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SPACE POWER SYSTE
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Volume I-Summa

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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NOVEMBER 1968

PARAMETRIC STUDY OF SPACE POWER SYSTEMS
FINAL REPORT

NOVEMBER 1968

DAC-62303

Volume I-Summary

A. D. Tonelli

A.D. TONELLI
STUDY MANAGER
ADVANCE SECONDARY POWER SYSTEMS BRANCH

APPROVED BY

K.H. HOUGHTON, CHIEF
ADVANCE BIOTECHNOLOGY & POWER DEPARTMENT
RESEARCH AND DEVELOPMENT DIRECTORATE

STUDY PERSONNEL
R.S. COFFIN
J.V. COGGI
J.J. DEANE
S.D. DIAMOND
J.M. FRANK
R.H. RIEDEL
A.M. TAYLOR
H. WEINER

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MISSION ANALYSIS DIVISION – OART
MOFFETT FIELD, CALIFORNIA 94035
CONTRACT NAS2-4482

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY
WESTERN DIVISION

MCDONNELL DOUGLAS
CORPORATION

ABSTRACT

This report presents a summary of the study methodology and significant results of the Parametric Study of Space Power Systems. Included in this report is a description of the study objectives and methodology; a listing of the power subsystems, systems and mission constraints that were investigated; a description of the developed H-521 computer program indicating the flow network, examples of input and output data, and sensitivity analysis performed on a typical space power system using the H-521 program. Also included in the report are recommendations of future work to increase the versatility and capability of the computer program.

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INTRODUCTION

The summary of the Parametric Study of Space Power Systems is presented in this document. The study was conducted for the Mission Analysis Division of NASA by the McDonnell Douglas Astronautics Company - Western Division (MDAC-WD) under Contract Number NAS2-4482. The study consisted of four program phases with the first three phases being the technical effort and the fourth phase being the documentation effort.

This document, Volume I, is one of four volumes. The subtitles of the final reports are as follows:

Title	Volume No.	Report No.
Summary	I	DAC-62303
Technical Report	II	DAC-62304
Power Subsystem Parametric Data	III	DAC-62305
Computer Manual		
Book 1 - Power Subsystem Analysis	IV	DAC-62306
Book 2 - Program Operation	IV	DAC-62307

STUDY OBJECTIVES

Many possible manned and unmanned space missions are being investigated and evaluated by NASA. An accurate evaluation of the feasibility and effectiveness of these missions is strongly dependent upon the predictability of the characteristics of the several spacecraft systems such as secondary power systems. Consequently, comprehensive and reliable information on secondary space power systems is essential to meaningful mission studies and planning.

The objective of the study is to provide the mission analyst and spacecraft designer with adequate information about secondary power systems to permit meaningful appraisals of these systems in the context of spacecraft design and mission integration. The results of the study provide the analytical tools and techniques by which space power systems can be compared in a common framework and thereby permit the mission analyst and spacecraft designer to make accurate design analyses, tradeoff choices, and subsystem selections of space power systems. More specifically, the study provides a computer program and supporting documentation which permit the prediction of space power system characteristics (such as mass, volume, area, cost and reliability) as a function of mission parameters (such as mission duration, launch date, trajectory, power load profile, nuclear radiation levels, etc.).

The final report contains the parametric data, analysis, logic networks, system design data, and recommendations. The report contains tables, diagrams, and drawings in sufficient detail to explain the methodology of the power system analysis. The computer code is written in Fortran IV, Version 13 for use on the IBM 7094 computer. The programmer's manual contains: (1) a synopsis of each program and the principal techniques involved in coding; (2) top level flow diagrams describing the structure of each program; and (3) a description of input and output variables, data cards, and symbolic names.

STUDY METHODOLOGY

A large number of space power system designs and configurations have been proposed for advanced missions and a rationale was developed in the study which would allow representative coverage of the maximum number of systems. First, only those systems which were considered to be major candidates for future space missions were examined, and second, wherever possible, nominal or representative configurations were used to represent a wide variety of configuration variations. Within reasonable limits, uniform and unbiased methods were used to collect information and construct power system analytical models.

In order to meet the study objectives the major program tasks that have been performed are as follows:

1. Space power systems and their component subsystems were screened for potential applicability to future space missions.
2. Parametric data were determined and documented for each of the selected systems and subsystems.
3. Mathematical models or logic networks for determining power system characteristics from the parametric data were derived.
4. A computer code was developed that uses the derived power system math models and analytical expressions.

POWER SYSTEMS AND SUBSYSTEMS

For the purposes of this study the space power system consists of five major subsystems: energy source subsystem, the power conversion subsystem, the heat rejection subsystem, the power conditioning subsystem, and the power distribution subsystem. The power conversion subsystem is the key element in determining the power system configuration. The selection of one of eight possible conversion subsystems determines the applicability of the various types of energy sources, heat rejection subsystems, and other supporting subsystems. The five major subsystem categories and the subsystem alternatives used in the study are illustrated in Figure 1.

The energy source subsystem includes the major components and accessory equipment used to generate and transfer thermal or chemical energy to the conversion subsystem.

The power conversion subsystem includes all major components and accessory equipment required for the generation of electrical energy from thermal or chemical energy. Both static and dynamic power conversion subsystem which generate dc and ac power respectively are investigated.

The heat rejection subsystem includes all major components of direct-conduction radiators, single-phase-fluid (gas or liquid) radiators, and condensing-type radiators. Both flat-plate and cylindrical shapes are considered.

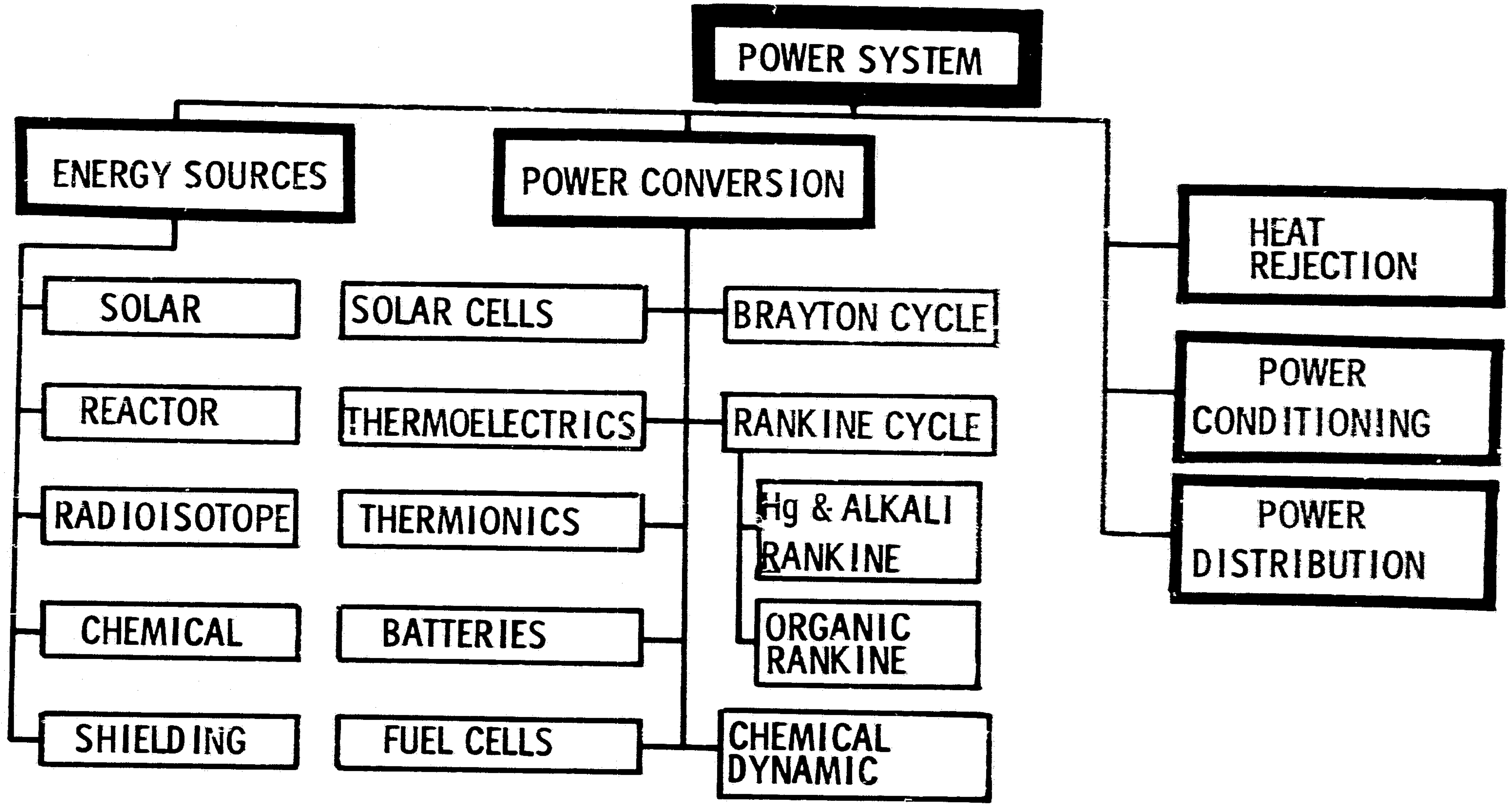

Figure 1. Major Power Subsystems

The power conditioning subsystem includes components required for preparing the raw ac and dc power for the power using subsystems.

