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Radioisotope Power Systems

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INTRODUCTION

Generally, radioisotope power systems are attractive for space applications with electrical power requirements up to approximately 30 KW. Battery, fuel cell, chemical dynamic, photovoltaic and radioisotope systems, and certain combinations of these, are all competing power generation techniques that might logically be considered for a specific space mission with power requirements in this range. If mission duration is in excess of several months, considerations usually dictate a photovoltaic or radioisotope system, the selection depending on mission length and operating environment. Selection of a photovoltaic system implies provision for a solar array, a deployment and orientation mechanism, and an energy storage system (usually battery). For deep space probes, where the solar flux is greatly decreased, or planetary landings, where atmospheric conditions and diurnal cycling affect the available sunlight, a radioisotope system is the most attractive means of power generation.

Radioisotope power systems are differentiated from reactor space power systems which may employ similar energy conversion devices in that, in the former, thermal energy is derived from the naturally occurring decay of a radioisotope. Under the present SNAP (Systems for Nuclear Auxiliary Power) designation system, radioisotope power systems are assigned odd-numbered values (e.g., SNAP 19 and SNAP 27), and reactor systems are assigned even-numbered values (e.g., SNAP 8 and SNAP 10).

SCOPE - The scope of this report is limited to a discussion of candidate radioisotope power systems which are presently in varying stages of development, and is oriented principally towards aerospace applications.

1. SYSTEM CONFIGURATION

- 1.1 **Overall Description:** In a radioisotope system, decay heat from a radioisotope is converted into electricity by means of a static or dynamic energy conversion system. Figure 1 is a schematic of a typical radioisotope power system and depicts the major subsystems. These include:

- (1) Radioisotope heat source
- (2) Energy conversion subsystem
- (3) Space radiator
- (4) Power-flattening device.

The first three subsystems are characteristic of all radioisotope power systems; the last subsystem is necessary only when the mission duration is a substantial fraction of the half-life of the radioisotope fuel selected for the heat source. Operation of the system is as follows: The thermal energy generated in the heat source by the decay of the radioisotope is introduced into the energy conversion subsystem from the heat source. In the energy conversion subsystem, a portion of the input heat is converted to electrical energy by either a direct conversion process (i.e., thermoelectric and thermionic systems) or dynamic conversion process (i.e., Rankine and Brayton cycle systems). The unconverted heat is transported from the energy conversion subsystem to the space radiator and then rejected to the environment.

If a short half-life radioisotope is utilized in the heat source, excess fuel must be provided at the beginning of the mission to assure that sufficient thermal energy is available at the end of the mission. For example, when polonium-210 (138-day half-life) is employed as the radioisotope, radioactive decay reduces the initial thermal output by one-half after 138 days of the mission. Some means of controlling the thermal input to the energy conversion system must be provided to prevent an overtemperature of the energy conversion system and heat source at the beginning of the mission. To date, this has been accomplished most effectively by allowing the heat source to radiate this heat directly to space through movable shutters which are controlled by a sensor at a critical temperature location.

Currently, only thermoelectric systems have been extensively developed for use with radioisotope heat sources and practically applied to space missions. These efforts have culminated in numerous terrestrial and space-oriented systems. Development of radioisotope-powered thermionic systems has been embodied primarily in the SNAP 13 program which is currently inactive. Development of Brayton and Rankine cycle systems for use with radioisotope heat sources is currently in progress.

Generally, the efficiency of radioisotope power systems range from 4 to 8 per cent for a thermoelectric system to potentially 20 to 25 per cent for Brayton and Rankine cycle systems with thermionic systems in the intermediate range of potentially 10 to 15 per cent. (The term "potentially" is used since no extensive system data are available for these latter systems.) Typical current "flight-qualified" radioisotope thermoelectric space power systems have specific powers of approximately 1-watt per pound and system efficiencies near 5 per cent.

- 1.2 **Radioisotope Heat Source:** The primary requirements for the radioisotope heat source are that:

- (1) It provide a surface for heat input to the power conversion subsystem
- (2) The half-life of the radioisotope be compatible with the intended mission length
- (3) Mating components be chemically compatible at the anticipated operational temperatures
- (4) The launch and aerospace nuclear safety requirements are satisfied.

The radioisotope heat source contains a naturally decaying radioisotope fuel. This heat source is completely static and requires no control mechanism since the thermal output of the fuel is self-regulating, decreasing exponentially with time. Thus, the output at any time can be precisely determined if the output at a former time t_1 is known using the relation

$$P(t) = P(t_i)e^{-\lambda t}$$

where:

$P(t)$ = power at time t

$P(t_i)$ = power at some former time

λ = disintegration constant = $\frac{0.693}{T_{1/2}}$

$T_{1/2}$ = half-life of radioisotope

t = time since $P(t_i)$ was determined.

