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Technical Memorandum 33-321

RTG Integration Problem Areas and Parametric Analysis

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Abstract

Current radioisotope thermoelectric generator (RTG) design concepts for space power systems are often unrealistic or incomplete from two standpoints. They generally lack understanding of, or regard for, the total mission and spacecraft requirements, and are usually unsupported by sufficient reliable data or technical information. Too little differentiation is made between proof-of-principle hardware concepts and mission applications. In the former, flights of specific RTGs or families of RTGs are planned for the purpose of determining the feasibility of new RTG sizes, weights, and fuels; in the latter the RTG has functional importance, utilized as a component whose sole purpose is to support the primary goals of the mission.

RTG Integration Problem Areas and Parametric Analysis

I. Introduction

A practical consideration of radioisotope thermoelectric generator power sources for space applications requires an understanding of both the total system into which the RTG will be integrated and the interface constraints imposed by such a system. Stated another way, RTG design and integration analysis should be tested against the following standard: *Given any variety of missions, with their full spectrum of interface constraints, is the use of an RTG feasible? If so, what RTG size and weight can be expected, all interface constraint conditions being met?*

The above premise suggests a wide range of possibilities:

(1) An RTG is not feasible for these missions.

(2) An RTG may be feasible for definite and limited types of missions only.

(3) RTGs have broad applicability.

(4) RTGs are limited in their potential only to the extent that some interface constraints are either unrealistic or too stringent.

The above possibilities, in turn, suggest that an RTG as an isolated component or piece of hardware is somewhat unrealistic; at no time can the RTG be taken out of context to its ultimate application as part of a total system.

1966 thermoelectric and fuel capsule state-of-the-art indicates that RTG integration feasibility is indeed real. The extent of the conditions under which this feasibility exists is, unfortunately, ill-defined, and can be clarified only through a total system approach. Feasibility must be determined on a mission-to-mission and spacecraft-to-spacecraft basis.

II. Interface Constraints

Starting with a given mission and only its power requirements, a first rough-cut RTG sizing is relatively straightforward. Characteristics curves are available for thermoelectric materials, such as lead telluride and silicon germanium, and optimum values of thermoelectric module size and weight can be determined for specific power and voltage requirements. These temperature dependent values must be based upon the assumed availability of a heat source and heat sink capable of providing a usable thermal flux. Similarly, the thermal pattern selected to determine the thermoelectric output values can be used for rough determinations of the heat source and heat sink sizes and weights.

However, a mission consists of more than its power requirements alone. Conditions of long life, severe environmental stresses, and load variations, among others, impose restrictions that strongly affect thermoelectric performance. To compensate for anticipated debilitating effects that result in RTG performance degradation, or even to prevent such effects, if possible, changes in such areas as generator design, assembly techniques, and operating temperature range may have to be made. These *a priori* changes, when they occur, must be made in light of the overall mission and its interfaces.

Four distinct and equally important interface constraint areas must be considered in context with the mission power requirements:

(1) Generator oriented constraints.

(2) Mission environment constraints.

(3) Safety-oriented constraints.

(4) Spacecraft (system)-oriented constraints.

The mission power requirements may be considered a fifth interface constraint area.

III. Generator Oriented Constraints

The generator oriented constraints are those RTG operating limits beyond which reliable thermoelectric performance can neither be predicted nor expected. This constraint area provides the primary feedback network necessary for keeping the RTG design consistent with its capabilities. The generator operating limits are essentially the physical, thermal, and electrical tolerances of the thermoelectric module. These, in turn, are influenced by:

(1) Ambient thermal conditions.

(2) Impact and vibration stresses.

(3) Mission time duration.

(4) Ambient atmospheres.

IV. Mission Environment Constraints

The mission environment constraint area differs from the other three constraint areas to the extent that it is rather inflexible. Once a mission has been selected there is relatively little that can be done to change conditions such as Martian or interplanetary ambient atmospheres or temperatures, or launch and entry vibrations and impacts. The importance of the mission environment constraints is to point out those areas where generator protection is needed, and to indicate the size and weight penalties associated with such protection. The fact that the mission environment may impose severe operating conditions upon the generator suggests that a direct matrix relationship exists between it and the generator oriented-constraint area.

V. Safety-Oriented Constraints

The safety-oriented constraints are externally established requirements, compliance with which results in the addition of structural features to the thermoelectric generator, increasing size and weight but without a commensurate increase in generator output or performance. These external requirements are political, philosophical, and economic, as well as technical in nature, and are germane to nuclear-fueled power sources to a degree never experienced with chemical or solar photovoltaic devices. Their result is the consideration and use of RTG-spacecraft structural integration members; intact or burn-up re-entry structural and control members; and thermal and nuclear radiation protection members. The safety-oriented constraints are most traceable, designwise, to the heat source, but their influence on mission science and electronics suggests a direct matrix relationship with the system-oriented constraint area.

VI. Spacecraft (System)-Oriented Constraints

The system-oriented constraints are those restrictions imposed upon the generator parameters which, if exceeded, could be a threat to the achievement of the mission objectives. That is, the desired generator output cannot be achieved with side effects that pose a hazard to the spacecraft and the science and electronics it contains. Factors to be considered are:

(1) Radiation tolerance levels of spacecraft components and electronics.

(2) Temperature tolerance levels of the spacecraft structure and on-board components.

(3) Orientation and placement of RTGs with regard for spin or three-axis spacecraft stabilization.

(4) Threshold levels of on-board experimentation, such as magnetometers and ionization chambers.

(5) Spacecraft weight allowance.

(6) Spacecraft and accessory space availability.

