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RADIOISOTOPE HEAT SOURCE DEVELOPMENT FOR AN ARTIFICIAL HEART DEVICE

PHASE I FINAL REPORT

APRIL 1973

Prepared for
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DIVISION OF APPLIED TECHNOLOGY
OFFICE OF ISOTOPES DEVELOPMENT
CONTRACT AT(04-3)-858

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ABSTRACT

Detailed parametric analyses of vented radioisotope heat sources were performed to arrive at a design optimized in weight, volume, and safety. The top rated system was a single-layer Hafnialloy heat source. Due to limited mechanical property, compatibility, and heat source test data available for this material, however, the three-layer Pt-20Rh/T-111/Pt-20Rh design, which rated next highest, was selected as the baseline design. The heat source, 0.984 inch in diameter by 1.795 inches long, contains 33.1 watts of electro-refined PuO_2 and weighs 0.62 lb. A nonselective pressure relief device/capillary assembly is connected between the noble metal liner and clad to allow venting of the helium gas generated by fuel decay and also to allow decay of the generated radon-220 gas to allowable levels.

Pressure relief device tests verified its flow stability and fuel fines retention capability. Radon attenuation tests indicated a 0.001-inch I.D. capillary is required to reduce the radon levels to acceptable levels if it is assumed that all generated radon is released from the fuel.

Safety design verification tests, including granite impact, bullet impact, crushing, fire, and post-accident oxidation, indicated both the baseline and Hafnialloy designs to survive all accident environments except one by containing the fuel simulant in at least one totally integral capsule component. Neither design was capable of containing the fuel simulant under a 2000 ft-lb 30-06 rifle bullet impact. Further studies in this area as related to heat source design are required.

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1. INTRODUCTION

This report summarizes the development of a radioisotope heat source to be used as the energy source for an artificial heart device. The program was sponsored by the Atomic Energy Commission, Division of Applied Technology, Office of Isotopes Development, under Contract AT(04-3)-858. The program was initiated in April, 1971, and was completed in April, 1973. The purpose of the program was to analyze, design, and develop a vented radioisotope heat source, optimized in weight and volume and consistent with established nuclear safety criteria and the end-use environments and constraints. Successful completion of the program was to include the delivery of three fueled heat sources for use in the practicability evaluation of a thermal converter system for an artificial heart device. This work was to serve as the basis for more detailed analyses and tests with the ultimate objective of quantity production of a power source for a clinically useful cardiac prosthesis.

A summary of the program is given in Section 2 of this report. The results of a materials survey and parametric analyses, and the safety criteria, design selection, and final design are described in Section 3. The fabrication of piece parts and heat source assembly are described in Section 4, and the results of the vent tests and the heat source design verification safety tests are described in Sections 5 and 6, respectively.

The study was conducted under the direction of Dr. H. Lurie. Messrs S. E. Bramer, E. L. Nezgoda, R. W. Northup, T. H. Smith and A. J. Steinberger, and Mesdames G. Gold and C. McGuire contributed significantly to this effort. Special thanks are also due to Mr. W. Holman of the AEC's Division of Applied Technology for his many helpful suggestions throughout the course of the program and for his careful review of this manuscript.

2. SUMMARY

The heat source for an artificial heart device must satisfy a large number of design constraints while utilizing near-term state-of-the-art materials and fabrication processes. The primary design constraint is the requirement to provide complete isotope containment during long-term operation and during potential accidents. Nuclear safety criteria include the ability of the heat source to survive impact (simulating an airplane crash or train collision), bullet impact, fire, crushing (multi-ton load), and long-term exposure to oxidizing environments. To allow fuel decay to negligible levels, the heat source should be able to contain the fuel for approximately 1000 years (~ 10 half-lives).

Alternate heat source designs were studied as a function of geometry, diameter, material choice, helium venting system, internal void volume, radioisotope thermal inventory, and cost. The purpose of these studies was to arrive at an optimum heat source design. The optimum heat source had earlier been defined as one having a proper balance of minimum volume and weight, environmental operational capabilities, metallurgical stability, satisfactory thermal converter interfaces, satisfactory nuclear safety characteristics, low cost, high reliability, and design flexibility. Relative weightings were assigned to these criteria.

The requirement that had the strongest influence on the design was the fragmentation resistance safety requirement. Impact by a high-velocity 30-06 bullet was the most severe fragment considered during a study of the environments to which the heat source might be exposed. The thicknesses of the candidate materials required to withstand the 30-06 bullet impact were experimentally determined in preliminary tests and were found to be strongly dependent on both the material and capsule diameter. Based on detailed parametric analyses of spherical and flat-ended or hemispherically-ended cylindrical designs of three-layer, two-layer, and single-layer construction, optimum heat source designs were selected for the 1350° and 2000°F applications under consideration. The top-rated system in each case was a

single-layer, nonselectively vented Hafnalloys* heat source. Due to limited compatibility and fabrication data for this material, however, this system was not recommended as the baseline design for the current program. The next highest rated system was the Pt-20Rh/T-111/Pt-20Rh design having a nonselective vent.

A detailed design of the heat source was generated based on the requirements of the thermal converter system. The heat source is flat-ended, 0.984 inch in diameter, 1.795 inches long, and contains 33.1 watts of PuO_2 . The maximum operating temperature is 1565°F. The weight of the unit is 0.62 lb. The Pt-20Rh liner is 0.020 inch thick and contains a nonselective pressure relief device (PRD). The T-111 strength member, originally sized to survive a 30-06 rifle bullet impact, is 0.095 inch thick. The Pt-20Rh clad is 0.015 inch thick. A capillary tube is welded to the PRD, routed through a clearance hole in the strength member, and is welded to the bottom of a recessed chamber in the clad. A second coiled 4-inch long capillary tube lies in this chamber with one end open to the chamber and the other brought through the clad wall and seal welded. The strength member is thus completely sealed and protected from contamination by either the fuel or the external atmosphere. In addition, the combination of PRD and capillary coil reduces the radon-220 emitted by the heat source to acceptable levels.

Liner, PRD, strength member, and clad components, and thoria and alumina fuel simulants were fabricated for use in weld development and fabrication of simulant-fueled test units. The three units fabricated for use in bench model tests of the thermal converter system were fueled with pressed and sintered medical grade plutonium-238 dioxide pellets produced by Los Alamos Scientific Laboratories. Both the simulant-fueled test units and the PuO_2 -fueled units were assembled by Mound Laboratory, Monsanto Research Corporation. To assess the applicability of Hafnalloys to the artificial heart application, Hafnalloys units, also sized to contain 33.1 watts of PuO_2 , were fabricated. Since the capsule wall thickness required to survive bullet impact was not

*A hafnium-based alloy which has a unique combination of good high-temperature strength and oxidation resistance, now under development for radioisotope space power applications.

well defined for Hafn alloy, two different wall thicknesses (0.140 and 0.115 inch) were employed.

The heat source venting system was subjected to tests to verify flow stability, fines retention capability, and radon permeation characteristics. Helium flow was extremely stable over 2000 hours at 1565°F and extensive testing of six PRD's indicated complete retention of fuel fine particles. The 0.005 inch I.D. capillary was not effective in reducing radon levels appreciably. However, a smaller-sized capillary was extremely effective and allowed reduction of radon levels to below the maximum allowable values. Radon attenuations of 10^{-6} are obtainable with a PRD/capillary system compared with an attenuation of 2×10^{-3} with a PRD alone.

Both the baseline design and Hafn alloy test units were tested at TRW to verify the design and demonstrate the ability of the heat source to survive typical accident environments. To verify the ability of the heat source to survive the crash of an airplane or the head-on collision of two trains, test heat sources were subjected to granite impact at 216 ft/sec at the maximum operating temperature of 1565°F. To test the ability of the heat source to survive accidental or deliberate shooting, units were impacted by 30-06 rifle bullets at various energies and by a 45-caliber hand gun at point-blank range. Crushing and fire survivability were verified by subjecting test heat sources to a static 5000-lb load while resting on concrete, and to a 2500°F fire for two hours, respectively. Finally, three units previously subjected to impact and bullet impact were subjected to long-term oxidation tests at typical post-accident temperatures of 1000° and 1300°F.

Both baseline design and Hafn alloy heat sources demonstrated the ability to contain fuel under all test environments except that of 30-06 rifle bullet impact at 2,000 ft-lbs (2210 ft/sec). The baseline design survived a 900 ft-lb impact (1500 ft/sec) and the Hafn alloy units survived 650 to 800 ft-lb impacts (1270 ft/sec to 1420 ft/sec) depending on wall thickness. Both the baseline and Hafn alloy units survived impact of a 45-caliber bullet without capsule breach. Minor hairline cracks occurred in two baseline capsule clads during granite impact and in one baseline clad during crush tests. All other units survived intact. Such cracks did not affect fuel simulant containment since one oxidation resistant member (the liner) was always completely intact. Both baseline and Hafn alloy units also successfully

resisted the short-term high-temperature fire environment. In the case of the long-term post-accident oxidation tests where the cladding was deliberately breached on the baseline design, rapid oxidation of the T-111 occurred but the noble metal liner remained undamaged. Similarly, the Hafnialloy heat source, though somewhat oxidized on its outer surface, remained completely intact through the oxidation tests. In summary, all established nuclear safety criteria were met except that of bullet impact. This criterion must be reviewed for validity; if it is determined to be valid, the design of the heat source will need to be modified to survive this criterion.

3. HEAT SOURCE DESIGN

3.1 SAFETY CRITERIA

Foremost among the artificial heart heat source design constraints is the requirement to provide complete isotope containment, not only during long-term exposure to operating environments but also during potential accidents which could occur during, or at the end of, the proposed minimum 10-year life of the artificial heart. Fuel containment during normal operation of the artificial heart system will be assured by proper selection of materials and design, as discussed in Section 3.2 below. To assure complete containment of the fuel during potential accident environments, these environments must be identified, worst case conditions must be defined, and tests must be performed to verify heat source survivability under such conditions.

The selected safety criteria must be sufficiently comprehensive and sufficiently representative for all possible adverse accident environments. Since for the purposes of this study there were to be no activity limitations on the recipient of an artificial heart, all facets of human behavior and accidental and deliberate deaths were considered in establishing the environments during which the radioisotope fuel must be contained. The only limiting constraint in establishing such environments was the concept of credibility, or the probability of occurrence of a certain event.

The various potential accidents to which the artificial heart heat source may be exposed were divided into five separate categories: impact, fragmentation, fire, crushing, and oxidation/corrosion. An artificial heart heat source must, as mentioned above, be capable of surviving these environments at any time during, or soon after, its 10-year service. Survivability is defined as completely containing the fuel by having at least one heat source shell integral. In addition, that integral shell must remain intact and contain the fuel in air at the bare heat source equilibrium temperature. To allow the fuel to decay to negligible levels, containment of the fuel for ten half-lives in air is desirable.

3.1.1 Impact

A variety of possible accident events, specifically those associated with the crash of an airplane against a mountainside, head-on collision of fast moving trains, and automobile accidents, were examined in the process

of identifying the worst possible impact environment to which the artificial heart heat source may be exposed. An airplane crash was considered likely to be the most severe impact environment, and all other impact events were related to the airplane crash for comparison.

A great variety of airplanes exists and many types of crashes could occur. In a first attempt to generalize to a single impact environment, the minimum performance standard for the commercial aircraft flight recorder was examined (Reference 1). The impact requirement for the flight recorder is essentially the ability to remove the recorded data from the tape, rather than have the container survive, assuming a half sine wave impact shock is applied in each of the three main orthogonal axes with a 1000g peak deceleration of a duration of at least 5 milliseconds. The origin of this environment could not be ascertained and the environment cannot be correlated with specific accident events without either applying several gross assumptions or considerable analysis and test. Furthermore, the location of the artificial heart heat source within the body of the recipient will definitely reduce this impact shock environment. Therefore, this generalized criterion was rejected in favor of duplication of a more specific accident event which can be directly related to occurrence probabilities, and subsequently risk.

Commercial jet planes today travel at air speeds of up to about 500 mph while cruising, and ground speeds of 700 mph are not uncommon on transcontinental flights. Most aircraft crashes occur during the takeoff and landing phases, when velocities are considerably lower. Nevertheless, the lower probability but significantly more severe impact environment caused by an aircraft crashing into a mountainside at cruising speed was chosen for detailed analysis. The heat source will, of course, be contained within the body of the artificial heart recipient inside the aircraft at the time of the crash. Bare heat source impact at terminal reentry velocity was not considered because cases where the body is completely blown apart at high altitude, such as could happen if the person were to detonate a bomb in his lap, were not considered at this time to be reasonable accident events.

Drawings of the Boeing 747 were obtained from the manufacturer to examine the intervening materials between the heat source and the mountainside.

The Boeing 747 was selected because the forwardmost passengers probably have less material between them and the nose of the aircraft than with any other commercial jet in service today and because the future projected usage of the Boeing 747 for transcontinental (i.e., over land) flights is very high. Selection of the Boeing 747 in no way reflects on its reliability since numerical probabilities of occurrence were not a part of this study.

Two important considerations must be taken into account. First, a considerable amount of energy may be absorbed by the intervening material between the heat source and the impact medium such as a mountain. Secondly, the actual impact medium will be the forward wall of the aircraft, which is, in turn, backed by the rock of the mountain. In the case of the Boeing 747, very little energy would be absorbed by the intervening material because most of the material is already in sheet form (aluminum), with the exception of the fiberglass honeycomb in the Radome. Consequently, the reduction of heat source energy by intervening material deformation was neglected.

To retain the concept of a more standardized impact environment than that unique to a particular aircraft, an analytical conversion was made from the impact velocity of 700 mph (1027 ft/sec) against the aircraft materials backed by rock to the velocity associated with just bare granite. Such a conversion would also allow testing at a velocity lower than that of the actual crash with an impact medium of bare granite, thereby eliminating the need to simulate the aircraft forward wall. Straightforward, but approximate, analytical relationships for stresses generated in impacting bodies were used to determine the equivalent velocities. However, design of the impact medium was first examined to determine whether sufficient aluminum will be present between the capsule and the rock to cause the medium to act essentially as an infinite aluminum block rather than a complicated combination of aluminum and rock. For the rock to have a negligible effect on the capsule, the capsule must not penetrate the aluminum and the energy transfer from the high deformation zone, in the form of a transient compression wave, must closely approximate the transfer in aluminum only.

Approximate penetration equations for nearly rigid projectiles (the capsule) impacting plastic, semi-infinite targets (aluminum) have been developed assuming that the volume of the crater produced is directly proportional to the kinetic energy of the projectile (Reference 2):

$$v = K (1/2 mV^2) = 2/3 \pi r^3 + \pi r^2 h$$

$$s = r + h = \frac{K(1/2 mV^2)}{\pi r^2} + \frac{r}{3}$$

where

v = crater volume

m = projectile mass

V = projectile velocity

K = constant (material dependent)

r = projectile radius

Using a value for K for aluminum of $0.45 \times 10^{-4} \text{ in}^3/\text{ft-lb}$ (Reference 2), a capsule weight of 0.6 pound, a radius of 0.5 inch, and an impact velocity of 1027 ft/sec, a penetration of 0.72 inch is predicted. Since a total of more than one inch of aluminum is present in the forward section of the aircraft, the capsule will not penetrate the aircraft wall.

As the transient compression wave passes the interface between the aluminum and the granite, some of the energy of the wave is reflected and some will continue into the granite. The intensity of the reflected wave relative to the incident wave is given by (Reference 2):

$$\frac{\sigma_R}{\sigma_I} = \frac{\rho_1 C_1 - \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2}$$

where

σ_R = amplitude of reflected stress wave

σ_I = amplitude of incident stress wave

ρ_1 = density of aluminum = $.098 \text{ lb/in}^3$

ρ_2 = density of granite = $.097 \text{ lb/in}^3$

C = sonic velocity in material = $\sqrt{\frac{E}{\rho} \frac{1-\nu}{(1+\nu)(1-2\nu)}}$

E_1 = modulus of elasticity of aluminum = 10^7 psi

E_2 = modulus of elasticity of granite = $7 \times 10^6 \text{ psi}$

ν_1 = Poisson's ratio of aluminum = $.3$

ν_2 = Poisson's ratio of granite = $.28$

Using the above values, the ratio of the reflected wave amplitude to incident amplitude is 0.1. That is, ninety percent of the wave energy continues through to the granite and only ten percent is reflected. Impact effects on the capsule can therefore be considered dependent only on the aluminum properties and not on those of granite, and an equivalent granite impact velocity can be determined.

The dynamic stress in the capsule strength member during impact with a non-yielding medium (granite) may be approximated by (Reference 2):

$$\sigma_p = \rho_p C_p V$$

where the subscript p refers to the projectile moving at velocity V. During impact on a non-rigid medium (aluminum), the impact surface will deform. Assuming this velocity of deformation to be v_2 and assuming the origin of the frame of reference to be on the impact surface, the velocity of the projectile relative to this frame of reference is $v_1 = V - v_2$. Assuming, furthermore, that the area of contact between the two objects is constant, the dynamic stress in each material will be the same. Thus,

$$\sigma_p = \sigma_{Al}$$

$$\rho_p C_p v_1 = \rho_{Al} C_{Al} v_2$$

$$\frac{v_1}{v_2} = \frac{\rho_{Al} C_{Al}}{\rho_p C_p}$$

and

$$\frac{V}{v_1} = 1 + \frac{v_2}{v_1} = 1 + \frac{\rho_p C_p}{\rho_{Al} C_{Al}}$$

$$v_1 = \frac{V}{1 + \frac{\rho_p C_p}{\rho_{Al} C_{Al}}}$$

The stress in a projectile impacting a non-rigid target is thus

$$\sigma_p = \rho_p C_p v_1 = \frac{\rho_p C_p V}{1 + \frac{\rho_p C_p}{\rho_{Al} C_{Al}}}$$

The above equations can now be used to determine the required granite impact velocity which will result in a dynamic stress equal to that generated by impact against aluminum at 1027 ft/sec.

$$\sigma_p]_{\text{granite}} = \sigma_p]_{\text{aluminum}}$$

$$\rho_p C_p V_{gr} = \frac{\rho_p C_p V_{Al}}{1 + \frac{\rho_p C_p}{\rho_{Al} C_{Al}}}$$

$$\frac{V_{Al}}{V_{gr}} = 1 + \frac{\rho_p C_p}{\rho_{Al} C_{Al}}$$

Using the properties of T-111 for the projectile ($\rho = 0.604 \text{ lb/in}^3$, $E = 25 \times 10^6 \text{ psi}$, and $\nu = 0.3$), a velocity ratio of 4.9 between aluminum and granite impact is obtained. An impact velocity of 210 ft/sec against granite is thus roughly equivalent to impact at 1027 ft/sec (700 mph) against aluminum.

A similar analysis was performed for a train crash, assuming a train velocity of 175 mph and a passenger in the forward compartment impacting the steel engine. The equivalent impact velocity against bare granite is 108 ft/sec, considerably less severe than the airplane crash. If, however, a head-on collision of two trains is assumed, each travelling at 175 mph, an effective impact velocity of 350 mph is obtained. The equivalent granite impact velocity is thus 216 ft/sec. A considerable amount of energy will be absorbed by the train itself and the actual equivalent velocity will be considerably below 216 ft/sec, but it is difficult to estimate this energy and it was therefore ignored.

An investigation into automobile crash literature was also performed to determine the most severe impact environments encountered and the methods of analysis developed to date. Although the forward portion of the automobile may have a peak deceleration of more than 250 g's, the passenger compartment for the same crash has a peak deceleration in the vicinity of only 25 g's. The head may also experience high decelerations at the time of

impact with the dashboard, but the torso, and hence the heart system, will generally experience decelerations similar to those of the passenger compartment. The most severe automobile impact environment for the heat source would thus be considerably less severe than in the airplane or train crashes.

The selected impact environment which the artificial heart heat source must survive is, therefore, a 216 ft/sec impact, at any orientation angle, against a rigid medium such as granite, while at the in-vivo operating temperature.

3.1.2 Fragmentation

The most severe fragmentation environments other than bullets to which an artificial heart recipient may be exposed are those associated with exploding gas bottles or pressure vessels. Rarely are civilians exposed to exploding high explosive shells or hand grenades. However, bullet impact, especially from a high-powered rifle, is much more severe than any of the above fragmentation environments, and consequently such impact was selected to represent the fragmentation environment.

