Apr 1st, 8:00 AM

Radioisotope Heaters for the Thermal Control

J. K. Evert

Atomics International, Canoga Park, California, A Division of North American Rockwell Corporation

RADIOISOTOPE HEATERS FOR THERMAL CONTROL

By

J. K. Evert

and

R. Y. Parkinson

Atomics International, Canoga Park, California

A Division of North American Rockwell Corporation

I. Summary

The recent development and fabrication of a series of small radioisotope heaters has opened the door to an entirely new and unique tool for thermal control. The devices are completely passive and generate heat with a reliability of 1. The design and construction of these heaters is discussed along with qualification tests to which the heaters have been subjected. These tests include crush forces of 20,000 pounds, thermal shock from 1700°F to -320°F, and impact into granite at a velocity of 355 ft/sec. Radiation shielding data are presented which will permit preliminary design estimates. General licensing requirements are also included.

Some applications are discussed with comparisons made between radioisotope and electrical heating systems. In these comparisons a radioisotope heater shows both a weight and cost advantage over solar cells or batteries. Typical radioisotope heater characteristics over a power range of 1 to 50 watts are presented.

II. Introduction

There are many applications in space, marine, terrestrial, and airborne systems for small quantities of heat, where this heat must be provided with a very high reliability, approaching 1.0. A new tool for thermal control has now been developed which can provide this highly reliable heat. The tool is a radioisotope heater, called ThermoPac.

ThermoPac represents a concept for a family of heating devices which employs radioisotopes as the heat producing medium. The radioisotope material is suitably encapsulated in a structural container to yield a heater which has been demonstrated to be extremely rugged, highly reliable, and flexible in thermal performance. The concept is schematically illustrated in Figure 1. The structure may be surrounded by an oxidation cladding for some applications. In its simplest form, the heater may be fastened to the component requiring heat by means of a threaded stud or placement in a well or receptacle. Thermal performance of the heater is determined in several ways: proper choice of one of a number of heat-producing radioisotopes, each having different characteristics; amount of exposed surface area; and emissivity coating used or insulation employed. Any shielding required is normally provided by the structure necessary for mechanical containment of the radioisotope. For some aerospace applications it may be desired to employ the radioisotope heater adjacent to an instrument which is sensitive to the particular frequencies of the emissions of the radioisotopic fuel. In this case, additional shielding may be necessary. For this consideration a section on radiation shielding is included.

III. Radioisotope Selection

The source of heat in ThermoPac devices is a radioisotope, a material which undergoes continuous decay from an excited energy state to a lower energy state. This decay is not affected by outside forces and, therefore, occurs with 100% reliability. The decay follows an exponential relationship with time in accordance with $P = P_0 e^{-\lambda t}$. [P = power; λ = decay constant = 0.693/half life; t = time] This decay is plotted for several radioisotopes in Figure 2. Decay is accompanied by the emission of particles, such as alpha (α), beta (β), and neutron (η), as well as electromagnetic radiations called gamma (γ) rays. The interactions of the decay products with matter result in the generation of heat. It is this unique characteristic of radioisotopes, that is, their ability to produce usable heat over long periods of time with a reliability of 1.0, which is the basis for these new heating devices.

A variety of radioisotopes exist which may be considered for their heat producing capability. Some of the more attractive ones are shown in Table 1, along with some of their pertinent characteristics. Generally, selection of a particular fuel will depend on parameters such as desired thermal source lifetime, system weight and volume limitations, shielding requirements, and isotope availability and cost. These parameters must be examined for each specific application in order to select the most suitable fuel for that application. For example, if a one year space mission is postulated, the half-life of the radioisotope may be the parameter which plays an over-riding part in fuel selection. Choice of a short half-life fuel such as Po 210 (138 days) would necessitate initial overfueling by a factor of 3 to 4, would require provision for thermal control during the mission to dissipate this excess thermal power, and would make fuel scheduling during fabrication and delivery more critical. In addition, overfueling required by use of short half-life isotopes also necessitates the additional weight and volume associated with this extra fuel, plus its encapsulation materials, and any ablative protection which may be required. On the other hand, long half-life fuels such as Pu 238 (86 years) result in less than 1% degrdation over a one year period, and about 4% over 5 years. Therefore, minimum or no thermal control system would be required to dissipate excess power with use of this fuel.

TABLE 1

RADIOISOTOPE FUEL CHARACTERISTICS

Class of Emitter	Gamma	Beta						Alpha			
Radioisotope	Co^{60}	Sr^{90}	Ru^{106}	Cs^{137}	Ce^{144}	Pm^{147}	Tm^{170}	Po^{210}	Pu^{238}	Cm^{242}	Cm^{244}
Half-Life (years)	5.3	27.7	1.0	30	0.78	2.6	0.35	0.38	86	0.45	18
Principal Decay (Mev)											
α	-	-	-	-	-	-	-	5.3	5.49	6.11	5.80
β	0.31	2.24	3.54	0.529	1.321	0.223	0.96				
γ	1.33	1.734	$\sim$1.2	0.66	2.18	0.121	0.084	0.8	0.044	0.04	2.5
Fuel Form	Metal	$SrTiO_3$	Metal	CsCl	CeO_2	Pm_2O_3	Tm_2O_3	GdPo	PuO_2	Cm_2O_3	Cm_2O_3
Watts/Gram Compound	1.7	0.23	1.1	0.12	3.8	0.286	1.07	1.34	0.39	98	2.27
Density of Compound g/cm^3 actual or 90% TD	8.7	3.7	12.2	3.6	6.6	7.43	8.5	9.3	10	9	9
Power Density w/cm^3 compound	15.2	0.94	13.4	0.42	25.3	2.13	9.1	1210	3.9	882	20.4
Shielding Required	Heavy	Heavy	Heavy	Heavy	Heavy	Minor	Moderate	Minor	Minor	Minor	Moderate
Curies/Watt	65	148	102	207	126	2788	500	32	30	28	29
Melting Point (°C)	1480	1900	2450	646	2680	2270	2300	1675	2280	1950	1950
MPC in Air (Ci/cm^3)	3×10^{-9}	10^{-10}	2×10^{-9}	5×10^{-9}	2×10^{-4}	2×10^{-8}	10^{-8}	7×10^{-11}	7×10^{-13}	4×10^{-11}	3×10^{-12}
Present Cost ($/watt) (approximate)	265	125				600	75	100	1040		

Radioisotopes are typified by their high power densities (watts/cc) compared to other energy sources. A comparative example will illustrate this. Using a Pu-238 fueled heater to provide 100 thermal watts for one year would require a volume of approximately 1/3 of a cubic foot. Compare this with approximately 600 ft^3 of primary nickel cadmium batteries which would be required to provide the same thermal power for one year. When selecting a particular radioisotope for a specific application, it is necessary to examine limitations which may be imposed on system weight and volume. Any such limitations would favor those fuels with high power densities. Examining Table 1 reveals several fuels having very high power densities, such as Po-210 with 1210 w/cc, Cm-242 with 882 w/cc and Co-60 with 15 w/cc. This is the power density of the fuel only; the complete heater, which includes structural encapsulation and radiation shielding, will be characterized by a lower power density. In the case of alpha emitters such as Pu-238, void volume may be required within the capsule to accommodate the helium gas build-up which occurs with these fuels over an extended period of time.

