by previous space power cost studies.

5. SYSTEM INTEGRATION

The system integration costs include the recurring effort required to integrate the space power subsystem with the payload and to verify its intended preliminary operational characteristics. Contractor management and technical direction are also included in this cost category. A percentage of the total hardware acquisition cost, which varies with the complexity of the selected energy source/conversion scheme combination, is used in determining the system integration cost.

B. PROCUREMENT COST ESTIMATING RELATIONSHIPS

Figures 1 through 7 represent the procurement CER's for candidate space power subsystems using the technique of this report. All cost curves are derived as a function of an appropriate performance or physical characteristic and are plotted against time to project the expected decrease in procurement costs as technology progresses and the system approaches an off-the-shelf capability.

1. ENERGY SOURCES

a. Solar Cells

Figure 1 shows the CER's for silicon and thin film solar cell subsystems in terms of cost per sq ft of array area as a function of calendar year. Array area was selected as the cost-related variable in preference to power because the same curve is applicable to both oriented and nonoriented arrays. The costs derived from these curves represent all materials (cells, structure, and mechanisms), fabrication, wiring, quality control, and subsystem acceptance testing costs. The CER's are from Ref. 3 and are substantiated by Refs. 2, 4, and 5, and numerous Aerospace studies.

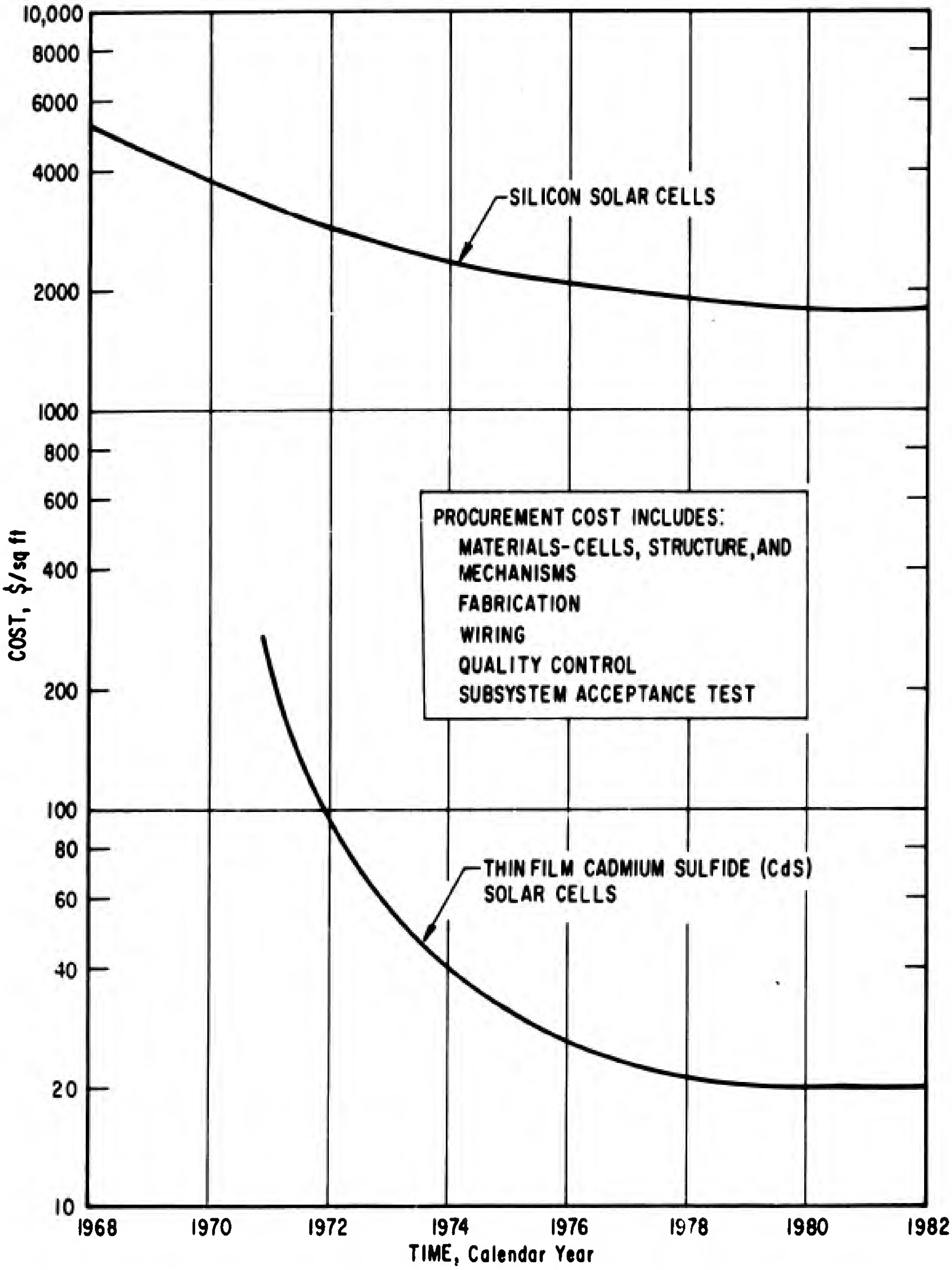

Fig. 1. Procurement Cost - Solar Cells

b. Solar Concentrator

Figure 2 shows solar concentrator costs per kw_t as a function of time through calendar year 1982. Curves are provided for one piece and petaline type concentrators. The required concentrator area relative to the area available in the vehicle payload section determines which type of concentrator is used. The data shown are from Ref. 3 and are substantiated by other space power studies.