The power distribution subsystem consists of the wires, connectors, and supporting structure of all the wires in the space vehicle.

MISSION CONSTRAINTS

Typical mission constraints that were used in establishing the math models and computer program logic for designing a space power system for advanced missions are as follows:

●	Launch date	1970 to 2000
●	Mission duration	Days to 5 years
●	Class of missions	Manned and unmanned, Earth orbital and interplanetary
●	Power levels	10W to 100kW
●	Type of power	ac and dc
●	Interplanetary trajectory	0.3 AU minimum to 40 AU maximum from the sun; special unmanned mission to 0.05 AU
●	Vehicle diameter	3 to 25 m
●	Loads	Launch loads to 10 g's; maneuvering loads to 2.5 g's

PARAMETRIC DATA PROJECTION TECHNIQUE

A growth projection technique as shown in the Figure 2 was developed to provide a coherent rationale for estimating performance parameters for the 1970 to 2000 time period. The growth projection technique is based on the solution of the differential equation $df(t)/dt = 1/\tau\,[f(\infty) - f(t)]$. The solution of the differential equation is

$$f(t) = f(\infty) + \left[f(t_i) - f(\infty) \right] e^{-(t-t_i)/\tau}$$

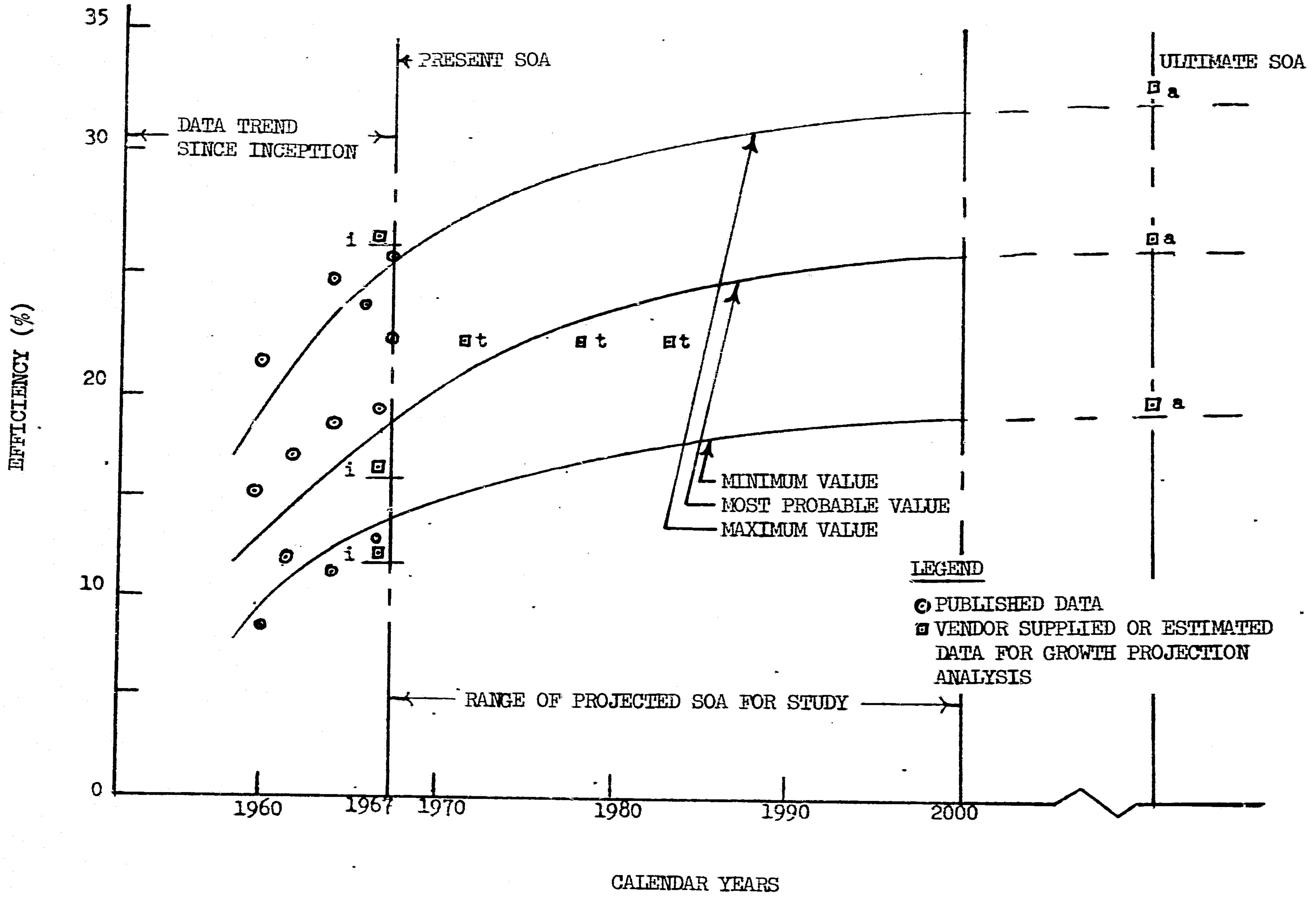

Figure 2. Basis for Projecting State of the Art Curves

where:

$f(t)$ = value of projected parameter at time t (□t points) (i.e., efficiency in Figure 2)

$f(\infty)$ = limiting value of the projected parameter (□a points)

$f(t_i)$ = value of parameter at start of projection (□i points)

t_i = initial time, years

τ = time constant, years

The values of $f(t_i)$, $f(\infty)$, and f(□t) as shown in the figure are found in the literature and from the results of investigations and development programs. The initial and asymptotic values that define the range are identified with the letters i and a, respectively. The points identified by t indicate the minimum, most probable, and maximum calendar year times required to progress from a most likely initial value to some arbitrary level. The limiting value of efficiency □a is assumed to be the most likely value of the asymptotic density. The level of efficiency at which the □t points are determined is selected arbitrarily. The □t values are transformed to time constants (τ) within the computer subprogram before the statistical computations are performed.

A typical example of the statistical growth projection technique applied to determining the efficiency of a mercury Rankine cycle turbine as a function of calendar year is shown in Figure 3.

A thorough survey of the parametric and design data of all the major components, subsystems, and power systems was beyond the scope of the study, and for some components, a complete set of parametric data was not available. To complete the set of parametric data (mass, area, volume, reliability, and cost), engineering estimates were made by power system manufacturers (in response to questionnaires) and by the study team members. To enable the user to understand the growth projection trends and the basic assumptions that were used in drawing the curve(s), and improvement index label is shown with each projection curve or family of curves. The improvement index (II) label and its meaning are presented on the following page.