VII. Interface Matrix

Figure 1 illustrates the interrelationship among the requirements, the interface constraints, and the subsequent factors affecting RTG sizing. It must be realized

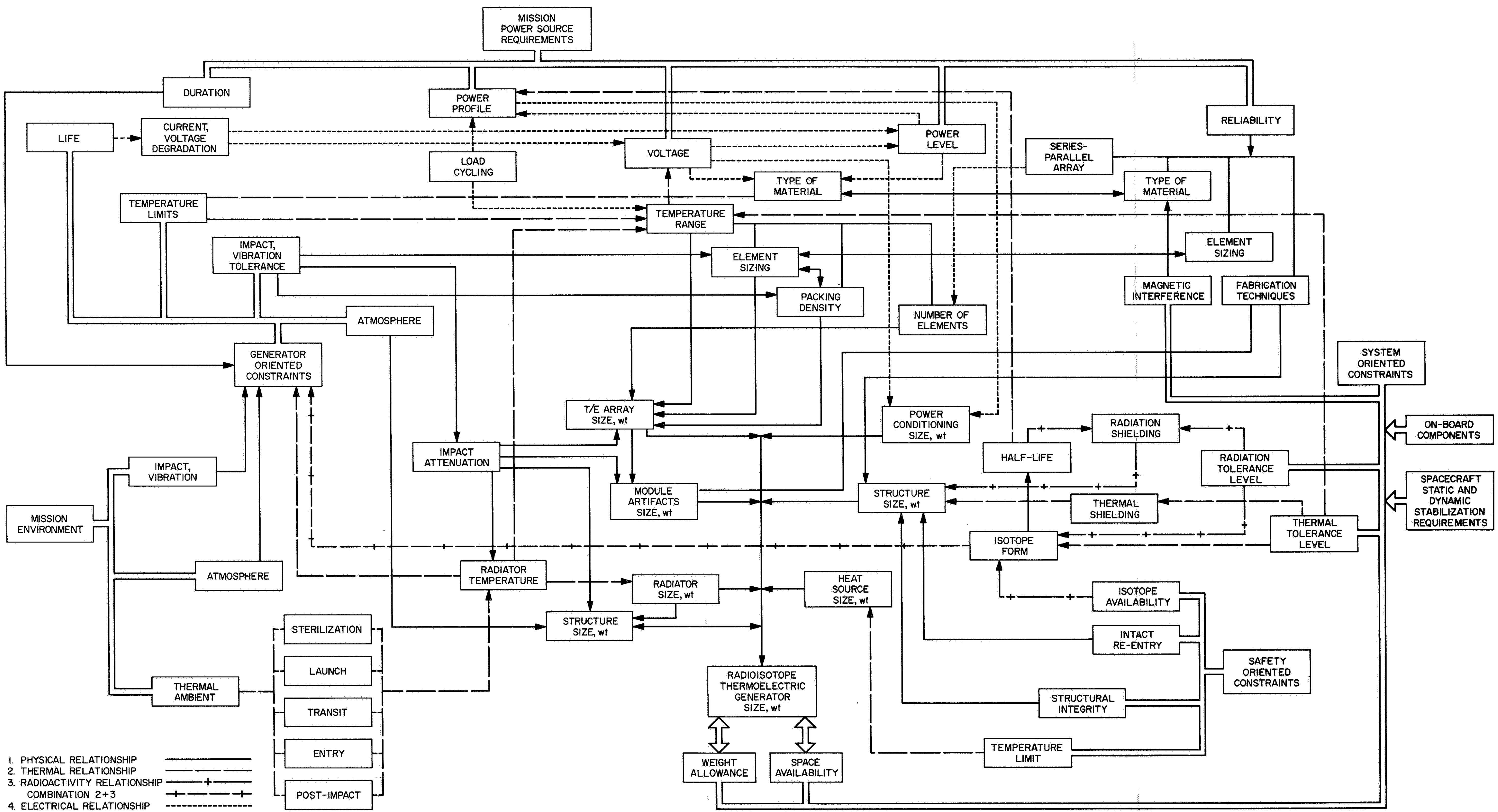
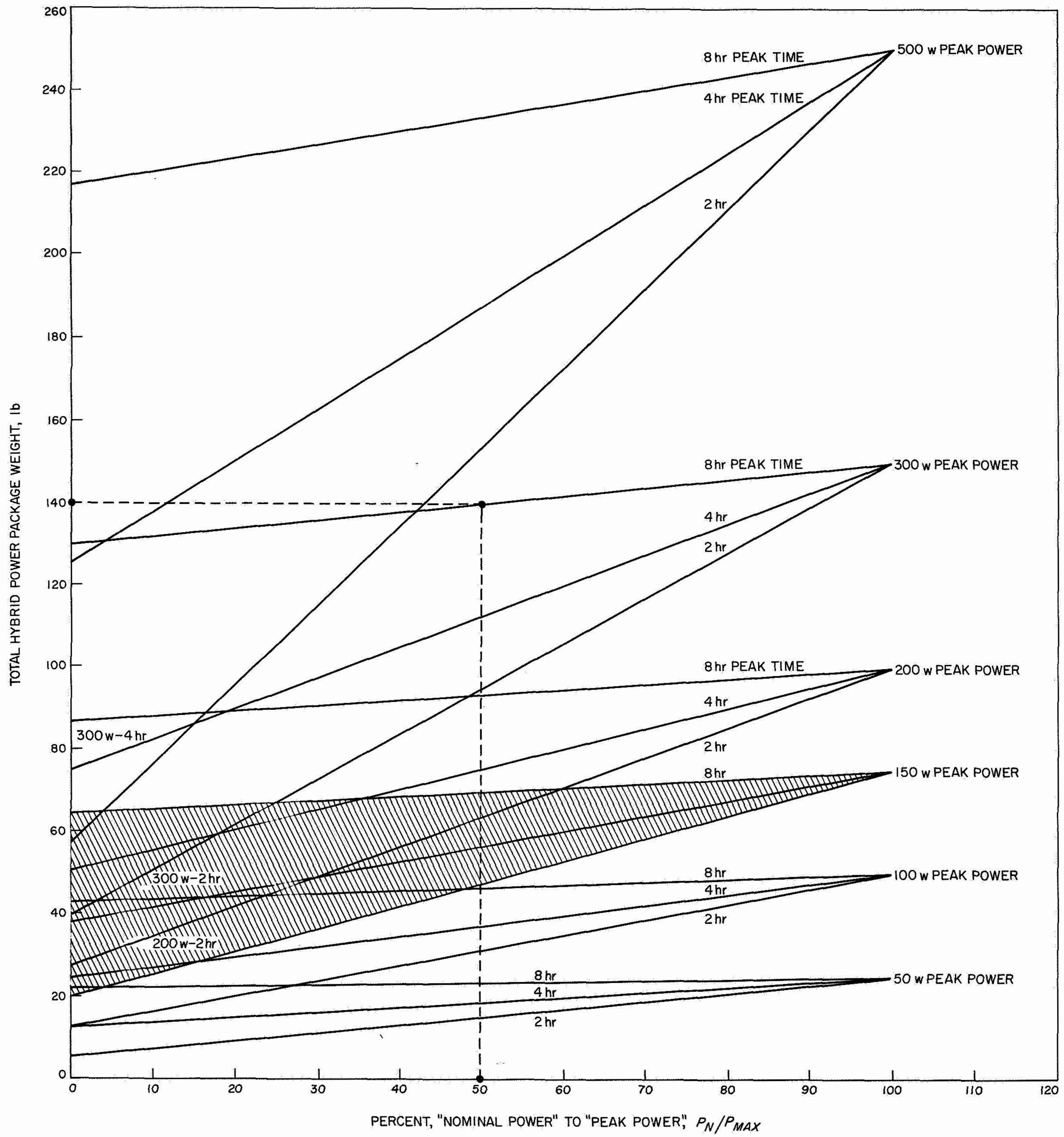