c. Radioisotope

The cost of isotope power subsystems is dominated by the isotope cost,[1] and unless the isotope is recovered and reprocessed, the isotope power subsystems are not competitive on a cost-effectiveness basis with the other power subsystems. In determining the cost of the isotope for low earth orbital missions, it should be assumed that the isotope fuel is recovered, reprocessed, and used again on later missions. Consequently, only 10 percent of the initial cost should be used in this type of subsystem cost analysis. The total isotope cost is used for unmanned synchronous orbital missions since it is assumed that the isotope is not recovered.

d. Nuclear Reactor

SNAP 2 and SNAP 8 reactor costs as a function of procurement year and pertinent performance characteristics are shown in Fig. 3. The data were acquired from Ref. 5 and confirmed by the manufacturer, Atomics International.

e. Fuel Cells

Total fuel cell power subsystem costs are estimated in the analysis at the rate of $300,000/kw. This rate was determined from previous studies and includes the fuel cells, tanks, power conditioning equipment, batteries, and integration costs.

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[1] Isotope fuel costs are controlled by the Atomic Energy Commission and are security classified; therefore, these data are not provided in this unclassified document. Reference 6 is recommended as a source for obtaining these data.

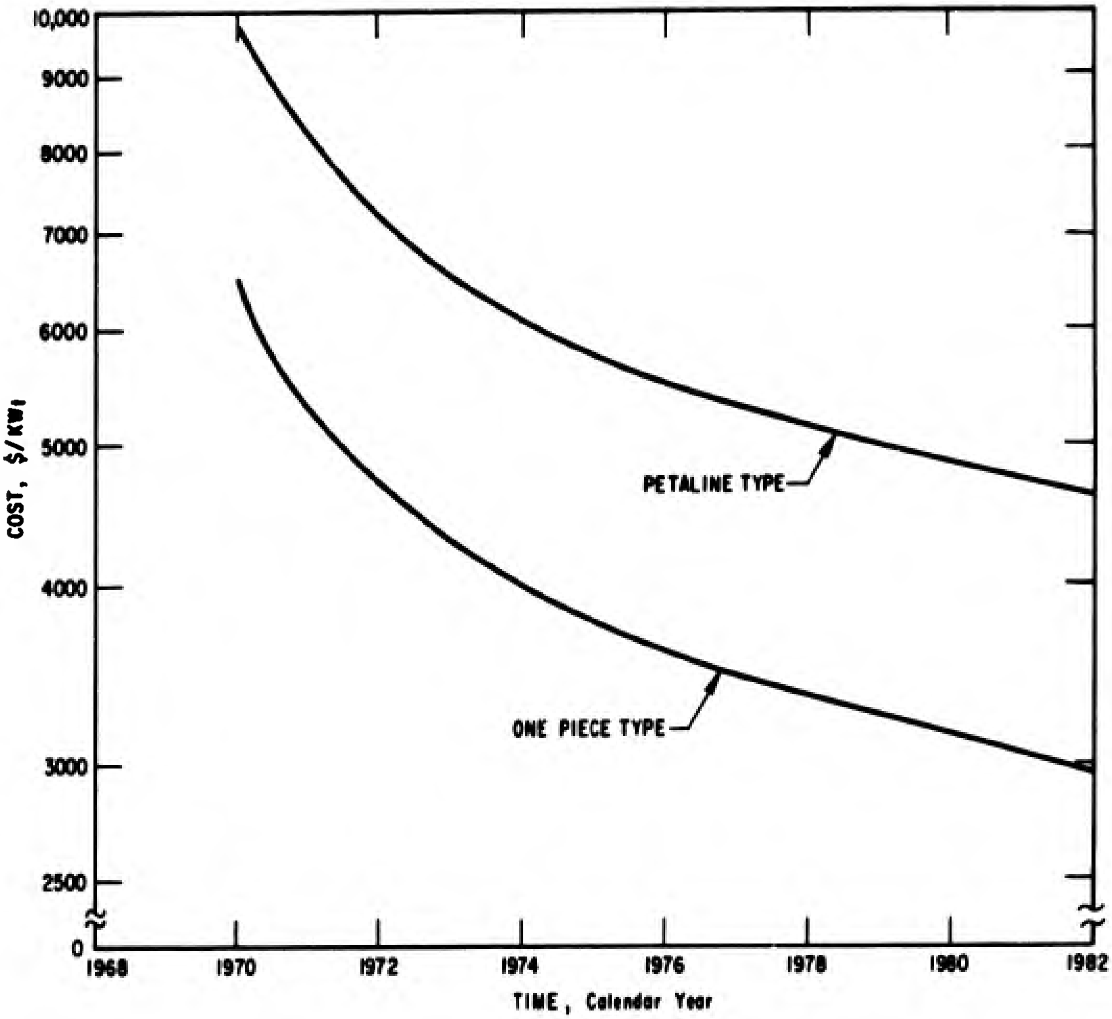
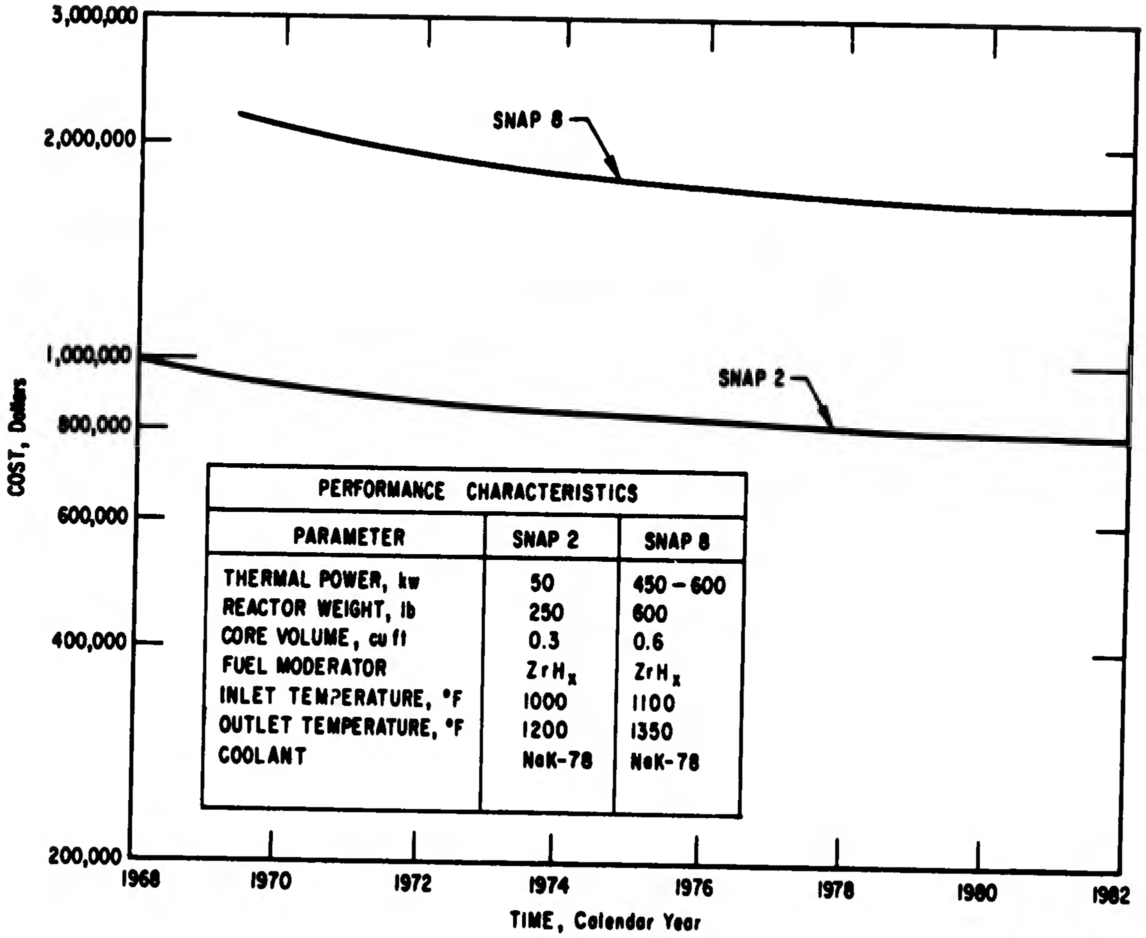