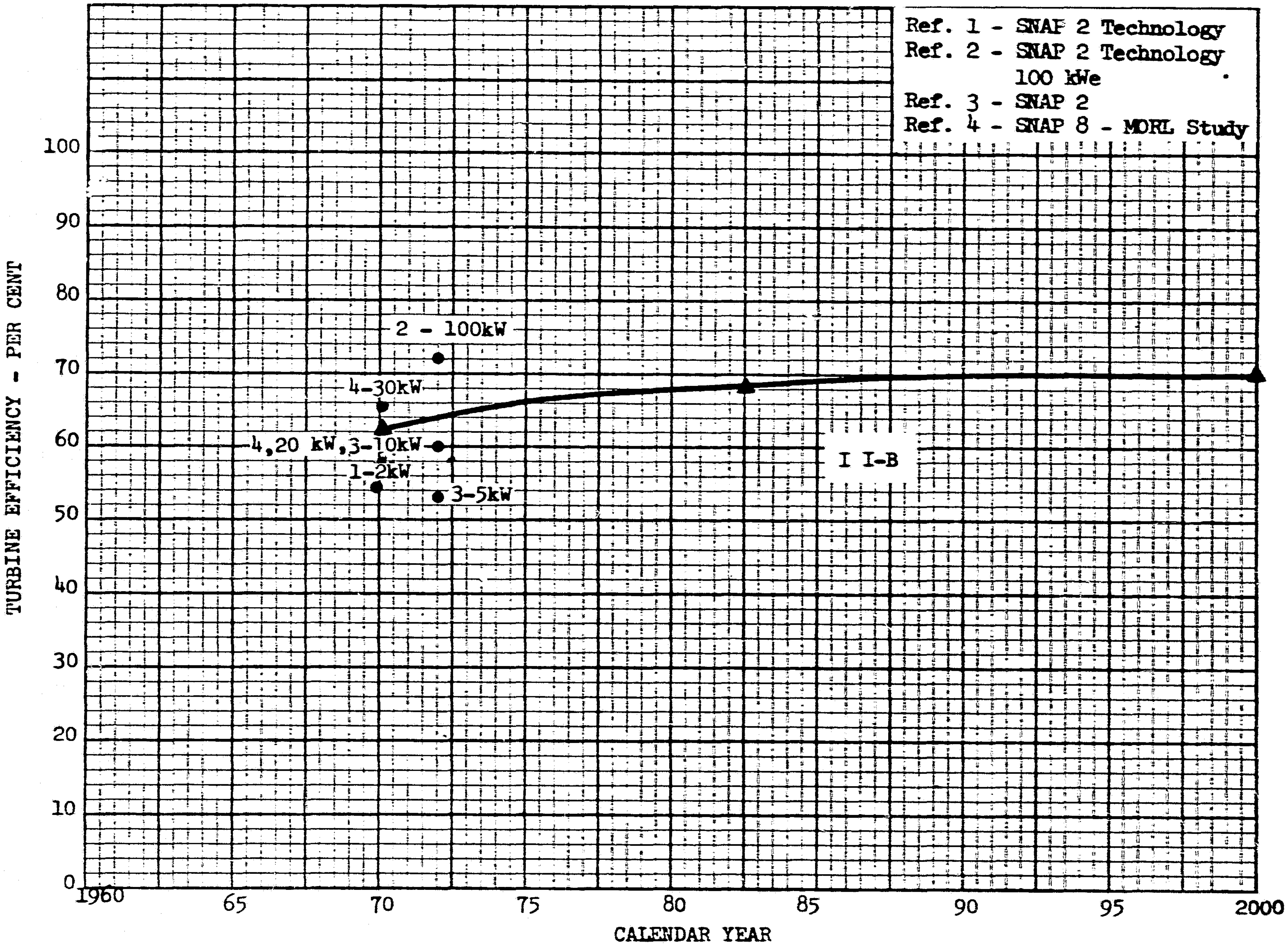

Figure 3 PROJECTION - MERCURY RANKINE TURBINE EFFICIENCY

Improvement Index	Definition
II-A	Product improvement through manufacturing technology or new materials development
II-B	Current level of effort of research and development or system development programs
II-C	Significantly expanded research and development or system development programs
II-D	Assumed value; based on lack of adequate published engineering data

POWER SYSTEM COMPUTER PROGRAMS

COMPUTER CODE NETWORK

There are eight computer programs in the Parametric Study of Space Power Systems Fortran (H-521) Computer Code. Each of the eight programs are specified by the type of power conversion subsystem and are as follows:

Static Systems

- Solar cell
- Thermoelectric
- Thermelectric
- Primary battery
- Fuel cell

Dynamic Systems

- Rankine cycle
- Brayton cycle
- Chemical-open cycle

Each power system program requires the use of six major subprograms in the following sequence: (1) power distribution; (2) power conditioning, load profile analysis, and energy storage; (3) power conversion; (4) heat rejection; (5) energy source; and (6) integration. The program will also require input data, block data, and the various design analysis and output subroutines and auxiliary subprograms. The configuration of the power system is an option that is available to the program user by appropriate selection of subsystems such as the selection of an isotope, or reactor heat source for a thermoelectric power system.

A typical diagram that illustrates the top level logic network or calculational flow diagram for the thermoelectric computer program is shown in Figure 4.

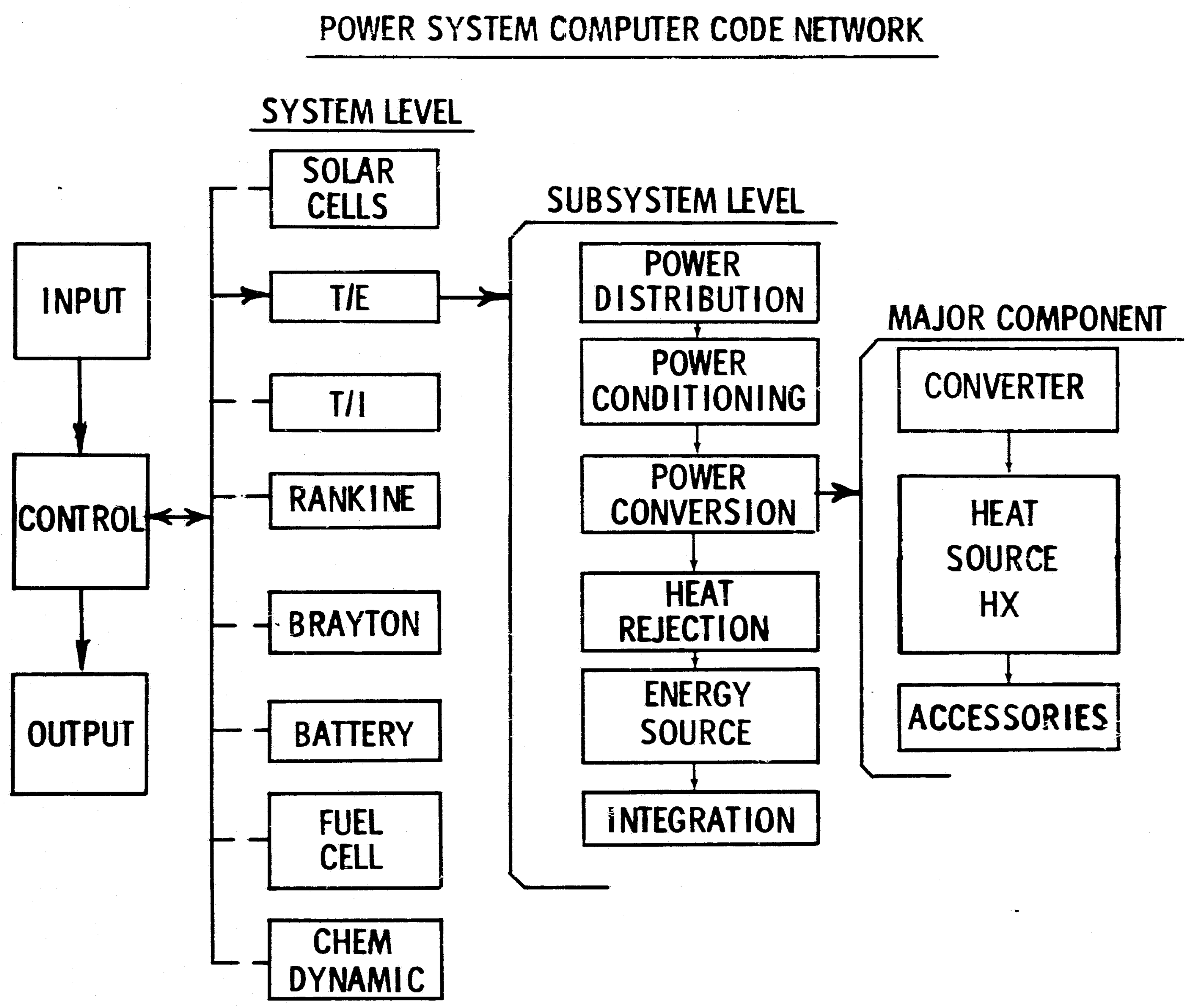

Figure 4. Example Thermoelectric Power System Computer Program Calculational Procedure Network

The general programming technique that is employed is a series programming process. Data are input to and output from the program at the system level. Subsystems are then designed in a specific order. Within each subsystem, major components are also designed with a specific order. The main program is used to read input design data and act as the monitor for successive design reference runs and cases. The power conversion subroutine serves a dual function--monitoring the overall program flow (calling of subsystem design routines and output subroutines) and design of the major components of the power conversion subsystem.

