SNAP THERMOELECTRIC SYSTEMS*

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Abstract

In the range of moderate electrical power requirements (approximately 1 kilowatt) thermoelectric power conversion techniques offer many advantages in the design of nuclear auxiliary power units for space application. The current temperature capability of the lead telluride class of thermoelectric materials, in the vicinity of 1100°F, can easily be met with the demonstrated performance of the SNAP reactor systems. Minimum system weights are obtained at Carnot cycle efficiencies of the order of 25%, yielding a total system efficiency of about 3%.

SNAP 10, a 300 watt system is now under development. This system will have the capability to withstand missile launch environment and accomplish complete orbital startup.

I. Introduction

The direct conversion of heat to electricity offers certain distinct advantages in nuclear reactor auxiliary power units. Thermoelectric conversion techniques appear to be particularly attractive when used in conjunction with the demonstrated capabilities of the SNAP 2 reactor. These systems can provide

1) Static operation (no moving parts)
2) Output independent of position with respect to sun or earth
3) Capability to withstand missile launch and space environments
4) Minimum hazard during all phases of missile launch and operation

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5) One year or more continuous operation.
All of these aspects are important in the selection of an auxiliary power unit for space operation. Static operation together with the independence of orientation reduce the number of constraints on the vehicle stabilization system with consequent increase in reliability. The components of the system will withstand the shock and vibration of missile launch and will operate without deterioration from the space environment. The reactor will be shut down throughout the ascent phase of the flight and will be started only after a successful orbit has been achieved. Proper selection of the operating parameters of the system will enable it to provide a reliable power source for periods of a year or more for long life space missions.

The system considered here will consist of a reactor heat source, a thermoelectric converter, and a radiator for heat rejection. As such, the boiler, turbine, generator, and condenser of a conventional power conversion system have been replaced by the direct conversion package. Variations in the method of transferring the heat between the components will be considered and the advantages of the methods summarized.

II. Environmental Aspects

The design of a space system is strongly influenced by the environment to which it is subjected. These effects include the high vacuum, meteoroids, and radiation as well as the missile environment. The system must perform reliably, delivering the required amount of power with a minimum weight and not subject the rest of the payload to an environment which would interfere with its proper operation.

Minimum weight is achieved by careful selection of the system operating parameters. The basic components tend to have the following weight characteristics:

1) Reactor: The reactor must have a certain minimum fuel inventory to permit operation. In the range of electrical power outputs considered herein, there is little increase in weight of the reactor with power required. The SNAP 2 reactor weight is approximately 200 pounds.
2) Converter: The converter weight will be in the range of 10 to 20% of the system weight at low powers, and will vary in approximate proportion to the electrical power output.

3) Radiator: The radiator area is proportional to the thermal power to be rejected and inversely proportional to the fourth power of the effective radiating temperature. These two factors are interrelated by the Carnot cycle efficiency term in the expression for the converter efficiency.

The parameters of the system must be selected to obtain a minimum weight. The thermoelectric converter is characterized by an efficiency which is very nearly a constant fraction of the Carnot cycle efficiency. Under this condition minimum radiator area is obtained when the heat rejection temperature is approximately 0.75 of the heat source temperature. This results in a Carnot cycle efficiency of 25% and an overall conversion efficiency of 3% with typical present day thermoelectric converters.

Protection must be provided against damage to the system by meteoroids. In systems utilizing a heat transfer fluid the puncture of a line would result in rapid loss of the fluid to the vacuum environment. The thermoelectric materials in the converter can, in many cases, provide the protection required against this environment.

The semiconductor class of thermoelectric materials has been described as having the strength of plaster. This feature, together with difficulties in maintaining contacts, makes the converter potentially vulnerable to the shock and vibration of missile launch environment. Careful design of the supporting structure has resulted in a demonstrated capability to withstand shocks of 50 g on all axis and vibration in accordance with a typical vehicle specification.

Virtually all of the electronic payloads for space missions incorporate transistor circuits. The radiation sensitivity of these units establish the shield requirements. The wide variety of vehicle and payload configurations precludes any general statements in regard to the shielding requirements, but the configuration of components about the reactor must be chosen so as to minimize scattering of radiation toward the payload.

III. Thermoelectric Converters

Minimum weight for the system would be obtained by operating the system at as high a heat source temperature as possible. The SNAP Experimental Reactor (SER) has demonstrated the capability of delivering 1200°F coolant on a continuous basis. It would thus be desirable to operate the converter as close as practical to this temperature and to develop the capability for higher temperature converter operation as the reactor performance is increased. The life of thermoelectric converters using materials such as lead telluride may, however, become a limiting factor when operated at 1200°F. Typical generators are currently being operated at hot junction temperatures of 1000 to 1100°F.