Fig. 2. Procurement Cost - Solar Concentrator



PERFORMANCE CHARACTERISTICS		
PARAMETER	SNAP 2	SNAP 8
THERMAL POWER, kw	50	450 - 600
REACTOR WEIGHT, lb	250	600
CORE VOLUME, cu ft	0.3	0.6
FUEL MODERATOR	ZrH_x	ZrH_x
INLET TEMPERATURE, °F	1000	1100
OUTLET TEMPERATURE, °F	1200	1350
COOLANT	NaK-78	NaK-78

Fig. 3. Procurement Cost - Nuclear Reactor

2. CONVERSION SUBSYSTEMS

a. Thermoelectric

Figure 4 projects the thermoelectric conversion subsystem costs per kw_e through calendar year 1982. Curves are provided for 1, 5, and 15 kw_e cascaded[2] silicon germanium - lead telluride (SiGe-PbTe) and SiGe thermoelectric subsystems. Reference 5 is the data source.

b. Thermionic

Figure 5 shows the thermionic conversion subsystem costs per kw_e as a function of calendar year. Reference 5 is the data source.

c. Dynamic Subsystems

Brayton and Rankine cycle dynamic power conversion subsystems are considered. The Rankine cycle may employ mercury, organic compounds, or alkali metals as the working fluid. Figure 6 projects the dynamic conversion subsystem costs per kw_e through 1982 per single dynamic conversion unit at electrical power outputs of 3, 6, 15, and 20 kw_e. No cost distinction is made in the type of dynamic cycle or working fluid employed. The total space power subsystem cost will reflect the choice of dynamic cycle and working fluid selections in the energy source cost due to each system's inherent conversion and over-all efficiencies. For example, the Brayton cycle is more efficient than the Rankine cycle and will require less energy to yield the same electrical output. The data were selected from Ref. 5 and substantiated from previous studies.

Radiator procurement costs per kw of thermal energy to be dissipated as a function of time are shown in Fig. 7.

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[2] The higher temperature SiGe and the lower temperature PbTe are connected in thermal series so that the output of the SiGe forms the input to the PbTe.