Data were collected on various bullet types, velocities, and energies for most types of cartridges and bullets sold commercially in the United States. One combination of bullet and weapon was desired to represent the most severe and yet credible conditions to be reasonably associated with accidental or deliberate shootings. Although most shootings involve handguns, a considerable fraction does involve rifles, including most hunting accidents. Complete statistical data on the ratio of deaths due to handgun shots versus rifle shots could not be found. Fifty-two percent of all murders occur by use of handguns as opposed to only 5 percent by rifle (Reference 3). Considering that there were 7.8 victims per 100,000 inhabitants in the United States in 1970, a 5 percent murder rate using rifles is high.

In neither hunting accidents nor deliberate shootings is the need for a deep piercing bullet present. Instead, the bullets are designed specifically to flare out and transfer most of the bullet kinetic energy to flesh rather than to penetrate and pass right through the body. Therefore, specific bullet designs such as armor piercing shells were not considered in this case. The

criterion for selection involved maximizing the muzzle and long-range kinetic energy of the bullet (i.e., hollow point, soft point, lead point, bronze point) which would likely cause the greatest degree of penetration at impact. The Springfield 30-06 rifle/cartridge with a 180 grain bullet, 9-1/2 primer, and 24-inch barrel has the highest muzzle kinetic energy (2910 ft-lbs), a high muzzle velocity (2700 fps), and the highest kinetic energy at 500 yards (1110 ft-lbs), of the commonly used high powered rifles. The bullet selected is soft pointed and 95 percent jacketed; that is, all but 5 percent, the point, is encased in a copper jacket.

In an actual event, the bullet would impact the body first and pass through the flesh of the artificial heart recipient and the converter system prior to impacting the heat source. Data to evaluate the energy loss to the recipient's body and the thermal converter are not available. It can be assumed, however, that the heat source will be surrounded by the thermal converter structure and that the entire system will be sealed in stainless steel to facilitate isolation of the system from the body. It was, therefore, assumed that approximately 900 to 1000 ft-lbs of energy would be removed from the bullet prior to heat source impact. It is also worth noting that 900 ft-lbs of energy are lost from the 30-06 bullet during the first 200 yards of air travel. Therefore, 2000 ft-lbs would also be representative of hunting accident conditions even when no energy loss to the body or converter system is assumed.

Typical hand grenades used over the last ten years are constructed of 1/8-inch diameter wire wrapped around the explosive charge. This wire is notched every 1/8 inch so that fragments produced upon detonation are short cylinders 1/8 inch diameter by 1/8 inch long. These fragments weigh 3 to 5 grains each and have a velocity of 3500 to 4000 ft/sec at about four feet from the point of detonation. The initial energy of the fragments is on the order of 300 ft-lb, but due to the high drag coefficient, the energy is rapidly attenuated. The 30-06 bullet (180 grains) has an initial energy of approximately 2900 ft-lb which is attenuated to approximately 2400 ft-lb at a distance of 100 yards. A 45-caliber bullet (230 grains) has an initial energy of approximately 370 ft-lb and an energy of 305 ft-lb at 100 yards.

Thus, a comparison of the energy of these three types of fragments indicates that the hand grenade fragment has less energy than the 45-caliber bullet and considerably less energy than the 30-06 bullet at any distance. Another aspect must also be considered, and that is the penetrating ability of the fragment. A typical hand grenade test requirement is that fragments be able to penetrate one inch of pine boards. The fragments are actually capable of penetrating one or two such boards. The 45-caliber bullet will penetrate twice as much, and the 30-06 bullet will penetrate over one-half dozen boards.

Both from the standpoint of projectile energy and penetrating capabilities, the hand grenade fragment is considerably less severe than a 45-caliber bullet and a 30-06 bullet. Thus the heat source will survive impact by a hand grenade fragment if it can survive either of the aforementioned bullets.

The fragmentation environment consists, therefore, of a direct hit on the heat source by a 30-06 rifle bullet travelling with a kinetic energy of about 2000 ft-lb while the heat source is at the in-vivo operating temperature.

3.1.3 Crushing

Gross weights, axle weights, bearing areas, and many other specifications were obtained for a wide variety of heavy excavating equipment used in this country to determine the magnitude of crushing loads should a person be run over by these mechanized vehicles. Contact pressures were found to be only 11 to 14 psi for the track-type vehicles (regardless of how large the vehicle was since they have been designed not to sink into the soil) and contact pressures for vehicles with tires are no larger than the pressure in the tires.

The most significant loads on the heat source would be created when the heat source rests on a firm base such as concrete and is run over by a track-type vehicle. Although the total weight of some of these vehicles is very large, they rarely travel on concrete because they would crack it. However, some track-type vehicles have optional equipment which includes tracks without grousers (the metal cleat which is used for traction in soil)

and travel on concrete is sometimes performed. It is clear, however, that if the heat source were as strong or stronger than typical highway and construction concrete, the heat source would be pressed into the concrete rather than be forced to bear a large fraction of the vehicle weight as the vehicle passed over it.

Other crushing environments such as being run over by automobiles, or being crushed by building rubble resting on the heat source are less severe. Dynamic crush environments, such as those due to a heavy object falling onto the heat source from a great height, were not considered at this time. The severity of such an environment needs to be analyzed relative to the impact, ballistic impact and static crush environments discussed above, and specific probabilities of such an accident must also be established. More severe environments, such as the heat source being wedged in the expansion joint of a railroad track and being run over by a train, were not considered due to the extremely low probabilities associated with such events.

Consequently, the crushing environment was defined in terms of the capability of the heat source; namely, the heat source must possess sufficient strength to deform concrete. Under all types of crushing loads, the heat source would merely be pushed into the concrete. Approximate analyses have determined (Reference 4) that a load of 5000 pounds, applied to the heat source resting on a concrete surface, generates bearing pressures large enough to fail the concrete without failing the heat source designs being considered.

3.1.4 Fire

Building and gasoline fire temperatures have been measured as high as 2000°F but only on rare occasions and in local areas rather than large areas. The National Fire Protection Association has defined a standard time-temperature fire curve which includes temperatures as high as 2300°F (see section 6.4). Cremation furnace temperatures have been measured as high as 2430°F although for short periods of time only. There is considerable doubt as to the accuracy of some of the commercially reported high temperature measurements for cremations.

Statistics reported by the Nuclear Materials and Equipment Corporation (NUMEC), which were obtained from actual cremations and furnace manufacturers (Reference 5), indicate that cremations last from 1-1/2 to 2 hours with a nominal temperature of 1600°F, a minimum temperature of 1350°F, and peaks of up to 2500°F for short durations (10 to 15 minutes). A test was conducted by NUMEC to determine the expected thermal conditions during cremation. The test was performed in a crematory using a simulated casket. The primary objective of the test was to determine the cremation temperature-time cycle. Pt-10Rh thermocouples were located inside the simulated casket. There was an initial temperature peak of about 2000°F after 25 minutes, when the oak casket was giving off its maximum energy. After a slight drop in temperature, the temperature gradually increased and reached a maximum value of about 2070°F near the end of the cycle at 110 minutes. Although the average temperature during the NUMEC test was higher than the nominal value of 1600°F indicated above, the peak value was considerably lower than 2500°F. The test results were, however, consistent with the crematorium statistics.*

In light of the fact that a fire may remove the body of the artificial heart recipient from around the heat source and will at the same time provide a very active environment in terms of moving air and combustion products, it is very important that radioisotope fuel not be released and possibly distributed over significant areas by the rising blast of air. The selection of a fire environment having a temperature of 2500°F and a duration of about 2 hours was, therefore, made to conservatively encompass the observed data. Although longer exposures (on the order of 8 hours) are feasible at 2300°F they are not as critical, since material interactions are much more sensitive to temperature than to time.

3.1.5 Oxidation/Corrosion

The heat source must survive in a post-accident oxidation or corrosion environment sufficiently long to permit retrieval, or in cases where retrieval

*Recent results reported by ARCO Nuclear (previously NUMEC) in their December, 1972, Monthly Report confirm these previous data. The highest temperature obtained in 34 U.S. crematories was 2200°F. Cremation cycle duration was 1 to 5 hours.

is not possible, sufficiently long to allow fuel decay to negligible levels. In most accident situations, heat source retrieval will occur within a few hours, or at most a few days. Although no specific statistical data on the time required to retrieve airplane crash victims have been obtained, a review of airplane crashes over the last few years indicates that retrieval in most cases occurred within a few days of the accident, but that in some cases it took several months to locate the airplane. On rare occasions, airplanes have not been located for several years after disappearance.

The temperature of the heat source in air is approximately 800°F. Fully buried, the temperature of the heat source is approximately 1300°F, the exact value depending on the depth of burial and type of soil. Under such conditions, however, the fuel is immobilized. Assuming partial burial, a heat source temperature of 1000°F can be assumed. It is important to note, though, that the temperature of the heat source will drop with time as the power of the fuel diminishes due to decay. Since oxidation and material interactions are extremely sensitive to temperature, a considerable reduction in oxidation rate would therefore occur with time.

As a goal, the heat source, at its post-accident steady state temperature and in its post-accident condition (impact, fragmentation, or crushing damage), should contain all the fuel in any possible post-accident environment for approximately 1000 years (11.4 half-lives).

3.2 MATERIALS SURVEY

A comprehensive material survey was undertaken early in the program to select optimum materials and material combinations for the artificial heart radioisotope heat source. Selection of materials was based on past experience in radioisotope heat source programs, a review of the pertinent literature, and discussions with material suppliers and fabricators. Compatibility data for $^{238}\text{PuO}_2$ fuel were obtained from the Mound Laboratory, Los Alamos Scientific Laboratory and Donald W. Douglas Laboratory efforts, and heat source material interaction data were obtained from past heat source technology programs. Selection of materials was based on material availability, cost, material properties, compatibility with other materials and with the fuel, fabricability, and availability of quality assurance procedures. The results of this survey, with final material recommendations, are presented in

Reference 6. A brief summary of the materials survey is presented below but no detailed data are included. An update on the advanced hafnium alloys (Hafnallo) being developed by TRW is presented in Appendix A.

3.2.1 Materials

The encapsulation system of the isotopic fuel must serve three primary functions:

- 1) Provide material compatibility between the fuel form and the encapsulating member,
- 2) Provide sufficient strength to insure fuel containment, and
- 3) Provide oxidation and corrosion resistance.

Capsule concepts for the artificial heart device consist of three-layer, two-layer, and single-layer construction. In the single-layer capsule, the material must obviously serve as liner, strength member, and clad. In the two-layer system, the inner layer can act as a liner/strength member and the outer layer can act as a strength member/clad. Finally, in the three-layer system, the functions of the three layers are separated.

3.2.1.1 Material Candidates

The operational and accident environments to which the artificial heart heat source may be exposed dictate that high-temperature superalloys, the refractory metals, and the noble metals should be the candidate materials of construction. The nickel- and cobalt-based superalloys, although less expensive, and having good fabricability, oxidation resistance, and lower density, cannot be considered for the heart heat source because their relatively low melting points would not satisfy the fire requirement delineated in Section 3.1, above. In addition, prolonged operation at high temperatures may result in degradation of their metallurgical and mechanical characteristics, thus seriously impairing their ability to survive impact, fragmentation, or crushing environments. The refractory metal alloys of columbium, molybdenum, tantalum, and tungsten will satisfy the operational and accident environmental requirements if protected by an oxidation resistant outer clad. These alloys have high melting points, excellent stability at high temperatures in inert or vacuum environments, and adequate ductility at typical impact temperatures. The noble metal alloy candidates include the

platinum-rhodium alloys, palladium and iridium. These alloys have excellent stability at high temperatures in an oxidizing environment and can be used as a liner material to contain the fuel or as a clad to protect the refractory metals from oxidation. In addition, the high strength oxidation resistant alloys being developed by ORNL (Pt/Rh/W alloys) and TRW Systems (Hafnallo) must be considered.

As mentioned above, the superalloys have been eliminated from consideration. In addition, columbium alloys were eliminated because they offer no advantages over the tantalum and molybdenum alloys and no experience or data are available on their use in this type of application. The only tungsten alloy having been considered for very high temperature (>2000°F) radioisotope heat source applications is W-25Re alloy because of its considerably higher strength and good fuel compatibility. Current radioisotope heat sources utilize tantalum-based or molybdenum-based alloys in conjunction with a Pt-20Rh clad. Of the noble metals, Pt-20Rh and iridium may be considered for liner materials because of their demonstrated fuel compatibility, and iridium could be considered as a strength member because of its high strength. Use of iridium as a strength member was, however, eliminated because sufficient quantity of the metal will probably not be available since the projected amount required per year is greater than the new raw material output. Advanced alloys such as ORNL's noble metal-tungsten alloys and TRW's hafnium-noble metal alloys were considered because of their promise to enhance fuel containment in accident environments.

Table 3-1 lists the candidate heat source materials for each of the three heat source concepts. The possible number of material combinations based on this table is, of course, quite large. However, a considerable number of these material systems can be eliminated on the basis of material availability and unfavorable data such as tensile strength, fuel compatibility, and inter-material compatibility.

3.2.1.2 Property Data

The principal elements (tantalum, molybdenum, hafnium, and tungsten) of the candidate refractory metals are readily available. However, several of the material candidates for the liner and clad contain elements which are not very abundant. Specific material availability and cost must, therefore,

Table 3-1. Candidate Capsule Materials

Single-Layer Capsule Systems	Two-Layer Capsule Systems		Three-Layer Capsule Systems		
	Liner	Clad	Liner	Strength Member	Clad
Hafn alloy	Ta-10W	Pt-20Rh	Ta-10W	T-111	Pt-20Rh
Oak Ridge Alloy	TZM	Oak Ridge Alloy	TZM	TZM	Pd
Pt-20Rh	Mo	Pd	Mo	W-25Re	Oak Ridge Alloy
Pd	Mo-50Re	Hafn alloy	Mo-50Re		
	W-25Re		W-25Re		
	Pt-20Rh		Pt-20Rh		
	Ir		Ir		

be evaluated since the radioisotope heat source for the artificial heart device is projected to be a high production item.

Detailed material property data for the candidate heat source alloys are presented in Reference 6. The properties reported include density, melting point, thermal conductivity, specific heat, thermal expansion, emissivity, tensile strength, stress rupture, cost, and availability. Gaps in the data presented do exist and are due primarily to the fact that some properties have never been determined or have been determined on only specific forms of the material. A considerable amount of data has been generated for the Oak Ridge alloy and for Hafnialloy since the publication of Reference 6. The Oak Ridge alloy data are presented in Reference 7. The Hafnialloy data are summarized in Appendix A.

3.2.1.3 Fuel Compatibility

No fuel/liner compatibility data are available for the very high purity (0.05% or 500 ppm total impurity content) electrorefined pressed and sintered PuO_2 , the candidate fuel form for the artificial heart heat source. Data have, however, been obtained for production grade fuel (1-2% total impurity content) and purified fuel (0.23% or 2300 ppm total impurity content) with the candidate liner materials. The fuel forms used were $^{238}\text{PuO}_2$ microspheres and pressed and sintered $^{238}\text{PuO}_2$ (PPO). Test durations were reported for considerably shorter times than 10 years, and in some cases the test temperatures were considerably higher than the 1350-2000°F operating range of the heart heat source. These data do include an evaluation of stoichiometric versus substoichiometric PuO_2 fuel. In addition, the data were obtained on test specimens whose fuel volume-to-container area ratio or fuel volume-to-container volume ratio may have been different from the actual hardware system, to result in different degrees of interaction observed; i.e., if the ratio were greater, the interaction would be expected to be greater. Because of these factors and others, such as temperature and time effects on material solubility in plutonia, vapor transport, diffusion, and oxide precipitation, complications arise in the development of satisfactory mathematical correlations that are usable for predicting other time/temperature conditions. Thus a fuel/liner compatibility program aimed at simulating the artificial heart heat source conditions as to type of fuel used, containment materials, exposure conditions, and geometry/volume considerations, would be advisable.

However, the available compatibility data presented in Reference 6 do provide an insight as to fuel/liner response and justification as to candidate fuel containment materials recommended. The liner materials discussed are Ta-10W, unalloyed molybdenum, TZM, Mo-50Re, W-25Re, Pt-20Rh, Oak Ridge Alloy (Pt-30Rh-10W), and Hafnialloy. T-111 and Pd were not considered as liner materials.

3.2.1.4 Compatibility of Combined Material System Candidates

Contact between dissimilar materials in multilayered radioisotope heat sources raises a question of compatibility between adjacent components. The data reported in Reference 6 are based on compatibility testing performed under closely-controlled conditions and predictions based on analyses of phase diagrams. A parabolic relationship was used to extrapolate data in time, and a Larson-Miller type relationship was used to correlate the thickness of the interaction zone with temperature and time. Ten-year compatibility estimates were then made on the basis of these correlations. Excessive interaction between materials may necessitate the use of diffusion barriers. Data on alumina, platinized alumina, zirconia, tantalum carbide, and zirconium carbide as diffusion barriers are presented in the reference. Also, in Reference 6, the compatibility data for the following material combinations are presented: Ta-10W/T-111, Ta-10W/TZM, TZM/T-111, W-25Re/TZM, Pt-20Rh/Ta-10W, Pt-20Rh/T-111, Pt-20Rh/TZM, Pd/Ta-10W, Pd/T-111, and Pd/TZM. No data are presented for combinations where Mo-50Re, Oak Ridge Alloy and Hafnialloy are candidates because no testing had been performed. Additional material combinations of interest for which no data were available include: Mo/T-111, W-25Re/T-111, Mo/W-25Re, W-25Re/Pt-20Rh, and W-25Re/Pd.

In general, it can be concluded that the liner/strength member/clad combinations considered in Table 3-1 may interact chemically to some extent, but no low melting point eutectics are known. Combinations of materials synthesized from the same base materials interact less than those synthesized from different base materials.

3.2.2 Fabrication

Capsules utilizing refractory and noble metals have been successfully produced for a number of radioisotope heat source applications. Piece parts were produced by a number of different methods. Tantalum and platinum alloy

piece parts were produced from sheet material by deep drawing, hydroforming, and tube drawing, whereas molybdenum alloys were prepared by machining of bar stock. Molybdenum alloy piece parts can, however, also be produced from sheet by roll-forming, radial draw-forming, spinning, hydroforming, or drop hammer and Ceko stamp forming and tube drawing. Joining of the refractory metal candidates by TIG and EB welding has been demonstrated.

3.2.2.1 Candidate Forming Methods

The method employed to produce the heat source components depends on the selected configuration. Similar techniques will produce hemispherically ended cylindrical piece parts and hemispherical piece parts from sheet material. Deep drawing, in either a mechanical press or hydropress, has been shown in past programs to be capable of producing high quality refractory metal heat source parts of this geometry. Tubular sections have been produced by drawing, spin forging or machining bar stock by gun drilling.

To improve fabricability, the Ta-10W, T-111, Mo-50Re and platinum-rhodium alloys would be obtained in the recrystallized condition, whereas the commercially pure molybdenum and TZM would be obtained in the as-worked, stress-relieved condition. The relatively poor ductility of TZM at room temperature means that this alloy requires care in machining and in handling fabricated parts during inspection and assembly. Although the tantalum and platinum-rhodium alloys are more fabricable than the molybdenum alloys, it has been demonstrated by TRW and others that TZM parts can be satisfactorily formed and welded.

No large quantity sheet metal forming studies have been initiated for the advanced Oak Ridge alloy. Large capsule piece parts, sized for a typical 650-watt capsule, and small capsules sized for the artificial heart heat sources have been successfully fabricated from Hafn alloy sheet. Section 4.2.2 below discusses the fabrication of Hafn alloy piece parts.

3.2.2.2 Candidate Welding Processes and Joint Designs

Sound, reliable weldments can be consistently produced to join refractory metal components. To accomplish such welds, however, the joint design and fit-up during assembly, weld processes and procedures, and materials must be considered. These factors also affect total cost and ease of production of fueled assemblies at the fueling agency.

A butt-type joint provides an assembly of minimum weight. Four different joint configurations can be considered: the straight-butt, step-butt, and angular butt which can be used to weld hemispherical sections, and the melt-down, which is an extension of the straight-butt and can be used to weld a flat disc to a tube section. Figure 3-1 illustrates each of these joints. Each has been successfully utilized in joining refractory metal alloys, and each has advantages and disadvantages depending on fabrication, fixture requirements, and assembly design.

Figure 3-1. Candidate Weld Joint Designs

To obtain optimum welds, only the tungsten inert gas (TIG) and electron beam (EB) weld processes, with no introduction of externally-fed filler metal, were considered for this program. These processes are capable of producing the clean, uncontaminated welds of minimum weight that have been successfully obtained in past heat source programs. It is known that the EB process is always more costly than the TIG process because of the need to provide a vacuum as well as amortizing high equipment costs. However, the EB process is the only one that can consistently produce good weldments in molybdenum alloys. Other considerations in making sound weldments include the need for atmosphere control, start-up and shut-off slope controls, and pre-heat of the weld joint. The detailed considerations affecting the selection of the welding process for assembly of fueled heat sources are discussed in Reference 6. These considerations include the flexibility of the TIG versus EB processes, the need for expensive duplicate EB facilities if burn-through should occur and the weld chamber becomes contaminated with radioactivity, complexities imposed by transporting the heat source in and out of the EB weld chamber, and the possible effect of poor heat transfer in the heat source gaps.