Each subsystem consists of major components and a typical example of the major components of a thermoelectric power conversion subsystem are also shown in Figure 4. The major components for a thermoelectric conversion subsystem include converters, heat source heat exchanger, and accessories (including pump). The design of a major component utilizes information on the variation of parametric design data with year, size, thermodynamic data, etc. The data are used to analyze the efficiency, weight, volume, heat rejection rates, cost, reliability, and thermodynamic and electrical state points of the component.

COMPUTER PROGRAM INPUT

The minimum information needed to perform a series of computer runs is divided into (1) reference run data, (2) initial case data, (3) additional case data, and (4) end of data. Individual component and system performance data (defined as block data) are an integral part of the code but may change with advancement in technology. Block data can also be entered into the code at the option of the user and the new block data then overrides the original block data in the code. A summary list of the type of computer input data is shown in Table 1. The input load sheets have been designed for use by the engineer and permit considerable flexibility in changing mission and power system design data. It is not required that the program user learn a special input nomenclature, but simply input the desired numerical quantity under each heading on the load sheets.

Table 1

COMPUTER PROGRAM DATA

Primary Data

Input

Power level and time on the line Voltage, Frequency	Reference Run data
Type of system (subsystems) Launch date Mission duration Trajectory (orbit, AU, etc) Vehicle dimensions Permissible radiation levels Launch and maneuvering g-loads Redundancy pattern of power system Contingency factor	Case data

Secondary Data

Block Data

- State of the art projection data
- Component efficiency and thermodynamic data

Physical constants and coefficients

Output Data

First level:
- Summary of power requirements
- Subsystem characteristics
  - (Weight, volume, area, reliability, cost)
- Total system characteristics

Second level:
- Subsystem component characteristics
  - (Weight, volume, area, reliability, cost)
- Total subsystem characteristics

Third level:
- Detailed component characteristics and data
  - (Thermodynamic data, reliability, efficiency, volume, redundance, cost, etc.)
- Gross system characteristics
  - (Mass, volume, area, cost, power, reliability, efficiency, heat flow)

Fourth level:
- Power load profile and battery performance analysis
  - (ac and dc user loads, charge discharge requirements, primary power output level, battery characteristics, etc.)

Fifth level:
- Major component electrical power load schedule
  - (Power levels, voltages, frequency, etc.)

The reference run data consist of the power load profile information of the user subsystems. The initial case data consist of mission and power system descriptive parameters such as launch date, mission duration, type of power subsystems, etc. and the additional case data are used for iterative runs on the initial case data. Sensitivity of power system characteristics to various subsystem and components can be determined by varying configurations via the additional case input data. The sensitivity of the power system to changes in mission parameters, such as mission duration or vehicle configuration can also be found in a similar manner. The complete set of power system options and corresponding indicator flag that can be entered into the program as case data are shown in Table 2.

DATA ORGANIZATION AND CHANGE METHOD

The Parametric Study of Space Power Systems Fortran Computer Code (H-521) requires input data and secondary data for calculating the performance and characteristic data of space power systems. The input or primary data consist of reference run data, case data, additional case data and end of data. The secondary data consists of block data and permanent type data that is built into the code. Figure 5 shows the general location of these types of data within the program deck. The method used to make changes in the data are as follows:

Reference Run Data -- These data comprise the information that is required for a series of cases based on power load profile data. Reference run data or power load profile data are changed by filling out new input sheets and replacing the input cards as required.

Case Data -- These data include specific values of major variables that are desired. Thus to obtain power conversion system data for three calendar years such as 1975, 1985, and 1995, input sheets are filled out for two additional cases plus the first case. When a change in variable is not indicated on a subsequent case input sheet, it reverts back to the values of the first case.

Table 2

POWER SYSTEM CONFIGURATION AND INDICATOR FLAG SPECIFICATION

Subsystem													
Conversion	IF	Heat Source	IF	Heat Rejection	IF	Power Conditioning	IF	Energy Storage	IF	Power Distribution	IF	Vehicle Integration	IF
Rankine Cycle		Solar Concentrator		Direct Conduction		DC	00	Secondary		DC Loads		No Integration	00
				Radiator		AC	10	Batteries				Shroud*	01
1. Organic	01	1. Rigid one piece	01	Flat Plate	01					1. Cu wire	00	Interstage*	02
2. Mercury	02	2. Folding	02					1. NiCd	01	2. Al wire	01	Boom Only	03
3. Alkali metal	03			Single-Phase Fluid				2. AgCd	02				
				Radiator				3. AgZn	03	AC Loads			
Brayton Cycle	11	Reactants and		1. Flat plate									
		Tankage		Argon	11					1. Cu wire	10		
Silicon Solar		1. H_2 - O_2		FC-75	14					2. Al wire	11		
Cells		Subcritical	11	NaK	17								
1. Flat plate	21	Supercritical	12	Dowtherm	20								
2. Cylindrical	22	Gaseous	13							AC/DC Loads			
		2. N_2O_4 and	15										
Thin-Film Solar		aerozine		2. Cylindrical						1. Cu wire	20		
Cells				integrated						2. Al wire	21		
1. Flat plate	25	Isotope and Shield		Argon	12								
2. Cylindrical	26	1. Sr - 90	21	FC-75	15								
		2. Co - 60	22	NaK	18								
Thermionic	31	3. Pu-238	23	Dowtherm	21								
		4. Cm-244	24	3. Deployed									
Thermoelectric				cylindrical									
1. PbTe	41	Reactor		Argon	13								
2. SiCe	42	1. UZrHx		FC-75	16								
3. Cascaded	43	Instrument		NaK	19								
		Shielded	31	Dowtherm	22								
Fuel Cells		Man shielded	32										
1. H_2-O_2		2. Fast spectrum		Direct-Condensing									
reactant	51	gen shielded	33	Radiator									
2. Storable		3. In-core		1. Flat plate									
reactant	52	thermionic	34	Mercury	31								
				Potassium	34								
Chem Dynamic				2. Cylindrical									
1. H_2-O_2				integrated									
reactant	61			Mercury	32								
2. Storable				Potassium	35								
reactant	62			3. Cylindrical									
				deployed									
Primary Battery	71			Mercury	33								
				Potassium	36								