From this equation it is evident that the power available (and quantity of radioisotope present) with time depends on the half-life of the radioisotope chosen as the fuel. Ideally, it is desirable to select a radioisotope with a half-life of such length that during the mission the reduction in fuel thermal power is negligible, thus eliminating the complexity of a thermal control device. However, radioisotope availability, nuclear safety requirements and cost must be considered in fuel selection. Presently, plutonium-238 ($T_{1/2} = 87$ years) has been considered primarily for space-oriented systems with missions of 1 year and greater, while curium-242 ($T_{1/2} = 163$ days) and polonium-210 ($T_{1/2} = 138$ days) have shown feasibility for missions up to approximately four months.

- 1.2.1 **Nuclear Radiations:** Present emphasis in radioisotope power generation is on utilizing the decay energy in a heat engine. The energy from a radioisotope initially appears as motion of the emitted alpha or beta particle, or as the energy of gamma photons. The slowing down and/or absorption of these radiations causes an increase in the temperature of the surrounding material and, in some cases, secondary radiations are produced. Any radiation which is not absorbed to produce heat will become unavailable for use in the heat engine.

Alpha (α) particles (helium nuclei) have a comparatively large mass and a high positive electrical charge. This means that a high energy alpha particle (all important alpha emitters produce about 5 Mev per disintegration) will have a relatively low velocity, and because of its charge, interacts strongly with other matter; it will be thermalized in a few hundredths of a millimeter of solid material. Thus, for all practical purposes the thermal energy of an alpha emitter is produced within the decaying material. In some cases gamma radiation is also emitted and carries a small portion of the decay energy. The absorption of an alpha particle in a light-element nucleus can produce secondary neutrons, but this usually represents a radiation hazard rather than a large energy loss. Some alpha emitting materials also undergo a small amount of spontaneous fission, but for practical purposes this has no effect on the heat production rate with the radioisotopes usually considered for power production. It can, however, lead to high neutron fluxes that present a biological hazard.

Alpha particles are helium nuclei, consequently when they have lost the kinetic energy associated with decay, they will capture free electrons and form helium atoms. This helium appears as a free gas in the fuel container and may either be contained in the fuel encapsulation or vented to prevent pressure buildup.

Beta (β) particles (electrons) of the energy associated with fuels used in radioisotope power systems will penetrate one to three millimeters of solid material and, hence, for practical purposes will not escape the fuel container. However, in the process of slowing down these particles, high energy electromagnetic radiation known as bremsstrahlung is produced. This radiation, identical to gamma radiation, can contribute about 1% heat loss since the photons produced can have energies ranging up to that of the beta particle. Of more seriousness is the biological shielding problem associated with the bremsstrahlung. Bremsstrahlung production is approximately proportional to the square of the atomic number of the beta absorber and, consequently, can be minimized if beta particles are not allowed to interact with high atomic number materials. The isotopes which have low beta energies (<1 Mev) produce the least-penetrating bremsstrahlung, but have corresponding low power densities.

There are no radioisotopes that decay by pure gamma emission that are of interest for space missions due to the biological shielding problem and the weight of the absorbing material required to capture the energy of the gamma for generation of thermal energy.

From the above discussion it is seen that alpha emitting radioisotopes are generally the most attractive for space applications considering their relatively low biological shielding requirements and their high energy density. They are unattractive from the standpoint of helium gas generation, which presents high-temperature pressure-containment problems unless venting devices are provided.