3.2.3 Summary

Factors affecting material selection include density, raw material availability, raw material cost, forming and welding experience, compatibility, and strength. Compatibility with the fuel and between the various capsule materials becomes a dominant factor, especially at 2000°F, the highest projected temperature of the system. Ability to withstand accident environments and contain the radioisotope fuel is, however, the key factor in selecting the heat source materials.

An analysis of the raw material availability, strength, fuel compatibility, and material interaction data permitted initial selection of candidate material system combinations for the parametric study. A summary of the single-, two-, and three-layer material systems for heat sources containing nonselective and selective vents and operating at 1350 or 2000°F is given in Table 3-2. The following ground rules were used in deriving the candidate materials systems:

- Iridium can be eliminated as a clad candidate because of the limited supply of the raw material.
- Palladium can be eliminated as a clad candidate because no compatibility data with other materials are available, because its melting point is only 300°F above the maximum anticipated fire temperature, and because its stress to rupture is extremely low.
- Pt-20Rh and palladium can be eliminated from consideration for single-layered capsules because of their low relative strength and their susceptibility to grain growth at elevated temperatures.
- W-25Re can be eliminated as a liner or strength member material because no compatibility data are available between it and other capsule materials such as T-111 and Pt-20Rh, because of its extremely high density (0.714 lb/in³), and because of difficulties in machining and fabricating this alloy.
- Ta-10W can be considered a liner material at 1350°F only because of potential incompatibility with the fuel at 2000°F.
- T-111 can be considered as a strength member at 2000°F if an adequate diffusion barrier is found to eliminate interaction with Pt-Rh alloys.
- For three-layer systems Mo and Mo-50Re are preferred as a liner over TZM because of their lower ductile/brittle transition temperatures and easier fabricability. In a two-layer system having a combined liner/strength member, TZM will be used because of its higher strength.

Table 3-2. Candidate Material System Combinations for Parametric Study

<u>Non-Selective Vent - 1350°F</u>		
<u>Single-Layer</u>	<u>Two-Layer</u>	<u>Three-Layer</u>
Hafnalloys	Ta-10W/Pt-20Rh	Ta-10W/T-111/Pt-20Rh
Oak Ridge Alloy	Ta-10W/Hafnalloys	Mo/T-111/Pt-20Rh
	Ta-10W/Oak Ridge Alloy	Mo-50Re/T-111/Pt-20Rh
	TZM/Pt-20Rh	Pt-20Rh/T-111/Pt-20Rh
	Mo/Hafnalloys	Ta-10W/TZM/Pt-20Rh
	Mo/Oak Ridge Alloy	Mo-50Re/TZM/Pt-20Rh
	Mo-50Re/Hafnalloys	Pt-20Rh/TZM/Pt-20Rh
	Mo-50Re/Oak Ridge Alloy	
	Pt-20Rh/Hafnalloys	
	Pt-20Rh/Oak Ridge Alloy	
<u>Selective Vent - 1350°F</u>		
<u>Single-Layer</u>	<u>Two-Layer</u>	<u>Three-Layer</u>
Oak Ridge Alloy	Ta-10W/Pt-20Rh	Ta-10W/T-111/Pt-20Rh
	Ta-10W/Oak Ridge Alloy	Ta-10W/T-111/Oak Ridge Alloy
	TZM/Pt-20Rh	Mo/T-111/Pt-20Rh
	Mo/Oak Ridge Alloy	Mo/T-111/Oak Ridge Alloy
	Mo-50Re/Oak Ridge Alloy	Mo-50Re/T-111/Pt-20Rh
	Pt-20Rh/Hafnalloys	Mo-50Re/T-111/Oak Ridge Alloy
	Pt-20Rh/Oak Ridge Alloy	Pt-20Rh/T-111/Pt-20Rh
		Ta-10W/TZM/Pt-20Rh
		Ta-10W/TZM/Oak Ridge Alloy
		Mo-50Re/TZM/Pt-20Rh
		Mo-50Re/TZM/Oak Ridge Alloy
		Pt-20Rh/TZM/Pt-20Rh
<u>Non-Selective Vent - 2000°F</u>		
<u>Single-Layer</u>	<u>Two-Layer</u>	<u>Three-Layer</u>
Hafnalloys	TZM/Pt-20Rh	Mo/T-111/Pt-20Rh
Oak Ridge Alloy	Mo/Hafnalloys	Mo-50Re/T-111/Pt-20Rh
	Mo/Oak Ridge Alloy	Pt-20Rh/T-111/Pt-20Rh
	Mo-50Re/Hafnalloys	Mo-50Re/TZM/Pt-20Rh
	Mo-50Re/Oak Ridge Alloy	Pt-20Rh/TZM/Pt-20Rh
	Pt-20Rh/Hafnalloys	
	Pt-20Rh/Oak Ridge Alloy	
<u>Selective Vent - 2000°F</u>		
<u>Single-Layer</u>	<u>Two-Layer</u>	<u>Three-Layer</u>
Oak Ridge Alloy	TZM/Pt-20Rh	Mo/T-111/Pt-20Rh
	Mo/Oak Ridge Alloy	Mo/T-111/Oak Ridge Alloy
	Mo-50Re/Oak Ridge Alloy	Mo-50Re/T-111/Pt-20Rh
	Pt-20Rh/Hafnalloys	Mo-50Re/T-111/Oak Ridge Alloy
	Pt-20Rh/Oak Ridge Alloy	Pt-20Rh/T-111/Pt-20Rh
		Mo-50Re/TZM/Pt-20Rh
		Mo-50Re/TZM/Oak Ridge Alloy
		Pt-20Rh/TZM/Pt-20Rh

- A three-layer system of TZM or Mo/TZM/clad will not be considered since it has no advantages over a TZM/clad system.
- Selective vent technology allows this vent to be welded into the noble metal alloys only (including the Oak Ridge Alloy). Thus one of the capsule members must be a Pt/Rh-based alloy.
- The Oak Ridge Alloy has little advantage over Pt-20Rh in a three-layer capsule containing a nonselective vent. For a selective vent, however, this material must be considered because of its higher strength.

3.3 PARAMETRIC ANALYSES

Parametric analyses were performed to determine the optimum heat source configuration relative to established selection criteria. Heat source sizes, weights, volumes, material interaction depths, and thermal expansion differentials between the various components were calculated for all candidate designs. These analyses included single-layer, two-layer, and three-layer designs of flat-ended and hemispherically-ended configurations of all material combinations under consideration (Section 3.2).

Selective and nonselective vent systems were designed to vent the fuel-generated helium from the heat source and to retain and/or decay the radon-220 to levels below the maximum allowable body burdens. The capsule wall thickness required to survive bullet impact, granite impact, and crushing was determined for the various configurations, and the thickness of a selectively-vented capsule required to survive creep due to the internal helium pressure was also determined. Based on these analyses, minimum required wall thicknesses were determined and an optimum design of each material configuration was generated.

3.3.1 Selection Criteria

To enable a comparison to be made among the various candidate design concepts and to select a single concept for final design, selection criteria were established. Each of the criteria, however, had a different relative importance in determining the most suitable heat source candidate. A set of weighting factors based on heat source design, nuclear safety, and on an overall performance point of view were, therefore, established. Seventeen selection criteria were grouped into seven categories, and one-hundred weight points were distributed among these categories, as shown in Table 3-3.

Table 3-3. Criteria Weightings

Category	Category Weighting	Criteria	Criteria Weighting
Heat Source Characteristics	31	Volume	17
		Weight	10
		Operability in Inert Gas/Vacuum	2
		Handling in Air	2
Compatibility	18	With Fuel	9
		With other Heat Source Materials	9
Thermal Converter Interfaces	17	Heat Flux	4
		Gas Management	9
		Mechanical Interfaces	4
Nuclear Safety	15	Impact	3
		Fragments	3
		Cremation	3
		Crushing	3
		Oxidation	3
Cost	8	Cost	8
Reliability	8	Reliability	8
Design Flexibility	3	Design Flexibility	3
	100		100

3.3.1.1 Heat Source Characteristics

There are four criteria in this category: volume, weight, operability in an inert atmosphere and/or vacuum, and handling in air.

Due to the limited volumes available for implantation, the artificial heart heat source must be as small as possible. Each candidate design was therefore minimized in volume and designs having large void volume were heavily penalized. To keep the artificial heart device components in a fixed location within the body, their overall specific gravity should, moreover, be close to unity. Weight must, therefore, also be minimized. Because of this critical interface with the human recipient, the volume and weight criteria were given the highest weighting of 27 points. The volume of the heat source, however, is more critical than the weight since it may result in a disproportionate increase in both the volume and weight of the total converter system. Seventeen points were therefore assigned to the volume criterion and 10 points to the weight criterion.

The heat source should be capable of operating for ten years in either an inert atmosphere or a vacuum environment. However, installation into the thermal converter would be simplified if the heat source were also capable of being exposed to air. Both of these criteria are equally important and were assigned two points each.

3.3.1.2 Compatibility

The ten-year compatibility of the heat source liner with the fuel and the inter-heat-source-component compatibilities are important criteria in heat source selection. Specifically, the inner heat source members must not detrimentally react with the fuel, and if more than one encapsulating member is used, these members must not detrimentally react with each other. Compatibility of the heat source with fuel, and compatibility of heat source components with each other are of approximately equal importance; hence, the 18 points in the compatibility category were evenly divided.

3.3.1.3 Thermal Converter Interfaces

This category consists of three criteria, heat flux, gas management, and mechanical interfaces, and must have enough points assigned to it to heavily penalize any design that does not satisfy interface requirements.

Seventeen points were assigned to this category for that reason. The relative importance of the three criteria depends on the converter system to be employed. Gas management, however, appeared most important; hence, distribution of the 17 points in this category consisted of 4 for heat flux, 9 for gas management, and 4 for mechanical interfaces.

3.3.1.4 Nuclear Safety

Nuclear safety criteria include the ability of the heat source to survive impact, bullets or fragments, fire, crushing and exposure to oxidizing environments, body fluids, and molten salts. An artificial heart heat source must be capable of surviving these environments at any time during, or soon after, its 10-year service, as described in Section 3.1 above.

Fifteen points were given to the Nuclear Safety Category. To this date, there is no information that indicates one nuclear safety environment to be more important than another; hence, the 15 points were evenly distributed among the five criteria.

3.3.1.5 Cost

When evaluating candidate designs, the requirement of a mass-produced end product must be considered. Simplified designs that lend themselves to low cost, state-of-the-art, mass production techniques were stressed. Cost to be considered included materials, special processing, forming, fueling, welding, assembling, and acceptance testing. The cost category was assigned 8 points.

3.3.1.6 Reliability

The reliability of the design is of utmost importance. The final design chosen must have the inherent ability to be developed into a highly reliable design for a 10-year service period. Some facets of reliability are inherently included in other selection criteria, such as compatibility with the fuel, inter-material compatibility, and safety. Additional reliability aspects, not already explicitly accounted for, are included in the "Reliability" criterion. This criterion includes such aspects as the reproducibility of sound welds, possibility of failure prior to assembly into the thermal converter, and heat source/thermal converter assembly and implantation failures.

3.3.1.7 Design Flexibility

The chosen heat source design must be flexible enough to incorporate changes that may be forthcoming from other tasks in the heat source program, such as safety requirements. Furthermore, the heat source design must have adequate design flexibility to accommodate system design changes that will be generated as the thermal converter design evolves. Of particular importance will be power level changes. Ideally it should be possible to modify the heat source design, based on these new inputs, with little or no impact on work completed. The design flexibility criterion was assigned three points.

3.3.1.8 Go/No-Go Criteria

There were four conditions under which a design and/or material was given no credits and thus eliminated from the program without further consideration. They were:

- Catastrophic material compatibility failure in less than 10 years
- High probability of failure under accident environments
- Inability to be mass produced
- Inability to survive exposure to air/body fluids/molten salts.

The inappropriateness of retaining a design or material with any of these characteristics is readily apparent.

3.3.2 Parametric Analyses and Tests

The primary objective of the parametric analyses was to determine the optimum heat source configuration, relative to the selection criteria, of each set of materials identified in the Materials Survey (Section 3.2 above). Figure 3-2 identifies the analyses that were performed. The following basic assumptions were made in the analyses:

- There are two nominal design operating temperatures - 1350°F and 2000°F
- Minimum design life is 10 years
- The baseline design power is 40 watts, but some calculations will be conducted over the range of 20 to 60 watts

Figure 3-2. Design Procedure

- The fuel shall be electrorefined, oxygen-16 enriched, PuO_2 having a power density of 4.3 watts/cc
- The fuel can be supplied in any geometry required. Single units up to 60 watts can be obtained
- For steady state analyses (vent sizing and creep), it was assumed that 100% of the helium will be released from the fuel
- Vent systems must also accommodate a helium-release pressure surge when the heat source is exposed to a 2500°F fire
- Minimum heat source volume is accomplished by designing no void volume in the capsule other than that required for assembly clearances
- The selective vent can only be welded into high platinum content alloys
- The minimum selective vent thickness is 0.040 inch
- All inter-component reaction zones, including fuel/liner, are non-load carrying zones. The reaction thickness must, therefore, be deducted from the wall thicknesses when making structural calculations.

3.3.2.1 Fragment Resistance

Tests performed during the Pioneer Radioisotope Heater Unit (PRHU) program and safety analyses of the various accident environments to which the artificial heart heat source may be exposed indicated that bullet impact is the worst accident environment for the heat source. The bullet impact environment was defined in Section 3.1 as that imposed by a 30-06 (180-grain) rifle bullet having an energy of 2000 ft-lb (2210 ft/sec).

The problem of bullet impact is not amenable to mathematical solution. Furthermore, data with which the wall thickness required to survive such bullet impact could be estimated are not available for the materials under consideration. Hence, in light of the lack of data and the importance of this requirement, a series of tests was performed to generate the necessary information. However, only a restricted number of tests could be performed and the effects of the various variables (material, configuration, diameter, and temperature) could only be roughly obtained. The tests were performed on the candidate strength member materials Ta-10W, T-111, TZM, and Hafnialloy.

Tubular specimens of the four materials, having various wall thicknesses and diameters, were fabricated. The specimens were tested at 1500°F in an argon atmosphere or at room temperature in air using 30-caliber, pointed, 180-grain, 95% jacketed, bullets. Bullet energy was changed by offloading powder until a marginal specimen rupture was obtained. Thus, by changing the bullet energy (velocity) and/or specimen wall thickness, the maximum survival energy per unit wall thickness was found for each candidate material. Data from these tests are presented in Table 3-4. The bullet energy for each test was calculated using the bullet mass and velocity. The energy was then divided by the specimen wall thickness to give the test energy per unit wall thickness in ft-lbs/milli-inch.

The T-111 specimen having a diameter of 0.35 inch and containing a liner and fuel simulant did not fail at an energy of 26.5 ft-lb/mil wall but did fail at 29.8 ft-lb/mil wall when tested at 1500°F. The maximum energy for specimen survival was estimated to be very near 26.5 ft-lb/mil wall because of the severity of the failures at higher energies. All failures were ductile.

The Ta-10W specimen having a diameter of 0.35 inch and containing a liner and fuel simulant very nearly failed at an energy of 14.5 ft-lb/mil wall when tested at 1500°F and exhibited the same deformation characteristics as the 26.5 ft-lb/mil T-111 specimen. Hence, its maximum energy for survival was estimated to be very nearly 14.5 ft-lb/mil wall. All failures were ductile.

The 1500°F TZM specimen having a diameter of 0.35 inch and containing a liner and fuel simulant very nearly survived impact at 23.2 ft-lb/mil; the 16.6 ft-lb/mil specimen survived with a large margin. The maximum allowable energy for specimen survival was estimated to be approximately 21 ft-lb/mil wall. The TZM failure was also by ductile deformation.

Both Hafnialloy specimens having a diameter of 0.35 inch and containing fuel simulant but no liner failed at 1500°F. Failures were, however, partly attributable to the forming process and brittle welds. If this brittle failure zone along the weld, which was probably caused by poor control of the welding atmosphere, is ignored, the remainder of specimen 1D-2 looked much like the 33.5 ft-lb/mil T-111 specimen. If it is assumed that this

Table 3-4. Bullet Specimen Summary

Specimen No.	Material	O.D. (inch)	Wall (inch)	Liner Included	Temperature (°F)	Bullet Velocity (ft/sec)	Energy ft-lb/mil	Comments
1A-1	Ta-10W	0.346	0.040	Yes	1500	1700	29.8	Severe fracture
1A-2	Ta-10W	0.347	0.041	No	70	1200	14.5	Marginal
1A-3	Ta-10W	0.348	0.043	No	1500	1200	13.8	No fracture
1A-4	Ta-10W	0.348	0.043	No	70	1400	18.8	Fracture
1B-1	T-111	0.347	0.041	Yes	1500	1200	14.5	No fracture
1B-2	T-111	0.346	0.040	Yes	1500	1600	26.5	No fracture
1B-3	T-111	0.347	0.041	Yes	1500	2000	40.2	Severe fracture
1B-4	T-111	0.346	0.040	Yes	1500	1800	33.5	Severe fracture
1B-5	T-111	0.346	0.040	Yes	1500	1700	29.8	Marginal fracture
1C-1	TZM	0.346	0.040	Yes	1500	1700	29.8	Severe fracture
1C-2	TZM	0.347	0.040	Yes	1500	1500	23.2	Fracture
1D-1	Hafn alloy	0.349	0.048 + .002	No	1500	1700	24.8	Severe fracture
1D-2	Hafn alloy	0.350	0.050 + .002	No	1500	1500	18.6	Fracture
2A-1	Ta-10W	0.358	0.056	No	70	1500	16.5	Marginal fracture
2A-2	Ta-10W	0.359	0.056	Yes	1500	1400	14.5	No fracture - Marginal
2C-3	TZM	0.359	0.056	Yes	1500	1500	16.6	No fracture
2D-1	Hafn alloy	0.420	0.100 + .005	—	—	—	—	Not tested because of cracks in test specimen
6A-1	Ta-10W	0.900	0.042	No	1500	1200	14.1	Hole in front surface
6A-2	Ta-10W	0.900	0.042	No	70	1175	13.6	No fracture
7A-1	Ta-10W	1.399	0.039	No	70	1175	14.6	Hole in front surface close to edge of specimen
Flat Sheet	Ta-10W	∞	0.039	No	70	705	5.2	Excellent condition
PRHU	T-111	0.346	0.040	Yes	1500	1700	29.8	Fracture

18.6 ft-lb/mil Hafn alloy specimen was overstressed by the same factor as the 33.5 ft-lb/mil T-111 specimen, a tentative maximum survival energy for Hafn alloy may be estimated using the ratio $\frac{18.6}{33.5} = \frac{X}{26.5}$, where 26.5 ft-lb/mil is the failure energy of the T-111. The estimated maximum energy for survival is thus 14.7 ft-lb/mil.

The effects of strength member diameter on wall thickness requirements were studied at room temperature and 1500°F using Ta-10W specimens. Specimen diameters were 0.35, 0.90, and 1.40 inches and flat sheet. Damage to the flat sheet was minimal and it was estimated that the specimen could have survived about twice the test energy. In order to apply these data to different materials and at elevated temperature, several assumptions were made. R_D is defined as the ratio of the Ta-10W failure energies at two diameters, that is,

$$R_D = \frac{\text{maximum energy/mil at which Ta-10W specimen of diameter } x \text{ survives}}{\text{maximum energy/mil at which Ta-10W specimen of diameter } y \text{ survives}}$$

It was assumed that:

- R_D is independent of temperature
- R_D is independent of material; i.e., the same ratio holds for T-111, TZM and Hafn alloy at the same diameters
- The failure energy at temperatures other than 1500°F may be approximated by assuming it varies as the ultimate tensile strength.

