ISOTOPE HEAT SOURCE FOR DYNAMIC POWER SYSTEMS

Alfred Schock

Fairchild Space and Electronics Company

Germantown, Maryland 20767

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Fairchild Space and Electronics Company, Germantown, Maryland 20767

Abstract

A design is described for automatically limiting the temperature excursion of an isotope heat source following loss of cooling in dynamic space power systems. Its purpose is to keep the resultant temperature rise small enough and brief enough to prevent fuel capsule degradation: i.e., not merely to avoid meltdown, but also to retain adequate capsule ductility to ensure fuel retention in case of subsequent reentry and earth impact. Applications of the concept in designs of heat source assemblies for Brayton, Rankine, and Stirling cycle power systems are illustrated.

INTRODUCTION

The Nuclear Research and Applications Division of ERDA is developing a number of new, isotope-fueled, electrical power systems in the $\frac{1}{2}$ -to-2 kw(e) range, for space and terrestrial applications. Included are both static (thermoelectric) and dynamic (Brayton, Rankine, Stirling) systems. Each system requires one or a few heat source assemblies in the low-kw(t) range, with built-in provisions for ensuring fuel retention under all credible accident conditions. This problem has already been solved in the isotope heat sources used in thermoelectric power systems in previous space flights.

The advent of high-efficiency dynamic power conversion systems, however, raises a new problem: disposal of the isotope decay heat after the dynamic system stops operating. Plutonium-238, the radioisotope used in space, has a half-life of about 87 years. Space power systems are designed for typical lifetimes of 5-to-10 years. Thus, most of the fuel is still active at the time of anticipated power system failure.

This is no particular problem in the case of the thermoelectric generators, where most of the heat (over 90%) is lost by conduction through the thermoelements and insulation, and only a small fraction is lost by Peltier cooling. Under those conditions, loss of Peltier cooling causes only a modest increase in heat source temperature.

In a well-designed dynamic power system, only a small fraction ($\sim 10\%$) of the heat is lost through the insulation during normal operation. Most of the heat is removed via the dynamic conversion system. Failure of that system (e.g., loss of working fluid) will cause the heat source temperature to rise slowly (i.e., at an initial rate of about $10^\circ\text{F}/\text{min}$). This process will continue until the heat source reaches a temperature where all of the isotope decay heat can be rejected through the thermal insulation. In well-insulated systems the resultant heat source temperature would exceed the melting point of the fuel capsules. Clearly, an arrangement is needed which will automatically reduce the thermal insulation effectiveness before the heat source can rise to a temperature where excessive capsule degradation occurs. Such degradation could lead to fuel release during subsequent atmospheric reentry or earth impact.

The required emergency cooling system (ECS) must activate automatically when needed, and be as close to

fail-safe as possible. One proposed ECS design, under current development for a Brayton power system [1], attempts to achieve these goals by using nickel foils for the thermal insulation. When the coolant flow stops, the heat source rises in temperature until all or most of the nickel foils melt and/or evaporate, which greatly reduces the effectiveness of the thermal insulation. Activation of such a system is certainly fail-safe, and analysis shows that it will prevent melt-down of the fuel capsules and subsequent fuel dispersion during atmospheric reentry.

The fuel capsules, however, must also perform a second function, namely containment of respirable fuel particles during and after earth impact. This second function requires not only that the iridium capsules not melt, but also that they retain their ductility, which is necessary for subsequent impact survival. This is a much more severe requirement, since tests indicate that grain growth may cause iridium alloys to lose much of their ductility far below the melting point of iridium or of the Ir-C eutectic.

A preliminary analysis of the melting-foil concept (which included the effects of radiation, conduction, foil meltdown and foil vaporization, but did not include the possible effects of sintering or self-welding) indicated that the concept, while adequate to prevent capsule meltdown, may not be adequate to prevent excessive ductility degradation. The analysis showed the ~ 10 hours of the temperature excursion elapse before the innermost nickel foil starts to melt, at which time the fuel capsule temperatures exceed 3000°F (compared to their normal 2400°F level) and are still rising. Retention of adequate ductility of current iridium alloys subjected to such a temperature excursion has not been demonstrated, and seems questionable. It therefore appears desirable to provide the heat source assembly (HSA) with another ECS arrangement, to terminate the temperature excursion more quickly, and at much lower peak capsule temperatures.

The use of foils with lower melting points than nickel has been considered, but lower-melting metals tend to have higher vapor pressures, which would lead to excessive evaporation rates at normal operating temperatures. The use of lower-melting, low-vapor-pressure eutectic mixtures has been proposed [2], but these would be difficult to form into thin foils, and would require an extensive development and test program to demonstrate their reliability.

One possible arrangement for avoiding the drawbacks of the melting-foil concept is to devise a system for automatically removing all or part of the thermal insulation when the heat source exceeds a predetermined temperature level. This insulation removal can be spring activated, triggered by meltdown of a fusible link which is thermally coupled to the heat source. The springs themselves can be located in a low-temperature region of the HSA.

One of the principal problems in devising a design to implement the above insulation-removal concept relates to the question of how to provide adequate structural support for the radioisotope heat source, without incurring excessive heat loss by thermal conduction. The support structure must be strong enough to withstand launch vibrations, yet compliant enough to allow for thermal expansion. This will be illustrated with respect to an actual heat source which has already flown as part of the Multi-Hundred-Watt (MHW) thermoelectric generator.