Fig. 1.Radioisotope thermoelectric generator system relationships

Fig 1-A
3-A



WEIGHT OF A HYBRID POWER SOURCE SYSTEM CONSISTING OF AN RTG AND RECHARGEABLE BATTERY PACKAGE AS A FUNCTION OF PEAK POWER, NOMINAL POWER, AND POWER PROFILE-FOR A 24-hr CYCLE BASED ON:

RTG SPECIFIC POWER OF 2 w/lb
BATTERY SPECIFIC ENERGY OF 20 w-hr/lb

RTG SIZE BASED UPON FORMULA $(G-P_N)(T_N)+(G)(T_{MAX})=(P_{MAX})(T_{MAX})$

WHERE: G = RTG POWER OUTPUT, w; T_N = NOMINAL POWER DURATION, hr; P_N = NOMINAL HYBRID POWER; T_{MAX} = PEAK POWER DURATION, hr; P_{MAX} = PEAK HYBRID POWER

EXAMPLE:
300 w PEAK POWER DESIRED FOR 8-hr; 150 w NOMINAL POWER REQUIRED FOR 16-hr
WHAT SIZE RTG IS REQUIRED? WHAT WILL BE THE WEIGHT OF A HYBRID SYSTEM?

ANALYSIS:
FROM ABOVE FORMULA, RTG IS SIZED AT 200 w
FROM GRAPH, HYBRID SYSTEM WILL WEIGH 140 lb

1. DURING NOMINAL POWER PERIOD, 150 w ARE REQUIRED FOR 16-hr, OR 2400 w-hr
2. 200 w RTG WILL SUPPLY 150 w FOR 16 hr OF NOMINAL POWER (2400 w-hr) AND ALSO PROVIDE 50 w OF BATTERY CHARGING FOR 16-hr (800 w-hr)
3. DURING PEAK POWER PERIOD, 300 w ARE REQUIRED FOR 8-hr, OR 2400 w-hr
4. 200 w RTG WILL SUPPLY 200 w FOR 8-hr PEAK PERIOD (1600 w-hr) AND RECHARGED BATTERY WILL SUPPLY 800 w-hr, FOR A TOTAL OF 2400 w-hr DURING PEAK PERIOD
5. 200 w RTG AT 2 w/lb WILL WEIGH 100 lb, 800 w-hr BATTERY PACK AT 20 w-hr/lb WILL WEIGH 40 lb
TOTAL WEIGHT = 100 + 40 = 140 lb

Fig. 2.A Hybrid system weight analysis

Fig. 2-B

that, for any given mission, RTG feasibility is possible only when the interrelationships of the interface matrix are in a state of equilibrium; that is, the ultimate RTG size and weight, after meeting all of the interface constraints, equals the size and weight allowance provided by the mission spacecraft.

Interface equilibrium cannot be achieved by common analytical processes; the matrix of all possible design and constraint variations is, for all practical purposes, infinite. RTG feasibility analysis and sizing can be achieved only through the translation of all interrelationships into parametric form.

The starting point for the analysis is thus a program of the following form:

(1) Determine the total program of information necessary to derive the required parametric relationships.