The estimated strength member thicknesses required to survive bullet impact at an energy of 2000 ft-lb (2210 ft/sec) are shown in Figure 3-3 for the four materials investigated as a function of capsule diameter. Curves for both the 1350° and 2000°F application are shown. No curve for Ta-10W at 2000°F is shown since this material is not a candidate at this high temperature. The four candidate strength member materials rank in the order of T-111, TZM, Hafn alloy, and Ta-10W, with T-111 requiring the minimum thickness. As will be discussed in more detail in Section 6.2, this sizing technique was later found to be incomplete. Extrapolation to larger diameters and higher energies was found to be non-linear and the T-111 and Hafn alloy wall thicknesses selected for the artificial heart heat source design did not

Figure 3-3. Estimated Strength Member Design Wall Thickness Vs Diameter

survive a 2000 ft-lb 30-06 rifle bullet impact. However, the above analysis is probably valid for a relative comparison of materials.

3.3.2.2 Impact Resistance Analysis

Numerous theoretical analyses of the response of radioisotope heat sources to impact against an unyielding surface such as granite, have been performed over the last few years. The problem of predicting the failure velocity of a fueled cylindrical or spherical capsule remains unsolved, and must be treated experimentally. As mentioned in the previous section, impact by a rifle bullet was considered to be the most severe accident environment to which the artificial heart heat source will be exposed. Thus it was not necessary to design the heat source to survive impact on granite, but rather to verify that the thicknesses required to survive bullet impact are also sufficient to survive granite impact. Since a rigorous theoretical analysis was not possible, the various heat source designs were compared to an empirical correlation of the available impact data.

One such correlation is presented in detail in Reference 4 and is summarized in Figures 3-4 and 3-5. The data points represent radioisotope heat source tests performed under the Transit, LRHSC, PRHU, DART, and Vented Capsule programs. The curves representing the impact failure criterion are drawn. Although some slight scatter in the data exists, points to the left of the curves represent impact in which the capsules survived; points to the right of the curves represent failures. As the impact velocity increases, the failure region is further penetrated.

The parameters S and M for an artificial heart heat source containing either a T-111 or a TZM strength member of the thickness estimated to survive bullet impact were calculated and are also shown in Figures 3-4 and 3-5. As can be seen, these points lie well within the "survival" region.

No such correlation could be developed for the remaining candidate strength member, Hafnialloy, due to the unavailability of adequate impact data for this material.

3.3.2.3 Crushing Resistance Analysis

The crushing criterion requires that the heat source crush strength be greater than that of concrete. Simplified conservative analyses of a spheri-

Figure 3-4. Impact Correlation for T-111 Capsules

Figure 3-5. Impact Correlation for TZM Capsules

cal shell and an infinite cylinder were performed to again verify that a capsule designed to survive bullet impact will survive the required crush environment. These analyses are discussed in detail in Reference 4.

For a given elongation to failure, allowable stress, and capsule dimensions, these analyses allow easy calculation of the required shell thickness for a given load or the allowable load for a given shell thickness. Table 3-5 presents a summary of the loads to failure and bearing stresses transmitted to the supporting medium, e.g., concrete, for cylindrical and spherical capsules having the wall thicknesses required to survive bullet impact. The loads required to fail the capsules range from 5000 to 66,000 pounds. The bearing stresses range from 12,600 to 30,000 psi. The compressive strength of concrete ranges from 3000 to 4000 psi, depending on the composition and curing, and the allowable bearing stresses are somewhat higher depending on the thickness and loading of the concrete structure. The heat source bearing stresses exceed these values and the requirement that the capsule have a crush strength greater than the crush strength of concrete is satisfied.

3.3.2.4 Material Interactions

Compatibility between the fuel and liner and between various components of the heat source is discussed in Section 3.2 above and in Reference 6. Based on these data, estimates were made of the various interactions and are presented in Tables 3-6 and 3-7 for the fuel and heat source, respectively.

3.3.2.5 Vent System Configurations

The capsule vent system must permit the flow of helium at a rate at least as high as the helium generation rate, assuming 100 percent release of the helium from the fuel. The vent must prevent the passage of fuel fines and limit the flow of radon gas to acceptable levels. Finally, it is also desirable that the vent system be capable of channeling these gases to an acceptable location within the thermal converter system or human body.

To accomplish these requirements, three vent systems were selected for investigation: a selective vent, a nonselective vent (PRD), and a capillary tube. These components were sized to minimize heat source volume and weight.

Table 3-5. Crush Analyses

Material	Temperature (°F)	Strain to Failure	Configuration	$\frac{\sigma_u t_f L}{P}$	σ_u (psi)	r_o (in)	ℓ (in)	Bullet Survival Thickness (in)	Load to Failure (lb)	$\frac{a}{r_o}$	$\sigma_{bearing}$ (psi)
T-111	1350	0.15	Cylinder	0.33	79,000	0.630	1.315	0.100	31,500	0.88	21,600
	2000	0.19	Cylinder	0.27	62,000	0.630	1.315	0.120	36,200	1.00	21,900
	1350	0.15	Sphere	0.70	79,000	0.600	-	0.100	6,780	0.50	24,000
	2000	0.19	Sphere	0.50	62,000	0.600	-	0.120	8,920	0.60	21,900
TZM	1350	0.10	Cylinder	0.45	78,000	0.625	1.340	0.126	29,300	0.72	24,300
	2000	0.13	Cylinder	0.37	65,000	0.625	1.340	0.137	32,300	0.82	23,500
	1350	0.10	Sphere	1.21	78,000	0.625	-	0.125	5,050	0.37	30,500
	2000	0.13	Sphere	0.85	65,000	0.625	-	0.136	6,500	0.45	26,400
Hafnalloys	1350	0.46	Cylinder	0.12	42,000	0.625	1.340	0.140	65,600	1.66	23,600
	2000	1.25	Cylinder	0.05	*						
	1350	0.46	Sphere	0.19	42,000	0.625	-	0.139	19,200	1.12	12,600
	2000	1.25	Sphere	0.10	*						

*The ultimate tensile strength of Hafnalloys at 2000°F is not well known.

Table 3-6. Estimated Fuel/Liner Interaction Depths at End of 10 Years

Material	Temperature °F	Interaction Depth* inch
Ta-10W	1350	0.003
Mo	1350	<0.001
TZM	1350	<0.001
Mo-50Re	1350	<0.001
Pt-20Rh	1350	<0.001
Hafn alloy	1350	0.002**
Ta-10W	2000	Not used
Mo	2000	0.003
TZM	2000	0.002
Mo-50Re	2000	0.002
Pt-20Rh	2000	0.002
Hafn alloy	2000	0.005**

*Includes intergranular attack

**Estimated

Selective Vent. The selective vent essentially permeates helium only. The vent consists of mullite fibers properly aligned in a metal matrix. Helium undergoes solid-state diffusion through the mullite lattice, which is impermeable to higher molecular weight gases. Only limited success has been obtained in fabricating curved vent surfaces or very thin vents, and for the present application it must be assumed that the selective vent is flat with a minimum thickness of 0.040 inch. A relatively large pressure differential (ΔP) is required to flow helium across this vent, and this ΔP is approximately proportional to the vent thickness and inversely proportional to the vent surface area:

$$\Delta P = \frac{14.7 \, tQ}{KA}$$

where

 ΔP = pressure differential (psi)

t = thickness (in)

Q = flow rate (cc/sec)

K = temperature dependent diffusivity constant (cc-in/sec-in²/atm)A = area (in²)

Table 3-7. Estimated Interaction Depths at End of 10 Years

Interface	Temperature °F	Interaction Depth Inch	Basis of Analysis
Ta-10W/Pt-20Rh	1350 ↓	0.003	Available Correlation*
Ta-10W/T-111		0.003	Available Correlation*
Ta-10W/TZM		0.002	Extrapolation of data*
Ta-10W/Hafn alloy		0.003	Assumed same as Ta-10W/T-111 since Hf from T-111 diffuses into Ta-10W.
Mo/T-111		0	Assumed same as TZM/T-111
Mo/Hafn alloy		0	Assumed same as Mo-50Re/Hafn alloy
Mo-50Re/T-111		0	Extrapolation of data*
Mo-50Re/TZM		0	Extrapolation of data*
Mo-50Re/Hafn alloy		0	Extrapolation of data
Pt-20Rh/T-111		0.002	Available Correlation*
Pt-20Rh/TZM		0.005	Available Correlation*
Pt-20Rh/Hafn alloy	2000 ↓	0	Assumed
Mo/T-111		0	Assumed same as TZM/T-111
Mo/Hafn alloy		0.002	Assumed same as Mo-50Re/Hafn alloy
Mo-50Re/T-111		0	Extrapolation of data*
Mo-50Re/TZM		0	Extrapolation of data*
Mo-50Re/Hafn alloy		0.002	Extrapolation of data
Pt-20Rh/T-111		0	Use HfO_2 diffusion barrier
Pt-20Rh/TZM		0	Use Al_2O_3 diffusion barrier
Pt-20Rh/Hafn alloy		0	Assumed

*Reference 6.

Since for the temperature range of interest the selective vent has only been successfully made of noble metals, it can only be installed into noble metal heat source components, that is, the liner or clad. For those heat source systems having both a Pt-20Rh liner and a Pt-20Rh clad, it was decided that the selective vent would be installed in the liner since the strength member could be used to structurally reinforce the liner to avoid liner creep failure. For those designs that do not have a Pt-20Rh liner, the vent must, of course, be placed in the clad. With a low creep-strength material such as Pt-20Rh, it is desirable to minimize the internal pressure and as large a vent as possible is desirable. The decision was therefore made to put selective vents into both ends of the clad and thus minimize the clad required thickness.

Pressure Relief Device (PRD). The Transit and Pioneer RTG type PRD was scaled down for use in the artificial heart heat source. This vent consists of a metallic core sprayed with alumina and pressed into a metallic housing. Pressure differentials for the range of flow rates under consideration are very low, and creep is therefore inconsequential. The alumina presents a very tortuous path for the venting gas and acts as an absolute filter for any fuel fines. Since gas flow occurs through the pores of the plasma-sprayed alumina, complete selectivity* is not obtained and therefore radon, in addition to helium, may flow out of the heat source. To assure reduction of the quantity of radon released from the heat source, a capillary tube is used as explained in the following section.

Since the PRD may be fabricated of any of the candidate heat source materials, no restrictions were imposed as to which component it must be inserted in. To protect it from bullet impact and other modes of damage, however, it was placed in the liner (or innermost member).

Capillary Tube. The extent to which a PRD attenuates the radon released from a heat source was not known at the time of these design studies, and a capillary tube was included in the design for conservatism. Flow through the capillary can be made sufficiently slow to effectively eliminate the

*Some selectivity is obtained simply due to differences in gas molecular size.

discharge of radon. In addition, use of a capillary results in a higher pressure drop between the heat source and the helium dissipation area, thus minimizing the effects of pressure and temperature fluctuations and the backflow of contaminants into the heat source.

The maximum permissible body (MPB) burdens for radon have not been clearly established. The International Commission on Radiological Protection has, however, established the MPB for many of the daughters in the decay chain of Rn-220 and these suggest that the MPB of Rn-220 be limited to approximately 0.01 μCi (Reference 8). An MPB of 0.03 μCi for Rn-222 can be inferred from the same reference. These values are based on an allowable exposure rate of 0.3 rem/week (15 rem/yr) for a period of 50 years, as compared to a design life of the artificial heart device of only 10 years.

An analysis was performed to determine the size of a capillary tube required to delay the emission of Rn-220 from the heat source long enough to limit the released activity to 0.01 μCi (Reference 4). Assuming no decay of radon in the PRD, and an ID of 0.005 inch, the capillary length was estimated to be 4 inches. Test data (Section 5) indicate the required capillary ID to be approximately 0.001 inch.

3.3.2.6 Creep Analyses

The radioisotope fuel generates helium at the rate of approximately 4×10^{-8} std cc/sec per watt of fuel. When the release of this helium from the heat source is restricted by a vent, a pressure drop (ΔP) across the heat source walls will result. At elevated temperatures, this ΔP may result in creep of the capsule components. If this ΔP is large enough creep failure may even occur. Two types of creep analyses were performed to determine how to best avoid such creep failure. The first analysis was performed assuming steady state flow rates and ΔP 's across the capsule wall during the operational life of the heat source. Worst-case creep is obtained when the selective vent is placed in the noble metal clad of the heat source. The second analysis was performed assuming a transient ΔP across the capsule wall resulting from the use of a void volume in which helium could accumulate. This analysis was performed to determine the most volume-efficient means of preventing creep; that is, increasing wall thickness or adding void volume.

Creep from Steady State Pressure. Creep life of the heat source is influenced by configuration, pressure, and temperature. Since the highest stresses occur in a flat-ended pressure vessel, and since the selective vent can only be incorporated in a flat-ended cylinder, this was the geometry selected for analysis. A parametric study was subsequently performed to determine the maximum pressure a Pt-20Rh wall could hold in creep as a function of various diameters, wall thicknesses, and temperature histories. The two temperature histories selected were step functions corresponding to steady state operation followed by a fire environment: 1350°F for 10 years followed by 2500°F for 2 hours, and 2000°F for 10 years followed by 2500°F for 2 hours. Diameters (inside diameter) from 0.2 to 2 inches and wall thicknesses ranging from 10 to 45 mils were investigated (Reference 4).

Two phenomena occur when the temperature of the heat source increases from the steady state operating temperature to the 2500°F fire temperature: the diffusion constant of the selective vent increases, and the capsule internal pressure increases in accordance with the perfect gas law.* In an actual fire environment, the heat source temperature increases gradually as a function of time. To avoid the necessity for a detailed transient analysis, the conservative assumption was made that the temperature varied as a step function from the operating temperature to 2500°F.

Capsule radioisotope inventory, diameters, wall thicknesses, temperature histories, and material properties versus temperature were used as input parameters to a computer program, and the computer iterated to find the initial pressure which would expend 100 percent of the heat source clad creep life when subjected to either 1350° or 2000°F for 10 years and 2500°F for 2 hours. For a given clad diameter and thickness, the maximum permissible pressure was thus determined. The vent was then sized to operate at a pressure lower than this value.

For a minimum volume heat source, these analyses indicated that for the case of an initial temperature of 1350°F, most of the creep life was expended during the two-hour exposure at 2500°F, whereas for the 2000°F

*The capsule internal pressure can further increase if some of the helium had been retained in the fuel at the normal operating temperature. This subject is discussed separately below.

case, most of the creep life was expended prior to the two-hour exposure at 2500°F.

Void Volume versus Wall Thickness. A study was performed to determine the most efficient means of minimizing the volume of a selectively-vented heat source (from the standpoint of creep). The heat source can be designed with a large void volume and thin walls, or with a small void and thicker walls. Increasing internal void volume reduces the rate of pressure increase in the capsule with time. Maximum steady state pressure is, however, achieved in times relatively short compared to the 10-year life of the heat source. Thus lower heat source volumes are still obtained by increasing the clad thickness rather than increasing internal void volume.

Release of Stored Helium. The previous analyses were based on the assumption of 100 percent (real-time) helium release from the fuel. Therefore, the fuel would not store helium which could suddenly be released upon exposure to a higher temperature thus causing a pressure spike. Data indicate that for the 2000°F application this is a good assumption, but there are no data for the 1350°F application.

Purely analytical techniques were unsuccessful. Without some boundary conditions, such as the ΔP across the fuel, neither the maximum spike pressure nor total helium stored, or even the general shape of the pressure curve, could be approximated.

It was concluded that additional data will be required before an approximate analysis can be completed. However, the pressure spike situation only presents a potential problem for the selective vent designs, and none of the selective vent designs scored high in the final design ratings (see Section 3.4). Inclusion of this factor could only make the selective vent design even less attractive by requiring larger vents or heavier-walled clads.

3.3.2.7 Thickness Selection

The final selection of heat source component thicknesses to be used in the parametric analyses was based on the preceding analyses.

The liner thickness depends on the type of vent used. If a PRD is used, the minimum thickness required is dictated by considerations of fuel compatibility, handling, and decontamination. This thickness is 0.020 inch. If a selective vent is to be installed into the liner, the thickness in the region of the weld should be approximately the same as the vent thickness

(0.040 inch). The remainder of the liner thickness could be reduced to 0.020 inch.

The strength member thickness depends on the selected material, adjacent materials, operating temperature, and diameter. A basic design assumption dictates that all intermaterial reaction zones be considered as non load carrying zones. Hence, the strength member thickness must equal the sum of the metallurgical interaction depths and the thickness required on the basis of structural considerations. Since material interaction depths are small, the interaction depth used for each strength member material was the worst-case interaction depth to which the strength member material is susceptible. For instance, at 1350°F, a T-111 strength member may be used in contact with Ta-10W, Mo, Mo-50Re, or Pt-20Rh. The T-111/Pt-20Rh interaction is the most reactive, and this reaction depth was used to size all designs that used a T-111 strength member. The same approach was applied to the other material combinations. This procedure made little difference in the final results of any of the heat source volumes or weights, since the maximum error introduced was less than one percent of volume or weight, but minimized the number of analyses required. Comparison of all the environmental requirements discussed above indicates that bullet impact is the most critical structural requirement imposed on the strength member. The total design thicknesses used to size the candidate heat sources, including both structural and material interaction considerations, are presented in Figure 3-6.

The required clad thickness again depended on the type of vent used. Two selective vents will be used (one in each end) for those designs incorporating selective vents in the clad in order to minimize internal pressure and wall stress. The minimum clad thickness required was estimated to be 0.034 inch for a heat source temperature of 1350°F and diameters on the order of 1.25 inches. Since the clad ends will be 0.040 inch thick (vent thickness) it was decided to provide additional margin of safety to the clad and use a wall thickness of 0.040 inch for all diameters. This thickness was subsequently verified at 2000°F and at larger diameters taking into account that the vent area may also need to be increased. If the vent is placed in the liner of the heat source, a 0.010-inch-thick clad is adequate.

Figure 3-6. Strength Member Design Wall Thickness Vs Diameter

3.3.2.8 Thermal Expansion and Gap Sizes

To prevent interference among the various heat source components (fuel, liner, strength member, and clad) during the fueling operation, assembly into the thermal converter, normal operation or fire environment, thermal expansion analyses were performed and the gaps between adjoining components were properly sized. Since the assembly and normal operating temperatures fall between the temperatures encountered in the fueling operation and fire environment, analyses for these environments need not be performed. Minimum gap sizes were dictated by the requirement for ease of assembly of the various components in a glove box.

During fueling of a heat source, the member being welded is held in a cooling chuck. This outer capsule member is, therefore, much cooler than the inner member containing the fuel and the difference in thermal expansion at these temperatures, if sufficient, could cause interference during assembly. In all cases the cooling chuck was assumed to maintain the outer capsule member at 200°F. All liner materials were assumed to be TIG welded except for molybdenum and TZM which require EB welding. Strength member thicknesses under consideration were large enough to require electron beam welding. Either helium or vacuum were assumed in the fuel/liner and liner/strength member gaps during TIG and EB welding, respectively. Since the clad will in all cases be TIG welded, helium was assumed in the strength member/clad gap. The analyses were performed for a 40-watt heat source and the resulting required gap sizes are shown in Table 3-8.

During exposure of the artificial heart recipient to a fire, the heat source may reach temperatures on the order of 2500°F. To avoid structural damage to the heat source and potential release of the plutonium fuel, stresses due to thermal expansion must be avoided. An analysis was performed to determine if the gaps given above are also adequate to prevent interference during the fire environment. Expansion differentials during the fire were not nearly as large as during welding; hence, there will be no damage to the heat source components.

3.3.2.9 Minimizing Heat Source Volume and Weight

There were a total of 43 heat source candidate designs sized for minimum volume and weight. Most of these sizings were done for 40-watt heat

Table 3-8. Assembly Diametral and Length Clearances

Material System	Fuel/Liner Gap, inch	Liner/Strength Member Gap, inch	Strength Member/Clad Gap, inch
Ta-10W/T-111/Pt-20Rh	0.020	0.015	0.015
Mo-50Re/T-111/Pt-20Rh	0.020	0.015	0.015
Pt-20Rh/T-111/Pt-20Rh	0.020	0.021	0.015
Mo/T-111/Pt-20Rh	0.020	0.015	0.015
Ta-10W/TZM/Pt-20Rh	0.020	0.015	0.015
Mo-50Re/TZM/Pt-20Rh	0.020	0.015	0.015
Pt-20Rh/TZM/Pt-20Rh	0.020	0.021	0.015
Hafn alloy	0.020	-	-
Ta-10W/Hafn alloy	0.020	0.015	-
Mo-50Re/Hafn alloy	0.020	0.015	-
Pt-20Rh/Hafn alloy	0.020	0.015	-
Mo/Hafn alloy	0.020	0.015	-

sources; the effect of thermal inventory was investigated for selected candidates.