The semiconductor class of materials present an array of problems to the successful operation of a thermoelectric converter. They must be protected both from reaction with surrounding materials and from their own deterioration. These effects are temperature dependent and become very critical for many materials above 1100°F. The details of the reactions that occur are beyond the scope of this paper, but they include oxidation and sublimation of the thermoelectric material and reaction and diffusion with adjacent materials to change its thermoelectric properties.

The design of a converter incorporates as many features as possible to prolong the life of the thermoelectric material. A coating or jacket is usually incorporated over the thermoelectric material to inhibit its sublimation and protect it against the atmosphere. In many of the converter designs a spring is used to place the material in compression between its contacts in order that they be maintained in spite of material reactions. Temperature drops are usually incurred in transferring the heat past the spring to the heat rejection surface. These combine with the temperature drops in the electrical insulation and other heat losses in parallel with the converter to reduce the efficiency considerably below the predicted value.

IV. SNAP 10, A Conduction Cooled Low Power System

The SNAP 10 system is a low power nuclear auxiliary power unit utilizing thermoelectric conversion. The characteristics of the SNAP 10 system are given in Table I.

The system consists of a conduction cooled reactor with a thermoelectric converter mounted on its surface. Fins are used to provide an extended surface area for heat rejection by radiation. The configuration of this system is shown in Figure 1.

The reactor is based on the SNAP 2 concept and uses similar fuel and reflector material. The low thermal power requirement permits heat to be removed from the core by conduction, thereby dispensing with a fluid and associated plumbing. The fuel material is fabricated in the form of circular plates which are stacked in a cylindrical array to form the core. Beryllium plates are placed between the fuel plates to improve the thermal conductivity. The core is reflected with beryllium and clad in two containers to permit positive shutdown by separation of the two reactor halves. This reactor is 12 inches in diameter by 18 inches long.

Table I

SNAP 10 System

Reactor	U^{235} - zirconium hydride fuel, beryllium reflector
Electrical power output	300 watts
Thermal power input	15 kw
Thermocouple hot junction temperature	1000°F
System weight	400 pounds

The system is handled and transported in a completely safe configuration with mechanical locks separating the two halves. These locks would be removed from the reactor at an appropriate time in the countdown. The reactor would remain shut down through the launch sequence and would be started up on ground command after a successful orbit had been achieved. A launch abort could only result in the spread of unirradiated uranium which would not constitute a major hazard.

The unit is placed in operation by a simple mechanism which drives the two reactor halves together to initiate the nuclear reaction. The unit comes up to power and is self regulating by means of its negative temperature coefficient. The system parameters permit operation for periods of one year or more without an active control system.

The weight of the SNAP 10 system for varying power outputs is given in Figure 2. The relative weights of the various system components is shown in the same figure. The system weights are based on a hot junction temperature of 1000°F. This temperature was chosen to insure reliable operation with present state of the art for thermoelectric conversion. As improved higher temperature materials become available they can be incorporated in the present systems with corresponding reductions in the system weight. In this operating temperature range the radiation damage will not present a problem because of the annealing of lattice damage.

V. Forced Convection Cooled Systems

Due to the large surface area required for waste heat rejection and the limited amount of area available on the reactor surface, the conduction cooled system described above is limited to relatively low power levels, probably something less than a few hundred watts. For higher power systems the reactor heat must be transported to a separate thermoelectric generator which must provide sufficient radiating area to reject the appropriate amount of heat. The SNAP 2 and SNAP 8 are both high temperature liquid metal (NaK) cooled reactors and hence are ideally suited to be used in conjunction with a separate thermoelectric generator. In addition, the available exit temperatures of these two reactors are sufficiently high as to be able to fully exploit the temperature capabilities of present day thermoelectric materials. The performance of thermoelectric systems which use a SNAP 2 reactor coupled by means of a liquid metal heat transfer fluid to an integral converter-radiator is shown in Table II. The analysis assumes current converter state-of-the-art.