***Includes boom if separation distance is greater than 0.4m**

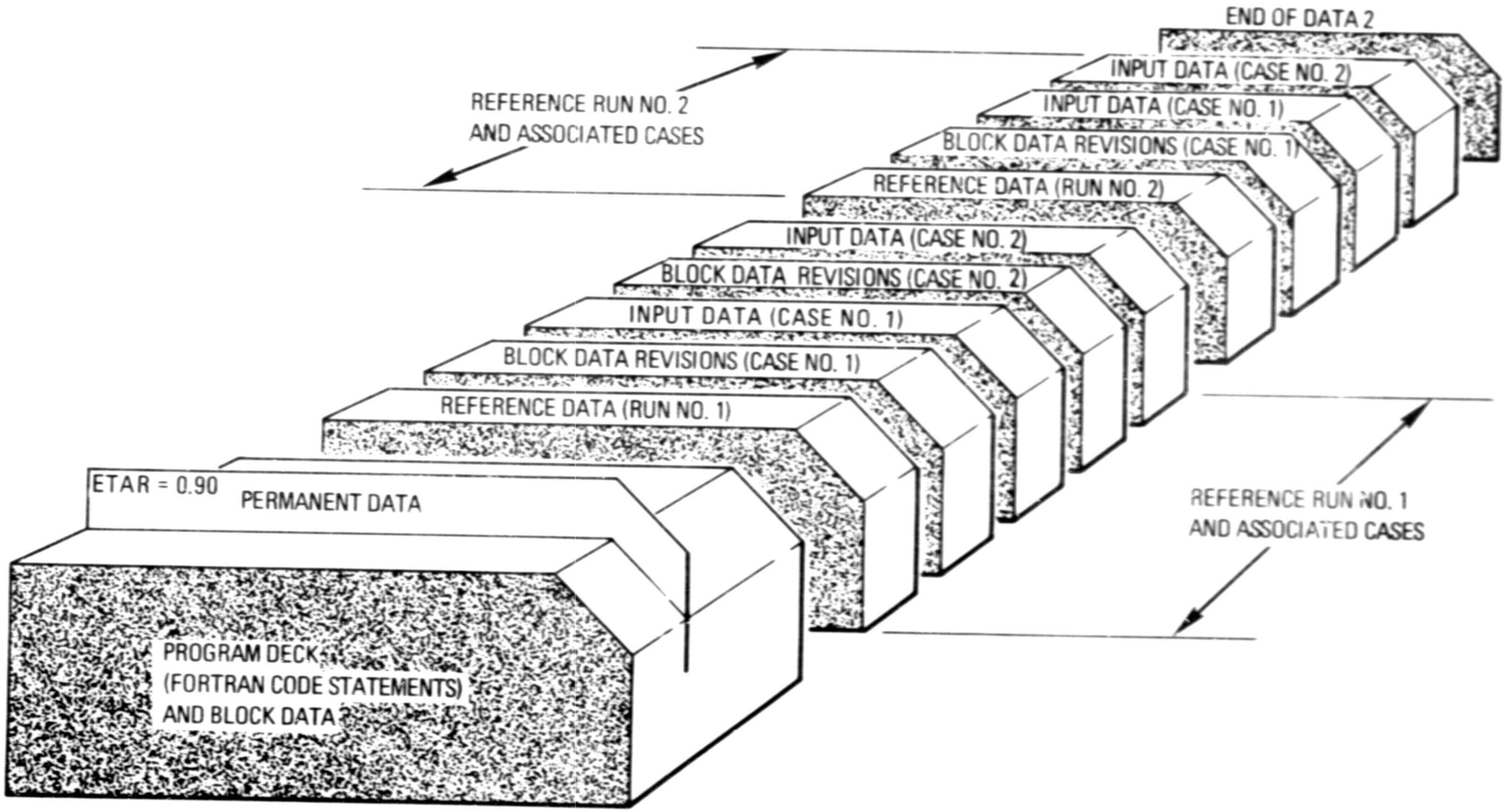

Figure 5. H-521 Computer Program Deck Organization and Change Method

Block Data -- Block data include the secondary level data that are supplied with the program and are not normally changed during a series of runs. Parametric data such as the specific masses of major components projected against calendar year are included in this category. These data can be changed readily by punching new data cards and inserting them in the parametric data change section. Cards placed in this location before the case data override the block data section of the deck, for that specific case only. The values of all parametric data revert back to the original block data for subsequent cases unless the parametric data change cards are included for each case run. An example of the use of this change procedure is as follows: If the program user has new parametric data on the specific mass of thermoelectric converters as a function of calendar year, he punches out new data cards and places them in the parametric data change section just ahead of the case data. The data on the new cards override the original block data for thermoelectric converter specific mass. Block data changes do not require that the Fortran program deck be recompiled. If after reviewing the data, the user decides to make the change permanent, he can do so by replacing the appropriate cards in the block data section of the Fortran code.

Built-In-Data -- Certain types of data normally not expected to be changed are built into the Frotran statements in the form of constants, and coefficients in equations. A typical data card of this type is the raised card in the figure in the Fortran statement section. Changes in this data require location and replacement of the card and recompilation of the Fortran deck.

COMPUTER PROGRAM OUTPUT

The output generated by the program can be presented in various levels of detail. Three output subroutines describe the power system design at the system, subsystem and major component levels. Two additional output subroutines detail the results of the load profile analysis at various points in the electrical network of the power system. The types of program output are listed in Table 1 and the top level or first level output is shown in Figure 6.

```
                          THERMOELECTRIC   SPACE POWER SYSTEM CHARACTERISTICS
                        ********************************************************
                        ********************************************************

MISSION TYPE          =  0                                   CREW SIZE                 =  3
ORBITAL INCLINATION   =    .0000 DEGREES                     ORBITAL ALTITUDE          =    4.0000+02 KM
LAUNCH DATE           = 1985.000 AD                          MISSION DURATION          =  416.000 DAYS
MINIMUM SOLAR VECTOR  =    1.000 AU                          MAXIMUM SOLAR VECTOR      =    1.000 AU
VEHICLE DIAMETER      =    5.000 METERS                      VEHICLE LENGTH            =   10.000 METERS
SEPARATION DISTANCE   =    5.000 METERS                      MANEUVERING         LOADS =     .500000 G,S

                                        NUCLEAR RADIATION LIMITS
                                      **************************

BIOLOGICAL DOSE =   10.000 REM /  MATERIAL DOSE =   -0.000    RAD / MATERIAL DOSE =   -0.000     NVT

 USER SYSTEMS POWER REQUIREMENTS                               COMPOSITE          DC            AC
**********************************                           *************     **********    **********

 AVERAGE POWER (KILOWATTS)                                       5.000            5.000          .000
 PEAK POWER    (KILOWATTS)                                       5.000            5.000          .000
 VOLTAGE       (VOLTS)                                         ********          28.000          .000
 FREQUENCY     (HERTZ)                                         ********        ********          .000

        SUBSYSTEM              MASS          VOLUME         AREA        RELIABILITY      COST (*)
                           (KILOGRAMS)    (CU.METERS)    (SQ.METERS)                       ($)
*************************  *************  *************  *************  *************  *************

 ENERGY SOURCE        23    2.92494+03     1.54945+00     3.83075+00     .99895685      1.18088+08
 POWER CONVERSION     41    4.31819+02     0.00000        0.00000        .98023003      1.81638+07
 ENERGY STORAGE        1    0.00000        0.00000        0.00000       1.00000000      0.00000
 HEAT REJECTION       19    6.14779+02     0.00000        5.73909+01     .99921325      6.88553+05
 POWER CONDITIONING    0    3.05015+01     2.21877-02     0.00000        .90083169      3.05018+05
 POWER DISTRIBUTION    0    9.80861+01     1.39222-02     0.00000        .99994010      6.28588+05
 VEHICLE INTEGRATION   3    3.35458+02     1.12849+00     0.00000        .99900000      1.35022+07

*************************  *************  *************  *************  *************  *************

 NET TOTAL                  4.43558+03     2.71405+00     6.12217+01     *********      1.51876+08
 CONTINGENCY                4.43558+03     2.71405+00     6.12217+01     *********      1.51876+08
 GROSS TOTAL                8.87116+03     5.42810+00     1.22443+02     .88047299      3.03751+08


             (*) INCLUDES PRODUCTION COSTS FOR    1.0 COMPLETE SPACE POWER SYSTEMS
```

Figure 6. First Level Output Sheet-PbTe Thermoelectric Space Power System Characteristics

EXAMPLE THERMOELECTRIC POWER SYSTEM ANALYSIS

The thermoelectric program includes developed subprograms for reactor, isotope, and solar concentrator heat sources; PbTe, SiGe, and cascaded thermoelectric power conversion converters; direct-radiating and single-phase-fluid radiators; dc power conditioning; ac, dc, and combined ac-dc power distribution; battery energy storage; and vehicle integration penalties. The top level flow network used in determining the T/E power system characteristics is shown in Figure 7, and the computer program calculational procedures showing the relationships of the various subprograms is shown in Figure 8. All the design options that are available in the configuration of a thermoelectric system are shown in Figure 9. The individual subsystem/subroutine selections are made by choosing the appropriate indicator flag (IF) in Table 2.

A typical first level computer output data sheet from a run made on the thermoelectric system is presented in Figure 6. Figures 10 through 12 are typical of the many possible curves that can be generated using the developed computer code. The curves indicate the type of data that can be calculated and the sensitivity of the power system to parameters such as launch date, power level, radiator temperature, type of converter, type of heat source and type of radiator. The program also includes an option that iterates radiator temperature in five steps over a range to permit tradeoff comparisons. The T/E power system mass as a function radiator temperature and power level is shown in Figure 10 and mass is a minimum at a radiator temperature 475°K. The thermoelectric power system mass (shown as a composite of the masses of the individual subsystems) versus radiator temperature for a Pu-238 isotope heat source and a 1-year mission in the 1985 time period is shown in Figure 11. The decrease in power system mass with launch date is shown in Figure 12 and is the result of advances in the PbTe converter efficiency and projected subsystem component performance and characteristics of the other subsystems.