Initial analyses were conducted to determine how a change in diameter affects weight and volume at 40 watts. In these analyses the weights and volumes of the PRD, capillary tube and coatings were omitted. A computer program was developed that used as input the material choices, vent type (flow characteristics), material densities, member thicknesses, gap sizes, and fuel volume and weight. By specifying a range of heat source outside diameters, the program computed all component sizes and weights for flat-ended cylinders, hemispherically-ended cylinders, and spheres. A typical heat source volume and weight versus diameter plot is depicted in Figure 3-7. The following conclusions were drawn from these analyses:

- The sphere has the smallest volume and weight
- There is little difference in volume and weight between a sphere and hemispherically-ended cylinders having short cylindrical sections 0.1 to 0.4 inch in length. (The limiting case of the hemispherically-ended cylinder is the sphere.)
- Minimum volume occurs at the same diameter as minimum weight

More detailed analyses were next conducted for the minimum volume and weight heat sources. For those designs which used PRD's, lower volumes and weights were obtained for the spherical designs than for the cylinders having hemispherical or flat ends. The geometry selected for further design, however, had a short cylindrical section to facilitate welding of the components. The designs that used selective vents, on the other hand, were flat ended, since the selective vent itself is flat and can only be installed into a flat surface. These detailed analyses included all necessary design features including vents, coatings and capillaries.

In all cases the volumes and weights calculated in this set of analyses were in excellent agreement with the calculations of the initial sizing analyses. These assembly volumes and weights thus represented an optimization of each candidate design and were used in scoring the various designs as presented in Section 3.4. The volumes ranged from 1.241 in³ for the single-layer Hafn alloy, 1350°F, design with a PRD, to 1.931 in³ for the

Figure 3-7. Total Heat Source Volume and Weight Vs Outside Diameter

three-layer Mo-50Re/TZM/Pt-20Rh, 2000°F, design with two selective vents. The weights ranged from 0.462 lb for the two-layer TZM/Pt-20Rh, 1350°F, design with a PRD, to 0.906 lb for the three-layer Pt-20Rh/T-111/Pt-20Rh, 2000°F design with one selective vent in the liner. Weights and volumes of all the candidate designs are given in Section 3.4.

The effect of power level was investigated by choosing several different designs that had been studied at 40 watts and resizing them for radioisotope inventories ranging from 20 to 60 watts. Typical plots of volume and weight versus diameter and radioisotope inventory are presented in Figure 3-8 for the flat-ended geometry. The curves were in turn cross-plotted to represent the minimum achievable volume and weight heat sources for the sample design candidate as a function of radioisotope thermal inventory (Figure 3-9).

3.3.2.10 Costs

The unit costs of each of the 43 candidate designs were estimated. For the large production quantities anticipated here (10,000 to 20,000 units per year), existing small lot procedures, such as those used on Transit and Pioneer, would not be practical from either a schedule or financial point of view. Hence, the cost estimates were based on the assumption that mass production techniques will be used. These costs did not include the cost of fuel or its forming, but did include material, piece part fabrication, loading of fuel, all subassembly and assembly welding, acceptance testing, scrappage, tool maintenance, production control, and packaging estimates.

The resulting costs ranged from \$580 each for the single-layer, 1350°F, design using Hafn alloy and a PRD, to \$1610 each for the three-layer, 2000°F, design using Mo-50Re/TZM/Pt-20Rh and two selective vents. Preproduction costs, fuel, tooling and facilities were not included but will be almost totally independent of the design candidate. Actual cost estimates are summarized in Section 3.4.

Figure 3-8. Total Heat Source Volume and Weight Vs Heat Source Diameter - Flat Ends

Figure 3-9. Minimum Total Volume and Weight Vs Power - Flat Ends

3.4 DESIGN SELECTION

Based on the analyses presented above, each of the candidate designs was scored against each of the established selection criteria. As described in Section 3.3.1, weighting factors were assigned to each of these criteria and a total of 100 points was distributed among them. The method of applying these points to the candidate designs is summarized in Table 3-9 and is described in detail in Reference 4. The 1350°F and the 2000°F designs were scored independently.

Forty-three designs were analyzed in detail -- twenty-six for the 1350°F application and seventeen for the 2000°F application, as listed in Tables 3-10 and 3-11, respectively. The letter in the design number indicates the general configuration as shown in Figure 3-10; the number following the letter indicates the material combination. The lower case letter, when used, indicates a difference only in end-cap configuration. These designs were basically similar to designs A and F but were flat-ended. There were eight candidate configurations; variations on each configuration were made by altering the materials used for containment.

- Configuration A utilizes a single-layer, hemispherically-ended containment member with a PRD and capillary tube in one end. There is only one candidate material for this configuration: Hafn alloy.
- Configuration B utilizes a two-layer, hemispherically-ended pair of containment members: a liner with PRD and a strength member with a capillary tube. There are four designs of this configuration for the 1350°F application. All use Hafn alloy as the strength member and the liner is Ta-10W, Mo, Mo-50Re, or Pt-20Rh. There are three designs of this configuration for the 2000°F application; these use Hafn alloy as the strength member and a Mo, Mo-50Re, or Pt-20Rh liner.
- Configuration C also utilizes a two-layer, hemispherically-ended pair of containment members. There is a strength member with a PRD and a clad with a capillary. There is one design of this configuration. The strength member is TZM and the clad is Pt-20Rh.
- Configuration D utilizes a two-layer, flat-ended pair of containment members. There is a clad with a selective vent in each end of the capsule, and a strength member. There is one design of this configuration: the strength member is TZM and the clad is Pt-20Rh.

Table 3-9. Scoring Techniques

Volume	Score = $17 \left(\frac{V_o}{V} \right)^2$	V_o = minimum volume system
Weight	Score = $10 \left(\frac{W_o}{W} \right)^2$	W_o = minimum weight system
Environment	Operable in both inert gas and vacuum - 2 points Operable in one - 0 point	
Air	Capable of being handled in air - 2 points Not capable - 0 point	
Compatibility w/Fuel	Score = $9 \left(\frac{\text{Unaffected thickness remaining in 10 years}}{\text{liner thickness}} \right)^2$	
Inter-Material Compat.	Score = $9 \left(\frac{\text{Unaffected thickness remaining in critical member}}{\text{member thickness}} \right)^2$	
Heat Flux	Score = 4, Criterion not relevant to selected thermal converter	
Gas Management	Score depends on vent system/material combination	
Mechanical Interfaces	Flat ended - 4 points Hemispherically ended - 2 points	
Impact	}	3 points if a significant amount of favorable data is available 2 points if minimal amount of favorable data is available 1 point if minimal amount of data is available and it is conflicting 0 point if no data are available
Fragmentation		
Cremation		
Crushing		
Oxidation		
Cost	Score = $8 \left(\frac{\text{Minimum Cost System}}{\text{Cost}} \right)$	
Reliability	By ranking	
Flexibility	By ranking	

Table 3-10. Candidate Design Identification -
1350°F Candidates

Design Number	Materials	Geometry	Type Vent
A1	Hafn alloy	H	PRD
A1a	Hafn alloy	F	PRD
B1	Ta-10W/Haf	F	PRD
B2	Mo/Haf	F	PRD
B3	Mo-50Re/Haf	F	PRD
B4	Pt-20Rh/Haf	F	PRD
C1	TZM/Pt-20Rh	H	PRD
D1	TZM/Pt-20Rh	F	SV
E1	Pt-20Rh/Haf	F	SV
F1	Ta-10W/T-111/Pt-20Rh	H	PRD
F2	Mo/T-111/Pt-20Rh	H	PRD
F2a	Mo/T-111/Pt-20Rh	F	PRD
F3	Mo-50Re/T-111/Pt-20Rh	H	PRD
F3a	Mo-50Re/T-111/Pt-20Rh	F	PRD
F4	Pt-20Rh/T-111/Pt-20Rh	H	PRD
F4a	Pt-20Rh/T-111/Pt-20Rh	F	PRD
F5	Ta-10W/TZM/Pt-20Rh	H	PRD
F6	Mo-50Re/TZM/Pt-20Rh	H	PRD
F7	Pt-20Rh/TZM/Pt-20Rh	H	PRD
G1	Pt-20Rh/T-111/Pt-20Rh	F	SV
G2	Pt-20Rh/TZM/Pt-20Rh	F	SV
H1	Ta-10W/T-111/Pt-20Rh	F	SV
H2	Mo/T-111/Pt-20Rh	F	SV
H3	Mo-50Re/T-111/Pt-20Rh	F	SV
H4	Ta-10W/TZM/Pt-20Rh	F	SV
H5	Mo-50Re/TZM/Pt-20Rh	F	SV

Geometry F = Flat-ended cylinders
 Geometry H = Hemispherically-ended cylinders
 PRD = Pressure Relief Device
 SV = Selective Vent

Table 3-11. Candidate Design Identification -
2000°F Candidates

Design Number*	Materials	Geometry	Type Vent
A1	Hafnallo	H	PRD
B2	Mo/Haf	H	PRD
B3	Mo-50Re/Haf	H	PRD
B4	Pt-20Rh/Haf	H	PRD
C1	TZM/Pt-20Rh	H	PRD
D1	TZM/Pt-20Rh	F	SV
E1	Pt-20Rh/Haf	F	SV
F2	Mo/T-111/Pt-20Rh	H	PRD
F3	Mo-50Re/T-111/Pt-20Rh	H	PRD
F4	Pt-20Rh/T-111/Pt-20Rh	H	PRD
F6	Mo-50Re/TZM/Pt-20Rh	H	PRD
F7	Pt-20Rh/TZM/Pt-20Rh	H	PRD
G1	Pt-20Rh/T-111/Pt-20Rh	F	SV
G2	Pt-20Rh/TZM/Pt-20Rh	F	SV
H2	Mo/T-111/Pt-20Rh	F	SV
H3	Mo-50Re/T-111/Pt-20Rh	F	SV
H5	Mo-50Re/TZM/Pt-20Rh	F	SV

Geometry F = Flat-ended cylinders

Geometry H = Hemispherically-ended cylinder

PRD = Pressure Relief Device

SV = Selective Vent

*Designs B1, F1, F5, H1, and H4 were deleted for the 2000°F application since they included Ta-10W as the liner material.

CONFIGURATION
A

CONFIGURATION B

CONFIGURATION C

CONFIGURATION D

CONFIGURATION E

CONFIGURATION F

CONFIGURATION G

CONFIGURATION H

Figure 3-10. Candidate Configurations

- Configuration E also utilizes a two-layer, flat-ended pair of containment members. There is a strength member and a liner containing a selective vent at one end. There is one design of this configuration: the strength member is Hafn alloy and the liner is Pt-20Rh.
- Configuration F utilizes a three-layer, hemispherically-ended set of containment members. There is a clad with a capillary tube, a strength member, and a liner with a PRD. There are seven designs of this configuration for the 1350°F application. Liner/strength member/clad combinations are: Ta-10W/T-111/Pt-20Rh, Mo/T-111/Pt-20Rh, Mo-50Re/T-111/Pt-20Rh, Pt-20Rh/T-111/Pt-20Rh, Ta-10W/TZM/Pt-20Rh, Mo-50Re/TZM/Pt-20Rh, and Pt-20Rh/TZM/Pt-20Rh. There are five designs of this configuration for the 2000°F application: Mo/T-111/Pt-20Rh, Mo-50Re/T-111/Pt-20Rh, Pt-20Rh/T-111/Pt-20Rh, Mo-50Re/TZM/Pt-20Rh, and Pt-20Rh/TZM/Pt-20Rh.
- Configuration G utilizes a three-layer, flat-ended set of containment members. There is a clad, a strength member, and a liner containing a selective vent. There are two designs of this configuration, both using a Pt-20Rh liner and a Pt-20Rh clad. One uses a T-111 strength member and the other uses a TZM strength member.
- Configuration H also utilizes a three-layer, flat-ended set of containment members. There is a clad with a selective vent in each end, a strength member, and a liner. There are five designs of this configuration for the 1350°F application. The liner/strength member/clad combinations are: Ta-10W/T-111/Pt-20Rh, Mo/T-111/Pt-20Rh, Mo-50Re/T-111/Pt-20Rh, Ta-10W/TZM/Pt-20Rh, and Mo-50Re/TZM/Pt-20Rh. For the 2000°F application, there are 3 designs: Mo/T-111/Pt-20Rh, Mo-50Re/T-111/Pt-20Rh, and Mo-50Re/TZM/Pt-20Rh.

The candidates were scored in accordance with the procedure outlined in Table 3-9, as shown in Tables 3-12 and 3-13 for the 1350° and 2000°F designs, respectively. For each candidate, the scores in all the criteria were summed. The 1350° and 2000°F candidates were ranked separately. The system which ranked first is considered the best overall design for the long-range artificial heart heat source application. The top six candidates for the 1350° and 2000°F applications are presented in Table 3-14. Note that the top two designs are the same for both temperatures.

The sensitivity of the scores and relative rankings of the various designs to changes in criteria weightings was analyzed. Three cases, in which the most heavily weighted criterion (volume) was reduced from 17 points to 10 points and the weightings of three other criteria (weight,

Table 3-12. 1350°F Design Candidates

Des gn Number	Characteristics							Criteria																			
	Volume (in ³)	Weight (lb)	Liner Thickness (in)	Un- affected Thickness (in)	Critical Member Thickness (in)	Un- affected Thickness (in)	Cost \$	$17\left(\frac{V_0}{V}\right)^2$	$10\left(\frac{W_0}{W}\right)^2$	Oper Gas Vac	Hand n Air	$9\left(\frac{\text{Rem Lin}}{\text{Lin Th}}\right)^2$	$9\left(\frac{\text{Rem Th}}{\text{Th}}\right)^2$	Heat Flux	Gas Mgmt	Mech Interface	Imp	Frag	Fire	Crush	Oxid	8	Min Cost Cost	Reliab	Flex	Total	Rank
								1	10			2	2														
A1	1 241*	0 529	0 139	0 137	0 139	0 139	580*	17 0	6	2	2	9 5	9 0	4 7	2	1 2	1 2	3	2 0	3 0	8 0	6	3 0	86 5	1		
A1a	1 348	0 579	0 138	0 136	0 138	0 138	710	14 4	6 4	2	2	8 5	9 0	4 7	4	1 2	1 2	3	1 8	3 0	6 5	6	3 0	83 0	3		
B1	1 407	0 606	0 020	0 017	0 140	0 137	740	13 2	5 8	2	2	6 5	8 6	4 4	2	1 2	1 2	3	2 0	3 0	6 3	6	3 0	73 8	18		
B2	1 407	0 587	0 020	0 019	0 140	0 140	780	13 2	6 2	2	2	8	9 0	4 4	2	1 2	1 2	3	2 0	3 0	6 0	1	3 0	70 9	22		
B3	1 407	0 597	0 020	0 019	0 140	0 140	1010	13 2	6 0	2	2	8 1	9 0	4 4	2	1 2	1 2	3	2 0	3 0	4 6	6	3 0	74 3	16		
B4	1 426	0 617	0 020	0 019	0 140	0 140	995	12 9	5 6	2	2	8 1	9 0	4 7	2	1 2	1 2	3	2 0	3 0	4 7	6	3 0	76 7	13		
C1	1 266	0 462*	0 123	0 122	0 123	0 118	720	16 3	10 0	2	2	8 9	8 3	4 4	2	2 6	3 0	3	3 0	1 0	6 4	0	1 5	78 0	11		
D1	1 595	0 657	0 124	0 123	0 124	0 119	1220	10 3	4 9	2	2	8 9	8 3	4 9	4	2 4	2 8	3	2 6	1 0	3 8	0	0 5	69 5	23		
E1	1 468	0 715	0 020	0 019	0 140	0 140	1240	12 1	3 8	2	2	8 1	9 0	4 9	4	1 2	3 0	3	2 8	3 0	3 7	5	1 0	76 7	12		
F1	1 269	0 585	0 020	0 017	0 099	0 094	785	16 3	6 2	2	2	6 5	8 1	4 4	2	3 0	3 0	3	3 0	1 2	5 9	8	2 5	80 7	7		
F2	1 269	0 566	0 020	0 019	0 099	0 097	820	16 3	6 7	2	2	8 1	8 5	4 4	2	3 0	3 0	3	3 0	1 2	5 7	7	2 5	82 0	5		
F2a	1 386	0 624	0 020	0 019	0 097	0 095	860	13 6	5 5	2	2	8 1	8 5	4 4	4	3 0	3 0	3	2 8	1 2	5 4	7	2 5	79 6	8		
F3	1 269	0 576	0 020	0 019	0 099	0 097	1060	16 3	6 4	2	2	8 1	8 6	4 4	2	3 0	3 0	3	3 0	1 2	4 4	8	2 5	81 5	6		
F3a	1 386	0 635	0 020	0 019	0 097	0 095	1070	13 6	5 3	2	2	8 1	8 6	4 4	4	3 0	3 0	3	2 8	1 2	4 3	8	2 5	79 4	9		
F4	1 285	0 595	0 020	0 019	0 099	0 094	1040	15 9	6 0	2	2	8 1	8 1	4 7	2	3 0	3 0	3	3 0	2 4	4 5	8	2 5	84 5	2		
F4a	1 408	0 656	0 020	0 019	0 097	0 092	1040	13 2	5 0	2	2	8 1	8 1	4 7	4	3 0	3 0	3	2 8	2 4	4 5	8	2 5	82 6	4		
F5	1 423	0 530	0 020	0 017	0 125	0 118	910	12 9	7 6	2	2	6 5	8 0	4 4	2	2 6	3 0	3	3 0	1 2	5 1	2	2 0	70 9	21		
F6	1 423	0 521	0 020	0 019	0 125	0 120	1240	12 9	7 9	2	2	8 1	8 3	4 4	2	2 6	3 0	3	3 0	1 4	3 7	2	2 0	71 9	20		
F7	1 443	0 540	0 020	0 019	0 125	0 115	1230	12 6	7 3	2	2	8 1	7 6	4 7	2	2 6	3 0	3	3 0	2 4	3 8	2	2 0	74 4	15		
G1	1 426	0 664	0 020	0 019	0 098	0 093	1040	12 9	4 8	2	2	8 1	8 1	4 5	4	3 0	3 0	3	2 8	2 4	4 5	8	0 5	78 1	10		
G2	1 614	0 600	0 020	0 019	0 124	0 114	1120	10 1	5 9	2	2	8 1	7 6	4 5	4	2 6	3 0	3	2 8	2 4	4 1	1	0	67 6	24		
H1	1 610	0 801	0 020	0 017	0 098	0 093	1350	10 1	3 3	2	2	6 5	8 1	4 9	4	2 8	3 0	3	2 6	1 2	3 4	8	0 5	73 5	19		
H2	1 610	0 781	0 020	0 019	0 098	0 096	1400	10 1	3 5	2	2	8 1	8 6	4 9	4	2 8	3 0	3	2 6	1 4	3 3	6	0 5	73 9	17		
H3	1 610	0 782	0 020	0 019	0 098	0 096	1560	10 1	3 5	2	2	8 1	8 6	4 9	4	2 8	3 0	3	2 6	1 4	3 0	8	0 5	75 6	14		
H4	1 816	0 752	0 020	0 017	0 124	0 117	1330	7 9	3 8	2	2	6 5	8 1	4 9	4	2 4	3 0	3	2 6	1 2	3 5	1	0	64 0	26		
H5	1 816	0 743	0 020	0 019	0 124	0 019	1580	7 9	3 9	2	2	8 1	8 3	4 9	4	2 4	3 0	3	2 6	1 4	2 9	1	0	65 5	25		