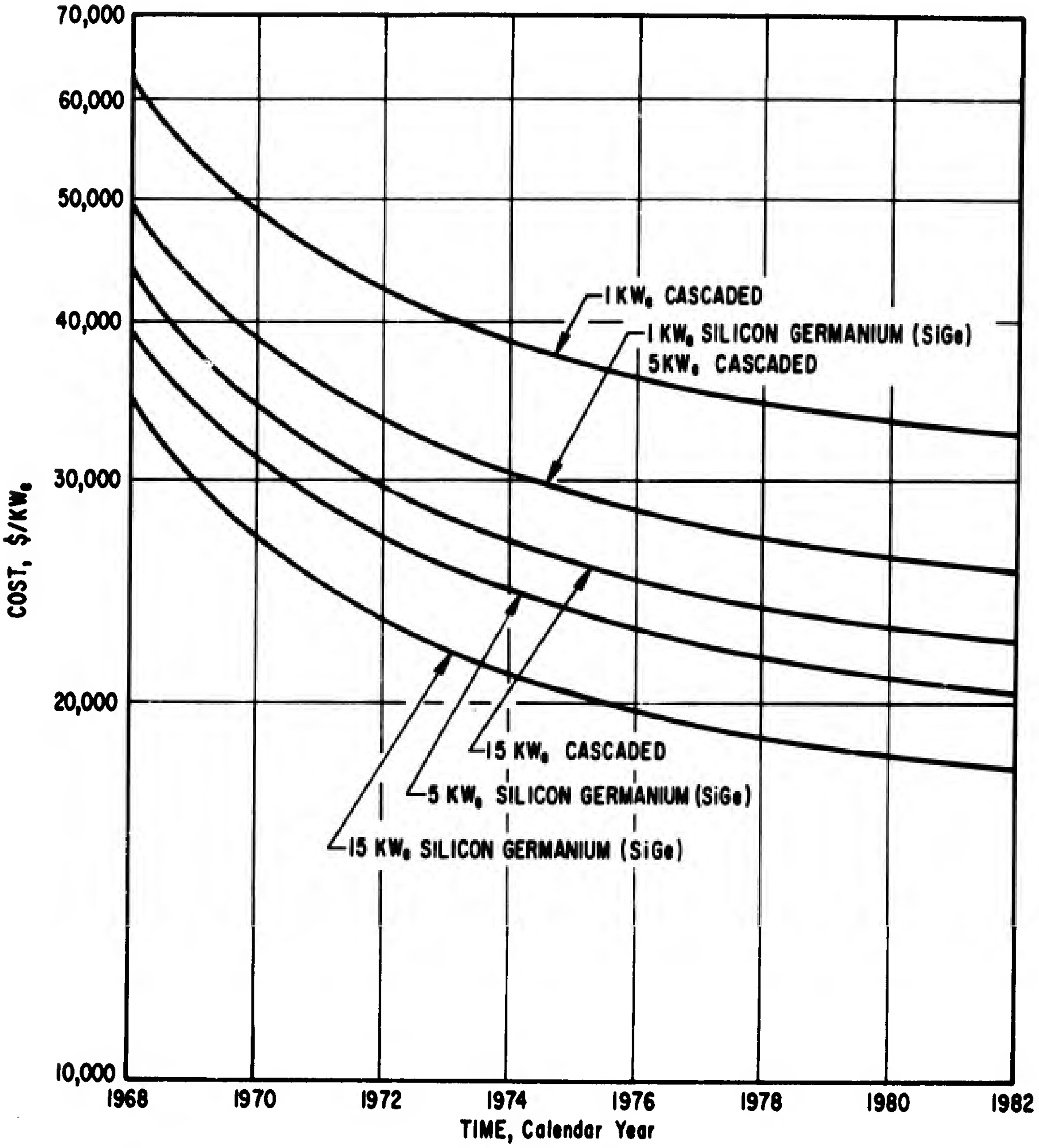

Fig. 4. Procurement Cost - Thermoelectric Conversion

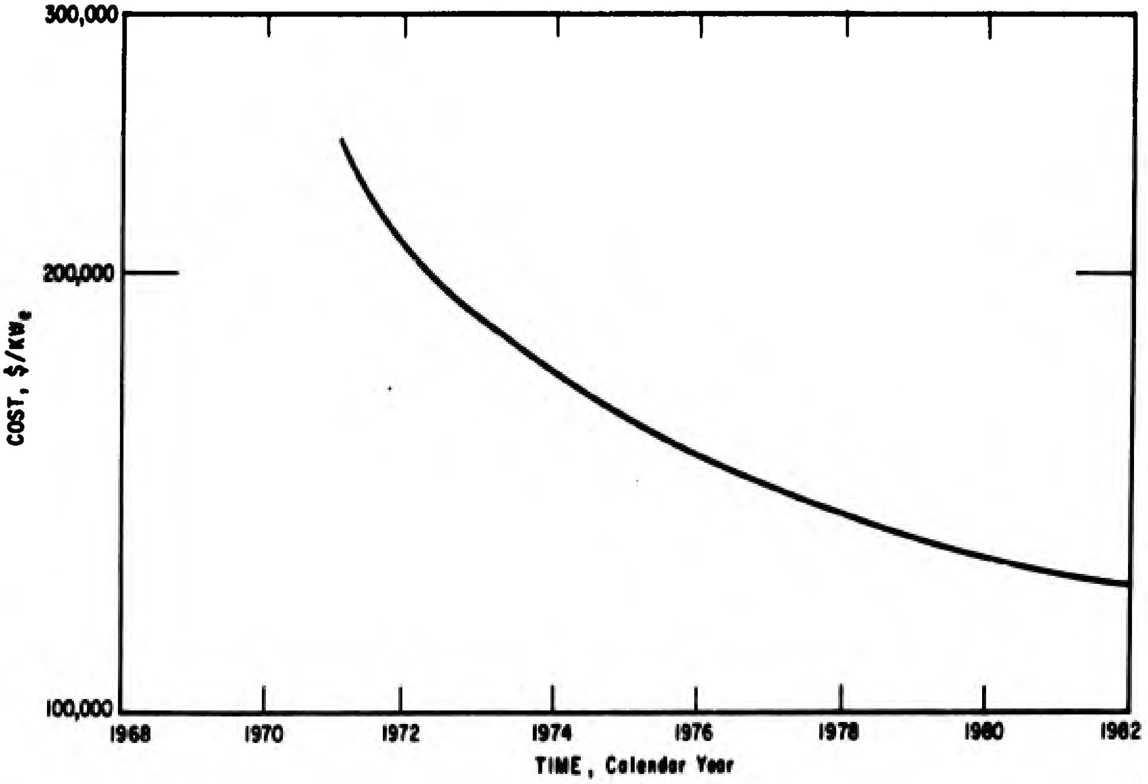

Fig. 5. Procurement Cost - Thermionic Conversion

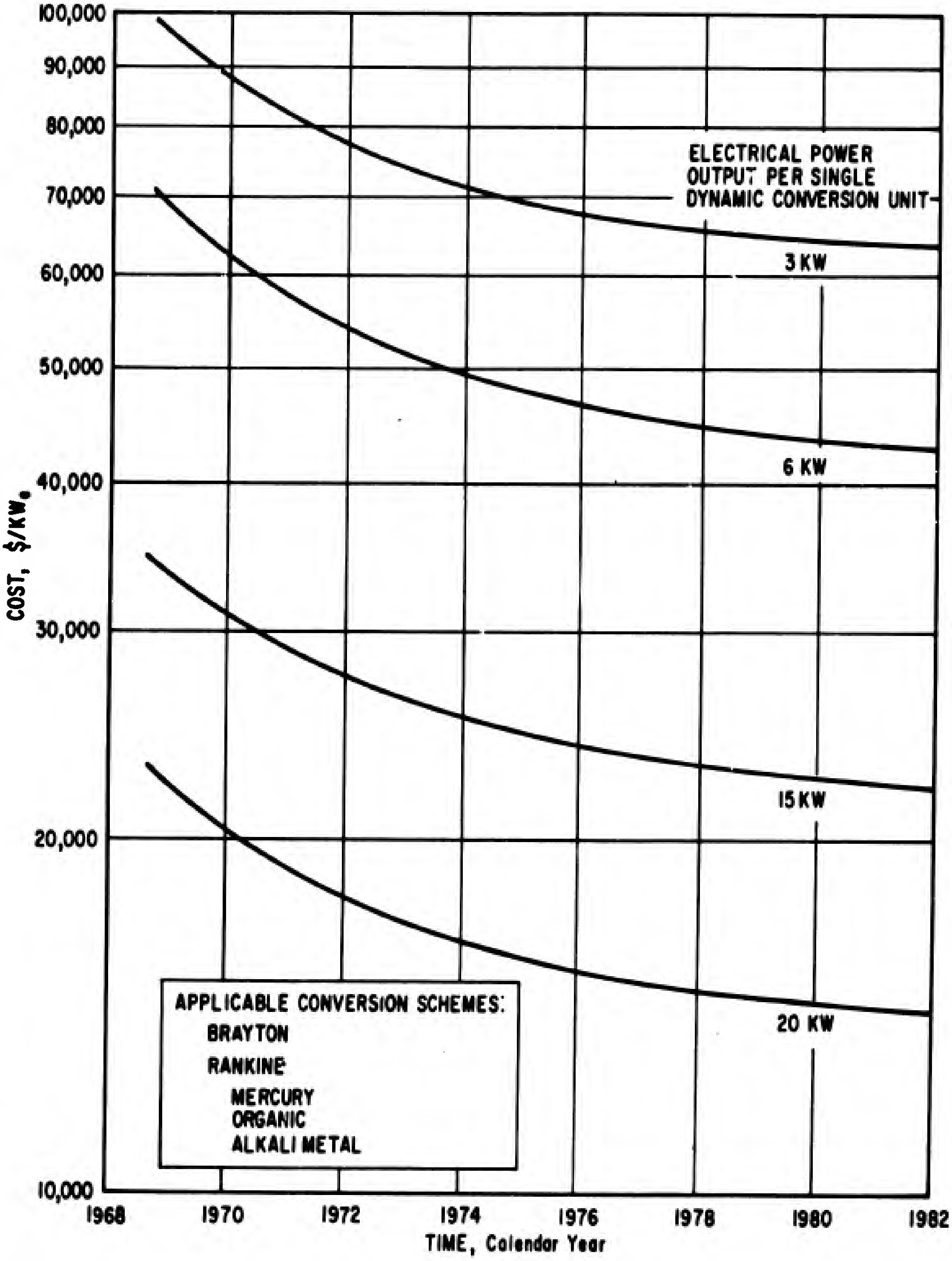

Fig. 6. Procurement Cost - Dynamic Power Conversion Unit

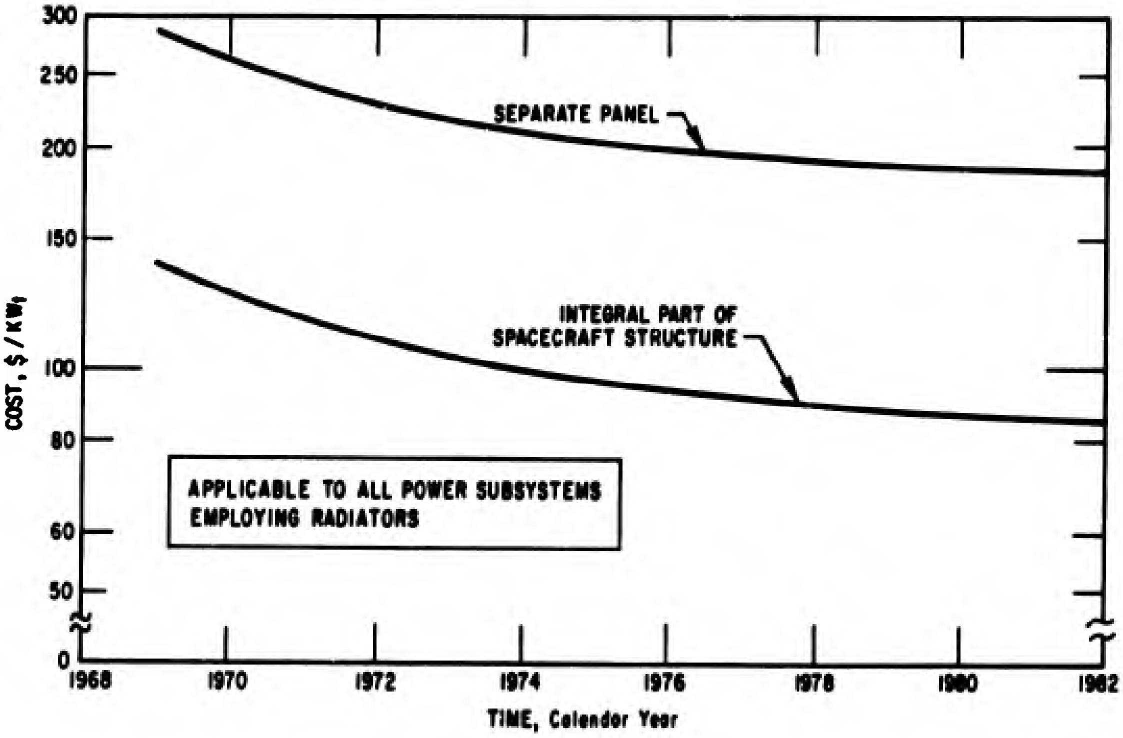

Fig. 7. Procurement Cost - Radiator

C. EXAMPLES OF ESTIMATING PROCUREMENT COSTS

Tables I through IV present sample calculations for estimating the first unit procurement cost by the previously described technique. Five space power subsystems are evaluated: silicon solar cell, oriented; thin film solar cell, nonoriented; solar/static; isotope/dynamic; and reactor/static subsystems. These five examples are only representative of the many available combinations of energy sources and conversion schemes.