The isotopes in Table 1 have been categorized by the type of primary radiation emission, that is, α, β, or γ. Note that the gamma and beta emitters are generally typified as requiring heavier amounts of radiation shielding than alpha emitters.

The influence of the radiation source strength of the isotope upon its attractiveness as a heat source depends on the particular application being considered. Factors such as the radiation tolerance of electronics or experiments in proximity to the source, the distance between source and receptor, and any physical material interposed between the source and receptor must be considered. If man is going to be in close proximity, his tolerance and exposure time also should be considered.

While technical considerations such as thermal performance, lifetime, and shielding requirements are one aspect of radioisotope selection, another important one is fuel availability and cost. These latter aspects are particularly critical when volume production is being considered, such as an aircraft battery application. Such an application involves large numbers of units with logistics demanding long shelf life or operating life. These criteria would tend to favor those fuels having long half-lives and would further limit the choice to those which could be provided in sufficient quantity to support the application. For example, while Pu-238 has an attractive half-life and power density, its limited availability at the present time would tend to discourage its use for anything but the most critical applications and ones wherein there may be a chance of recovering the fuel inventory after mission usage.

It is necessary to examine the cost of a radioisotope heater in terms of its cost to the total system in which it is to be used, rather than as a separate piece of hardware. Since no electrical connections are necessary, the cost of the electrical power generation, wiring, harnessing, switches, readout and display equipment, switching logic circuits, etc. are eliminated. In many cases, inclusion of these items involves other design compromises which can be related to cost. Another advantage of radioisotope heaters is their ease of integration after the major system has already been designed and, in many cases, fabricated. They can be added without major redesign or modification because of the absence of such items as those listed above. In general, an isotope heater can be easily tailored to an individual application, even at a late stage in system development, because of the extreme flexibility of the concept.

Most of the present heater development has used Pm-147, which has a half-life of 2.6 years. This radioisotope was selected because its half-life satisfies most of the applications examined; because of the extreme safety of the fuel form (Pm_2O_3); and because the radiation shielding requirements are nominal. Heaters using Pu-238 have also been designed at power levels up to 30 watts.

IV. Shielding Trade-Offs

In addition to generating heat with 100% reliability, radioisotope heaters also emit certain types of radiations during their natural decay. Direct radiation is in the form of gamma rays, alpha particles, beta particles, and neutrons, with each radioisotope having a typical spectrum of each radiation form. Only gamma rays and neutrons are important in the shielding analysis since they are far more penetrating than alpha and beta particles. The weight of shielding is a function of:

1. Radioisotope source characteristics
2. Form the radioisotope is in, i.e., oxide, metal, etc.
3. Impurities in the radioisotope fuel form
4. System geometry
5. Dose criteria

Gamma rays result from a variety of sources, the most important of which are those generated directly by the decay of the radioisotope and those resulting from the decay of impurities in the radioisotope. Neutrons are emitted from spontaneous fission of the parent radioisotope and also as a result of the (α, η) reaction with low atomic weight elements in the immediate vicinity of the radioisotope. Table 2 presents the gamma ray source strength per thermal watt of the radioisotope, for various photon energies. The source strength of Pm-147 and Pu-238 is strongly affected by trace amounts of impurities. In the case of Pm-147, the decay is by emission of a 0.121 Mev γ ray which is easily shielded with about 0.150 inches of steel. However, present production grade promethium contains Pm-146 as an impurity in quantities ranging from 0.25 to 4 ppm, depending on the reactor used to produce the Pm-147. Pm-146 decays with emission of two gammas at 0.45 and 0.75 Mev, this higher energy gamma dictating the shielding requirements in the use of Pm-147 as a heat source.

TABLE 2

GAMMA RAY SOURCE SPECTRUM

Radioisotope	Photon Energy (Mev)	Photons/sec-watt			
1. Co^{60}	1.17	2.385×10^{12}			
	1.33	2.385×10^{12}			
2. Sr^{90}	0.25	1.71×10^{11}			
	0.50	6.61×10^{10}			
	0.80	1.96×10^{10}			
	1.10	6.10×10^{9}			
	1.40	1.65×10^{9}			
	1.70	3.03×10^{8}			
	2.00	2.08×10^{7}			
3. Ru^{106}	0.5	2.62×10^{12}			
	1.0	2.01×10^{11}			
	1.5	4.42×10^{10}			
	2.5	1.63×10^{10}			
	3.3	8.26×10^{6}			
4. Cs^{137}	0.66	6.39×10^{12}			
5. Ce^{144}	0.35	8.2×10^{11}			
	0.90	1.36×10^{11}			
	1.50	2.03×10^{10}			
	2.15	9.64×10^{8}			
	2.60	2.00×10^{7}			
6. Pm^{147}	0.12	3.1×10^{9}			
(with 0.25 ppm Pm^{146})	0.45	1.7×10^{7}			
	0.75	1.7×10^{7}			
7. Tm^{170}	0.2	7.5×10^{11}			
	0.5	5.0×10^{10}			
	0.8	1.16×10^{9}			
8. Po^{210}	0.8	1.45×10^{7}			
9. Pu^{238} (with 1.2 ppm Pu^{236})	Age	1 Day	1 Yr	2.5 Yr	5 Yr
	0.8	8.25×10^{5}	8.5×10^{5}	9.7×10^{5}	1.20×10^{6}
	1.5	1.2×10^{4}	1.27×10^{4}	1.67×10^{4}	2.46×10^{4}
	2.5	2.76×10^{3}	2.36×10^{4}	1.16×10^{5}	3.0×10^{5}
	4.0	3.5×10^{2}	3.5×10^{2}	3.5×10^{2}	3.25×10^{2}
	6.0	5.7×10^{1}	5.7×10^{1}	5.7×10^{1}	5.5×10^{1}
10. Cm^{242}	0.6	1.8×10^{5}			
	1.0	2.7×10^{5}			
	1.5	1.29×10^{5}			
	2.3	6.88×10^{4}			
	2.8	3.18×10^{4}			
	5.0	1.27×10^{4}			
11. Cm^{244}	0.8	1.98×10^{7}			
	1.5	4.86×10^{6}			
	2.5	1.61×10^{6}			
	4.0	2.50×10^{5}			
	6.0	3.88×10^{4}			

A similar condition exists for Pu-238 which contains small amounts of Pu-236 (about 1.2 ppm). This impurity is formed in the reactor during irradiation of Np-237 to produce the desired Pu-238; there is, therefore, no way of avoiding the formation of Pu-236 in a reactor. In most cases the impurity content of Pu-236 will determine the gamma shielding requirement in use of Pu-238.