*Minimum

Table 3-13. 2000°F Design Candidates

Design Number	Characteristics							Criteria																		
	Volume (in ³)	Weight (lb)	Liner Thickness (in)	Un-affected Thickness (in)	Critical Member Thickness (in)	Un-affected Thickness (in)	Cost \$	$17\left(\frac{V}{V_0}\right)^2$	$10\left(\frac{W}{W_0}\right)^2$	Oper Gas/Vac	Hand r Air	$9\left(\frac{Rem L_n}{L_n Th}\right)^2$	$3\left(\frac{Rem Th}{Th}\right)^2$	Heat Flux	Gas Agmt	Me n Interface	Imp	Frag	Fire	Crush	Oxid	$8\frac{Min Cost}{Cost}$	Reliab	Flex	Total	Pank
								17	10	2	2	9	3	4	4	4	3	3	3	3	3	8	8	3	100	
A1	1 387	0 601	0 164	0 159	0 164	0 164	640*	1 8	4 5	2	2	3 4	3	4	7	2	1 2	1 2	3	2 0	3 0	8 0	6	3 0	84 1	1
B2	1 570	0 666	0 020	0 017	0 166	0 164	830	12 4	5 3	2	2	6 5	8 8	4	4	2	1 2	1 2	3	2 0	3 0	6 2	1	3 0	67 6	16
B3	1 570	0 676	0 020	0 018	0 166	0 164	1070	12 4	5 2	2	2	7 3	8 8	4	4	2	1 2	1 2	3	2 0	3 0	4 8	6	3 0	71 9	12
B4	1 591	0 697	0 020	0 018	0 166	0 166	1050	12 0	4 8	2	2	7 3	9 0	4	7	2	1 2	1 2	3	2 0	3 0	4 9	6	3 0	74 4	9
C1	1 338*	0 485*	0 135	0 133	0 135	0 135	740	17 0	10 0	2	2	8 7	9 0	4	4	2	2 6	3 0	3	3 0	1 0	6 9	0	2 0	80 2	3
D1	1 700	0 698	0 134	0 132	0 134	0 134	1230	10 5	4 8	2	2	8 7	9 0	4	3	4	2 4	2 8	3	2 6	1 0	4 2	0	0 5	70 5	14
E1	1 797	0 791	0 020	0 018	0 165	0 165	1440	9 4	3 8	2	2	7 3	9 0	4	9	4	1 2	3 0	3	2 8	3 0	3 6	5	1 0	73 1	10
F2	1 411	0 645	0 020	0 017	0 120	0 120	840	15 3	5 7	2	2	6 5	9 0	4	4	2	3 0	3 0	3	3 0	1 2	6 1	7	2 5	79 3	5
F3	1 411	0 655	0 020	0 018	0 120	0 120	1080	15 3	5 5	2	2	7 3	9 0	4	4	2	3 0	3 0	3	3 0	1 2	4 7	8	2 5	79 5	4
F4	1 428	0 670	0 020	0 018	0 120	0 120	1060	14 9	5 2	2	2	7 3	9 0	4	7	2	3 0	3 0	3	3 0	2 4	4 8	8	2 5	83 1	2
F6	1 570	0 555	0 020	0 018	0 136	0 136	1250	12 3	7 6	2	2	7 3	9	4	4	2	2 6	3 0	3	3 0	1 4	4 1	2	2 0	71 3	13
F7	1 535	0 567	0 020	0 018	0 136	0 136	1240	12 9	7 3	2	2	7 3	9 0	4	7	2	2 6	3 0	3	3 0	2 4	4 1	2	2 0	75 6	7
G1	1 602	0 763	0 020	0 018	0 118	0 118	1090	11 9	4 0	2	2	7 3	9 0	4	5	4	3 0	3 0	3	2 8	2 4	4 7	8	1 5	77 6	6
G2	1 730	0 642	0 020	0 018	0 135	0 135	1150	10 2	5 7	2	2	7 3	9 0	4	5	4	2 6	3 0	3	2 8	2 4	4 5	1	1 0	69 5	15
H2	1 798	0 888	0 020	0 017	0 118	0 118	1440	9 4	3 0	2	2	6 5	9 0	4	9	4	2 8	3 0	3	2 6	1 2	3 6	6	1 5	72 6	11
H3	1 798	0 899	0 020	0 018	0 118	0 118	1610	9 4	2 9	2	2	7 3	9 0	4	9	4	2 8	3 0	3	2 6	1 4	3 2	8	1 5	75 1	8
H5	1 937	0 790	0 020	0 018	0 134	0 134	1610	8 1	3 8	2	2	7 3	9 0	4	9	4	2 4	3 0	3	2 6	1 2	3 2	1	1 0	66 6	17

*Minimum

Table 3-14. Top Heat Source Candidates

1350°F Application

<u>System</u>	<u>Configuration</u>	<u>Score</u>
1. Hafn alloy	Hemispherical, PRD	86.5
2. Pt-20Rh/T-111/Pt-20Rh	Hemispherical, PRD	84.5
3. Hafn alloy	Flat-Ended, PRD	83.0
4. Pt-20Rh/T-111/Pt-20Rh	Flat-Ended, PRD	82.6
5. Mo/T-111/Pt-20Rh	Hemispherical, PRD	82.0
6. Mo-50Re/T-111/Pt-20Rh	Hemispherical, PRD	81.5

2000°F Application

<u>System</u>	<u>Configuration</u>	<u>Score</u>
1. Hafn alloy	Hemispherical, PRD	84.1
2. Pt-20Rh/T-111/Pt-20Rh	Hemispherical, PRD	83.1
3. Hafn alloy	Flat-Ended, PRD	*
4. Pt-20Rh/T-111/Pt-20Rh	Flat-Ended, PRD	*
5. TZM/Pt-20Rh	Hemispherical, PRD	80.2
6. Mo-50Re/T-111/Pt-20Rh	Hemispherical, PRD	79.5

*Not designed, but score is expected to have same relative position as the 1350°F designs.

cost, and safety) were increased, were investigated. The analysis showed that the top six designs remained at the top and in only one case the first- and second-ranked designs changed position and the third- and fourth-ranked designs changed position. Due to the severity of the changes made in the weightings, it was concluded that the rankings of the top designs were not very sensitive to the criteria weightings.

The top-rated heat source for both the 1350° and 2000°F applications was a single-layer Hafn alloy heat source with a PRD and hemispherical ends. This system, however, was not considered as a baseline design for the practicability demonstration of an artificial heart due to the limited compatibility, fabrication, and test data available for this alloy. The next-highest-rated system, and the one selected for the baseline design, was the Pt-20Rh/T-111/Pt-20Rh design having a nonselective PRD. As can be seen in Table 3-14, both the hemispherically-ended and flat-ended systems of this materials combination rank higher than all other systems evaluated, with the exception of the single-layer Hafn alloy system. In addition to this baseline design, it was decided to design, fabricate and test Hafn alloy heat sources in order to obtain further data on the basis of which future design selections can be made.

3.5 HEAT SOURCE DESIGN

The design of the heat source for the artificial heart device was based on the results discussed above. Basic design requirements were imposed by the Atomic Energy Commission as based on work performed on the artificial heart thermal converter system, and included:

Power	- 33.1 watts
Diameter	- 0.984 inch (2.5 cm)
Configuration	- flat-ended cylinder
Temperature	- 1565°F (1125°K)

The thermal converter uses a Stirling engine to convert the thermal energy of the heat source to mechanical energy. The heat source must be capable of being located either externally or internally at one end of the engine cylinder, or hot finger, adjacent to the displacer piston. Thermal insulation surrounds the heat source and cylinder. If mounted internally, the working fluid to which the heat source is exposed is krypton. The cyclic pressure

variation is nominally 11.7 ± 2.6 atm at a frequency of 10 cyc/sec. Placement of the heat source within the engine cylinder improves the efficiency of the system. To maximize this efficiency, however, it is also desirable to minimize the dead volume in the cylinder. Thus, clearances around the heat source must be extremely small and the heat source must have sharp rather than rounded corners and have no weld protrusions.

Based on the results of the parametric analyses discussed above, a three-layer, Pt-20Rh/T-111/Pt-20Rh flat-ended heat source was selected for the baseline design. A single-layer, flat-ended Hafnialloy heat source was also designed to allow better evaluation of Hafnialloy as a candidate material for the artificial heart heat source.

3.5.1 Baseline Design

3.5.1.1 Design Description

The baseline Pt-20Rh/T-111/Pt-20Rh heat source is 0.984 inch in diameter, 1.795 inches long, and weighs 0.62 lb. A schematic of the heat source is shown in Figure 3-11. The heat source consists of four basic components: PuO_2 fuel, a liner to contain the fuel, a strength member to ensure fuel containment under accident environments, and a clad to protect the refractory strength member from oxidation. In addition, a weld reflector ring is used within the liner to avoid contamination of the liner weld, a PRD is used to vent decay-generated helium, and a capillary tube is used in conjunction with the PRD to reduce the level of radon-220 emitted by the heat source.

If the heat source is located within the thermal converter engine, it is questionable whether a capillary is actually required since the engine is sealed, thus preventing the release of radon to the body of the artificial heart recipient. If the heat source is located external to the engine, a capillary will probably be needed; encouraging PRD test results may, however, allow deletion of the capillary. In order not to restrict use of the heat source, the capillary tube was included in the design. Since it was desired to minimize the dead space surrounding the heat source, however, it was necessary to place the capillary within the clad, permitting the configuration of a right circular cylinder.

DIAMETER = 0.984 INCH
LENGTH = 1.795 INCHES
WEIGHT = 0.62 LB.
POWER = 33.1 WATTS

Figure 3-11. Baseline Artificial Heart Heat Source

Table 3-15. Baseline Design Drawing Tree

Drawing No.	Title
C410628	Clad Assembly, AHHS
D410647	Capillary Clad Assembly, AHHS
D410585	Clad Components, AHHS
C410587	Strength Member Assembly, AHHS
D410584	Strength Member Components, AHHS
C410586	Liner Assembly, AHHS
D410646	Liner End Cap Assembly, AHHS
D410583	Liner Components, AHHS
D410571	Pressure Relief Device Assembly
D410581	Welding Reflector Ring, AHHS
D410582	Fuel - AHHS

The clearances between, and the thicknesses of, the encapsulating members were determined and optimized by the parametric analyses described above. A drawing tree for the baseline design heat source is given in Table 3-15; heat source design drawings are shown in Figures 3-12 to 3-23.

- The fuel is electrorefined, oxygen-16 enriched, pressed and sintered PuO_2 . It is pressed into a single puck 0.670 inch in diameter by 1.410 inches long, as shown in Figure 3-12. A chamfer at each edge prevents interference with the liner weld. A 0.010 inch weld reflector ring (Figure 3-13) is positioned on top of the fuel to minimize potential weld contamination in the final liner weld.
- The PRD is shown in Figure 3-14. It is a shortened and simplified version of the Transit PRD and consists of a metallic core sprayed with alumina and pressed into a Pt-20Rh housing. The alumina presents a very tortuous path for the venting gas and acts as an absolute filter for any fuel fines.
- The liner components are shown in Figure 3-15. The Pt-20Rh liner is 0.020 inch thick and each end cap has a 0.010-inch step to facilitate positioning during the welding operation. One of these caps accommodates the PRD which extends into a recess in the fuel and is welded flush with the liner cap, as shown in Figure 3-16. The complete liner assembly is shown in Figure 3-17.
- The T-111 strength member, originally estimated to survive all accident environments, is 0.095 inch thick, as shown in Figure 3-18. Each end cap includes a 0.040 inch step for positioning and ease of welding. The strength member subassembly is shown in Figure 3-19.

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	SEE DOCUMENT REVISED E.O. W.M.A 8 AUG 72	11 AUG 72	J. E. S.

- NOTES: UNLESS OTHERWISE SPECIFIED
- PART IDENTIFICATION MARKING PER TBD
 - POWER OF FUEL: 33.1±0.2 WATTS REQUIRED.
(POWER DENSITY 4.3 WATTS/CC REF).

QTY REQD PER ASSY		CODE IDENT NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC	REF DES	ITEM NO.
			-1	FUEL	Pu-238 OXIDE MEDICAL GRADE	2.		
PARTS LIST								
UNLESS OTHERWISE SPECIFIED				CONTRACT NO.		THE FOLLOWING EO'S HAVE BEEN ATTACHED TO THIS PRINT		
1. DO NOT SCALE DRAWING. 2. INTERPRET PER MIL-STD-100. 3. DIMENSIONS ARE IN INCHES. 4. SURFACE TEXTURE SHALL BE .125 5. REMOVE BURRS AND SHARP EDGES. 6. DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING. 7. PARENTHEetical DATA IS FOR REFERENCE ONLY.				DRAWN J. Bringman 3-27-72 CHECKED B. Davis 4-14-72 STRUCTURES 4-18-72 MATERIAL/PROCESS ENGINEER SUPERVISOR PROJECT		TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH, CALIFORNIA FUEL-AHHS SIZE CODE IDENT NO. D410 582 SCALE 2/1 SHEET		
TOLERANCES				ON ALL HOLE DIAMETERS				
				UNDER .0140 +.0020 -.0005 .501 THRU .750 +.008 -.001				
				.014 THRU .125 +.004 -.001 .751 THRU 1.000 +.010 -.001				
				.126 THRU .250 +.005 -.001 1.000 THRU 2.000 +.012 -.001				
				.251 THRU .500 +.006 -.001 OVER 2.000 +.015 -.005				
ON DECIMAL DIMENSIONS:				ON ANGULAR DIMENSIONS:				
XXX ± .010				MACHINED ± 0°30'				
XX ± .03				LOCATING ± 0°30'				
X ± .1				FORMED ± 2°				
				CHAMFERS ± 5°				
FINISH				OTHER APPROVALS				
HEAT TREAT								
APPLICABLE SPECIFICATIONS								
THE ABOVE TRW SYSTEMS GROUP SPECS FORM A PART OF THIS DRAWING								
USED ON		NEXT ASSY	NEXT ASSY QTY REQD					
AHHS		C410586	11-11	PR12-6				
APPLICATION								

MJO 1460-87

Figure 3-12. Fuel

- NOTES: UNLESS OTHERWISE SPECIFIED
- 1. PART IDENTIFICATION MARKING PER PR 12-6-0900 (BAG AND TAG).
 - 2. -2 MAY BE MADE FROM -3.
 - 3. DIMENSIONS APPLY AT 68°±1° F.
 - 4. PARTS MAY BE INSPECTED IN A RESTRAINED CONDITION.
 - 5. USE OF SILICON BASE COOLANTS, LUBRICANTS AND ABRASIVES IS NOT PERMITTED
 - 6. NO DISCOLORATIONS OF A CONTAMINATION NATURE PERMITTED

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REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	SEE DOCUMENT REVISE E.O. W.M.A. 8 AUG 72	11 AUG 72	
B	INCORPORATED EO BI Jw	8 MAR 73	E. Brinman 3-12-73

NOTES: UNLESS OTHERWISE SPECIFIED

1. PART IDENTIFICATION MARKING PER PR 12-6-0900.

2. DELETED

3. WELD PER PR 3-13, CLASS 2.

4. PENETRANT INSPECT PER MIL -1-6866

1				D410571-15	TUBE						
1				-12	ROD	.150 ±.002 DIA ROD PLATINUM-20 RHODIUM				MOULD LAB 1-13457	
-	1	-		-11	DUMMY PRD ASSY						
	1	1		D410583-2	LINER END CAP-VENT						
		1		D410571-1	PRESSURE RELIEF DEVICE-ASSEMBLY						
-11	-2	-1		CODE IDENT NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC	REF DES	ITEM NO.	
QTY REQD PER ASSY				PARTS LIST							
UNLESS OTHERWISE SPECIFIED						CONTRACT NO.	THE FOLLOWING EO'S HAVE BEEN ATTACHED TO THIS PRINT				
1. DO NOT SCALE DRAWING. 2. INTERPRET PER MIL-STD-100. 3. DIMENSIONS ARE IN INCHES. 4. SURFACE TEXTURE SHALL BE 63 5. REMOVE BURRS AND SHARP EDGES. 6. DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING. 7. PARENTHEetical DATA IS FOR REFERENCE ONLY.						DRAWN J. Brinman 4-10-72	TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH, CALIFORNIA LINER END CAP-ASSEMBLY AHHS				
						CHECKED R. Davis 4-15-72					
						STRUCTURES H. Lurie 4-18-72					
						MATERIAL PROCESS ENGINEER 4-18-72					
						SUPERVISOR 18 APR 72					
TOLERANCES						PROJECT H. Lurie 4-18-72	SIZE CODE IDENT NO. D410646 SCALE 10/1 SHEET				
ON ALL HOLE DIAMETERS						OTHER APPROVALS					
ON DECIMAL DIMENSIONS:											
ON ANGULAR DIMENSIONS:							FINISH HEAT TREAT				
XXX ± .010											
XX ± .03											
X ± .1											
MACHINED ± 0°30'							APPLICATION NEXT ASSY NEXT ASSY QTY REQD				
LOCATING ± 0°30'											
FORMED ± 2°											
CHAMFERS ± 5°											
APPLICABLE SPECIFICATIONS							THE ABOVE TRW SYSTEMS GROUP SPECS FORM A PART OF THIS DRAWING				
THE ABOVE TRW SYSTEMS GROUP SPECS FORM A PART OF THIS DRAWING											

NJO 1460-87

Figure 3-16. Liner End Cap - Assembly

TRW			I. MANDATORY SOURCES OF SUPPLY			I APPLICATION	
DASH NO.	APPL. SPEC.	CODE IDENT	PART NO.	DWG. OR DOCUMENT NO.	NAME & ADDRESS	USED ON	NEXT ASSY
-1	TO BE DETERMINED	19065		TO BE DETERMINED	MOUND LABORATORY MONSANTO RESEARCH CORPORATION MIAMISBURG, OHIO	AHHS	C410587-1
-2						AHHS	C410587 2

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	SEE DOCUMENT REVISED E.O. JW	3/8/73	B. Brumby 5-12-73

SOURCE CONTROL DRAWING

NOTES: UNLESS OTHERWISE SPECIFIED

- ONLY THE ITEMS DESCRIBED ON THIS DRAWING WHEN PROCURED FROM THE VENDORS LISTED HEREON IS APPROVED BY TRW SYSTEMS GROUP, APPLIED TECHNOLOGY DIVISION, FOR USE IN THE APPLICATION SPECIFIED HEREON. A SUBSTITUTE ITEM SHALL NOT BE USED WITHOUT PRIOR TESTING AND APPROVAL BY THE APPLIED TECHNOLOGY DIVISION.
- ALL ASSEMBLY AND INSPECTION PROCEDURES TO BE DETERMINED BY MOUND LABORATORY.
- PART IDENTIFICATION AND SERIAL NUMBER MARKING PER MDI 1-14709

1		D410646-2	LINER END CAP - ASSY - SIMULATED				
1	-	D410816-1	FUEL SIMULANT				
1	/	D410583-3	LINER END CAP-PLAIN				
1	/	D410583-1	LINER TUBE				
-	/	D410582-1	FUEL				
1	/	D410581-1	WELDING REFLECTOR RING				
1	/	D410646-1	LINER END CAP - ASSEMBLY				

QTY REQD PER ASSY	CODE IDENT NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC	REF DES	ITEM NO.
	-2	-1					
PARTS LIST				THE FOLLOWING E.O'S HAVE BEEN ATTACHED TO THIS PRINT			
UNLESS OTHERWISE SPECIFIED				CONTRACT NO			
1. DO NOT SCALE DRAWING 2. INTERPRET PER MIL STD-100 3. DIMENSIONS ARE IN INCHES 4. SURFACE TEXTURE SHALL BE 5. REMOVE BURRS AND SHARP EDGES 6. DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING 7. PARENTHEetical DATA IS FOR REFERENCE ONLY				DRAWN J. Bringman 3-29-72 CHECKED R. Davis 4-14-72 STRUCTURES MATERIAL/PROCESS ENGINEER SUPERVISOR PROJECT H. X. 5/12/72			
TOLERANCES ON ALL HOLE DIAMETERS UNDER 0140 +.0020 -0005 501 THRU 750 +.008 -001 ON DECIMAL DIMENSIONS XXX ± 010 XX ± 03 X ± 1 ON ANGULAR DIMENSIONS MACHINED ± 0°30' LOCATING ± 0°30' FORMED ± 2° CHAMFERS ± 5°				FINISH HEAT TREAT			
APPLICABLE SPECIFICATIONS THE ABOVE TRW SYSTEMS GROUP SPECS FORM A PART OF THIS DRAWING				OTHER APPROVALS			
AHHS C410587 1(-2) AHHS C410587 1(-1)				LINER ASSEMBLY, AHHS			
USED ON APPLICATION				SIZE CODE IDENT NO D 11982 C410586			
NEXT ASSY QTY REQD				SCALE 4/1 SHEET			

C410586 A

Figure 3-17. Liner Assembly

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	SEE DOCUMENT REVISED E.D. Wm A 8 AUG 72	11 AUG 72	H. H. H.

DETAIL C
SCALE 10/1

DETAIL D
TYP BOTH ENDS
SCALE 10/1

-2 S.M. END CAP-VENT

-1 S.M. TUBE

-3 S.M. END CAP-PLAIN

- NOTES: UNLESS OTHERWISE SPECIFIED
- PART IDENTIFICATION MARKING PER PR 12-6-0800
 - 2 MAY BE MADE FROM -3.
 - DIMENSIONS APPLY AT 68°±1° F.
 - USE OF SILICON BASE COOLANTS, LUBRICANTS AND ABRASIVES IS NOT PERMITTED.
 - NO DISCOLORATIONS OF A CONTAMINATION NATURE PERMITTED.