(2) Collect and assess the total information available.

(3) Determine the information remaining to be obtained.

A full program of parametric relationships is necessary not only for RTG sizing, but also for indicating the major design problem areas, such as radiation and thermal shielding, impact attenuating features, structural supports, etc. An understanding of those interface constraints whose limitations result in the greatest design size and weight penalties will make possible their isolation for purposes of special attention and development.

For practical utilization of the matrix of Fig. 1, numbers should be assigned to the blocks of the mission power source requirements. A thermoelectric material is then selected, and a design envelope of element sizing, number of elements, packing density, and operating temperature calculated. Numbers are next assigned to the generator oriented constraint blocks, and a check made to see that the numbers assigned to the thermoelectric module parameters do not exceed these figures.

Assignment of numbers should then be made to all of the blocks in the matrix. Wherever possible, the numbers should reflect measured hardware data; where no numbers are available, best estimates should be used for an initial rough cut. One of the functions of the matrix is to point out those areas where data is either nonexistent, or at best, rather sparse.

If any of the numbers within the matrix exceed the values assigned to the system or generator-oriented constraints, new iterations must be made with respect to the thermoelectric module, the heat source, or the heat exchanger design to bring the matrix back to equilibrium.

Thermal analysis provides an excellent example of the use of the matrix. Five blocks directly interrelated in this area are:

(1) Temperature Range (thermoelectric design).

(2) Temperature Limitations (generator-oriented constraint).

(3) Radiator Temperature (affected by mission environment).

(4) Thermal Tolerance Level (system-oriented constraint).

(5) Fuel Capsule Temperature Limit (safety-oriented constraint).

The selected thermoelectric hot junction temperature of item number 1 must be consistent with the numbers selected for the other four items. If, for example, the hot junction temperature exceeds the allowable fuel capsule temperature limit, the feedback process requires that new numbers be placed into the matrix. Either the module design temperature should be lowered, or a different capsule technology, reflected by a higher temperature capability, should be considered. The former may, in turn, require the selection of a new thermoelectric material, and hence, new parametric numbers for the matrix. The latter may require different fuels, and hence, new parametric numbers for the safety-oriented constraints.

VIII. Hybrid Systems

The integration and feedback technique required for RTG sizing and analysis becomes further complicated when considering shifts from a pure RTG power source to a hybrid system containing an RTG for continuous power and a battery package for short duration peak power. The benefits of such a system are indicated in Fig. 2, where certain basic assumptions are made for a battery recharging rate and for an RTG power-to-weight ratio. Figure 2, however, includes only electrical power characteristics, and does not factor in such important considerations as power conditioning, trickle charging circuitry, and structural packaging necessary to put together a hybrid unit. The mission power profile requirements should serve as a guideline in determining the trade-offs between pure RTG and hybrid systems.

Figure 2 illustrates the potential weight savings for a series of hybrid power systems sized from 50 w to 500 w peak power. The curves indicate that the shorter the duration of peak power requirement, the greater the potential weight savings for the system. This results from longer battery charging periods, hence the use of lower nominal power RTGs.

Two other significant relationships are indicated by Fig. 2. The first is that the lower the peak power requirement, the less the savings in weight by using a hybrid system; and second, the greater the ratio of nominal power required to peak power, the less the savings in weight by using a hybrid system. Thus, there exist power requirement limitations below which the power systems engineer must analyze very carefully the tradeoff between limited weight savings with a hybrid system and the reliability uncertainties involved with such a system.

Figure 2 indicates that for high power requirements of over 200 w, hybrid systems can produce as much as 10 w/lb of power system if the power profile requires a peak power at least 10 times greater than the nominal power, and for only 10% or less of the cycle duration.

IX. Parametric Relationships

Basic parametric relationships are easily established in the area of thermoelectric module design. For any given thermoelectric material (a variable itself), the following relationships can be constructed:

(1) Thermoelectric characteristics (Seebeck coefficient, electrical resistivity and thermal conductivity) as a function of temperature. These curves are available from the producers of thermoelectric material, and can be submitted to computer programming to translate the characteristics from functions of temperature levels to functions of temperature ranges (or differentials).

(2) Open circuit voltage as a function of temperature range (differential).

(3) Material efficiency as a function of temperature differential.

The module sizing process, although for exact analysis requiring a knowledge of all the assembly artifacts such as insulations, expansion compensators, etc., where needed, can be roughly determined from the following:

(4) Packing density as a function of element geometry and size.

(5) Thermoelectric array size and weight as a function of element packing density.

(6) Thermoelectric array size and weight as a function of the number of couples.

(7) Thermoelectric couple size and weight as a function of element sizing.

Since power output of thermoelectric couples is related to the electrical resistivity, and electrical resistivity to temperature and geometry, the following relationships should be considered for varying temperature differentials for a specific material:

(8) Power output as a function of element geometry.

(9) Output voltage as a function of the number of couples.

(10) Module specific power (w/lb) as a function of element packing density.

The following relationships indicate the extent to which mission requirements affect thermoelectric device performance. The inputs provide the basis for sizing iterations:

(11) The effect of long life on voltage degradation (diffusion effects).

(12) The effect of long life on current degradation (time versus resistance increase).

(13) The effect of thermal cycling on current degradation (thermal cycling versus resistance increase).

(14) Reliability as a function of the number of couples and their series-parallel arraying.

(15) Reliability as a function of element sizing.

(16) Reliability as a function of stress and temperature levels.

(17) Reliability as a function of fabrication techniques.

(18) Junction temperature changes as a function of load variations.