Table 3 presents the neutron source strengths for the alpha emitters. In the case of Po-210, all the neutrons result from the (α, n) reaction with impurities in the fuel form. This indicates that reduction of impurities would reduce shield weight required. In the case of $Pu^{238}O_2$, 91% of the emitted neutrons result from the (α, n) reaction with the oxygen in the fuel form. The balance is from spontaneous fission. This (α, n) reaction takes place only with the O^{17} and O^{18} isotopes which occur in natural oxygen with an abundance of 0.037% and 0.204%, respectively. The O^{16} (99.759%) does not yield an (α, n) reaction. It has been shown experimentally that reduction in the O^{17} and O^{18} content in the oxygen will reduce the neutron source from the (α, n) reaction. An economic tradeoff will determine whether additional neutron shielding should be used or if oxygen depleted in O^{17} and O^{18} should be used.

TABLE 3

NEUTRON SOURCE STRENGTH

Radioisotope	Source Strength (n/sec-watt)	% of Neutrons from (α, n)
Po^{210}	3.22×10^3	100
Pu^{238}	5.18×10^4	91
Cm^{242}	4.0×10^5	46.5
Cm^{244}	4.55×10^6	3

For $Cm_2^{244}O_3$ the neutron source from the (α, n) reaction with oxygen represents only about 3% of the total neutron emission, the balance being from spontaneous fission.

Shown in Figures 3 and 4 are parametric shielding curves for Pm-147 and Pu-238. These curves neglect self-shielding and thus give conservative shield thicknesses; however, they are adequate for preliminary work. The thicknesses are plotted versus a shielding parameter DS^2/P, which in the case of Pu-238 is multiplied by F or (1-F). These terms are defined below:

F = Fraction of dose rate from gamma rays (Using F = 0.7 for Pu-238 will result in a minimum shield weight.)

D = Average dose rate, i.e., total integrated dose allowed divided by exposure time (mrem/hr)

P = Thermal power (watts)

S = Effective separation distance (ft)

These curves assume the radioisotope to be a point source, which is generally valid at separations greater than one foot.

For Pu-238, if FDS^2/P is less than 0.17 (assuming Pu-238 aging of 2.5 years) then the curves of Figure 4 can be used. If FDS^2/P is greater than 0.17 and the expression $(1 - F)DS^2/P$ is less than 0.61, no uranium shield will be required but the lithium hydride shield thickness should be determined by calculating the following expression:

$$(1 - F')\frac{DS^2}{P} = \frac{DS^2}{P} - 0.17$$

F' = effective fraction of dose from gamma rays. Using this expression, Figure 4 will yield the lithium hydride thickness.

The effect of impurities on shielding requirements can easily be seen from the promethium curve, Figure 3. The Pm-147 contribution to radiation dose is very important for very small shield thicknesses (~0.1 inch) with Pm-146 becoming the major contributor for larger shield thicknesses. This curve assumes 0.25 ppm Pm-146 which is the approximate impurity content contained in the promethium fuel currently available.

The effect of separation distance between the source of radiation and the sensitive item can be seen from the promethium curves, Figure 3, illustrating that shielding thickness decreases as the inverse square of this distance. Therefore, by proper integration of radioisotope heaters into the overall system, it may be possible to reduce dose rates without the weight penalty required for shielding. Additionally, any pieces of system hardware or structure interposed between the heater and receptor helps attenuate any radiation which may be emitted.

For gamma shielding, such as with Pm-147, the heavy metals such as tantalum, tungsten, molybdenum, uranium, or their alloys, represent the most effective shield materials. In many cases these same materials are used for the structural containment of the radioisotope. In order to minimize shield weight, the particular application should be examined to determine if additional shielding is required beyond that already afforded by the basic structure and if this additional shielding could more effectively be placed adjacent to the source or adjacent to the sensitive equipment item.

In the hardware fabricated to date, and fueled with Pm-147, the structure has been sufficient to provide an external dose rate below 5 millirem per hour at one foot. For example, a 2.5 watt unit yields a dose rate of about 2 mr/hr at one foot and weighs 0.5 lb. The structure/shield comprises about 0.32 lb of this total. Two 5 watt designs have been built, one weighing 0.37 lb yielding a dose rate of about 5 mr/hr at one foot and the other weighing 2 lb yielding about 0.5 mr/hr at one foot. In the latter unit, approximately 1.6 lb of the total constitutes the structure/shield. This heavier unit was designed to a very conservative dose criteria expressly for manned application with extended exposure.

Another technique which can be employed to reduce shield weight is to contour or sculpture the shield. In this approach the radioisotope fuel is located off-center in the shield block resulting in a higher dose rate in one direction than in another. This technique is used in the particular 5 watt unit shown in Figure 5 resulting in 3.5 mr/hr at one foot in the forward direction and 0.5 mr/hr at one foot in the rearward direction. Fabrication of a spherical heater rather than a cylindrical configuration would also reduce the shield weight.

One of the major considerations in designing a radioisotope heater for a system is determination of the radiation tolerance of surrounding equipment or personnel. Table 4 illustrates acceptable radiation dose levels for some selected components and man. The tolerance shown for humans is that defined by the AEC for an industrial radiation worker who labors in this environment all his life. This is a very conservative value and not truly representative of that which could be permitted in a mission application, such as space. For example, for the Manned Orbiting Laboratory studies, 20 rem per mission has been used as a reference. This compares with 5 rem per year for a man exposed to radiation for his entire working lifetime. The radiation tolerance of the other components shown in the table is very high and much greater than the dose which would be received from a typical radioisotope heating device.

