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Nuclear Heat Source for Cryogenic Refrigerators in Space *

by

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Abstract

To supply the heat input required by space-borne Vuilleumier refrigerators, a possible design for a reliable Pu-238 radioisotope heat source, based on state-of-the-art technology, is described. The isotope heat source would replace electrical heaters powered by solar panels and batteries, and would be adaptable to existing VM refrigerators without redesign. The heat source contains all necessary safety features, and also a simple thermal control system to permit refrigerator shut-down for indefinite duration. A system for thermal interfacing with the spacecraft, the booster, and ground support is also described. The isotope heaters are compared with solar-electric heaters for the same application, and found to result in very significant weight and size savings.

1. Introduction

Spaceborne cryogenic refrigerators, e.g. for cooling infrared detectors, require thermal inputs on the order of 1000 watts. These can be provided in a number of ways, such as solar-electric, solar-thermal, and nuclear, to name the most obvious candidates. Those options were considered in an earlier study¹, which concluded that the solar-electric approach was preferable, mainly due to state-of-the-art readiness. However, the only nuclear option considered was the reactor-thermoelectric system, instead of an isotope heat source, which appears to be a much better choice for the intended power level.

Plutonium-238 heat sources in the range of 500 to 1500 watts(t) have been space-borne since 1963. Starting in 1969, 1500-watt heat sources were used to power the SNAP-27 generator for the Apollo Lunar Surface Experiments Package (ALSEP). The current-generation heat source, designed for the Multi-Hundred-Watt (MHW) generator² scheduled to be launched in 1975, produces 2400 watts(t). Such heat sources typically weigh less than 50 pounds in the power ranges noted, whereas the minimum-weight nuclear reactor system will be in the range of 700 to 1000 pounds, including shielding. Moreover, the radiation emitted by a Plutonium-238 heat source, without shielding, is orders-of-magnitude lower than that from an equal-power reactor with a several-hundred-pound shadow shield. Under these circumstances, the choice of radioisotope power in preference to reactor power for the cryo-refrigerator thermal requirement hardly needs belaboring.

The choice between radioisotope-thermal power and solar-electric-thermal power is not quite so obvious, and should properly be made in the systems context. However, certain general comparisons can be made on a first-order basis. These are summarized in Table 1 for a nominal 1000 watt(t) requirement.

Table 1.

Comparative Characteristics; 1000 watt(t) Requirement

Characteristic	Solar-Electric	Radioisotope
Current state-of-the-art	Roll-up arrays; Ni-Cd batteries	MHW heat source modules (100 w each)
Weight range, lb	200-400 (incl. batteries)	30-50
Size range	Several ft ³ stowed 80-150 ft ² deployed	~ $\frac{1}{2}$ ft ³
Cost range, k\$	1000 - 2000†	700- 1000
Orientation required	sun-pointed	none
Advantages	"standard" approach; control system developed; adaptable to Vuilleumier and Rotary Reciprocating Refrigerators	low-weight; eliminates batteries or thermal storage; adaptable to VM and R ³ (with thermal compressor)
Disadvantages	large extended area; requires deployment, sun orientation; high visibility	Requires: special ground handling and cooling; thermal-control mechanism for space shutdown

† Depending on hardness requirements

The major advantages of the radioisotope approach are low weight and size, permitting weight savings of several hundred pounds per spacecraft (depending on power requirements), as well as low cost for equal hardness levels. Relative to a fully-hardened roll-up solar array, the cost of an isotope heat source per thermal watt can be substantially lower, as indicated in Table 1. Moreover, 50 to 70% of this cost (that of the fuel material itself) is borne by an intra-governmental transfer of funds and is not subject to contractor and system-level burdens, as are solar-array costs.

The size difference between the two approaches is depicted to scale in Figure 1. Another potentially important advantage, i.e., the elimination of sun-pointing requirements, can only be fully exploited in a spacecraft which is all-nuclear, i.e., containing nuclear-electric as well as thermal power. The potential benefits of an all-nuclear spacecraft will be discussed in a separate report.