The thermoelectric device, unfortunately, is not without limitations; and the inputs required for module sizing must be compared with the generator's capabilities and limits being fed back into the integration analysis when design discrepancies occur. Parametric relationships 11, 12, and 13 are strong examples of important feedback areas. Other limiting relationships are:

(19) Effect of impact loads on thermoelectric power output.

(20) Impact strength as a function of element sizing and geometry.

(21) Impact strength as a function of element packing density.

(22) Module size trade-off as a function of impact resistance gain, for each specific attenuating feature.

(23) Thermoelectric module weight trade-off as a function of impact attenuating gain, for each specific attenuating feature.

At present, parametric information on impact strength and impact attenuating features such as resilient packing material, structural insulations, and couple supporting devices is almost non-existent. A testing program to obtain the information would include a series of impact tests starting at a nominal level of 100 g and increasing by 100 g increments, each test including thermoelectric couples of three or more geometries, mounted in all four directional orientations.

The result of system-oriented constraints is manifested in two ways: (1) directly increasing RTG size and weight in such areas as thermal shielding and radiation shielding, and (2) indirectly influencing RTG size and weight by affecting the thermoelectric module temperature range. Parametric relationships to be determined include:

(24) Types and amounts of science and electronics onboard as a function of mission requirement.

(25) Radiation tolerance levels of science and electronics.

(26) Type and amount of radiation as a function of isotope quantity, for each isotope and fuel form.

(27) Quantity of isotope fuel required (fuel inventory) as a function of mission power requirement.

(28) Thickness and amount of shielding material required as a function of attenuating effect, for given fuel inventories of each isotope and fuel form.

(29) Separation distance required between isotope fuel and target as a function of attenuating effect.

(30) Structural weight as a function of separation distance.

The dependence of the above relationships on reliable isotope data inputs demands consistent integration of the system-oriented and safety oriented constraints. The radiation tolerance level of spacecraft science and electronics may be the limiting factor in isotope selection. The availability affects not only the isotope and fuel form, but also the half-life, power profile, and equipment necessary for power flattening, if a short half-life isotope is selected.

Two complications exist in attempting to parametrically analyze the radiation relationships and problems. The first is that selective or shadow shielding may be possible. In place of a total system radiation shielding envelope, the more sensitive electronics and science components may be individually shielded, the weight penalty for small component shielding being far less. In addition, no clear cut definition of radiation damage has yet been established. The possibility exists that some components, such as semiconductors, although "damaged", by current usage terminology, may still function at levels sufficient for acceptable performance for the mission duration.

The size and weight penalties paid for the use of thermal insulations may be directly traceable to the thermoelectric module design and the fuel loading technique. Some parametric considerations are:

(31) Surface area of inter-couple insulation as a function of couple packing density.

(32) Surface area of flat plate-RTG insulation (which is approximately equal to the area of the housing) as a function of power level.

(33) Thickness of insulation as a function of temperature drop (for heat fluxes from 0.1 to 10 $w/in.^2$), for each insulation.

The final area of parametric consideration, thermal interfaces, touches all facets of RTG integration analysis. Variations in thermal ambient conditions due to mission requirements such as sterilization, launch, entry, and planetary or lunar day-night cycling result in changes in temperature throughout the RTG. External barriers to the rejection of RTG heat, such as sterilization shrouds and high entry velocity frictional heating, result initially in increasing the radiator temperature. The limiting allowance in thermal ambient variation occurs when an excessive radiator temperature rise is reflected by a hot junction temperature rise to the point where thermoelectric module failure occurs.

Compensation for temperature variations requires not only an analysis of radiator sizing to meet the heat transfer requirements, but also a reevaluation of the thermoelectric module design based on the potential fluctuations in heat flux.

RTGs may be reduced to three basic elements: the heat source, the thermoelectric module, and the heat exchanger. Assuming an ideal case, all of the isotope-generated heat passes into the thermoelectric array and, with the exception of that portion converted to electricity, is rejected at the module cold junction, T_c. For design purposes, the hot junction, T_h, is considered a constant.

If the amount of heat from the isotope is Q, and the thermoelectric power output of the module is P_0, the thermal energy left for rejection by the radiator is $Q - P_0$. By the Stefan-Boltzmann law this heat rejection, per unit of radiating surface is:

$$\frac{Q - P_0}{A} = \varepsilon \, \sigma \, T^4$$

where:

ε = thermal emissivity of radiator, dimensionless

σ = Stefan-Boltzmann constant, 5.67×10^{-12} w/cm² °K⁴

T = radiating surface temperature, °K

A = radiating surface area, cm²

and the power output of the RTG per unit radiating surface area is shown by

$$\frac{P_0}{A} = \eta \frac{Q}{A}$$

where:

η = overall RTG efficiency, %

and

$$Q = A\varepsilon\sigma T_c^4 + P_0$$

Combining terms,

$$Q - P_0 = \frac{P_0}{\eta} - P_0 = P_0 \left(\frac{1}{\eta} - 1\right)$$

However,

$$Q - P_0 = A\varepsilon\sigma T_c^4$$

and

$$\frac{P_0}{A} = \frac{\eta}{1 - \eta}\left(\varepsilon\sigma T_c^4\right)$$

The above equation indicates that the power output of an RTG per unit radiating surface area is proportional to the fourth power of the radiator surface temperature, and roughly proportional to the RTG efficiency if it is small (approximately 10% or less).