TABLE 4

ACCEPTABLE RADIATION DOSE LEVELS

Man (Industrial Radiation Worker)	
Whole body	100 mrem/week 5 rem/year
Hands and feet	18.75 rem/quarter
Photographic Film	1 - 100 rads
Optical Glass	
General	10^3 - 10^5 rads
Special glasses	10^9 rads
Semi-Conductors	5×10^7 rads 10^{15} n/cm^2
Electronic Components	
(Vacuum tubes, resistors, capacitors, etc.)	10^7 rads 10^{15} - 10^{18} n/cm^2
Lubricants, Hydraulic Fluids, Greases	10^8 rads
Elastomers (Seals, gaskets, "O"-rings)	10^8 - 10^9 rads
Plastics	10^6 - 10^9 rads
Metals and Ceramics	Gammas: negligible effect Neutrons: $>10^{18}$ n/cm^2

Table 5 compares the dose rate from a typical radioisotope heater with the dose rate from other radiation sources. Note that at a separation distance of 10 feet, a ThermoPac heater is indistinguishable from earth background radiation.

V. Heater Design

The primary heater requirement is to provide a given thermal power output throughout the mission lifetime. This must be done within the aerospace constraints which place a premium on weight, size, and reliability. In addition, the heaters must be designed so as not to present an undue hazard under any normal or accident environment from the time of heater manufacture, through mission lifetime, to eventual heater recovery or disposal.

TABLE 5

COMPARISON OF THERMOPAC DOSE RATE WITH OTHER RADIATION SOURCES

Typical ThermoPac Dose Rate at 1 ft	5 mr/hr
Typical ThermoPac Dose Rate at 10 ft	0.05 mr/hr
Natural Background Radiation on Earth	0.06 mr/hr
Radium Watch Dial	0.5 mr/hr (local) (at wrist)
Chest X-Ray	5 - 70 mr/exposure
Dental X-Ray	250 mr/exposure
Dose to Supersonic Transport Occupants	0.5 - 1 mr/hr

In the vast majority of heater applications investigated to date, heater temperature requirements are very modest — usually about room temperature — and, due to the nature of the components requiring heat, the heater environment during normal operation is equally mild. Thus, heater design to date has been dictated by two considerations: (1) the desire to reduce the radiation dose to a point where no special handling is required during heater assembly into the spacecraft and subsequent operation (most heaters can be held briefly in the bare hand), (2) the desire to insure complete containment of the radioisotope fuel under any conceivable accident situation throughout design lifetime. Although neither of these criteria are absolute requirements, they greatly aid in the effective utilization of the heaters. In addition, it has been found that any heater designed to the above two criteria will provide power throughout any conceivable mission lifetime and environment with a reliability of 1.

Figure 5 is a photograph of a typical radioisotope ThermoPac heater. The heart of the heater is the radioisotope fuel. The factors affecting the fuel selection were discussed in Section III. The optimum chemical compound and physical form of the selected radioisotope is based on considerations of fuel compatibility, relative inertness of the fuel form, power density (watts/cc), and ease of assembly. For example, Pm^{147} is commonly used as sintered pellets of Pm_2O_3. This form has been demonstrated to be compatible up to 1000°C with a number of containment materials, is quite inert, has a melting point of 2270°C, and has an adequate power density. The sintered pellets are quite strong and can be readily handled in capsule assembly operations. Pu^{238} is ordinarily used as PuO_2 in the form of a powder composed of a relative uniform size of sintered particles (microspheres).

A typical ThermoPac heater is triple-encapsulated. The fuel is enclosed in a thin liner. The purpose of this liner is to provide compatibility with the fuel and to isolate the fuel to prevent contamination of the primary structural weld in the next stage of encapsulation. The liner is then enclosed in the structural clad. This structure serves several purposes. It shields the radiation to an acceptable level for ease of handling; it provides the necessary strength to withstand all normal operating and abnormal accident environments; in the case of alpha-decay fuels, it is the pressure vessel to contain the helium gas build-up within the heater. The refractory metals have been used almost exclusively for the structural container. Refractory metals such as tantalum, molybdenum, and tungsten ideally provide the necessary combination of effective shielding, excellent strength at design conditions, and outstanding strength and creep resistance in the event of high temperature accident situations. Depleted uranium may also be used. A full-penetration electron beam weld is used to seal this structural container.

The final encapsulation is an oxidation clad. As with the structural container, this cladding is multifunctional. It protects the refractory structure from oxidation in the event of a high temperature accident; it provides an additional seal for the radioisotope fuel; it provides the integration between the heater and the component requiring heat. The clad may be made of stainless steel, or Haynes, Hastelloy, or Inconel alloys. Since the clad normally does not contribute materially to the shielding or structural effectiveness of the encapsulation, it can be shaped into a great variety of configurations without affecting the basic properties of the heater. It also can be coated with an emissivity coating, contoured to provide effective conductive or radiative heat transfer, or designed for use in a coolant loop.

Since radioisotope heaters are not confined to any particular configuration nor require any external connections for power supply or control, they can be designed to any shape and for any location, irregardless of accessibility. Heaters can be designed as spheres for use inside ball valves, as cylindrical shells for bearings, as plates for radiators, as wires for wrap-around heaters, etc. A spherical heater is usually optimum from shielding, mechanical strength, and total weight considerations. However, a cylindrical heater of $L/D \simeq 1$ is only slightly heavier than a spherical heater and is much easier to fabricate. All sources fabricated to date have been of the cylindrical configuration. Figure 6 illustrates three such ThermoPac heaters with power levels (using $Pm_2^{147}O_3$ fuel) of 5, 2.5, and 2 watts (left to right).

Under certain aerospace applications it may be necessary to show that the heater does not present an undue hazard in the event it reenters the earth's atmosphere after mission completion. In these situations the current design philosophy is to provide for intact reentry of the radioisotope. This is accomplished by enclosing the heater within a reentry body. In its simplest form, this body is a layer of protective material placed immediately about the heater. Conventional charring ablators are ordinarily not suitable for this application due to their low thermal conductivity which inhibits the flow of heat during normal heater operation. Thus new reentry protection concepts and materials have been developed. One such concept is a composite composed of a sacrificial material, having a high heat of vaporization, which is enclosed in a metal matrix. During normal operation the metal provides adequate thermal conductivity and strength to the composite. During reentry the sacrificial material acts as a conventional ablator, absorbing the aerodynamic heating by its heat of vaporization.

A second concept is to enclose the heater in a thin hollow shell of graphite. The graphite is sufficiently conductive to effectively transfer the heater power during normal operation. During reentry the hollow shell greatly reduces the heater ballistic coefficient and corresponding aerodynamic heating. The aerodynamic heat input is simply re-radiated to space.