The major disadvantages of a radioisotope system stem from its constant heat output and from its possible nuclear hazard. The former requires special means for heat removal on the ground and through the launch phase. Also, temporary space-shutdown of the refrigerator for an indefinite duration has been postulated, requiring some reversible method for switching the heat flow path directly to space during these shutdown periods.

These external thermal interface requirements, together with the internal thermal and safety requirements of the heat sources, provided the major design constraints to the heat source system described here. The various requirements appear to be amenable to rather simple and elegant solutions, which allow the use of existing refrigerator designs without alteration.

Section 2 of the report describes a possible state-of-the-art heat source design approach, based on the use of MHW fuel sphere assemblies (FSA's). The heat source is designed and qualified for safety under all credible accident conditions. A simple reversible thermal switching method, operated on command, is also described. The system is fail-safe, i.e., in the event of simultaneous failure of the refrigerator and thermal switch, an emergency heat dump will reduce the fuel temperature to a relatively low value.

The recommended spacecraft thermal interface unit, which also provides the thermal interface with the space-shuttle orbiter or with a disposable booster is described in Section 3.3.

Special ground-handling and safety requirements due to the use of radioisotope fuel are unavoidable. However, these have not proved to be an obstacle to its use in past missions. Experience in handling and launching radioisotope fuel has not been achieved at both Eastern and Western Test Ranges. The general ground-handling and launch methods which will apply to the nuclear heat sources are described in Section 3.4.

2. Reference Heat Source Design

The heat source design shown here is based on satisfying the thermal requirements of the existing Hughes Hi-Cap Vuilleumier (VM) refrigerator.³ However, these designs can be adapted with minor modifications to other refrigerators, including the Rotary Reciprocating machines now in development. To be operated thermally, the latter would be provided with thermal compressors.⁴ A basic design groundrule was that no modification of the VM machine would be required.

The electrically heated VM unit is depicted in Figure 2, and a more detailed view of one of its two hot-end assemblies is presented in Figure 3. The isotope heat source package replaces the electrical heater and insulation assembly which surround the hot cylinder. If desired, the isotope heat source can be installed after the VM unit has first been checked out with electrical heaters.

Isotope heat source designs are primarily dictated by safety constraints, since these are generally more difficult to satisfy than the operational requirements. The isotope heat source package must include an adequate complement of passive safety provisions to ensure that no fuel is released in any credible accident mode or combination of accidents. Such accidents include booster detonation, shrapnel dispersion, solid-fuel fire immersion, aerodynamic heating during reentry, impact on granite, post-impact burial and oxidation. All these problems have been addressed and solved on previous isotope-powered flight programs.

An isotope heat source design for the VM application can be based either on existing fuel elements, which have already been developed and qualified, or on new designs, using the lessons from previous development programs to guide the solution of the various safety and operational requirements. The latter approach would result in a lighter and possibly lower-cost heat source, since the design could be optimized for the specific mission. The former approach, i.e., the use of proven fuel element designs, minimizes schedule risk for near-term applications. The ultimate choice will depend on the relative importance of these competing factors in a given program.

The design described here is based on existing fuel elements; i.e., the fuel sphere assembly (FSA) developed for the multi-hundred watt (MHW) thermoelectric generator, scheduled for first flight in late 1975. The FSA design was qualified in a lengthy series of safety analyses and tests. Each FSA consists of a 1.6"-diameter PuO_2 sphere, encapsulated in a 0.020" -thick vented iridium shell, enclosed in a 0.45" -thick impact absorption shell made of a (Thornel) carbon-carbon composite. Each FSA has an initial thermal power of 100 watts, which diminishes at the rate of 0.8% per year as the result of fuel decay.

Since the exact heat input required by the VM unit is still somewhat uncertain, the design shown is based on a nominal number of ten FSAs (1000 watts) for each of the two hot-end assemblies. Higher or lower power levels, within reason, could be accommodated by relatively simple design modifications. A weight estimate for a 13-ball design (1300 watts) has also been made.

The FSAs have demonstrated adequate high-temperature physical and chemical stability, and resistance to vent plugging; particularly since their operating temperatures would be appreciably lower in the VM unit than in the thermoelectric generators. At the predicted heat source impact velocity (165 ft/sec at sea level) they also have more than adequate impact resistance, without any additional impact absorber.