All performance and physical characteristics provided in the examples (e. g., power requirements and battery weights) are considered known prior to the costing exercise. These characteristics are usually supplied by the technical design groups. The examples provided are realistic relative to the parameter inputs and cost outputs.

Table I. Procurement Cost - Solar Cell Examples

Item	Parameter	Characteristics and Costs	
1.	Candidate System	Silicon, Oriented	Thin Film, Nonoriented
2.	Operational Year	1971	1971
3.	Average Power, kw_e	0.515	0.515
4.	Solar Cell Array		
a.	Area, sq ft	71.5	277
b.	Dollars/sq ft (from Fig. 1)	3300	250
c.	Cost, $\$ \times 10^3$ (Item 4a × 4b)	236	69
5.	Battery Cost, $\$ \times 10^3$ (at $100/lb)	13	13
6.	Power Conditioning Cost, $\$ \times 10^3$ (at $1000/lb)	2	2
7.	Subtotal, $\$ \times 10^3$ (Items 4c, 5, and 6)	251	84
8.	System Integration, $\$ \times 10^3$	50[a]	8[b]
9.	Total, $\$ \times 10^3$	310	92

[a] Twenty percent of Item 7 for oriented arrays

[b] Ten percent of Item 7 for nonoriented arrays

Table II. Procurement Cost - Solar/Static Example

Item	Parameter	Characteristics and Costs
1.	Candidate System	Concentrator/ Thermionic
2.	Operational Year	1971
3.	Concentrator	One Piece
a.	Thermal Power Required, kw_t	14.6
b.	Dollars/kw_t (from Fig. 2)	5400
c.	Cost, $\$ \times 10^3$ (Item 3a × Item 3b)	79
4.	Conversion	Thermionic
a.	Electrical Power, kw_e	0.52
b.	Dollars/kw_e (from Fig. 5)	250,000
c.	Cost, $\$ \times 10^3$ (Item 4a × Item 4b)	130
5.	Radiator Cost, $\$ \times 10^3$ (from Fig. 7)	3[a]
6.	Battery Cost, $\$ \times 10^3$ (at $100/lb)	1
7.	Power Conditioning Cost, $\$ \times 10^3$ (at $1000/lb)	12
8.	Subtotal, $\$ \times 10^3$ (Items 3c, 4c, 5, 6, and 7)	225
9.	System Integration, $\$ \times 10^3$ (20% of Item 8)	45
10.	Total, $\$ \times 10^3$	270

[a] Cost of separate panel in 1971 is estimated from Fig. 7 to be $240/$kw_t$. That cost times Item 3a minus Item 4a results in radiator cost - 240 (14.6 kw_t - 0.52 kw_e) ≈ $3000.