1		-3	S.M. END CAP-PLAIN	SHEET, .100±.005 THICK T-III TANTALUM ALLOY	MOUND LAB. 1-13458		
1		-2	S.M. END CAP-VENT	SHEET, .100±.005 THICK T-III TANTALUM ALLOY	MOUND LAB. 1-13458		
1		-1	S.M. TUBE	.750±.001 ID X .095±.005 WALL T-III TANTALUM ALLOY	MOUND LAB. 1-13458		

QTY REQD PER ASSY	CODE IDENT NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC	REF DES	ITEM NO.
PARTS LIST							
UNLESS OTHERWISE SPECIFIED				CONTRACT NO.			
1. DO NOT SCALE DRAWING				DRAWN J. Bringham			
2. INTERPRET PER MIL-STD-100.				CHECKED E. Davis			
3. DIMENSIONS ARE IN INCHES.				STRUCTURES 3/1/72			
4. SURFACE TEXTURE SHALL BE 63				MATERIAL PROCESS 4-18-72			
5. REMOVE BURRS AND SHARP EDGES.				ENGINEER 10-18-72			
6. DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING.				SUPERVISOR 10-18-72			
7. PARENTHEetical DATA IS FOR REFERENCE ONLY.				PROJECT H. Lewis			
TOLERANCES				ON ALL HOLE DIAMETERS			
UNDER .0140				.501 THRU .750			
.0005				.001			
.014 THRU .125				.751 THRU 1.000			
.001				.001			
.126 THRU .250				1.000 THRU 2.000			
.001				.001			
.251 THRU .500				OVER 2.000			
.001				.001			
ON DECIMAL DIMENSIONS:				ON ANGULAR DIMENSIONS:			
XXX ± .010				MACHINED ± 0°30'			
XX ± .03				LOCATING ± 0°30'			
X ± .1				FORMED ± 2°			
				CHAMFERS ± 5°			
FINISH				HEAT TREAT			
APPLICABLE SPECIFICATIONS				OTHER APPROVALS			
THE ABOVE TRW SYSTEMS GROUP SPECS FORM A PART OF THIS DRAWING							

SIZE	CODE IDENT NO.	SCALE	AND NOTED	SHEET
D	11982	D410584		

AHHS	C410587	1(-2)
AHHS	C410587	1(-2)
AHHS	C410587	1(-1)
USED ON	NEXT ASSY	NEXT QTY REQD
APPLICATION		

Figure 3-18. Strength Member Components

TRW		I. MANDATORY SOURCES OF SUPPLY			I. APPLICATION	
DASH NO	APPL. SPEC	CODE IDENT	PART NO.	DWG OR DOCUMENT NO.	NAME & ADDRESS	USED ON NEXT ASSY
-1	TO BE DETERMINED	H065		TO BE DETERMINED	MOUND LABORATORY MONSANTO RESEARCH CORPORATION MIAMISBURG, OHIO	AHHS C410628-1
-2						AHHS C410628-2

REVISIONS		
LTR	DESCRIPTION	DATE
A	INCORPORATED E.O.S. A1 & A2	3/8/73

SOURCE CONTROL DRAWING

NOTES: UNLESS OTHERWISE SPECIFIED

1. ONLY THE ITEMS DESCRIBED ON THIS DRAWING WHEN PROCURED FROM THE VENDORS LISTED HEREON IS APPROVED BY TRW SYSTEMS GROUP, APPLIED TECHNOLOGY DIVISION, FOR USE IN THE APPLICATION SPECIFIED HEREON. A SUBSTITUTE ITEM SHALL NOT BE USED WITHOUT PRIOR TESTING AND APPROVAL BY THE APPLIED TECHNOLOGY DIVISION.
2. ALL ASSEMBLY AND INSPECTION PROCEDURES TO BE DETERMINED BY MOUND LABORATORY.

3. PART IDENTIFICATION AND SERIAL NUMBER MARKING PER MDI-14684

4. MACHINE 0.035 X 45° CHAMFER ON S M END CAP PLAIN AFTER WELDING TO BODY

1	-		C410586-2	LINER ASSEMBLY				
1	/		D410584-3	S.M. END CAP-PLAIN				
1	/		D410584-2	S.M. END CAP-VENT				
1	/		D410584-1	S.M. TUBE				
-	/		C410586-1	LINER ASSEMBLY				

QTY REQD PER ASSY	CODE IDENT NO	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC	REF DES	ITEM NO
PARTS LIST							
UNLESS OTHERWISE SPECIFIED				CONTRACT NO			
1. DO NOT SCALE DRAWING 2. INTERPRET PER MIL STD-100 3. DIMENSIONS ARE IN INCHES 4. SURFACE TEXTURE SHALL BE 5. REMOVE BURRS AND SHARP EDGES 6. DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING 7. PARENTHEetical DATA IS FOR REFERENCE ONLY				THE FOLLOWING EO'S HAVE BEEN ATTACHED TO THIS PRINT			
TOLERANCES ON ALL HOLE DIAMETERS UNDER 0140 +.0020 -0005 014 THRU 125 +.004 -001 126 THRU 250 +.005 -001 251 THRU 500 +.006 -001				DRAWN J. Bringman 3/31/72 CHECKED E. Davis 4-18-72 STRUCTURES 2-1/2 4-17-72 MATERIAL/PROCESS ENGINEER SUPERVISOR PROJECT			
ON DECIMAL DIMENSIONS XXX ± 0.10 XX ± 03 X ± 1				ON ANGULAR DIMENSIONS MACHINED ± 0°30' LOCATING ± 0°30' FORMED ± 2° CHAMFERS ± 5°			
FINISH				OTHER APPROVALS			
HEAT TREAT				SIZE CODE IDENT NO			
APPLICABLE SPECIFICATIONS THE ABOVE TRW SYSTEMS GROUP SPECS FORM A PART OF THIS DRAWING				D 11982 C410587			
USED ON NEXT ASSY NEXT ASSY QTY REQD				SCALE 4/1			

Figure 3-19. Strength Member Assembly

Figure 3-20. Clad Components

Figure 3-21. Heat Source Vent System

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	SEE EO	21 SEP 72	<i>[Signature]</i>

NOTES: UNLESS OTHERWISE SPECIFIED

- PART IDENTIFICATION MARKING PER PR12-6-0900 (BAG AND TAG).
- D410585-5 CAPILLARY TUBE TO BE BENT AND COILED EVENLY (APPROX AS SHOWN) WITHIN A .315 R AND .035 WIDTH. OUTLET OF TUBE TO BE FLUSH WITH D410585-4 COVER WITHIN $\pm .005$.
- WELD PER PR3-13 CLASS 2
- PENETRANT INSPECT PER MIL-I-6866

1		D410585-5	CAPILLARY TUBE						
1		D410585-4	COVER-CAPILLARY						
- /	CODE IDENT NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC	REF DES	ITEM NO		
QTY REQD PER ASSY		PARTS LIST							
UNLESS OTHERWISE SPECIFIED		CONTRACT NO		THE FOLLOWING EO'S HAVE BEEN ATTACHED TO THIS PRINT					
1 DO NOT SCALE DRAWING		DRAWN J Bringman 4-11-72		TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH, CALIFORNIA CAPILLARY CLAD ASSEMBLY AHHS					
2 INTERPRET PER MIL STD-100		CHECKED R Davis 4-14-72							
3 DIMENSIONS ARE IN INCHES		STRUCTURES							
4 SURFACE TEXTURE SHALL BE		MATERIAL/PROCESS							
5 REMOVE BURRS AND SHARP EDGES		ENGINEER		SIZE CODE IDENT NO D 11982 D410647 SCALE 10/11 SHEET					
6 DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING		SUPERVISOR							
7 PARENTHESES DATA IS FOR REFERENCE ONLY		PROJECT							
TOLERANCES		ON ALL HOLE DIAMETERS							
UNDER 0140		+ .0020							
0140 THRU 125		+ .0010							
125 THRU 250		+ .0005							
250 THRU 500		+ .0005							
OVER 500		+ .0005							
ON DECIMAL DIMENSIONS		ON ANGULAR DIMENSIONS							
XXX ± .010		MACHINED ± 0°30'							
XX ± .005		LOCATING ± 0°30'							
X ± .001		FORMED ± 2°							
FINISH		HEAT TREAT							
APPLICABLE SPECIFICATIONS		OTHER APPROVALS							
THE ABOVE TRW SYSTEMS GROUP SPECS FORM A PART OF THIS DRAWING									
USED ON	NEXT ASSY	NEXT ASSY QTY REQD							
APPLICATION									

Figure 3-22. Capillary Clad Assembly

TRW			I. MANDATORY SOURCES OF SUPPLY			I. APPLICATION	
DASH NO.	APPL. SPEC.	CODE IDENT	PART NO.	DWG. OR DOCUMENT NO.	NAME & ADDRESS	USED ON	NEXT ASSY
-1	TO BE DETERMINED	M065		TO BE DETERMINED	MOUND LABORATORY MONSANTO RESEARCH CORPORATION MIAMISBURG, OHIO	AHHS	
-2							

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	SEE E.O.	21 SEP 72	<i>[Signature]</i>
B	SEE DOCUMENT REVISED E.O.	18 MAR 73	<i>[Signature]</i>

SOURCE CONTROL DRAWING

NOTES: UNLESS OTHERWISE SPECIFIED

- ONLY THE ITEMS DESCRIBED ON THIS DRAWING WHEN PROCURED FROM THE VENDORS LISTED HEREON IS APPROVED BY TRW SYSTEMS GROUP, APPLIED TECHNOLOGY DIVISION, FOR USE IN THE APPLICATION SPECIFIED HEREON. A SUBSTITUTE ITEM SHALL NOT BE USED WITHOUT PRIOR TESTING AND APPROVAL BY THE APPLIED TECHNOLOGY DIVISION.
- ALL ASSEMBLY AND INSPECTION PROCEDURES TO BE DETERMINED BY MOUND LABORATORY. ACCEPT PER MD 1-14839
- PART IDENTIFICATION AND SERIAL NUMBER MARKING PER MD 1-14709. FINAL ASSY IS DESIGNATED PER MD-70149

- TRIM END OF CAPILLARY TUBE FROM D410571 PRESSURE RELIEF DEVICE TO ALLOW ASSY WITH D 410585-2 BEFORE WELDING
- THIS ASSEMBLY TO COMPLY WITH MRC ACCEPTANCE SPECIFICATION 1-14839
- COAT CYLINDRICAL SURFACE OF D410585-1 CLAD TUBE PER MRC ACCEPTANCE SPECIFICATION 1-14839

1	-	C410587-2	STRENGTH MEMBER ASSY				
1	/	D 410585-3	CLAD END CAP-PLAIN				
1	/	D 410585-2	CLAD END CAP-VENT				
1	/	D 410585-1	CLAD TUBE				
1	/	D 410647-1	CAPILLARY CLAD ASSY				
-	/	C410587-1	STRENGTH MEMBER ASSY				

-2		-1	CODE IDENT NO	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC	REF DES	ITEM NO.
QTY REQD PER ASSY			PARTS LIST						
UNLESS OTHERWISE SPECIFIED					CONTRACT NO.		THE FOLLOWING E.O.S HAVE BEEN ATTACHED TO THIS PRINT		
1. DO NOT SCALE DRAWING					DRAWN <i>J Brinkman</i>		3-30-72		
2. INTERPRET PER MIL-STD-100					CHECKED <i>R. Davis</i>		4-14-72		
3. DIMENSIONS ARE IN INCHES					STRUCTURES <i>R. Davis</i>		4-18-72		
4. SURFACE TEXTURE SHALL BE					MATERIAL/PROCESS <i>R. Davis</i>		4-18-72		
5. REMOVE BURRS AND SHARP EDGES					ENGINEER <i>R. Davis</i>		4-18-72		
6. DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING.					SUPERVISOR <i>R. Davis</i>		4-18-72		
7. PARENTHEetical DATA IS FOR REFERENCE ONLY					PROJECT <i>H. Lyne</i>		5-12-72		
TOLERANCES					ON ANGULAR DIMENSIONS		MACHINED ± 0°30'		
ON ALL HOLE DIAMETERS					MACHINED ± 0°30'		FORMED ± 2°		
UNDER .0140 +.0020					OVER 2.000 +.015		CHAMFERS ± 9°		
.014 THRU .125 +.004					.014 THRU 1.000 +.010				
.125 THRU .250 +.005					1.000 THRU 2.000 +.012				
.251 THRU .500 +.006					OVER 2.000 +.015				
ON DECIMAL DIMENSIONS					ON ANGULAR DIMENSIONS				
XXX ± .010					MACHINED ± 0°30'				
XXX ± .005					LOCATING ± 0°30'				
X ± .001					FORMED ± 2°				
FINISH					OTHER APPROVALS				
HEAT TREAT									
APPLICABLE SPECIFICATIONS					SIZE		CODE IDENT NO.		
THE ABOVE TRW SYSTEMS GROUP SPECS FORM A PART OF THIS DRAWING					D		11982		C 410628
					SCALE 4/11 AND NOTED				SHEET

- The Pt-20Rh clad consists of a 0.015-inch thick cylinder, one 0.020-inch end cap, and one 0.065-inch end cap designed to contain the capillary tube (Figure 3-20). Clad weld joints are similar to those described for the liner above. The capillary, 0.005 inch I.D. by 4 inches long, is coiled, welded to the clad cover and positioned within the clad end cap as shown in Figure 3-21. A second short capillary tube is welded to the PRD, is routed through a clearance hole in the strength member, and is welded to the clad. The strength member is thus completely sealed off and protected from contamination by either the fuel or the external atmosphere. The capillary clad assembly drawing and the overall heat source assembly drawing are shown in Figures 3-22 and 3-23, respectively.

3.5.1.2 Material Compatibility

Liner/Fuel Compatibility. Unfortunately, no data exist for the compatibility of electrefined fuel with any of the candidate liner materials or with a Pt-20Rh liner in particular. The bulk of the data available was generated using production grade fuel containing a considerable amount of cation impurities such as Fe, Cr, Ni and Co. The impurities in the 98-percent pure production grade material definitely contribute to the chemical interactions. Electrefined PuO_2 will have an impurity level of less than 0.05 percent (500 ppm) and will therefore be more compatible with the liner than the production grade fuel.

The stoichiometry of the fuel also strongly affects the fuel compatibility with the liner. The thermal decomposition of PuO_2 to PuO_{2-x} plus oxygen, and thermodynamic considerations, suggest that substoichiometric fuel, PuO_{2-x} is desirable in the case of refractory metal liners since there would be less oxygen to react with the refractory metal. In the case of Pt-20Rh, however, the opposite has been observed, namely, that the stoichiometric fuel is more compatible with Pt-20Rh than the substoichiometric fuel. Some small amount of interaction between the fuel and liner may, of course, be acceptable as long as that interaction does not degrade the mechanical and physical properties of the liner below levels required to meet the safety criteria.

Mound Laboratory conducted tests to determine the compatibility of production grade stoichiometric and substoichiometric fuel with Pt-20Rh at

1470°, 1830°, and 2190°F for time periods as long as 360 days (References 9 and 10). Samples were analyzed by means of metallography, microhardness measurements, X-ray diffraction, and electron microprobe analyses. The following conclusions were reached:

- In the absence of refractory metals, no penetration of plutonium into platinum or platinum-rhodium alloys was found, although reactions with fuel impurities occurred.
- Impurities which form solid solutions with platinum penetrated into the metal.
- In a reducing atmosphere, considerable reaction between PuO_2 and platinum occurred.
- In the presence of tantalum and/or molybdenum, extensive reaction between PuO_2 and platinum and platinum-rhodium alloys occurred.
- Extensive reaction occurred between $\text{PuO}_{1.82}$ and platinum.
- The microhardness of the reaction layer was greater than that of the parent material.
- Some spalling of the impurity-platinum reaction layer was observed.

Tests at Los Alamos Scientific Laboratories have also shown that stoichiometric plutonium dioxide is compatible with Pt-20Rh and Pt-40Rh for 5000 hours at 1650°F (Reference 11).

The fuel used for the artificial heart application is stoichiometric. As used in the proposed heat source design, the fuel will not be exposed to a reducing atmosphere or refractory materials, and it is therefore concluded that a Pt-20Rh liner can be used in a system venting to air or an inert gas. Venting to vacuum should be avoided, since the PuO_2 may decompose to PuO_{2-x} .

Intercomponent Compatibility. Since the liner and clad materials are the same, the only other material interface of concern in the baseline design is the Pt-20Rh/T-111 interface. A considerable amount of data has been collected for these materials, as shown in Table 3-16. The thickness of the interaction zone between Pt-20Rh and T-111 (consisting primarily of intermetallic compounds) after 271 days was only 0.002 inch at 1550°F and

Table 3-16. T-111/Pt-20Rh Compatibility

Reference	Time at Temperature Days	Interaction Depth (inches)					
		1200°F	1550°F	1900°F	2000°F	2250°F	2500°F
12	3.0	0.0001	0.0004	0.0012			0.0049
13	3.1						
13	4.2				0.0016		
13	16.8				0.0025	0.0028	
12	30.0	0.0002	0.0007	0.0030			
13	42.0					0.0072	
14	271		0.0021	0.0070			

0.007 inch at 1900°F. As indicated in Section 3.2, sufficient data are available for this material combination to enable a correlation between the interaction depth and temperature and time to be established, as given in Figure 3-24 taken from Reference 6. The predicted maximum interaction zone thickness between Pt-20Rh and T-111 in ten years at 1600°F is 0.0055 inch. This zone will exist at both the liner and clad sides of the strength member and will effectively remove 0.011 inch from the strength member thickness. The thickness of the strength member, however, was sized to incorporate this interaction depth. The thicknesses of the liner and clad are also larger than the thickness of the interaction depth. Thus the design is considered acceptable.

3.5.2 Hafnalloys Design

3.5.2.1 Design Description

Although the single-layer Hafnalloys heat source rated highest of all the heat sources analyzed for the artificial heart application, lack of compatibility, fabrication and test data prevented its selection as the baseline design. To obtain some of the necessary data, Hafnalloys heat sources were fabricated and tested in conjunction with the baseline safety verification tests. Since the Hafnalloys heat sources were to be used for test purposes only, retention of the exact outside diameter (0.984 inch) used in the baseline design was not considered critical. To allow use of the same fuel simulant as used in the baseline design, and thus reduce costs, the Hafnalloys

Figure 3-24. Pt-20Rh/T-111 Interaction

heat source design was based on the existing fuel simulant. The I.D. of the Hafnalloys heat sources was thus the same as the liner I.D. of the baseline design.

The Hafnalloys heat source consists of a single-layer Hafnalloys component, intended to fulfill the functions of the liner, strength member and clad. A PRD, similar in design to the baseline PRD but made of Hafnalloys, would allow venting of helium from the heat source. For the test heat sources, dummy PRD's were used. These units were made of solid Hafnalloys and had the overall dimensions of the real PRD's. Use of such dummy PRD's, of course, did not yield any information on the performance of the PRD, but did indicate the effect of the PRD on the capsule under the various accident environments. Since the PRD is small (only 0.150 inch in diameter), its effect on heat source survivability in any of the accident environments is expected to be very small.

Since the capsule wall thickness required to survive bullet impact (the worst accident environment) was not well defined for Hafnalloys (only two data points had been obtained during past testing, as described in Section 3.3.2), two different wall thicknesses were included in the design. Based on previous work, a 0.140-inch wall was believed to be required. Due to improvements in material processing, however, it was also believed that a lower thickness might be adequate. The two heat source designs are: 0.140 inch thick, 0.97 inch in diameter by 1.71 inches long, and 0.115 inch thick, 0.92 inch in diameter by 1.66 inches long. The weights of these two units, including fuel, are 0.51 and 0.44 lb., respectively. Component and assembly drawings of the Hafnalloys heat sources, using Hf-150* alloy, are shown in Figures 3-25 and 3-26, respectively.

During recent tests conducted under the Hafnalloys Development Program,** some of the emittance and tensile specimens tested at 2400°F or above failed with extremely low ductilities (Reference 15). Others, on the other hand, had very high ductilities. Upon conducting microstructural analyses, it appeared that hot-shortness accompanied by grain coarsening were the causes of failure. Based on available hafnium/iridium phase diagrams, it appears

*Hf-105: Hafnium, 1.0% platinum, 0.5% palladium

Hf-150: Hafnium, 1.5% platinum, 1.5% palladium

**"Oxidation Resistant Refractory Alloys for RTG Applications," Contract AT(04-3)-935, Atomic Energy Commission, Space Nuclear Systems Division.