Table II

Convection Cooled System

Hot junction temperature	900°F	
Converter efficiency	10% of Carnot	
Power output	300 watts	1000 watts
Reactor power (kw)	12 kw	35 kw
Radiator area	35 ft^2	100 ft^2
Weight		
Reactor	250 lb	250 lb
Shield	250	300
Converter radiator	100	300
Misc. (pump, structure, etc.)	100	150
TOTAL	700 lb	1000 lb

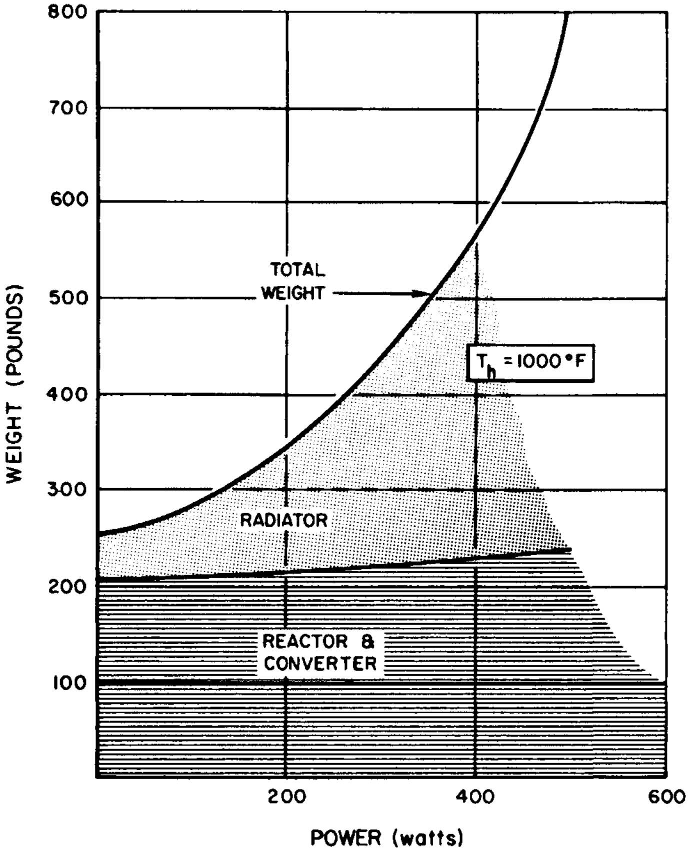

Fig. 1. SNAP 10 Auxiliary Power Unit.

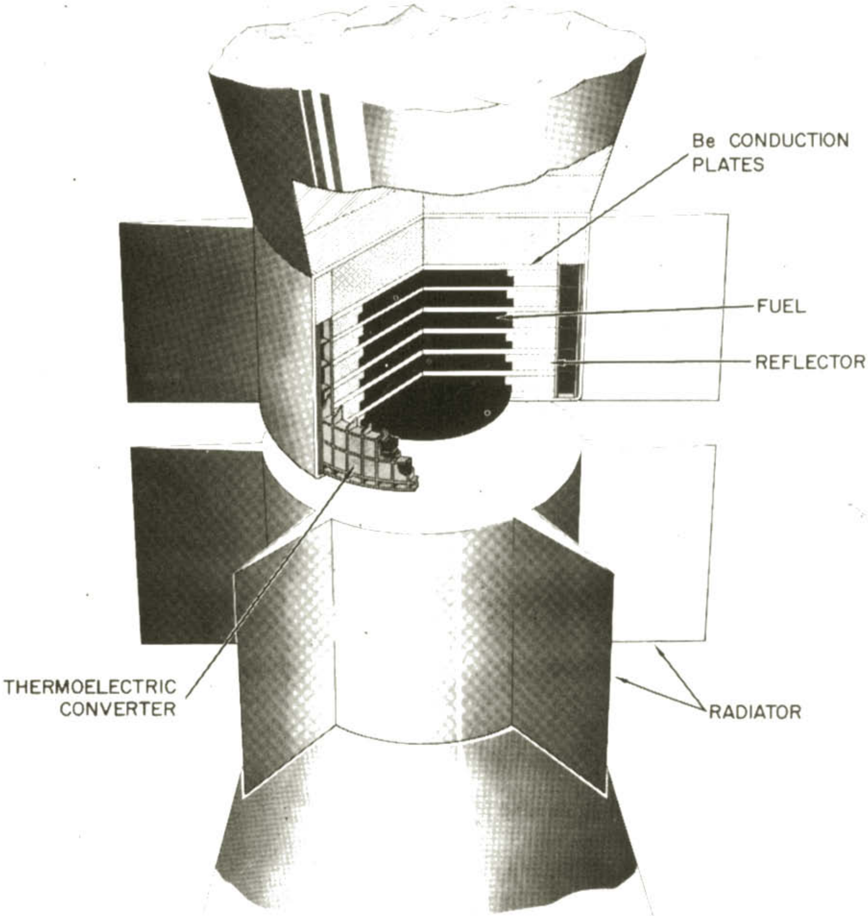

Fig. 2. Weight of SNAP 10 system (unshielded) vs electrical power output.