A continuing analytical, development, and test program is being conducted on reentry concepts, including arc jet testing at typical reentry heating rates. Table 6 presents typical reentry protection parameters for three concepts for protecting a 25 watt Pu-238 ThermoPac heater.

VI. Qualification Testing

The qualification effort conducted to date has been in support of the basic ThermoPac heater design goal — to fabricate heaters that will survive any conceivable normal or accident environment. This approach has two advantages: (1) the system designer need not concern himself with providing any special environment for the heater; he can be assured the heater will survive conditions far in excess of anything to be encountered in normal system operation, (2) assuring heater survivability under all accident situations greatly simplifies the safety analysis and assures a straightforward safety review and timely approval for use in the system.

The heaters previously shown in Figure 6 have passed the qualification tests shown in Table 7. The criteria used for survivability is that the fuel remain positively sealed within the heater by one or more of the claddings. The aerospace and man-rated heaters have passed all the qualification tests without any failures of any of the claddings.

The bolt heater was the original design concept to be developed and tested. The concept was that the bolt would be threaded into a structural member such as a strut or flange which would provide the desired mechanical protection for the bolt. This concept has now been put aside in favor of heaters which in themselves are strong enough to resist all mechanical forces. The aerospace and man-rated heaters represent this latter class of heater. Testing of the bolt did show the adequacy of stainless steel for thermal shock and high temperature resistance, however, and this material has been retained in the follow-on designs.

For the most part, the qualification levels of Table 7 are based on potential accident environments. An external pressure of 3000 psig is in excess of the pressure to be expected 50 feet from the center of a SV booster explosion. The vibration qualification is in excess of that experienced during the SV boost phase. The crush

TABLE 6

EXAMPLES OF REENTRY PROTECTION REQUIREMENTS

Basis: 25 watt radioisotope heater
Fuel – $Pu^{238}O_2$
Heater Shape – Spherical
Heater O. D. – 1.5 inches
Heater Weight – 0.8 pounds

	1	2	3
Type of Reentry Protection	Ablator	Ablator	Refractory Shell
Shape	Cylinder, L/D = 1	Cylinder, L/D = 1	Sphere
Reentry Protection Concept	Sacrificial material absorbs heat	Sacrificial material absorbs heat	Hollow shell lowers ballistic coefficient and heat input. Heat re-radiated.
Material	ZnO in Mo matrix	AlF_3 in Ni matrix	Graphite
Ballistic Coefficient (lb/ft^2)	100 (end on)	75 (end on)	20
Maximum Heater Wall Temperature During Reentry (°F)	~2800	~2200	~2200
O. D. of Heater With Reentry Protection (in.)	2.2	2.8	4.0
Total Weight of Heater With Reentry Protection (lb)	2.1	2.6	1.2

TABLE 7

THERMOPAC QUALIFICATION TESTING

	Bolt Heater	Aerospace Heater	Man-Rated Heater
Mechanical			
External pressure	3000 psig for 15 min	3000 psig for 15 min	3000 psig for 15 min
Vibration	-	1/2-in. DA 20-35 cps 30g 35-2000 cps	-
Crush	-	20,000 lb for 1 hr	23,000 lb for 1 hr All axis
Shear	-	-	10,000 lb across structural weld
Impact	-	120 ft-lb	120 ft-lb
Puncture	-	-	30 ft-lb on 1/8-in. diameter hardened steel pin
Terminal velocity impact	-	355 ft/sec into granite block	-
Thermal			
High temperature soak	2200°F in air for 1 hr	2200°F in air for 1 hr	1900°F in air for 1 hr
Shock	1700°F to -320°F	1700°F to -320°F	2000°F to room temperature water

test is in excess of the load to be expected should any mobile equipment or vehicle run over the heater. A 120 ft-lb impact (fall height times heater weight) simulates an accidental dropping of the heater from some considerable height. Terminal velocity impact simulates the heater falling as a free body from an airplane or spacecraft. The high temperature soak simulates the effects of an industrial fire, a jet aircraft fire, or a launch vehicle abort fireball. The thermal shock qualification simulates the maximum possible extreme that could be experienced in an industrial or launch abort fire. It is evident from the qualification testing conducted to date that radioisotope ThermoPac heaters of the present design will easily withstand any normal spacecraft environment with a reliability of 1.

VII. License Requirements

The manufacture, shipment, and use of radioisotope heaters is controlled by state and federal agencies. This control is exercised by the granting of radioactive material licenses which authorize the heater manufacturer to fabricate and ship the heater, and the user to accept, test and utilize the heater. If the heater is to be used on a spacecraft, launch approval is required from the Space Council. For example, AI receives its license to manufacture radioisotope heaters from the State of California, Department of Public Health. This license, written by AI and approved by the State, specifies the method of manufacture, materials and dimensions of encapsulation, weld requirements, leak check tests, decontamination procedures, etc. Through reciprocity agreements with other states, those heaters licensed by the State of California may be brought into and demonstrated in other states. Through a separate license with the USAEC, Division of Materials Licensing, approval is received to demonstrate the heaters in areas under federal jurisdiction. AI presently has State of California and AEC approval to demonstrate several of its heaters anywhere in continental United States. Sources are transported by cargo aircraft, train, truck, or personal auto.

The user of a radioisotope heater obtains a license to use the heater from either the AEC or his home state, depending upon jurisdiction. The user describes the conditions of heater storage, testing, and utilization in his license application. AI maintains on file with the AEC and State of California a description of the qualification testing the source has successfully passed, and the maximum environments the source may be exposed to. The user requirements are compared with the source description, and if compatible, a license is issued.

The value of a very rigorous qualification program may now be seen. Qualifying the heaters to extremes of mechanical and thermal environments greatly simplifies the user licensing procedure. The home state or AEC review agency is presented with a clear cut case and may give straightforward and timely approval of license applications. Within the past year, AI has assisted private companies, DoD agencies, and NASA agencies in obtaining user licenses. Review and approval has been straightforward and no technical difficulties have been experienced.

If a radioisotope heater is to be used on a spacecraft, the source manufacturer prepares a Safety Analysis Report. This report is reviewed by the nuclear flight safety offices of the AEC, NASA, and DoD. Their recommendations are forwarded to the Space Council for final launch approval. Again, an adequate heater qualification program, demonstrating substantial margins of safety under all situations, will ensure a straightforward review and timely launch approval.