Table III. Procurement Cost - Isotope/Dynamic Example

Item	Parameter	Characteristics and Costs
1.	Candidate System	PU-238/Brayton
2.	Operational Year	1979
3.	Isotope	Pu-238
a.	Average Power Required, kw_t	12.1
b.	Dollars/kw_t (assumed)[a]	80,000
c.	Cost, $\$ \times 10^3$ (Item 3a × Item 3b)	968
4.	Conversion	Brayton Cycle
a.	Power, kw_e	3.31
b.	Dollars/kw_e (from Fig. 6)	65,000
c.	Cost, $\$ \times 10^3$ (Item 4a × Item 4b)	215
5.	Radiator Cost, $\$ \times 10^3$ (from Fig. 7)	2
6.	Battery Cost, $\$ \times 10^3$ (at \$100/lb)	3
7.	Power Conditioning Cost, $\$ \times 10^3$ (at \$1000/lb)	30
8.	Subtotal, $\$ \times 10^3$ (Items 3c, 4c, 5, 6, and 7)	1218
9.	System Integration, $\$ \times 10^3$ (50% of Item 8)[b]	609
10.	Total, $\$ \times 10^3$	1827

[a] Actual isotope cost is classified information. The isotope cost assumed here is 10 percent of the acquisition cost for usage of a recoverable isotope.

[b] System integration cost is increased from 20 to 50 percent due to increased complexity of a nuclear/dynamic conversion system.

Table IV. Procurement Cost - Reactor/Static Example

Item	Parameter	Characteristics and Costs
1.	Candidate System	Reactor[a]/Static
2.	Operational Year	1979
3.	Power, kw_e	3.31
4.	Dollars/kw_e	600,000[b]
5.	Cost, $\$ \times 10^3$ (Item 3 × Item 4)	1986
6.	System Integration, $\$ \times 10^3$ (50% of Item 5)	993
7.	Total, $\$ \times 10^3$	2979

[a] SNAP 10A reactor

[b] Figure 3 gives costs for the SNAP 2 and SNAP 8 systems. This cost is for an upgraded SNAP 10A system and the dollars/kw_e shown is indicative of that system.

III. DEVELOPMENT COSTS

A. BASIC ASSUMPTION

The space power subsystem development costs derived in this study are based on state-of-the-art technology. This explicitly implies that:

- a. Candidate power subsystems do not require any advanced technology programs
- b. Flight demonstration tests are not required
- c. No new development facilities are required by the contractors or government

B. COST CATEGORIES

Three basic cost categories comprise the total development cost for each specific candidate system as defined in this study.

1. DESIGN, TEST, AND ENGINEERING

The design, test, and engineering (DT&E) costs were derived by estimating the number of engineering hours required for design studies, drawings, specifications, reliability analyses, and testing. Figure 8 is used to estimate the engineering hours for each type of space power subsystem.

Solar cell DT&E manpower requirements, shown in Fig. 8, were obtained from Ref. 3. The solar cell data from Ref. 3 appeared realistic based on available development cost data, but the development costs for reactor, solar concentrator, isotope, and fuel cell systems appeared unreasonably high. Therefore, the following rationale was employed:

- a. Solar concentrator, isotope, and fuel cell systems cost 50 percent more than solar cell systems to develop
- b. Reactor systems cost twice as much as solar cell systems to develop

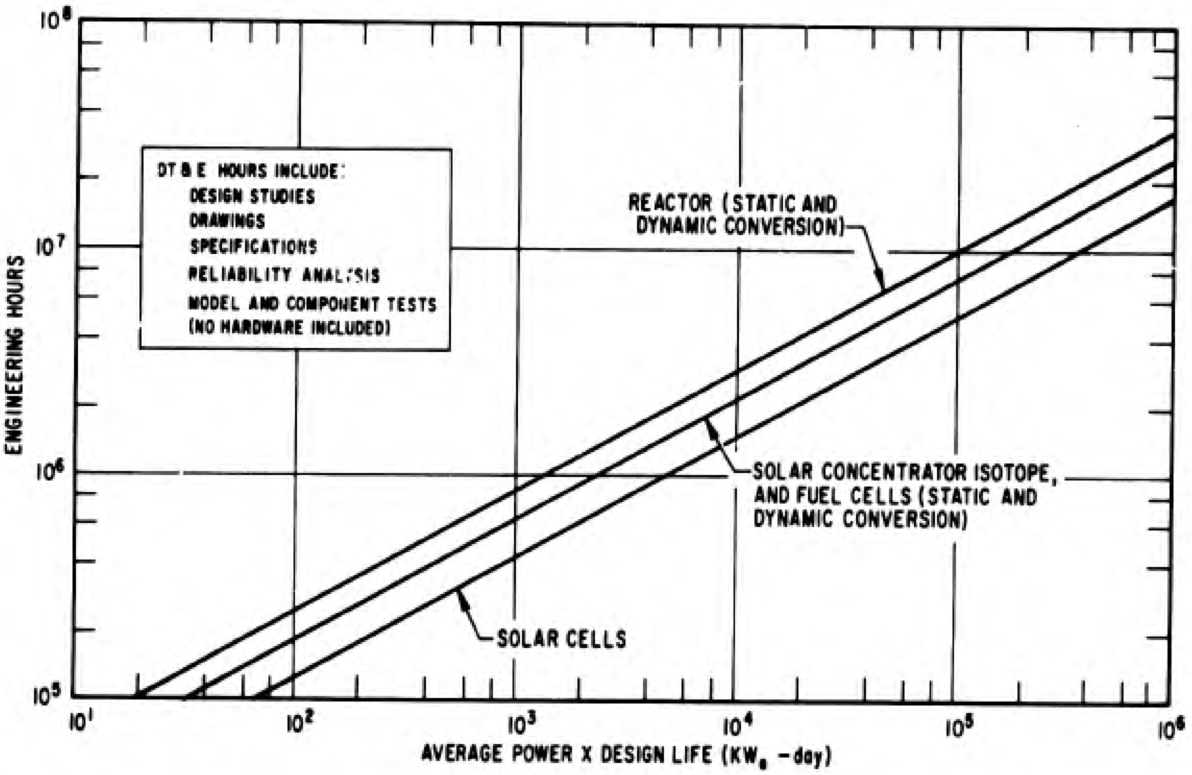

Fig. 8. Design, Test, and Engineering Hours

The engineering man-hours were converted to costs by assuming the following burdened rates, which represent a 3 percent yearly cumulative escalation.