Unfortunately, two opposing effects are dependent upon the radiator temperature. Increasing the radiator temperature (T_c) increases the heat rejection rate, and to a point, the power output per unit radiating surface area. On the other hand, increasing T_c while T_h remains constant decreases the voltage, power, and efficiency of the thermoelectric module. This is not to imply that a change in a radiator temperature will not be reflected by a change in hot junction temperature for an operating device; it will, since the nuclear heat source is a constant heat flux rather than a constant temperature device. This is mentioned only to point out that once a hot junction design temperature has been selected, the designer is limited in his selection of a cold junction temperature to a trade-off optimization between module performance and radiator size and weight.

The relationship between efficiency and radiator temperature is virtually inversely linear. By combining the various effects, the relationship between power output per unit radiating surface area and efficiency can be established. Other parametric curves involved with radiator sizing include:

(34) Radiator surface area as a function of radiator temperature, per given power output.

(35) Radiator weight as a function of surface area, per given material and thickness.

(36) Radiator size and weight as a function of surface area, per given radiator geometry.

X. Conclusion

The end result of the total system analysis should be the assignment of size and weight numbers to all of the components that make up the RTG. This should be done not on the basis of absolute component capability, but on the basis of relative component capability in concert with all other components. Confidence in RTG sizing will be upheld only when data is available to substantiate these numbers.

One word of caution is in order here, and that is that not all factors in RTG sizing lend themselves to parametric translations. Many of the AEC safety requirements, such as controlled intact reentry, may result in hardware additions of retro-rocket blow-off mechanisms, recovery aids, ablation shields, or stabilization fins, whose weights, at best, can only be estimated. The same is true with RTG modularizing, locating, and orienting, where spin or three-axis stabilization requirements are not readily determinable on a parametric basis.

Appended to this document is a glossary of common thermoelectric definitions and symbols to be used as a reference in examining the available thermoelectric literature.

Appendix

Thermoelectric Definitions

I. Thermoelectric Material Effects and Parameters

A. Seebeck Effect

The generation of an EMF resulting from a difference in temperature between the junctions of a circuit composed of two homogeneous conductors of dissimilar composition.

B. Seebeck EMF

(Also called *Seebeck voltage, thermal voltage, open circuit voltage.*) The EMF resulting from the Seebeck effect; the product of the Seebeck coefficient and the temperature difference between the circuit junctions, in volts.

C. Seebeck Coefficient

An algebraic factor indicating the proclivity of a given material to produce an EMF at any given temperature, in μv/°C.

1. Absolute. The integral, from absolute zero to the given temperature, of the quotient of the Thompson coefficient of the material divided by the absolute temperature.

2. Relative. The coefficient of a couple composed of a given material and a specified standard material, such as platinum or copper.

3. Of a couple. The algebraic difference of either the relative or absolute Seebeck coefficients of the two conductors.

D. Peltier Effect

In a circuit composed of two dissimilar conductors carrying current, the evolution of heat at one junction of the circuit and absorption of heat at the other junction.

E. Peltier Heat

The thermal energy absorbed or evolved as a result of changes in the current in the circuit (and, hence, in the Peltier effect).

F. Joule Effect

The creation of thermal energy in a current-carrying conductor resulting from the Joule effect.

G. Joule Heat

The thermal energy resulting from the Joule effect.

H. Figure-of-Merit of a Thermoelectric Material

An algebraic factor indicating the proclivity of a thermoelectric material for converting heat into electricity; algebraically, the quotient of the square of the absolute Seebeck coefficient and the product of the electrical resistivity and the thermal conductivity, in dimensionless units/°C or °K.

I. Figure-of-Merit of a Thermoelectric Couple

An algebraic factor indicating the proclivity of a thermoelectric couple, composed of an N-type and P-type leg of specific materials, for converting thermal energy into electrical energy. Algebraically, equal to

$$\alpha^2 \, [(\rho_1 k_1)^{1/2} + (\rho_2 k_2)^{1/2}]^{-2}$$

J. Figure-of-Merit of a Thermoelectric Couple, Ideal

Essentially the same as above, but average values are used in the equation, the averages being obtained by integrating the parameters over the operating temperature range of the couple.

II. Performance Criteria

A. Power Output

The rate of electrical energy produced by a thermoelectric device, w.

B. Efficiency

A performance factor equal to some specific output quantity divided by a specific input quantity, in percent.

1. Overall generator. The ratio of electrical power output to total consumed thermal input.

2. Module. The ratio of electrical power output of a thermoelectrical set to its utilized thermal power input.

3. Carnot. The ideal thermal efficiency of a heat engine, equal to $(T_h - T_c)/T_h$.

C. Specific Power

The ratio of electrical power output of a thermoelectric device to its weight, w/lb.

D. Voltage

1. Open circuit. The generated Seebeck voltage measured across the unloaded, open terminals of a thermoelectric device, v.

2. Load voltage. The voltage drop measured across the terminals of a device with a current flowing.

3. Matched load voltage. The voltage drop measured across the terminals of a thermoelectric device when the resistance of the current-causing load is exactly equal to the internal resistance of the device.

E. Current

1. Load. The dc current flowing through a thermoelectric device when the generated voltage is impressed across a given resistive load.

2. Short circuit. The dc current flowing through a thermoelectric device when its output terminals are short circuited.

F. Internal Resistance

The total resistance of the thermoelectric circuit of a thermoelectric device, measured between the output terminals, and including the thermoelectrical materials, the electrical connectors, and the thermoelectric couple contacts.

G. Contact Resistance

The resistance measured across the interface where the thermoelectric material is contacted to a shoe.

H. Degradation

The ratio of the change in a measured electrical parameter at any given time to the initially measured electrical parameter, measured consistently at operating temperature or at ambient temperature, in percent. The change will be an increase for internal resistance, and a decrease for current or voltage.