VIII. Applications

The spacecraft designer faced with a requirement for heat has at his disposal several means to provide this heat. These include primary batteries, a system of solar cells plus secondary batteries, or a radioisotope heater. These candidates must be compared on the basis of system weight and volume allowances, cost to the total mission or system to employ the particular concept selected, the reliability requirements, and the degree of accessibility of the heating device. The relative importance of these criteria will vary with each particular application. Furthermore, these criteria are often not mutually exclusive. For instance, reliability of electrical heating systems can be improved with appropriate incorporation of redundancies which may be reflected in increases in both system weight and cost. System weight can also be translated directly into dollars as illustrated by a succeeding example. In some applications, inaccessibility may be an overriding design consideration. An inaccessible ball valve in a cryogenic system may require heat to prevent freeze-up. Electrical heaters require wires and adequate redundancy. On the other hand, the valve may be designed to incorporate a radioisotope heater which does not require accessibility and which will produce heat with 100% reliability.

To compare the cost of radioisotope heaters with electrical heaters, assume a satellite in which 20 watts of continuous thermal energy is required. With today's technology in solar power systems, it would take approximately 25 lb of solar array, rechargeable batteries, charging equipment, heaters, wiring, redundancies, etc., to provide this 20 watts. Using a solar cell packing factor of 400 cells/ft^2 and cost of $14 per cell installed, yields $17,000 for array. The cost of batteries plus the balance of the heater system might be expected to raise this cost to about $20,000 to $25,000. Using $3,000 per pound in orbit as typical of Atlas/Agena or Atlas/Centaur vehicles, this 25 lb system could be placed in orbit for $75,000. The total cost to the mission to use this solar cell/battery heating system is therefore very close to $100,000.

A radioisotope ThermoPac heater to provide this 20 watts would weigh about 2 lb and cost approximately $15,000 to $20,000. At the same launch cost of $3,000 per lb, the total cost to use radioisotope heaters is about $25,000 or one-fourth that of its more conventional competition.

Another application for which a radioisotope heater was designed involved an electronics package requiring 10 watts of heat to permit its operation under low temperature conditions. The package was to be man-carried into the field and deployed, unattended for a period of 3 months. The conventional manner of providing the required heat would be with primary batteries, some performance data for which is shown in Table 8. Employing primary silver zinc cells would require about 300 lb of batteries, far in excess of what one or two men could pack into the field. The five watt ThermoPac unit pictured in Figure 5 weighing 2 lb was designed and built for just such an application, the weight savings being very apparent.

TABLE 8

BATTERY PERFORMANCE

	watt-hr/lb
Primary	
Leclanche (C-Zn)	20 - 30
Mercury	40 - 50
Ag Zn	50 - 80
Ag Cd	20 - 50
Secondary	
Automobile (Pb Acid)	12 - 15
Ag Cd	25 - 35
Ag Zn	50 - 55
Ni Cd	10 - 15

The radioisotope heater is essentially a constant power device, generating its power continuously regardless of the environment. For some mission applications, such as interplanetary probes, this constant power, completely static heater system may be acceptable. There are other mission applications in which a temperature sensitive piece of equipment may be alternately exposed to environmental conditions of high and low temperature, which may be an intolerable situation. An example of this latter application may be a lunar surface experiment which is required to function or survive both lunar day and lunar night. In this case, the heater must be supplemented with a preferential heat dissipation device which will dump the heat during the lunar day but be inactive during cold night hours.

In systems where the total thermal output of the heater can continuously be utilized by the system, integration of the heater(s) into the system is fairly straightforward. In the simplest integration case, the heater may be affixed directly to the component requiring heat, transferring its thermal energy by conduction. In this case, heat transfer is accomplished with the same high reliability with which the heat is generated, an ideal situation. If the heat requirement is large, it may be necessary to determine whether it can better be provided by one large heater or several smaller capsules. Minimum weight favors a single capsule over a distributed source since concentrating the radiation source reduces the weight of shielding and structure required. Economics also favors a single source as there are fewer manufacturing operations.

There may be situations where it is not possible to provide heat by direct conduction to the component requiring it. In this case the thermal energy may be transferred by radiation or convection. Convective means include fluid transport and heat pipes. Such thermal energy transport methods also can be employed for applications wherein the heat is only intermittently required.

Two non-fluid techniques which may be used to provide selective dissipation are shown conceptually in Figure 7. These two schemes were examined for an application wherein a radioisotope heater was to maintain a group of electrochemical cells within a temperature range, where a specified electrical performance could be obtained, during extreme variations in ambient temperature — between -65°F and 160°F. The amount of thermal power which could be incorporated into the heater was limited by that which could be effectively dissipated at the high ambient temperature. The scheme depicted in the upper picture employs a change in the effective emissivity to regulate the amount of heat which is dissipated by a combination of radiation and natural convection. This is accomplished by sliding a slotted plate over the face of the box on which is painted alternate stripes of high (ϵ = 0.9) and low (ϵ = 0.1) emissivity coating. The plate is completely coated with the low ϵ coating. The result is that at low ambient temperatures, the entire face shows ϵ = 0.1, while at high temperatures, the face is about 40% ϵ = 0.9 and 60% ϵ = 0.1. Lateral motion of the plate is controlled by a pivoted lever actuated by a fluid-filled bellows and piston. This actuator is inserted within the matrix of cells and is filled with a fluid which expands at the higher temperature limit, thereby causing the lever to move the plate to a position where the face appears to be 40% ϵ = 0.9. The sides of the battery box are insulated to prevent heat loss.

The lower picture of Figure 7 illustrates another scheme, in which a fluid activated piston moves a plate, on which is mounted the heater, either into contact with the cells or into contact with the containment box. When in contact with the cells, an insulating air gap exists between the plate and box and almost the entire heater output is conducted to the cells. When the cell temperature rises to the upper limit, fluid expansion forces the piston to move the thermal plate across the air gap and into contact with the box. The heater output is then conducted directly to the box from which the thermal energy is dissipated by natural convection and radiation. The heat dissipating face of the box is covered with a coating for which ϵ = 0.9. With this scheme, approximately 3.6 watts of radioisotope heat can be dissipated at the 160°F ambient condition without having the cells exceed their upper operating limit of 190°F. When the ambient drops to -65°F, the battery will be at about -17°F.

If dissipation is permitted from both faces of the battery box and using this latter thermal-plate scheme, approximately 7.2 watts of thermal power will maintain the battery at a temperature of +15°F when the ambient drops to -65°F. The dissipation is also sufficient to preclude the battery from exceeding 190°F in an ambient of 160°F. Use of forced convection cooling and dissipation by conductive means would improve thermal performance but were excluded in the brief examination made.