Initial Operational Capability	Dollars/Engineering Man-Hours[a]
1970	15
1973	16
1976	17
1981	20
1983	21
1984	22

[a] Includes direct labor, burden, and general and administrative costs

2. TEST HARDWARE

The following quantities of equivalent sets of test hardware (both energy source and conversion) were assumed adequate for the development program. The cost of a set of test hardware is assumed equal to twice the cost of a set of operational hardware in order to account for development support that is not included in the DT&E cost.

Energy Source	Equivalent Sets[a]
Solar Cell	1
Solar Concentrator/Static and Dynamic	4
Isotope and Reactor/Static and Dynamic	5[b]
Fuel Cell	5

[a] One equivalent set of hardware may be a complete set or several partial sets

[b] Two nuclear and three non-nuclear

3. MISSION INTEGRATION AND PROGRAM MANAGEMENT

A survey of historical cost data on space power subsystems indicated that the mission integration and program management costs could be approximated as 20 percent of the DT&E and test hardware costs.

C. EXAMPLES OF ESTIMATING DEVELOPMENT COSTS

Table V presents sample calculations for estimating the development cost of the subsystems that were used in the procurement cost examples, Tables I through IV.

Table V. Development Cost - Solar Cell, Solar/Static, Isotope/Dynamic, and Reactor/Static

Item	Parameter	Space Power Subsystem			
		Solar Cell	Solar/Static	Isotope/Dynamic	Reactor/Static
1.	Candidate System	Silicon, Oriented	Solar Concentrator/Thermionic	Pu-238/Brayton	Reactor/Static
2.	Initial Operational Capability	1973	1973	1979	1979
3.	Average Power, kw_e	0.515	0.515	3.31	3.31
4.	Design Life, days	1095	1095	365	365
5.	Average Power - Design Life, kw_e - days (Item 3 × Item 4)	564	564	1208	1208
6.	Engineering Hours Required, (from Fig. 8)	315,000	460,000	700,000	940,000
7.	Dollars/Engineering Man Hour (from Section III. B. 1)	16	16	20	20
8.	Design, Test, and Engineering Labor Cost, $\$ \times 10^6$ (Item 6 × Item 7)	5.04	7.36	14.0	18.8
9.	Test Hardware Cost, $\$ \times 10^6$	0.60[a]	2.16[b]	9.6[c]	22.4[d]
10.	Subtotal, $\$ \times 10^6$ (Item 8 + Item 9)	5.64	9.53	23.6	41.2
11.	Mission Integration and Program Management, $\$ \times 10^6$ (20 percent of Item 10)	1.13	1.91	4.7	8.2
12.	Total Development, $\$ \times 10^6$	6.77	11.44	28.3	49.4

[a] Estimated at twice the first unit procurement cost - from Table I (\$0.3 million × 2 = \$0.6 million); from Section III. B. 2 only one equivalent set of hardware is required.

[b] Estimated at twice the first unit procurement cost - from Table II (\$0.27 million × 2 = \$0.54 million); from Section III. B. 2 four equivalent sets of hardware are required (0.54 × 4 ≈ \$2.16 million).

[c] Estimated at twice the first unit procurement cost; form Section III. B. 2 two nuclear and three non-nuclear equivalent sets of hardware are required.

Nuclear - two sets at twice the cost from Table III $2 \times 2 \times 1.83 = \$7.32$ million

Non-nuclear - three sets at twice the cost from Table III (total cost less isotope cost × 1.5) $3 \times 2\,[1.83-(0.968 \times 1.5)] = \$2.28$ million

$9.6 million

[d] From Section III. B. 2 two nuclear and three non-nuclear equivalent hardware sets are required. The cost of the non-nuclear sets is estimated from independent analysis.

IV. SUMMARY

This report describes a technique for estimating the development and procurement costs of space power subsystems. Current state-of-the-art technology was assumed. Decreases in costs are projected for applications of fifteen years hence.

Cost estimating relationships are provided for numerous types of energy sources and power conversion schemes. Examples of total power subsystems' procurement and development costs are shown in order to demonstrate the recommended procedure for using the technique.

Although the technique was developed for evaluating the two contractors' results in the 1966 DOD Space Power Study, its utility is not restricted to the applications of that study. The technique is a simple, straightforward approach to estimating costs of numerous different types of space power subsystems.

It is expected that this technique will be expanded to include all known types of space power subsystems and will incorporate data from other similar studies that have been recently completed. The report presenting the revised technique will be classified in order to include data about sensitive subsystems that were omitted in this report.

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13. ABSTRACT

A technique is presented for estimating development and procurement costs for space power subsystems. The data employed in deriving the costing relationships primarily stem from the 1966 DOD Space Power Study and the Aerospace Corporation's experience and data sources. These sources represent the most current and extensive survey of both costs and technologies of the space power field that exist today.

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14.

KEY WORDS

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Development Cost
Economic Analysis
Future Cost Estimates
Space Power Energy Sources
Space Power Conversion Schemes

Abstract (Continued)