I. Failure

The occurrence of a complete open within the thermoelectric circuit, a complete short between the terminals within the circuit, or degradation to some preestablished level.

III. Thermoelectric Hardware — Heat Sources

A. Heat Source

Any source of thermal energy to be converted into electrical energy, such as solar energy, fossil fuels, nuclear reactors, etc.

B. Heat Transfer Mode

The means by which energy from the heat source is transmitted to the thermoelectric set.

1. Thermal conduction. The transmission of heat from one part of a body to another part of the same body, or from one body to another in physical contact with it, without displacement of particles of the body, and at a rate proportional to the temperature gradient of the body.

2. Thermal convection. The transfer of heat from one region to another within a gas or liquid by the mixing of one portion of the fluid with another.

3. Thermal radiation. The transfer of heat by the emission of radiant energy from one body and the absorption of that energy by another body of lower temperature.

C. Heat Input

The total thermal power delivered by a given quantity of a heat source.

D. Useful Heat Input

The total thermal power actually absorbed by a thermoelectric set.

E. Temperature

1. Hot junction. The temperature, in degrees centigrade, at the contact interface between the thermoelectric material and the hot shoe.

2. Hot side. The temperature, in degrees centigrade, measured in the region of the hot junction, such as at the hot shoe or in the thermoelectric element, but not actually at the hot junction.

3. Hot wall. The temperature, in degrees centigrade, measured at the surface of the hot wall facing the thermoelectric set.

F. Hot Wall

The device component sandwiched in between the heat source and the thermoelectric set for the specific purpose of receiving heat from the source and transferring it, either by conduction or radiation, to the thermoelectric set.

G. Hot Frame

The structural member, surrounding or adjacent to the heat source, used to support the thermoelectric set on the hot side.

H. Hot Side

Any section of a thermoelectric device which includes any or all components from, and including, the hot junction to the center or centerline of the heat source.

I. Hot Junction

The contact interface plane between the thermoelectric material and the hot shoe of a thermoelectric device.

IV. Thermoelectric Hardware — Thermoelectric Assemblies

A. Hot Shoe

(Also called *contact, cap, electrode, connector.*) The electrically conducting member, either metallurgically or mechanically in contact with the hot side of a thermoelectric element, to which an electrical connection may be made with an adjacent member to form a portion or all of a thermoelectric circuit.

B. Thermoelectric Element

(Also called *pellet.*) An uncontacted piece of processed thermoelectric material fabricated into a definite geometrical configuration.

C. Thermoelectric Leg

(Also called *member.*) A thermoelectric element which has been contacted on both the hot and cold ends; the main component of a thermoelectric couple.

D. Thermoelectric Couple

An electrically connected pair of thermoelectric legs, one P doped and one N doped.

E. P-Leg

A thermoelectric leg made from thermoelectric material with P dopant added.

F. N-Leg

A thermoelectric leg made from thermoelectric material with N dopant added.

G. Thermoelectric Set

Any general array of interconnected thermoelectric legs, couples, or modules.

H. Thermoelectric Module

A structurally sound and fully assembled array of two or more thermoelectric couples.

I. Thermoelectric Generator

A complete thermoelectric power package, with operational capability, including the heat source, the thermoelectric array, and the heat exchanger.

J. Thermoelectric Device

Any thermoelectric hardware, from a couple to a generator.

K. Insulation

1. Electrical. The dielectric material used to prevent individual thermoelectric couples in a circuit from electrically shorting with each other when the thermoelectric set is in contact with an electrically conducting common hot or cold wall.

2. Thermal. Material of low thermal conductivity used to prevent thermal energy from the heat source from bypassing the thermoelectric set.

L. Cascading

Aligning two or more thermoelectric devices thermally in series, with the cold side of the first stage device, the hot side of the second stage device, etc.

M. Segmenting

The fabrication of a thermoelectric leg with two or more distinct and finite regions between the hot and cold junctions having either different compositions or dopant levels.

V. Thermoelectric Hardware—Heat Rejection

A. Heat Exchanger

The heat transfer mechanism for removing heat from a thermoelectric generator, including radiator fins, convection fins, and liquid metal loops.

B. Cold Wall

A device component sandwiched between the cold side of the thermoelectric set and the heat exchanger.

C. Cold Strap

(Also called *cold connector, bridge.*) A metallic thermoelectric circuit member electrically connecting adjacent N or P thermoelectric legs.

D. Cold Shoe

(Also called *contact, cap, electrode, connector.*) The electrically conducting member, either metallurgically or mechanically in contact with the cold side of a thermoelectric element, to which an electrical connection may be made with an adjacent member to form a thermoelectric circuit.

E. Cold Frame

The structural member, internal to or adjacent to the heat exchanger, used to support the thermoelectric set on the cold side.

F. Cold Side

Any section of a thermoelectric device which includes any or all components from, and including, the cold junction to the extremities of the heat exchanger.

G. Cold Junction

The contact interface plane between the thermoelectric material and the cold shoe of a thermoelectric device.

H. Fin Efficiency

A decimal number indication of the potential of a heat exchanger fin to maintain a uniform temperature along its length.

I. Effective Radiating Area

The area of a prismatic surface just enclosing a finned generator with its fin length reduced by the fin efficiency.

J. Temperature

1. Root. The temperature of a radiating fin at its base, °C.

2. Radiator temperature. The average temperature, measured in degrees Centigrade, of the radiating fin.

3. Cold side. The temperature, °C, in the region of the cold junction, such as at the cold shoe or in the thermoelectric leg, but not actually at the cold junction.