TABLE 9

EXAMPLES OF RADIOISOTOPE HEATER APPLICATIONS

Area of Application	Problem	Solution
Restartable spacecraft engines.	Propellant freezes in lines and valves during engine-off periods.	Individual heaters used on propellant line support brackets to limit heat loss through bracket to spacecraft.
Catalytic bed thrustor for spacecraft.	Catalytic bed cools, resulting in unacceptable delay in ignition.	Heater buried in center of catalytic bed maintains proper temperature at all times without external control.
Existing spacecraft being considered for expanded mission.	Additional thermal power required for long periods. Conventional methods of supplying additional power require extensive redesign and requalification.	Heaters used for spot application of heat. No redesign or requalification required.
Electronics package for remote terrestrial locations.	Package requires thermal power for proper operation of electronics. Size and/or weight restrictions prevent use of conventional power source such as batteries.	Heater placed inside insulated electronics package. Absolute reliability, long life, low size and weight.
Dormant space stations to be occupied at later time.	Freezing of critical components such as instrument bearings.	Heaters located in bearings, or in bearing lubricant reservoir.
Experiments on surface of moon.	Experiments freeze or inoperative during lunar night. Batteries inadequate at nighttime temperatures.	Use radioisotope heaters to heat experiments directly, or to heat battery and raise efficiency.
Quick start-up avionics gear.	Inadequate performance at low temperatures. Onboard power supply inadequate.	Self-contained heater with capability to maintain desired temperature with absolute reliability, having an operational lifetime of several years.

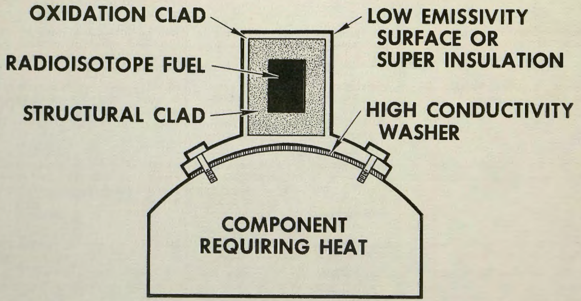
TABLE 10

TYPICAL RADIOISOTOPE HEATER CHARACTERISTICS

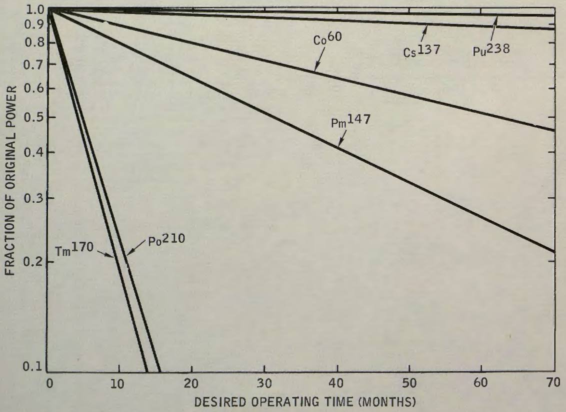
Heater Power (watts)	Radio-isotope Fuel	Radiation Dose Rate at 1 Foot (MR/Hr)	Heater Size (in.)	Heater Weight (lbs)
2.5	$Pm_2^{147}O_3$	2	Cylinder 0.5 OD x 0.5 L	0.5
5	$Pm_2^{147}O_3$	3.5	Cylinder 1.1 OD x 1.5 L	0.8
5	$Pm_2^{147}O_3$	5	Cylinder 0.76 OD x 1.25 L	0.3
10	$Pm_2^{147}O_3$	2.5	Cylinder 1.3 OD x 1.3 L	2
30	$Pm_2^{147}O_3$	10	Cylinder 1.5 OD x 1.5 L	3
30	$Pu^{238}O_2$	5	Sphere 1.6 OD	0.8
30	$Tm_2^{170}O_3$	10	Cylinder 2.5 OD x 2.5 L	42
55	$Pm_2^{147}O_3$	10	Cylinder 2.0 OD x 2.0 L	10

Several potential applications in which the use of a radioisotope heater may provide the most effective solution, are summarized in Table 9. These areas of application have been studied in considerable detail and heaters have been designed for several of them. Table 10 shows typical ThermoPac heater characteristics, primarily oriented toward space applications. One of these heaters, the 5 watt, 0.3 lb device, was designed to warm the catalytic bed of a small restartable attitude control thrustor for spacecraft. This heater is shown in Figure 8 integrated with the catalytic bed support members.