1.2.2 Isotope Selection: A number of criteria must be considered in selecting a radioisotope fuel. These include:

- (1) Power Density - The power density required for a particular heat engine is dictated in part by the engine characteristics. For example, a thermionic power system is characterized by high temperatures and high heat fluxes, thus, a high power density fuel is desirable. For a thermoelectric power system, which operates at a considerably lower heat flux, a lower power density fuel is acceptable. An upper limit on permissible power density exists due to fuel-handling and capsule-area considerations.
- (2) Half-life - By definition, the half-life of a radioisotope is the time period in which exactly half of the material decays. An electrical power supply is usually required to produce power at a relatively constant rate during its lifetime. To accomplish this with no thermal control technique requires that the heat source decay no more than 10 to 20%. If thermal control techniques, such as shutters, are employed to allow heat rejection directly from the heat source, mission times up to about one half-life are feasible. The mission length requirement consequently dictates the minimum permissible fuel half-life.
- (3) Fuel Availability - It is sufficient to mention that fuel quantities are limited and this parameter becomes important in the selection of the radioisotope.
- (4) External Nuclear Radiation - In general, the lower the external radiation, the more attractive is the particular radioisotope fuel. As discussed previously, this consideration makes alpha emitting fuels particularly attractive. Shielding considerations are discussed later in this report.
- (5) Radioisotope Cost - Generally, the alpha emitting fuels are relatively expensive, and the fuel cost will exceed that of the remainder of the power system. Thus, a high conversion efficiency is imperative. Depending on the particular mission, the over-all program cost (launch vehicle, payload, etc.) may decrease if a heavier power system design results in a sizeable system efficiency advantage. Beta emitters are generally less expensive, and fuel cost in comparison to power system cost is not as critical. Beta emitters have been primarily limited to terrestrial applications where the heavy radiation shielding required is not as penalizing as for a space application.
- (6) Radiological Effects - For space missions, the usefulness of a radioisotope is directly influenced by the consequences of fuel release and by the measures that must be taken so that potential hazards are reduced to acceptable proportions. These effects are determined by detailed nuclear safety studies which determine the hazard associated with a particular fuel.
- (7) Fuel Forms and Technology - The fuel forms in all presently considered space systems have been limited to the solid state to minimize corrosion problems with containment internals. Consequently, the fuel form melting point becomes an important consideration for high temperature power systems. Also, the fuel form directly affects the biological and radiation hazard of the radioisotope since it usually characterizes seawater solubility and secondary radiations.

- 1.2.3 Heat Source Design: The specific fuel encapsulation requirements are dependent on the radioisotope selected and heat source operating temperatures characteristic of the power system. Generally, it is necessary that the isotope be sealed in a noncontaminated container which is structurally adequate to contain the fuel during normal operation and specified credible accidents. Although varying with specific missions, these credible accident conditions usually encompass shipping, launch pad explosions and mission aborts. Additionally, the encapsulation must be chemically compatible with the isotope fuel and possible abort environments. If an alpha emitting radioisotope is used it may also be necessary to contain the helium pressure buildup within the sealed capsule.

Generally, in a radioisotope heat source the fuel is contained within a liner that has demonstrated chemical compatibility with it (see Fig. 2). The liner and fuel are contained within a primary capsule which functions as the strength member for pressure containment (if required) and land impact. If the primary capsule material is subject to oxidation, it is usually contained within a corrosion barrier. This complete capsule assembly is then fitted into a heat accumulator block (typically graphite) which may provide protection against reentry heating.

- 1.3 Energy Conversion Subsystem: Although many types of energy conversion subsystems can be coupled with a radioisotope heat source, thermoelectric, thermionic, Rankine cycle and Brayton cycle- types are presently considered to be the most attractive for foreseeable space applications. The first two types are considered to be "direct conversion" subsystems in that the thermal input to the conversion device is converted directly into electrical energy without intermediate conversion steps. The latter two types employ turbo-alternators for power generation and are generally referred to as "dynamic conversion" subsystems.

At present, thermoelectric subsystems are the most fully developed of the subsystems under consideration. Numerous terrestrial and space applications have demonstrated the feasibility and reliability of the radioisotope-powered thermoelectric system for unattended, remote operation. The potentially more efficient thermionic and Rankine and Brayton cycle systems are still in the development stages but could be available for application in the mid or late 1970 decade.

- 1.3.1 Thermoelectric Conversion: Thermoelectric systems operate on the principle of the common temperature-measurement thermocouple; when two dissimilar materials are connected at two points which are at different temperatures, a voltage is produced which causes an electron current flow around the circuit. Such systems are more efficient in converting thermal to electrical power when the Seebeck voltage so produced is high, the electrical resistance of the materials is low, their thermal conductivity is low, and the Carnot efficiency is high.

Figure 3 is a schematic of a thermoelectric subsystem. The heat input from the radioisotope establishes a temperature differential across the thermoelectric elements. This temperature difference results in a portion of the input heat being converted directly into electrical energy. The unconverted heat is rejected to space from the thermoelectric converter by means of the radiator subsystem.

Current radioisotope thermoelectric systems operate at hot junction-to-cold junction temperature ratios near 2, producing Carnot efficiencies of about 50%. The semiconductor thermoelectric couples currently used have internal efficiencies between 10 and 15% which, for current Carnot efficiencies, yield operating efficiencies in the 4 to 8% range. New thermoelectric materials, fabrication techniques, design improvements, and heat pipe heat rejection systems provide the potential to produce couples of about 20% internal efficiency so that efficiencies approaching 10% appear available in the foreseeable future.