Their resistance to launch pad accidents and the reentry heat pulse, however, is much more design specific, since it depends on the protection provided by the package in which the FSAs are contained.

In general, that package consists of a graphite ablator, thermal insulation to prevent excessive iridium temperatures during a solid-fuel fire and during reentry, and an outer metallic can to protect the other components from shrapnel damage.

The heat source design can be based on an individual package for each fuel element, for groups of fuel elements, or on a single package for all ten FSAs. The design shown uses the single-package approach.

The other main feature of the design relates to the question of thermal control. Unlike an electrical heater, an isotope heat source can never be turned off. Therefore, a reliable method must be provided for removing the isotope decay heat during the non-operating period of the VM refrigerator. That method must be reversible, to permit resumption of VM operation, and must not add any significant heat losses when the VM unit is operating. Moreover, the entire system must be fail-safe, in the sense that even when all active control systems fail, passive systems will keep the fuel elements cool enough to prevent fuel release.

These thermal requirements are satisfied by surrounding the outside of the heat source with multiple layers of nickel foil. During normal operation, the space between the foils is evacuated (i.e., open to space) and the foil assembly acts as a very effective thermal radiation shield. When the refrigerator is to be shut down, the heat source is kept at a benign temperature by admitting helium into the interfoil space. As little as ten torr of helium will effectively spoil the thermal insulation, allowing heat rejection from the heat source's outer surface. This thermal switching process is reversible, since the interfoil space can be repeatedly filled and vented to space. Thus the refrigerator can be turned on and off, as desired. As will be explained, the helium supply is continually replenished by the helium generation resulting from the fuel's alpha decay.

The fail-safe emergency cooling feature is achieved by making the insulating foil out of nickel or ferrous alloy rather than refractory metal. Thus, in case of a serious malfunction, the insulation package would melt before the fuel elements reach excessive temperatures. This principle is already being tested under a NASA-LeRC-sponsored program to develop an isotope heat source for a Brayton-cycle generator.⁵

The proposed heat source design is shown in Figure 4. The ten fuel sphere assemblies nest in a graphite reentry body, 4.4 inches high and 11.8 inches in outer diameter. The body is split, to permit FSA insertion, and its two halves are held together by a graphite snap ring. This is the same locking arrangement as that used in the MHW heat source for the Mariner-Jupiter/Saturn (MJS-77) mission. The reentry body is Pyrocarb, which is a composite formed by graphite-bonding stacked layers of graphite cloth. It has excellent thermal stress resistance, is a good thermal insulator in the transplanar direction (to reduce the peak FSA temperature during reentry or in a solid-fuel fire), and provides additional impact protection.

The reentry body is contained in an inner and outer can of superalloy. The inner can has a cavity of 4.57-inch diameter, which fits over the outside of the 1275°F hot cylinder of the VM unit. The sides and end face of the outer can are surrounded by multiple layers of nickel foil insulation, as mentioned earlier. These are contained in an outside can of steel, whose end face is stiffened by an integral honeycomb structure. The nickel foils are coated with small spheres of zirconia, to minimize thermal conduction between foils.

Figure 4 also shows the toroidal helium reservoir, which is separated from the reentry package by a multi-foil heat shield. Since the reservoir is in communication with the vented fuel sphere assemblies, there is a constant supply of fresh helium from alpha decay. Excessive pressure buildup is prevented by helium leakage through the Viton O-ring which joins the inner and outer heat source cans. Leak rates of such O-rings as a function of temperature have been extensively measured in previous isotope power programs, and are quite predictable. For the present design, they will be dimensioned to yield a reservoir equilibrium pressure of approximately one atmosphere. Note that the interior volume of the heat source is always flooded with helium. This promotes heat transfer across interface gaps.