4. Cold junction. The temperature, °C, at the contact interface between the thermoelectric material and the hot shoe.

VI. Nuclear Applications

A. RTG

Radioisotope Thermoelectric Generator.

B. SNAP

Systems for Nuclear Auxiliary Power.

C. Radioisotope

Radioactive isotope of an element.

D. Half-Life

The time period required for disintegration of one-half the atoms of a radioisotope.

E. Alpha Emitter

A radioisotope whose decay results in a preponderance of alpha particle radiation, which, because of its large mass and ionized state, needs relatively minor shielding.

F. Beta Emitter

A radioisotope whose decay results in the simultaneous emission of an electron and a neutrino, with the sum of the energies of the two emissions being equal to the total beta decay energy for that particular transition.

G. Gamma Emitter

A radioisotope whose decay leaves the product nucleus in an unstable energy level, subsequently decaying to the ground state with the emission of one or more photons.

H. Tolerable Radiation Level

The level of radiation which will be harmful, if exceeded, to personnel, electronics, and scientific experimentation associated with the nuclear-fueled generator.

I. Shielding

The requirement for reduction of raw nuclear radiation to acceptable levels through the use of radiation attenuation materials placed between the nuclear source and vulnerable targets.

J. Shadow Shielding

The use of partial radiation shielding to protect only those areas of extreme radiation sensitivity.

K. Fuel Capsule

The sheath or enclosure within which the radioisotopic fuel is contained.

L. Fuel Form

The chemical compound and/or the physical condition of a radioisotopic fuel.

M. Intact Reentry

The nuclear safety philosophy which requires complete containment or retention of nuclear fuels following reentry of a generator into the earth's atmosphere and onto the earth's surface.

N. Burn-up Reentry

The nuclear safety philosophy which requires the consumption of nuclear fuels by aerodynamic heating and subsequent product dispersion due to atmospheric reentry of a generator.

O. Fuel Inventory

The quantity of nuclear fuel in a generator, in curies.

P. Power Flattening

The technique of maintaining a constant electrical power output from an RTG fueled by a nuclear heat source with a relatively short half-life.

Q. Power Density

The amount of thermal power produced per unit volume of radioisotope, w/cm^3.

R. Specific Power

The amount of thermal power produced per unit mass of radioisotope, w/g.

VII. Mission and Application Considerations

A. Mission

A preplanned and fully integrated space program or project in which performance of the power source is only a portion of the total objective.

B. Application (as opposed to a *mission*)

A space project whose primary objective is performance of the power source; or any terrestrial program or project using an auxiliary power source, but whose objective is the production of electrical power for specific reasons.

C. Beginning of Life

The initial time, during a mission or application, when the thermoelectric generator first reaches design temperature or becomes operational.

D. End of Life

The point in time when the mission or application for which the thermoelectric generator was intended is ended, even though the generator itself may still be functioning.

E. Power Profile

The pattern of power level (w) and power duration (hours) requirements for a given time period.

F. Reliability

The statistical expectation for a complete thermoelectric power system to meet performance specifications for a full mission or application duration.

G. Mission Environment

1. Hard impact. The requirement for an RTG to survive an impact of over 1000 g at greater than 150 ft/sec velocity.

2. Orientation. The direction of the radiator fins of an RTG relative to a clear view of space and any obstructions to that view.

3. *Atmosphere.* The pressure, temperature, and fluid velocity external to the RTG at any given time after beginning of life.

H. Heat Sterilization

The requirement that the RTG be enclosed in a hermetically sealed shroud in which the ambient temperature will be held at some discrete temperature for a preplanned period of hours until all contaminating organisms have been thermally destroyed.

I. Interface Constraints

In a mission context, the design limitations with which the RTG must live with to be fully compatible electrically, thermally, volumetrically, weight-wise, and radiation-wise with the payload, the spacecraft, and the ultimate mission objectives.

Nomenclature

- α relative Seebeck coefficient for a couple composed of legs P and N
- π relative Peltier coefficient for a couple composed of legs P and N
- ρ resistivity, Ω-cm
- R resistance, Ω
- k thermal conductivity, w/cm °C
- K thermal conductance, w/°C
- V voltage, v
- I current, amp
- T temperature, °C
- ΔT temperature difference between the hot and cold junctions
- P electrical power, w
- Q quantity of heat, w
- η efficiency, %
- Z figure-of-merit of a thermoelectric material
- P' specific power, w/lb
- E energy, w/hr
- t time (hr, day, etc.)
- w weight, (g, lb)
- l/A length over area ratio, cm^{-1}

Subscripts

- a available (Q_a, E_a)
- c cold junction (T_c)
- ca carnot (N_{ca})
- cs cold side (T_{cs})
- co couple (V_{co}, R_{co}, N_{co}, w_{co})
- e electrical (Kw_e, E_e)
- f final (t_f, R_f, N_f)
- in internal (R_{in}, V_{in})
- i initial (T_i, R_i, N_i)
- j joule (Q_j)
- l load (V_l, I_l, R_l)
- hs hot side (T_{hs})
- h hot junction (T_h)
- n N-leg (V_n, R_n, W_n, l/A_n)
- oc open circuit (V_{oc})
- o output (P_o)
- p P-leg (V_p, R_p, w_p, l/A_p, α_p, k_p)
- sc short circuit (I_{sc})
- t thermal (Kw_t, E_t)
- r relative (α_r)
- m module (η_m)
- ml matched load (R_{ml}, V_{ml})
- x loss (Q_x, P_x)
- Σ total, overall (Q , P , η)