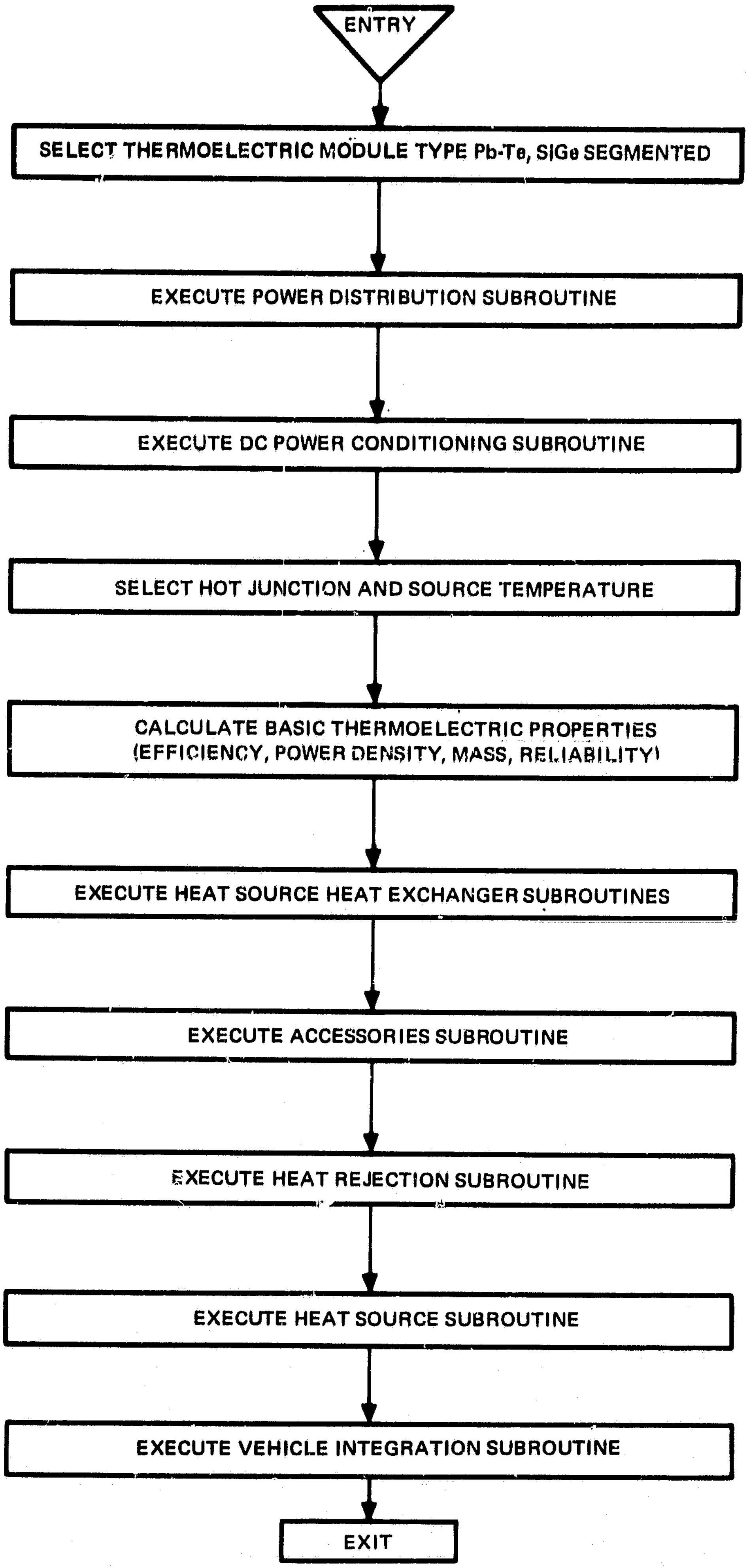

Figure 7. Top Level Thermoelectric Computer Program Flow Network

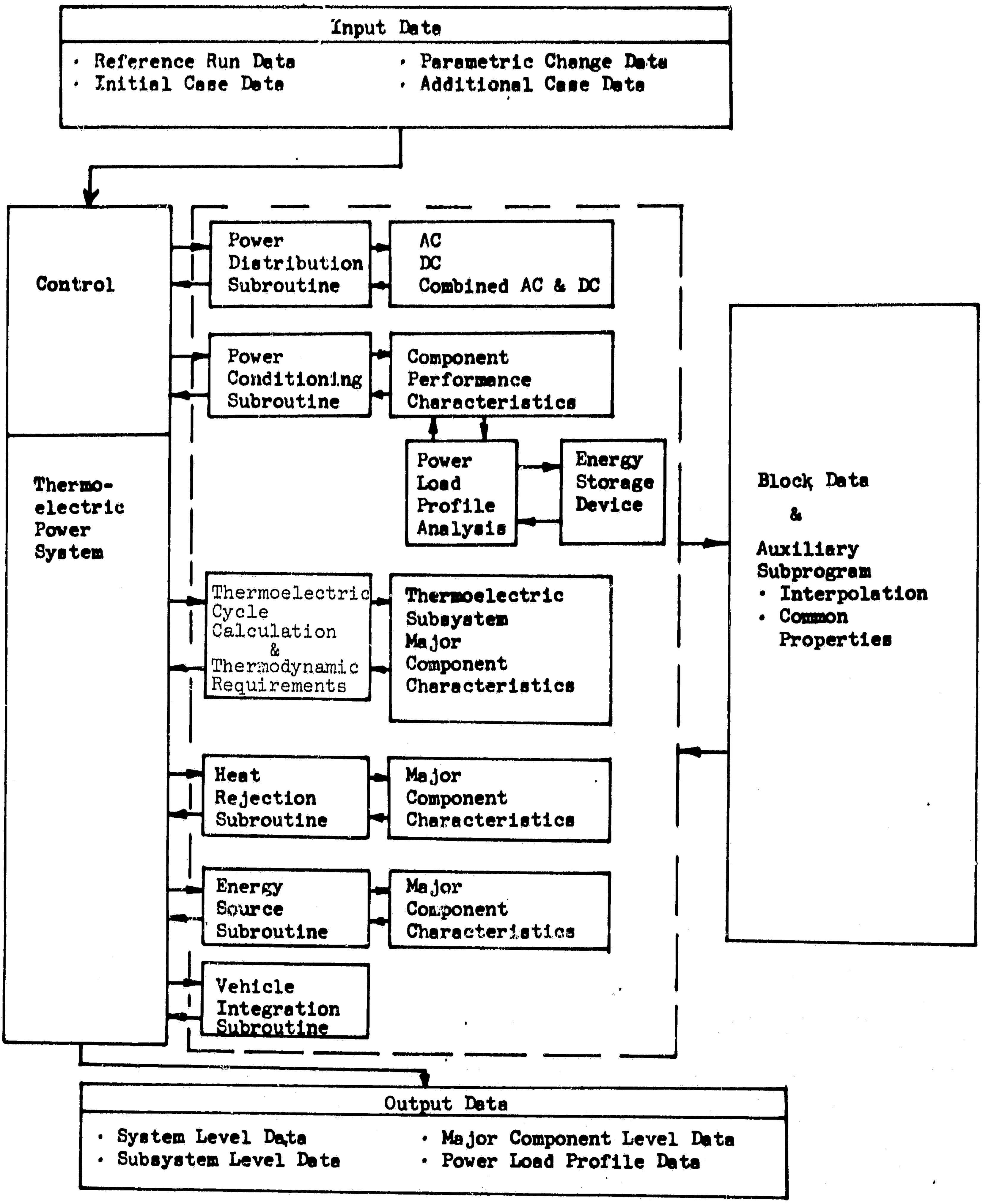

Figure 8. Thermoelectric Power System Computational Program Calculation Procedure