Finally, Figure 4 shows the solenoid-actuated insulation spoiler valve, which is used to switch the multi-foil assembly from its operational (low-conductance) to its non-operational (high-conductance) mode. The valve body is integral with the closure ring which seals both the heat source can and the heat shield can. With the solenoid actuator passive as shown, the spring raises the valve stem, which seals the reservoir and vents the interfoil volume to space vacuum. When the VM refrigerator is to be shut off, the solenoid is actuated, which lowers the valve stem to connect the helium reservoir to the interfoil space. Reversing the cycle vents the helium from the interfoil volume to space, permitting resumption of VM operation. Since the interfoil volume is but 2 to 3% of the reservoir volume, only a small fraction of the helium supply is lost on each on-off cycle. Thus, even if there were no helium replenishment from alpha-decay, more than 100 on-off cycles would be possible before the helium pressure drops below the pressure (10 torr) required to spoil the insulation.

The weight breakdown of the 1000-watt heat source assembly (HSA) is shown in Table 2. The heaviest component is seen to be the 17.8 lb graphite reentry body, which has been rather conservatively designed and could probably be lightened. The ten FSAs have a combined weight of 9.8 lbs, and the total heat source weight is almost 42 lbs. The weight of a 1300-watt HSA is also shown in Table 2.

Table 2. Heat Source Assembly Weight Summary (lbs.)

Item	1000 Watt(t)	1300 Watt(t)
1. Heat Shield Can (inc. honeycomb)	4.2	5.4
2. Heat Source Can	2.9	3.5
3. Inner Heat Source Can	1.3	1.7
4. Heat Shield	1.0	1.7
5. Closure Ring	1.4	1.7
6. Attachment Ring	0.5	0.5
7. Foil Thermal Shield	1.3	1.6
8. Fuel Sphere Assemblies	9.8	12.8
9. Graphite Reentry Body	17.8	29.7
10. Misc.	<u>1.6</u>	<u>1.7</u>
	41.8	60.31

3. Spacecraft Thermal Interfaces

The spacecraft thermal interface requirements pertain not only to normal operation, but also to ground assembly, launch sequence, including extended hold periods, and to in-orbit shutdown periods when the refrigerator is not operating. During non-operational periods, the insulation will be spoiled, thereby dumping the HSA heat to the ambient environment.

When the VM unit is shut down in orbit, the heat passing through the spoiled insulation must be radiated to space. This could be done directly, by requiring that the VM heat sources be located external to the spacecraft and the VM radiator. To avoid this undesirable design constraint, the already present radiator of the VM refrigerator can be used to reject the waste heat during non-operational as well as operational periods.

To accomplish this, each heat source is surrounded by a small thermal shroud, through which the VM coolant passes before going to the VM unit's space radiator (As shown schematically in Figure 5). During normal VM operation, practically no heat passes through the multi-foil insulation, and the thermal shroud has virtually no effect on the coolant. When the VM unit is off, the coolant still receives essentially the same amount of heat as during VM operation; only instead of receiving it via the operating refrigerator, it receives it directly from the heat source, through the spoiled multi-foil insulation. Thus, the radiator always operates at the same temperature of less than 100°F. It can therefore be used to surround the spacecraft payload with a benign-temperature envelope, regardless of external or load variations.

Since the coolant flow path is always the same, and always operating, there is no need for valving, venting, start-ups, or shut-downs. The low-temperature cooling system should therefore be highly reliable. A redundant coolant pump could be readily provided.

The above system can be easily modified to also satisfy the thermal requirements before and during launch, and the post-launch requirement before the shuttle bays are opened. This can be done by providing the thermal shroud with a second, water-cooled loop; which is connected to the ground-support or launch-vehicle auxilliary cooling system. Thus, the heat collector would act as a heat exchanger. In the shuttle, the auxilliary cooling loop would transfer heat to the cargo bay heat rejection system, which will be available for heat-dissipating payloads.

The thermal shroud is in the form of an aluminum cylinder, with a 16-inch I.D., and an 8.5-inch height. It weighs approximately 5 lbs. With the coolant at 100°F, the outside of the heat source will equilibrate at approximately 740°F with the sides-only arrangement shown in Figure 4, and at 590°F if the thermal shroud covers the side and end face of the heat source as shown in Figure 7. Although the sides-only arrangement gives a somewhat higher stand-by temperature, it permits permanent installation of the thermal shroud on the VM unit, without use of flexible lines. The isotope heat source can then be installed through the shroud's open end.