To date, five thermoelectric radioisotope systems, two SNAP 3A's, two SNAP 9A's and one SNAP 19, have been put into Earth orbit; two have already exceeded 5 years of continuous operation. Also, one thermoelectric system, SNAP 27, has been placed on the moon by Apollo astronauts to power the Apollo Lunar Surface Experiment Package (ALSEP); later landings will place additional units on the moon. The SNAP 19 system has been selected as the primary power source for the Pioneer mission (Jupiter fly-by) scheduled for launches in 1972 and 1973, and the Viking Mission (Mars soft landing) scheduled for two launches in 1975.

- 1.3.2 **Thermionic Conversion:** In thermionic conversion a radioisotope is used to heat a refractory-metal emitter to a temperature exceeding 2500 F, causing electron currents of several amperes per square centimeter to leave the surface (see Fig. 4). Each electron carries a potential equal to the work function of the surface, perhaps 2.8 volts. The electrons travel across a small (about 0.01 inch) cesium vapor-filled gap to a cooler (approximately 1200 F) collector electrode with a work function of perhaps 1.7 volts. This diode then has an open-circuit voltage of about 1.1 volts; under power-operating conditions the voltage is degraded to perhaps 0.6 volts by collisions of the electrons with cesium atoms and ions in the plasma-filled gap. The cesium serves two functions: to adsorb on emitter and collector surfaces to reduce their normal metallic work functions of above 4 volts to useful values, and to form positive ions to neutralize the spare charge which would otherwise obstruct electron flow.

Thermionic systems should provide about 50% greater efficiency than thermoelectric systems, ranging from about 8% in initial systems to perhaps 15% in foreseeable advanced systems. Their greatest potential advantage is the vast reduction in required radiator area by factors of 10 to 50 over thermoelectric systems. The prime disadvantage is the need for isotope heat sources which can operate at a high power density above 2500 F and yet satisfy safety criteria.

Under the SNAP 13 program, many unfueled (electrically heated) power systems operated successfully for lifetimes of many thousands of hours. The final fueled system showed initial success, but the fuel form demonstrated that additional fuel development is necessary to assure complete encapsulation at high temperatures.

Since termination of the SNAP 13 program only limited emphasis has been placed on radioisotope thermionic systems. Realization of the excellent potential of these systems to provide very lightweight, compact, reliable power must await the resolution of fuel containment and safety problems.

- 1.3.3 **Rankine Cycle:** A radioisotope heat source when coupled with a closed Rankine cycle conversion subsystem has been considered for space applications. In this type conversion cycle, shown schematically in Fig. 5, a liquid is boiled to produce vapor. This vapor expands through a turbine driving an alternator and pump. After the expanded vapor is condensed and subcooled, it is pressurized by the turbine-driven pump and enters the boiler to repeat the cycle. Several working fluids could conceivably be utilized in this type cycle including mercury, rubidium, biphenyl and the freons. However, if early availability and demonstrated reliability of the subsystem components is desired, the mercury and biphenyl systems must be given major consideration.
- 1.3.4 **Brayton Cycle:** A Brayton cycle conversion subsystem is shown schematically in Fig. 6. This cycle utilizes argon, neon, krypton, helium, xenon or mixtures of inert gases as the working fluid, and offers the inherent advantages of a single noncondensing loop, and a noncorrosive inert gas working medium. In this cycle the working fluid is continuously in the gaseous state. "Cold" gas is compressed in the compressor and passed through a regenerator where it is preheated by gas from the turbine exhaust. The gas is then heated to its maximum temperature in the heater, and expanded in a turbine which drives the compressor and alternator. The turbine exhaust gas then passes through the "hot side" of the regenerator where it gives up some of its heat to gas leaving the compressor. Additional waste heat is transferred to the radiator where it is radiated to space. The "cool" gas leaving the radiator enters the compressor and initiates the cycle again.
- 1.4 **Radiator Subsystem:** Since the energy conversion processes associated with radioisotope power systems exhibit efficiencies of 25% or less, the greater part of the thermal heat generated within the heat source must ultimately be rejected to the environment. This function is performed by the radiator subsystem. Depending on the particular application, this subsystem usually relies on either a dynamic cooling loop, heat pipes or simply thermal conduction to transfer the unconverted heat from the energy conversion subsystem to the radiating surface. Where feasible, thermal conduction is employed. However, where the heat flux is too high or the radiating surface must be located remotely from the energy converter, either a dynamic cooling loop or heat pipes must be employed.