The heat source contains twenty four 100-watt spherical fuel elements, each with its own fuel containment capsule and impact protection shell. Reentry protection for the heat source is provided by a cylindrical graphite shell with end caps. In the MHW generator the cylindrical heat source is supported solely by axial compression from its two ends. An axial preload of 1200 lbs is required to withstand launch loads. The compressive supports pass out through the center of the end insulations, where they transmit the preload through compliant spiders to the generator housing. This specific support arrangement would be incompatible with the insulation-removal ECS concept discussed above, since the support structure must not obstruct the insulation which is to be removed. A different support arrangement is therefore required.

For a cylindrical heat source, an ECS design can be based on the removal of either the side or the end insulation. Either arrangement seems to be feasible. Removal of the side insulation would be thermally more effective. However, as shown in Reference [3], removal of the two end insulators also gives adequate overtemperature protection. Analysis indicates that with both end insulators removed, the heat source surface equilibrates at 1076°F at its ends, and at 1640°F at its hottest point, near the mid-plane. These equilibrium values, as well as the transient temperatures experienced after ECS activation, are well below the normal operating temperatures of the Brayton system heat source. The end-insulation removal scheme was therefore selected, because it permits a somewhat simpler solution of the structural support problem.

To have removable end insulators, the support members connecting the heat source to the HSA housing must pass through the cylindrical side insulation. A possible arrangement for doing this is illustrated in Figure 1.

At the center of the HSA, and occupying most of its volume, is the cylindrical heat source, which is essentially identical to that of the MHW generator. Surrounding the cylindrical heat source is a helical tube heat exchanger, in which the isotope decay heat is transferred to the Brayton system's inert gas working fluid. The helical heat exchanger is in turn surrounded by multi-foil insulation, to minimize heat losses to the cool (~200°F) generator

housing. The coolant inlet and outlet ports of the heat exchanger penetrate through the side insulation and the HSA housing.

Figure 1. Illustrative Heat Source Design for Brayton-Cycle Power System

The axial and lateral loads exerted by the heat source during launch are supported by three equispaced flat tabs at each end of the HSA. As shown in Figure 1, each support tab passes through a narrow axial slit at the end of the side insulation blanket. The inside end of each tab is connected to an inner ring which supports the end of the heat source; and the outside end of each tab is connected to an outer ring, which is mounted to the HSA housing.

The ring-tabs-ring structure at each HSA end is dimensioned to yield the desired degree of strength and compliance, and the mounting to the HSA housing is adjusted to give the desired compressive preload. The support structure is stiff axially and radially (but not tangentially, since rotational forces are small). The portion of each support tab within the HSA's insulation blanket is itself insulated with multi-foil (not shown in Figure 1), to lengthen the heat conduction path and reduce thermal losses.

The end covers are sealed to the HSA housing by means of Viton O-rings. Viton has long-term reliability up to 392°F. Before and during launch, the HSA may be filled with helium, to prevent excessive heat source temperatures even when the Brayton system is

not operating. After launch, the seals are no longer needed, since the HSA is vented to space.

Each end cover has an integral multi-foil insulation blanket. A stepped mitre joint is used between the sides and end insulations. Each end cover assembly is acted on by three compressed springs trying to push it away from the HSA housing. The springs are outside the housing and therefore cool. A stiffened retaining plate on the inside of each end cover insulation blanket assures removal of that insulation with its cover.

The spring force on each cover is resisted by a centrally located axial tube, which penetrates through the end insulation and connects that end cover assembly to the heat source. The tube's cross-sectional area is designed to give adequate creep strength to resist the tension produced by the six springs, and its length is chosen to yield adequate thermal resistance.

The portion of the axial tube inside the insulation package, adjacent to the heat source, contains a braze joint designed to melt at a predetermined temperature. That temperature is chosen low enough to minimize the magnitude and duration of the coolant-loss temperature excursion, but high enough to avoid the danger of inadvertent end cover deployment due to temperature fluctuations during normal operation. The braze joints at the two ends of the HSA may have different melting points, to reflect the normally present axial temperature gradient of the heat source. The braze bond connects two coaxial tubes by means of a lap joint, which is made long enough to reduce the shear stress sufficiently to avoid creep failure.

The insulation-removal system described above does not necessarily have to replace the previously mentioned foil-meltdown system. The two systems can be used in conjunction, to supplement each other. Such a combined ECS would protect the fuel capsules against loss of ductility, and still retain the extremely reliable foil meltdown concept as backup protection against capsule melting.

While the above discussion has dealt primarily with the Brayton power system, the same insulation-removal emergency cooling concept can also be applied to other power systems. Figure 2 illustrates a very similar HSA design for the Organic Rankine system, with the helical heat exchanger tube acting as the boiler for the Dowtherm working fluid. And Figure 3 illustrates the application of the same ECS principle to an HSA design for a Stirling-cycle power system, with the HSA in thermal contact with the cylinder head of the engine.

REFERENCES

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Figure 2. Illustrative Heat Source Design for Rankine-Cycle Power System

Figure 3. Illustrative Heat Source Design for Stirling-Cycle Power System.