4. Ground Handling Sequence and Requirements

Ground handling of the HSA is governed by two major considerations: radiological safety and thermal control. Personnel access can proceed with essentially no restrictions beyond a few meters of an unshielded Pu-238 heat source. At one meter, a worker can experience approximately 200 hours of exposure per calendar quarter without exceeding the occupational dose limit. Access to the surface of the heat source for several hours per calendar quarter is also permissible, but will most likely be limited as much by thermal as by nuclear considerations. Typically the HSA will be handled on the ground by long-handled tools and by portable lifts.

A generalized ground-handling sequence for the radioisotope heat sources is shown in Figure 6. Final assembly of the HSA will be performed at the facility of the fuel fabricator, using the components and assembly procedure developed by the heat source contractor (1.0).

Following final radiological check-out for fuel integrity and container cleanliness, a final test of the helium thermal control apparatus will be conducted (2.0). The system will then be sealed with a full helium charge (nominally 1 atmosphere) within the foils and HSA. Heat source cooling will be accomplished by inserting the HSA into a finned structure which clamps securely to the outer case of the HSA. The HSA with its protective coating structure is then loaded within the DOT-approved shipping container (Figure 7) and shipped to the launch site via dedicated truck with security escort (3.0).

At the launch site the shipment is received by contractor personnel and transferred via a fork-lift vehicle or small crane (Figure 8) to a special nuclear material handling room in the payload operations building (4.0). There the HSA is removed from its shipping container and checked again for radiological integrity and thermal control operation. These operations are performed with the HSA inserted within an air-or water-cooled launch-site heat exchanger (LSHX). The LSHX can simply be a distribution duct which directs cooled air over the external surface of the HSA (5.0).

At this point testing of the refrigerator with the HSA installed can be performed within the payload operations building, if desired. Transfer of the payload to the launch pad should probably be performed with the HSA removed, however, due to the possible difficulty of cooling the latter within the payload structure, until the shuttle cooling system is accessible. The HSA would then be transported to the launch pad in a separate vehicle, still mounted to the portable LSHX (6.0).

At the launch pad, all payload elements are assembled in the payload check-out room prior to insertion into the cargo bay. This would provide the most convenient access to all sides of the payload and would be the preferred location for final installation of the HSA to the refrigerator, possibly through a local cut-out in the radiator (Figure 9). This would be the final step of the payload assembly process, prior to insertion of the payload into the cargo bay. Short periods without active cooling of the HSA are of no concern, because of its high heat capacity. The temperature rise without any cooling whatsoever is only in the range of 5-to-10°C/min. Radiation and natural convection will tend to reduce this figure still further. Following payload insertion within the cargo bay, connection of the thermal shroud to the shuttle payload heat exchanger can be made.

This approach would obviate the need for a separate storage cannister for nuclear fuel within the cargo bay, and subsequent on-orbit assembly of the HSA to the refrigerator by the payload manipulators. Although that may be a viable option for many missions, in this case the refrigerator will probably be enclosed within its own radiator, and thus be relatively inaccessible for on-orbit operations.

Finally, the basic handling approach described can also be readily adapted to operations with disposable boosters. As before, the HSA is mounted as a final assembly step. In this case, the usual launch-pad air cooler, suitably uprated in capacity, will keep the HSA exterior surface within proper temperature limits prior to the lift-off. After lift-off and umbilical disconnect of the air conditioning system, the temperature rise of the HSA will be negligible until the shroud is removed and the radiator is exposed. The refrigerator coolant pump can then be started, thus beginning active cooling of the HSA.

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Figure 1.

COMPARISON OF POWER OPTIONS FOR VM REFRIGERATOR

Figure 2. VM REFRIGERATOR ASSEMBLY

Figure 3. VM REFRIGERATOR HOT-END ASSEMBLY

Figure 4.
ISOTOPE HEAT SOURCE FOR VUILLEUMIER COOLER

Figure 5

THERMAL CONTROL SYSTEM

Figure 6

HEAT SOURCE GROUND FLOW

Figure 7
HEAT SOURCE ASSEMBLY SHIPPING CONTAINER

Figure 8

SHIPPING CONTAINER HANDLING TOOL

Figure 9

ON-PAD LOADING OF HEAT SOURCE ASSEMBLY