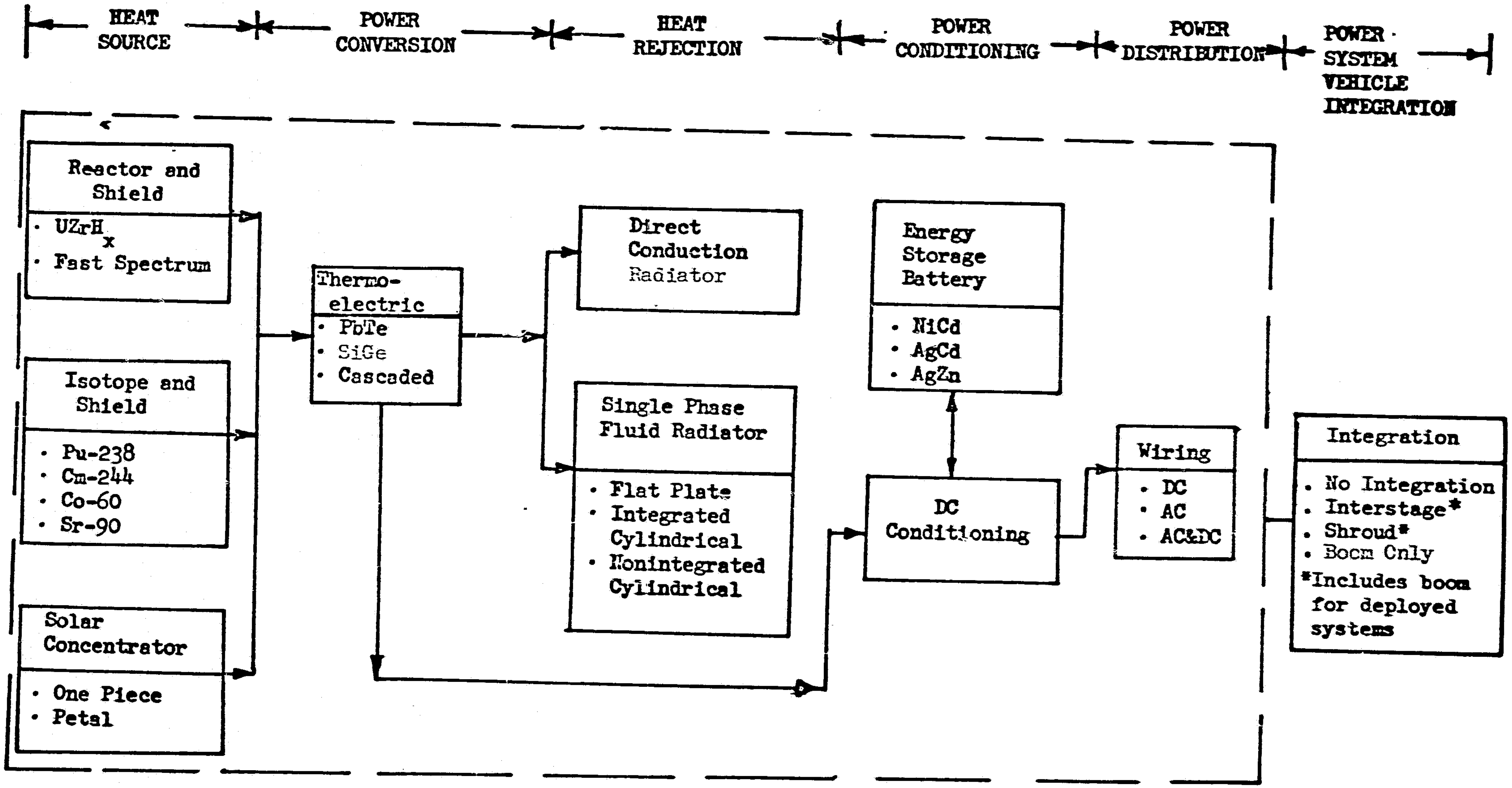

Figure 9. Thermoelectric Power System Configuration Options

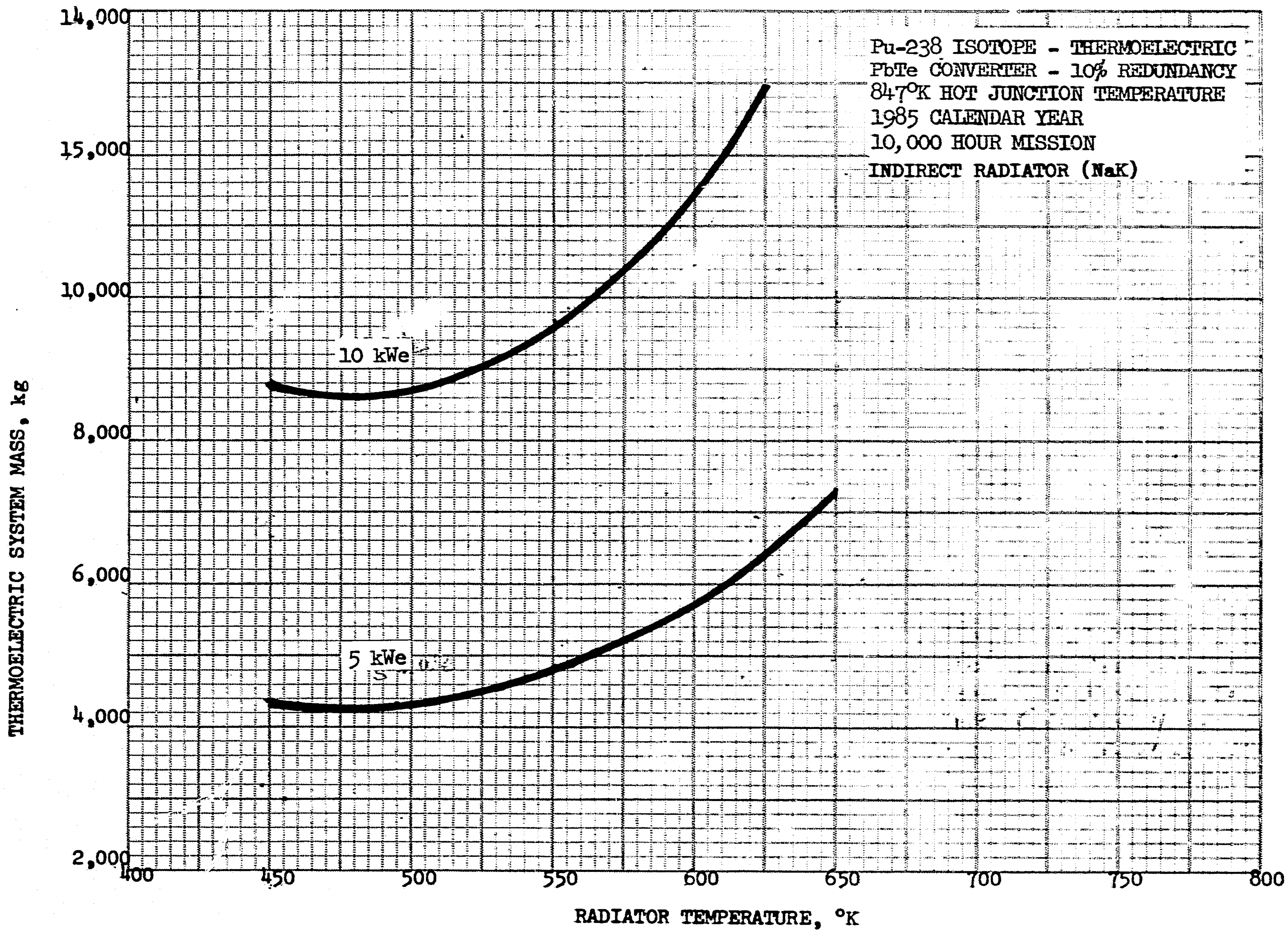

Figure 10. Isotope Thermoelectric Power System Mass

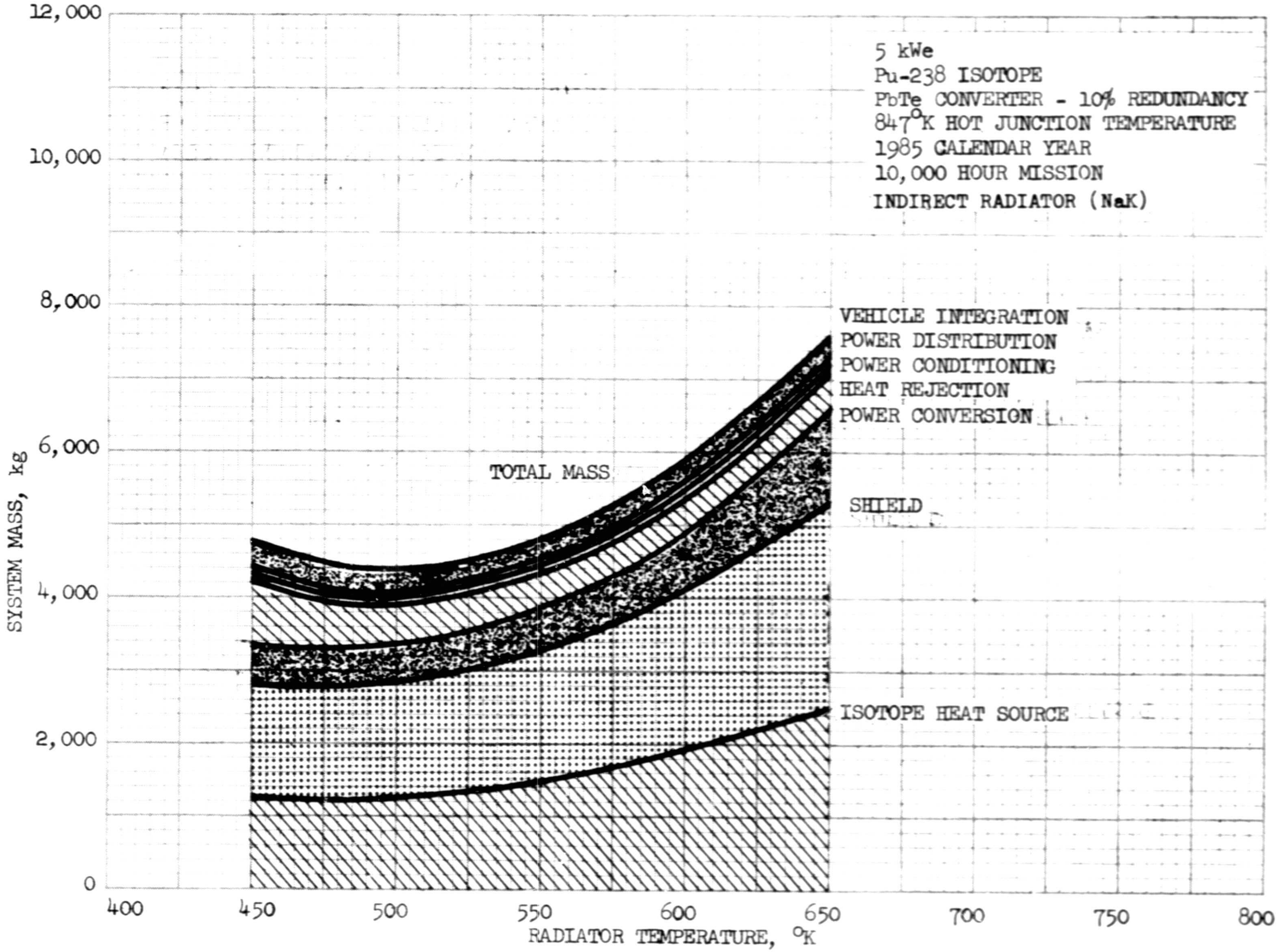

Figure 11. Isotope Thermoelectric Component Mass Variation

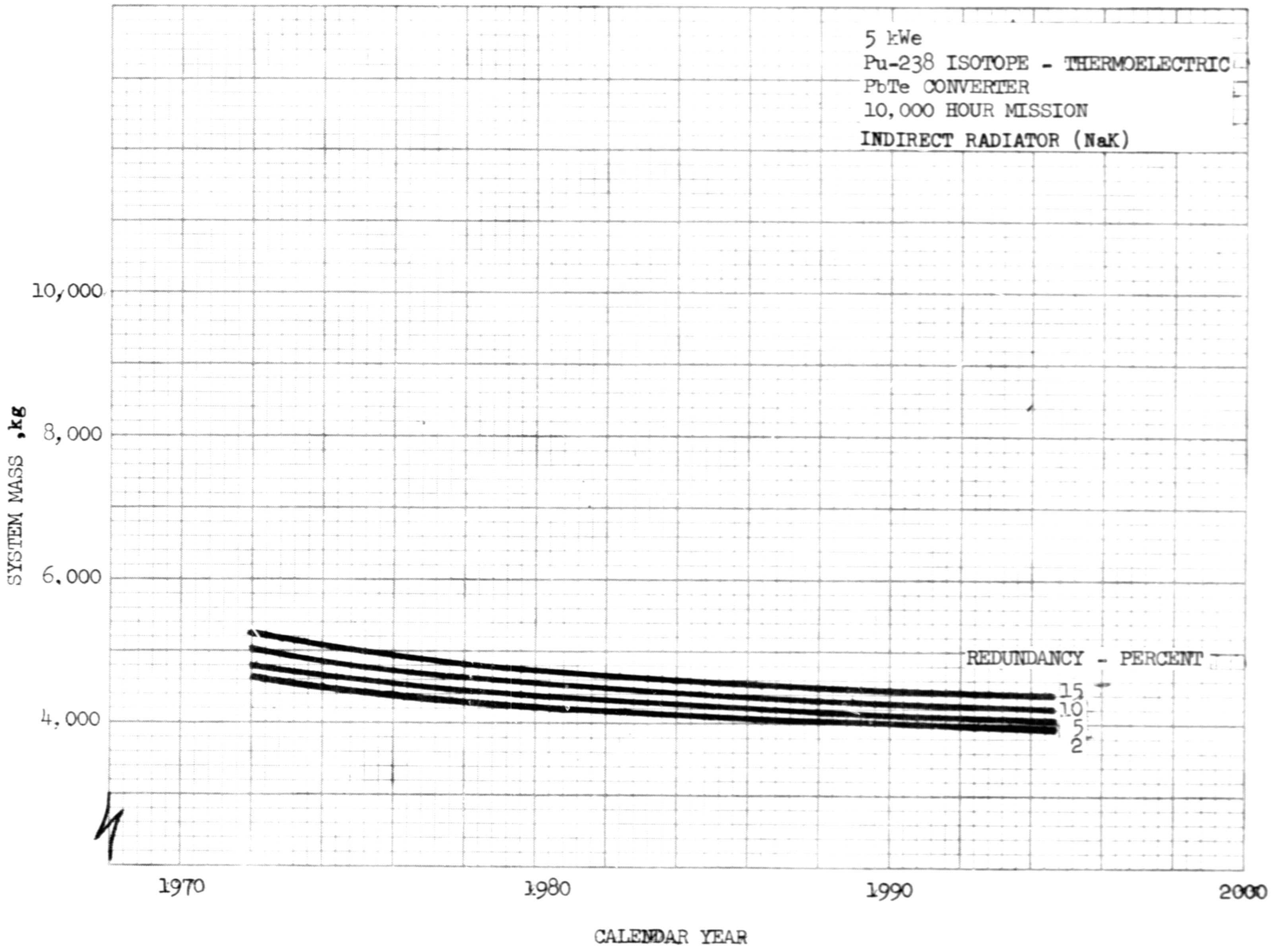

Figure 12. Thermoelectric System Mass Variation with Calendar Year

RECOMMENDATIONS FOR FUTURE WORK

As the design data were being collected and the computer code was being developed, it became evident that within the schedule and scope of the study that (1) certain detail data were not published or available, (2) simplified analytical equations had to be used for the various power subsystems, and (3) all the potential subsystems or major components could not be investigated.

The following recommendation for future work are made:

1. Acquisition and refinement of parametric and design data.
    - A. Visit vendors and government agencies to obtain reliability and cost data at the major component level.
    - B. Submit generated parametric design curves to vendors and government agencies and correlate the results of their recommendations to upgrade existing computer program data.
2. Analytical modeling and scaling laws.
    - A. Include orbit-keeping penalties for deployed solar cell, solar concentrator, and nuclear power systems.
    - B. Include specific speed-performance data for Brayton and Rankine cycle power conversion dynamic machinery.
    - C. Set up math models for thermally integrating power system with environmental control and on-board reaction control thrusters.
    - D. Write math model for heat pipe heat rejection subsystem.
3. H-521 computer programming.
    - A. Modify program to optimize power system on a weight basis.
    - B. Develop additional ac and dc power conditioning and distribution subroutines.
    - C. Develop a more detailed power system space vehicle integration subroutine.