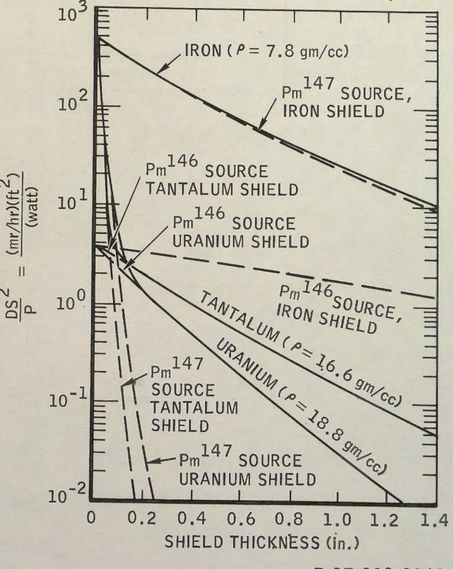
HEAT SOURCE CONCEPT



POWER DECAY WITH TIME FOR VARIOUS ISOTOPES

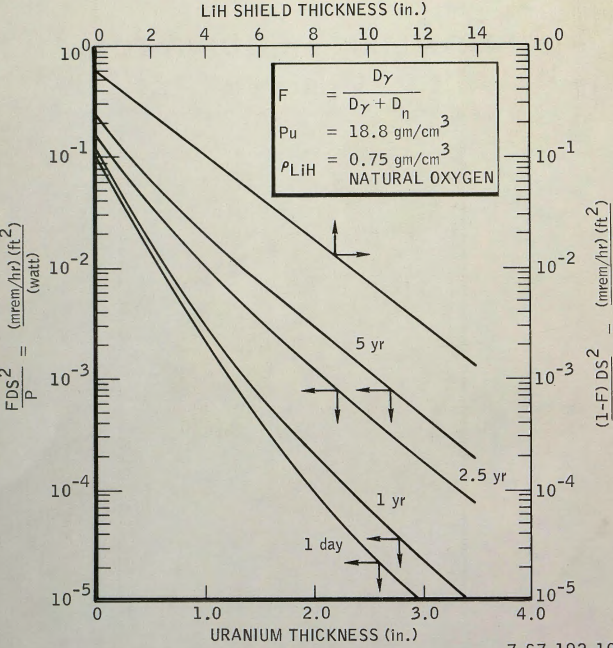


PARAMETRIC SHIELDING FOR Pm^{147} WITH 0.25 ppm Pm^{146}, NO Pm^{148}



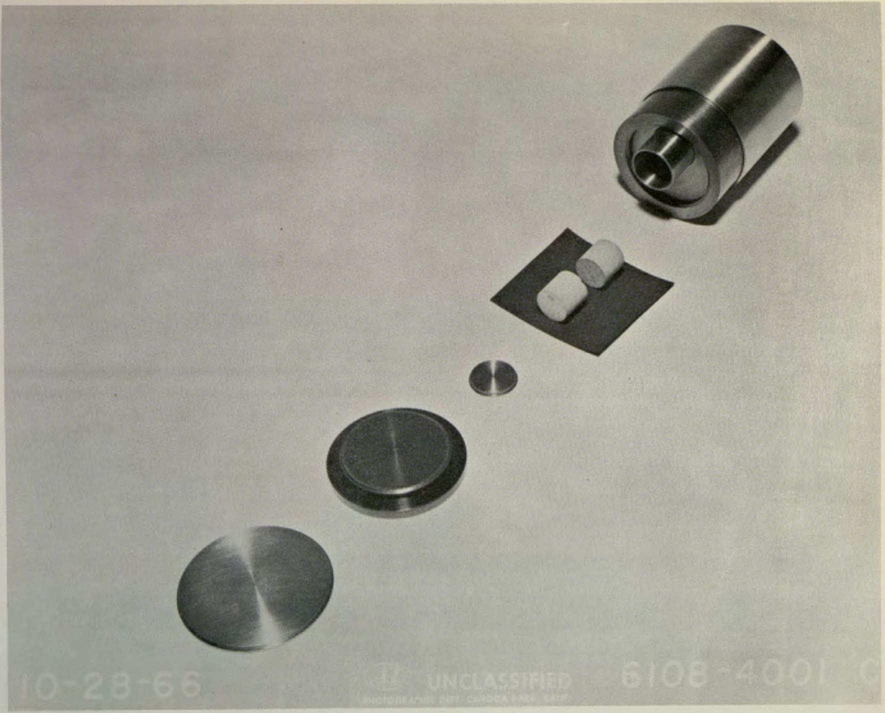
7-S7-192-106A

PARAMETRIC SHIELDING FOR Pu^{238}



7-S7-192-108

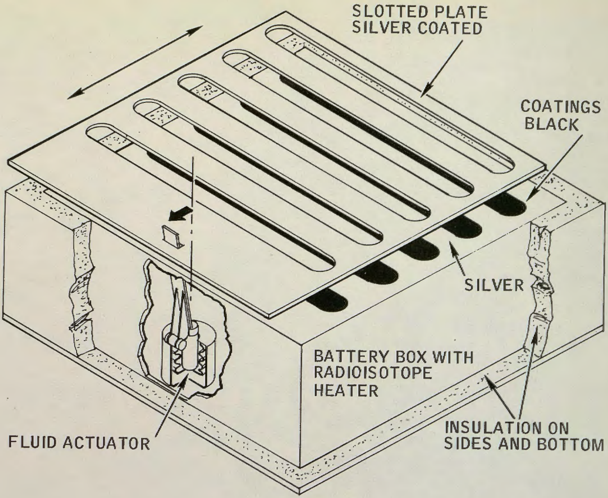
17.4-15

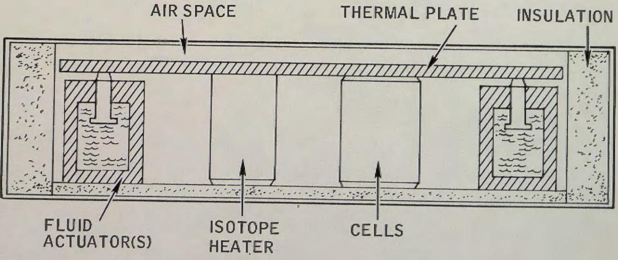


5. Components of 5 watt Heater Assembly

6. Typical ThermoPac Heaters

17.4-16

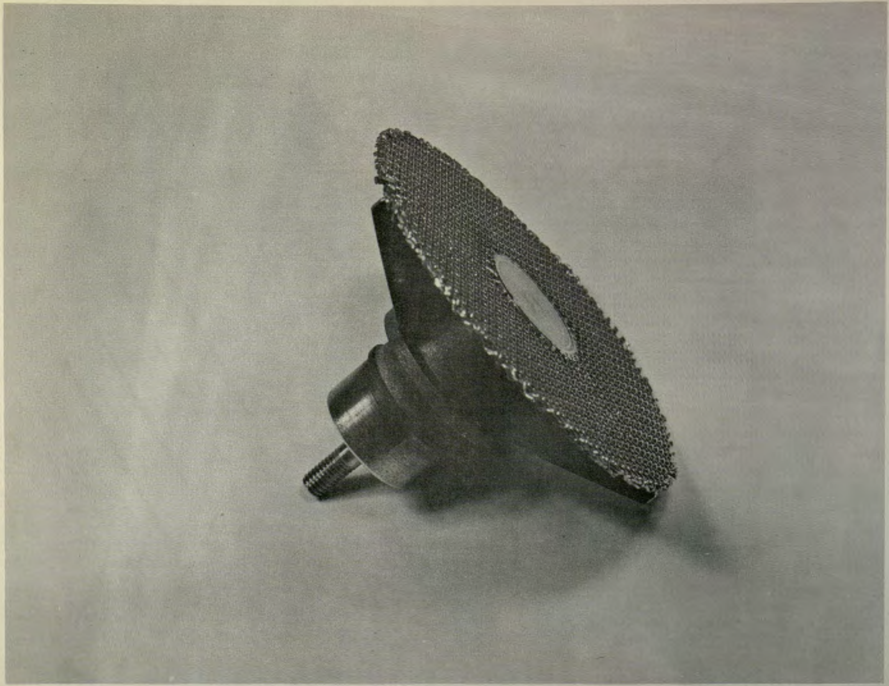




1-9-68 UNCL

6108-4041

7. Thermal Modulation Devices for Radioisotope Heaters



17.4-18

8. ThermoPac Heater for Catalyst Bed Heating