DASH NO.	X	Y (Dia)	Z (Dia)
-1	0.16	0.969 ± 0.001	0.993 ± 0.005
-2	0.14	0.919 ± 0.001	0.943 ± 0.005

1				-8	SIMULATED PRD	0.16 x 0.16 x Stock	HAFNALLOY (Hf-150)
1				-7	SIMULATED PRD	0.16 x 0.16 x Stock	
1				-6	H.S. END CAP	0.14 x 0.950 Dia.	
1				-4	H.S. END CAP	0.14 x 0.950 Dia.	
1				-2	H.S. TUBE	0.14 x 5.0 x 5.0	
1				-5	H.S. END CAP	0.16 x 1.000 Dia.	
1				-3	H.S. END CAP	0.16 x 1.000 Dia.	
1				-1	H.S. TUBE	0.16 x 5.0 x 5.0	HAFNALLOY (Hf-150)

NOTES: UNLESS OTHERWISE SPECIFIED

1. Identification Marking Per PR 12-1 Type I Class 6 (Electrochemical Etch) D/N and S/N Located Approximately as Shown.
2. Anneal Material at 1700 °F/One Hour in Vacuum of 10⁻⁵ torr or Better Prior to Machining End Caps and Simulated PRD's.

AHHS	X411172	
USED ON	NEXT ASSY	NEXT ASSY QTY REQD
APPLICATION		

QTY REQD PER ASSY	CODE IDENT NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPEC	REF DES	ITEM NO
PARTS LIST							
UNLESS OTHERWISE SPECIFIED				CONTRACT NO.			
1. DO NOT SCALE DRAWING.				DRAWN <i>[Signature]</i> 7/24/72			
2. INTERPRET PER MIL-STD-100.				CHECKED <i>[Signature]</i> 7/24/72			
3. DIMENSIONS ARE IN INCHES				STRUCTURES			
4. SURFACE TEXTURE SHALL BE 63				MATERIAL PROCESS ENGINEER <i>[Signature]</i> 7/24/72			
5. REMOVE BURRS AND SHARP EDGES				SUPERVISOR <i>[Signature]</i> 7/26/72			
6. DIMENSIONS APPLY BEFORE PLATING OR CONVERSION COATING.				PROJECT <i>[Signature]</i> 7/26/72			
7. PARENTHEetical DATA IS FOR REFERENCE ONLY				OTHER APPROVALS			
TOLERANCES				THE FOLLOWING EO'S HAVE BEEN ATTACHED TO THIS PRINT			
ON ALL HOLE DIAMETERS				TRW SYSTEMS GROUP			
UNDER .0140 +.0020 -0.0005 .501 THRU .750 +.008 -0.001				ONE SPACE PARK • REDONDO BEACH, CALIFORNIA			
.014 THRU .125 +.004 -0.001 .751 THRU 1.000 +.010 -0.001				AHHS HAFNALLOY COMPONENTS			
.126 THRU .250 +.005 -0.001 1.000 THRU 2.000 +.012 -0.001				SIZE CODE IDENT NO. X411171			
.251 THRU .500 +.006 -0.001 OVER 2.000 +.015 -0.005				SCALE 4/1 MJO 2080-94 SHEET 1 of 2			
ON DECIMAL DIMENSIONS: .00X ± .010 .00X ± .003 X ± .1							
ON ANGULAR DIMENSIONS: MACHINED ± 0°30' LOCATING ± 0°30' FORMED ± 2° CHAMFERS ± 5°							
FINISH							
HEAT TREAT							
APPLICABLE SPECIFICATIONS							
THE ABOVE TRW SYSTEMS GROUP SPECS FORM A PART OF THIS DRAWING							

Figure 3-25(a). Piece Part Drawing X-411171 of Hafnalloxy Heat Source Components

DASH NO	R	S (DIA)	T (DIA)	W	U
-3	0.140 ± 0.001	0.969 ± 0.001	1.000	0.160	
-4	0.115 ± 0.001	0.919 ± 0.001	0.950	0.140	
-5	0.140 ± 0.001	0.969 ± 0.001	1.000	0.160	
-6	0.115 ± 0.001	0.919 ± 0.001	0.950	0.140	
-7					0.407
-8					0.382

SIZE	CODE IDENT NO.	X411171
C	11982	
SCALE	4/1	SHEET 2 of 2

Figure 3-25(b). Piece Part Drawing X-411171 of Hafnialloy Heat Source Components

Figure 3-26. Assembly Drawing X-411172 of Hafn Alloy Heat Source

that the intermetallic Hf_2Pt (Pd) forms a eutectic with the α -hafnium and is responsible for the hot-short behavior. Under certain conditions of temperature and time, a liquid phase may form, which although transitory and unstable may cause failure under load. To alleviate this problem, the noble metal content of the alloys must be reduced. Two alloys, Hf-.25%Pt-.25%Pd and Hf-.30%Pt-.15%Pd are currently being investigated under the Hafn alloy Development Program. Two additional alloys, Hf-.20%Pt-.20%Pd-2.5%Sn and Hf-.30%Pt-.15%Pd-2.5%Sn are also being investigated. All four alloys have been shown to be extremely oxidation resistant at elevated temperatures.

Since hot-shortness of Hf-150 does not appear at temperatures below approximately 2400°F, its impact on the artificial heart application is minimal. With the exception of the fire environment, during which no substantial loads are applied to the heat source, all operational or accident temperatures are below 1600°F. Moreover, since the modifications to the current alloys are slight and tend to strengthen the alloys, tests performed with the current alloys are still applicable and results of these tests will aid in the overall evaluation of the alloy.

3.5.2.2 Fuel Compatibility

LASL recently conducted a program to determine the compatibility of Hafn alloy with PuO_2 fuel. The fuel consisted of pressed and sintered discs of production grade PuO_2 . Hf-105 and Hf-150 alloy discs, in both the as-processed (machined surface) and pre-treated (machined surface and pre-oxidized) condition, were tested. The test temperature was 1830°F and the duration was 2000 hours. Prior to test, oxygen, microstructure and microhardness determinations were made on control samples. The post-test examination consisted of visual inspection, microhardness measurements and metalurgical examinations.

The results of the tests, as reported by LASL (Reference 16), are as follows:

- The oxygen content of the as-received, untreated samples of both alloys was 15 to 20 ppm; the oxygen content of the as-received treated Hf-150 samples, after removal of the surface oxide, was 1100 ppm versus 420 ppm for the Hf-105 samples.
- There was no visual interaction between the fuel and any of the test discs or the Hafn alloy capsule side walls; the fuel was freely removed from the capsules when they were opened.

- The microhardness (DPH-50 gm load) of the disc samples following the test was as follows:

Material	Control		Test	
	Treated	Untreated	Treated	Untreated
Hf-105	195 - 296	218 - 329	332 - 381	435 - 566
Hf-150	321 - 460	175 - 227	613 - 810	739 - 1072

The untreated Hf-150 disc had a slight reaction layer after contact with the fuel pellet.

- The capsules indicated only a slight increase in microhardness, as follows:

Material	Control	Test
Hf-105	175 - 229	239 - 332
Hf-150	192 - 262	272 - 358

It should be noted that the interaction, as seen by an increase in the hardness of the material, was much more severe between the fuel and polished discs (an unrealistic situation) than between the fuel and the capsules. These results indicate that a total lack of interaction does not exist. At the same time, massive interaction does not occur either. Sufficient scatter and inconsistencies existed in the data to require additional tests to be performed, especially with electrorefined fuel at the artificial heart heat source temperatures. A program to determine the effect of oxygen contamination on the strength properties of Hafnium alloy is currently underway at TRW Systems.

4. FABRICATION

As discussed in Section 3.4 above, the three-layer Pt-20Rh/T-111/Pt-20Rh heat source was selected as the baseline design. Twelve heat sources of this design, fueled with a fuel simulant, were fabricated for use in safety verification tests. In addition, three heat sources were fueled with electro-refined, oxygen-16 enriched, pressed and sintered PuO_2 for eventual use in bench model tests of the artificial heart thermal converter system.

Hafnialloy heat sources were also fabricated to assess the applicability of this material to the artificial heart application. Since the capsule wall thickness required to survive bullet impact was not well defined for Hafnialloy, two wall thicknesses were selected. Five heat sources, simulant fueled, were fabricated of each wall thickness for safety verification tests.

4.1 HEAT SOURCE COMPONENT FABRICATION

4.1.1 Baseline Design

The number of heat sources required and the purpose of the various units are listed in Table 4-1. In addition to the twelve heat source assemblies required for the safety test program and the three assemblies required for use in the practicability evaluation of a thermal converter, additional units were required for weld development and control. It was anticipated that the fueling agency (Mound Laboratory) would perform a weld development program prior to assembly of the test heat sources. Using materials previously used in heat source design, such a program normally requires approximately 20 units. In addition, several units were required for example welds for both the test units and live fueled units. Finally, seven contingency units were included to yield a total of 50 heat source assemblies.

Platinum-20 rhodium and T-111 alloy materials were purchased from Engelhard Industries and Norton Metals using Monsanto Research Corporation material specifications MDI-13457 Rev. 10 and MDI-13458 Rev. 4, respectively. The tensile and ultrasonic tests required by these specifications were waived and materials were only certified to meet these requirements in order to

Table 4-1. Heat Source Requirements

Item	Number Required
Test Program Heat Sources (simulated fuel)	
Impact 5	
Fragmentation 3	
Crushing 2	
Fire 2	
Subtotal	12
Fueled units	3
Weld development	20
Example welds for test heat source fabrication	2*
Example welds for fueled heat sources	6**
Contingency	7
Total	50

*Assuming the test heat sources would be produced in two lots, each of which would require one example weld.

**Assuming the fueled heat sources each require a "before" and "after" example weld.

reduce costs and expedite delivery. Material for the liner, strength member, and clad bodies was purchased in tube form of proper diameter and wall thickness in order to minimize machining and scrap costs; additional sheet and tube material was obtained for the remaining heat source components. A listing of the Pt-20Rh and T-111 material obtained is given in Table 4-2.

A considerable number of discrepancies were encountered in the as-received material. Approximately two-thirds of the T-111 tube material was discrepant on the inside diameter, much of the Pt-20Rh liner material was oversized on the inside diameter, and most of the liner and clad tubes were not straight and were out of round. Rework of the affected components, or of the components mating with them, was possible in many cases. However,

Table 4-2. Material Purchases

Material	Dimensions, inches
T-111 Tube	.750 $\pm$.001 ID x .095 $\pm$.005 wall x 115 long
T-111 Sheet	.100 $\pm$.005 x 150 in ²
Pt-20Rh Tube	.150 $\pm$.002 OD x .020 $\pm$.002 wall x 144 long
	.688 $\pm$.002 ID x .020 $\pm$.002 wall x 120 long
	.954 $\pm$.002 ID x .015 $\pm$.002 wall x 124 long
	.005 $\pm$.001 ID x .025 $\pm$.002 wall x 300 long
Pt-20Rh Rod	.125 $\pm$.002 D x 40 long
	.150 $\pm$.002 D x 24 long
Pt-20Rh Sheet	.010 $\pm$.002 x 60 in ²
	.015 $\pm$.002 x 90 in ²
	.020 $\pm$.002 x 130 in ²
	.020 $\pm$.002 x 90 in ²
	.070 $\pm$.002 x 90 in ²

some material had to be rejected outright. Due to the long lead time of both platinum and T-111 alloys, it was decided to rework the parts at TRW as opposed to returning discrepant stock to the supplier for rework or replacement. The major impact on the heat source design was that the gap between the liner and strength member was less than anticipated whereas the gaps between the fuel and liner and between the strength member and clad were greater than anticipated. In addition, weld joint tolerances were difficult to maintain due to the variability from tube to tube. The liner, strength member, and clad tubes were all machined to finished dimensions.

Metallography also indicated that the noble metal material did not meet the grain size and microhardness requirements of the material specification. The tube material had very elongated rather than equi-axed grains, and a DPH microhardness of 260. The end cap material had an ASTM grain size of 3 to 4 and a hardness of 176. The minimum grain size allowed by the specification is 5, and the maximum hardness is 150. Bend tests performed on the as-received material indicated the material to be very ductile. Specimens were subsequently annealed at 1600°F for one hour and at 1700°F

for one hour. The 1600°F anneal was sufficient to bring the tube material within the specification (grain size 6 to 7, hardness of 120) as shown in Figure 4-1. Following the anneal, the end caps had a grain size of 4 and a DPH hardness of 152. The fueled heat sources may thus be allowed to self heat to 1600°F for one hour, or may be allowed to anneal when in actual service at 1565°F in the thermal converter system.

To obtain reproducible end caps having close tolerances, the liner end caps and the plain clad end caps were coined. Blanking and coining dies were used and after only a minimal effort end caps which varied from each other by only a few tenths of a milli-inch were produced. Some end caps were also machined. Contrary to expectations, the machined end caps met the dimensional requirements as well as, or better than, the coined piece parts. The clad end cap containing the capillary cavity and the strength member end caps were too thick to be coined. These components were precision machined.

Maximum diametral gaps in the strength member and clad weld joints were maintained below 0.004 and 0.005 inch, respectively. Due to the discrepancies discussed above, some liner weld joint gaps were as high as 0.0075 inch. All piece part dimensions were accurately gauged and any discrepancies were noted. Records of all inspections were forwarded to the fueling agency with the corresponding heat source components. As described in Section 4.4, the slightly higher than desired gap sizes in the liner did not prevent the attainment of excellent liner welds. A complete set of heat source components is shown in Figure 4-2.

4.1.2 Hafn alloy

The general fabricability of Hafn alloy had been demonstrated during the AEC/SNS-sponsored development program, "Oxidation Resistant Refractory Alloys for RTG Applications."* Five-hundred pounds of starting material (250 pounds of each of two alloys) yielded 375 pounds of high quality Hafn alloy sheet. The sheet material was shown to be formable, machinable

*Contract AT(29-2)-3003

As Received - ASTM Grain size not determined

Annealed 1600°F/1 hr - ASTM Grain size 6-7

Figure 4-1. Pt-20Rh Tube Photomicrographs, 100X

Figure 4-2. Pt-20Rh and T-111 Heat Source Components

and weldable by both the TIG and EB processes, and the results of these activities formed the basis for developing the spinning, machining, and welding techniques required to produce the artificial heart heat source capsule piece parts described below. Approximately 40 lbs of Hf-150 sheet 0.160 and 0.140 inch thick were obtained from the Hafnialloy Development Program.

As indicated in Section 3.5 above, the Hafnialloy wall thickness required to survive bullet impact had not been well defined, and two wall thicknesses, 0.140 and 0.115 inch, were selected for fabrication and test. The total heat source requirements are given in Table 4-3. Ten units were required for tests, five for weld development, and five for contingency, resulting in a total of 20 heat sources. Due to the developmental nature of these heat sources and the fact that none was to be fueled with actual PuO_2 , a less extensive weld development and control program was required than was used by Mound Laboratory for the three-layer design.

Table 4-3. Hafnialloy Heat Source Requirements

Item	Number Required	
	0.140 inch	0.115 inch
Test Program Heat Sources		
Impact	2	2
Fragmentation	2	2
Fire	1	1
Weld Development	3	2
Contingency and/or test	<u>3</u>	<u>2</u>
	11	9

To obtain maximum advantage of the previously gained spinning experience, the same vendor* was selected to produce the cups shown in Figure 4-3. A single mandrel and temperatures of 750 to 1500°F, as obtained by heating with an oxyacetylene torch, had previously been used to produce piece parts

*Coast Metal Craft Division of Anaconda Copper and Brass, Inc., Compton, California.

SK-3000-SB

CHS LTR

DASH NO	A	B
-1	0.993 ± 0.005	0.160
-2	0.943 ± 0.005	0.140

NOTES:

1. Identification Marking Per PR12-1 Type II Class IG (Bag and Tag)
2. Anneal Sheet Metal Blanks at 1700°F/One Hour in Vacuum of 10^{-5} torr or Better Prior to Forming.

ORIGINATOR	DATE	TITLE	ENGINEERING SKETCH
<i>SS Brown</i>	7/18/72	AHHS Heat Source CAPSULE PREFORM	TRW SYSTEM GROUP ONE SPACE PARK REDONDO BEACH CALIFORNIA
MJO	2080-94		SK-3000-SB
			SHEET OF

Figure 4-3. Spun Cup Drawing SK-3000-SB

for a 650-watt capsule. The length-to-diameter ratio for this capsule was about 1.5 and the diameter-to-thickness ratio was about 100, making this a relatively easy part to produce. The manually spun cup for the artificial heart heat source capsule, however, was considerably more difficult to fabricate because of its small I.D. (0.668 inch), length of 2.2 inches, and wall thicknesses of 0.140 and 0.160 inch. These dimensions resulted in a length-to-diameter ratio of about 3 to 1 and diameter-to-thickness ratios of only about 4.8 and 4.2 for the 0.140- and 0.160-inch thick material, respectively. As can be seen, these ratios are significantly different from those for the 650-watt components.

Six attempts (3 on each wall thickness) were made to spin the required cups using a single mandrel and forming temperatures of 1550° to 1850°F. The primary difficulty in producing these parts was due to yielding of the mandrel away from the roller as a result of the high temperatures employed and the high roller forces required to bend the Hafnialloy material to the mandrel configuration. The continuous working of the metal at the closed end of the cup reduced the metal thickness in this area which eventually resulted in failure of the closed end of the cup. Based on past experience in spin forming of molybdenum and tungsten at elevated temperatures, the forming operation was revised to use three break-down mandrels and one pre-form mandrel prior to forming the final configuration over the final mandrel. Tear-out of the cup bottom and yielding of the mandrel during spinning were prevented by use of a female follow-block that fit over the cup bottom during the final spinning operation. Figure 4-4 schematically shows the tooling sequence developed and Figure 4-5 shows the spun Hafnialloy cups.

A slight taper existed from the closed end of each cup to its open end, and the I.D.'s and O.D.'s varied slightly from tube to tube. Insufficient wall thickness was available to allow machining of the tubes to the required dimensions. Following machining, the wall thicknesses varied from 0.114 to 0.128 inch for the thick-walled configuration and from 0.104 to 0.111 inch for the thin-walled configuration. Additional tooling and processing development is obviously required to produce uniform, close-tolerance Hafnialloy piece parts.

BREAK-DOWN #1

BREAK-DOWN #2

BREAK-DOWN #3

PRE-FORM

FEMALE FOLLOW-BLOCK

FINAL CONFIGURATION

Figure 4-4. Schematic of Tooling Required to Produce Hafn alloy Heat Source

Figure 4-5. Hafnium Alloy Spun Cups

The end-caps and simulated PRD's were produced by machining blanks excised from the sheet material. In each case the end cap diameters were tailored to fit individual tubular bodies so that a close-tolerance fit-up would exist. Table 4-4 gives the wall thicknesses and designated tests for the ten test units. Four additional sets of components were also machined for weld development.

Table 4-4. Wall Thickness and Test Assignment for the Hafnialloy Artificial Heart Heat Source Capsules

Sample No.	Wall Thickness		Test Assignment
	PRD End	Plain End	
12A	0.127	0.1215	Ballistic Impact
12B	0.124	0.128	Ballistic Impact
14B	0.118	0.115	Impact
17A	0.119	0.114	Impact
5B	0.101	0.128	Fire
15A	0.110	0.110	Ballistic Impact
17B	0.1105	0.1105	Ballistic Impact
16B	0.110	0.110	Impact
18A	0.110	0.110	Impact
18B	0.104	0.111	Fire

A comparison of the material's microstructure before and after spinning is shown in Figures 4-6 and 4-7, respectively. In both cases, the material consisted of two phases: alpha hafnium (the individual grains) and an intermetallic of the form $\text{Hf}_2\text{Pt}_x\text{Pd}_{1-x}$ (the evenly dispersed spherical particles). Prior to spinning, the material had a fine-grained, recrystallized microstructure, whereas the material in the spun condition shows a finer microstructure with some evidence of working.

Since the spin forming operation was performed at elevated temperatures in air, a check was made of the amount of oxygen that was present in the machined spun part as compared to the oxygen content in the as-received material. The oxygen interstitial analysis was made by the vacuum fusion method. The results showed only a slight increase in oxygen content after spinning (70 ppm compared to 60 ppm before spinning).

Figure 4-6. Photomicrograph of Fine-Grained Hafnialloy Starting Sheet Material. Recrystallized at 1700°F for One Hour. Note the two phase condition: the grains are alpha hafnium; the spheroidized particles are the intermetallic $\text{Hf}_2\text{Pt}_x\text{Pd}_{1-x}$. Magnification = 200X.

Figure 4-7. Photomicrograph of Hafnialloy Spun Tube Material. Note the retention of the intermetallic $\text{Hf}_2\text{Pt}_x\text{Pd}_{1-x}$ and the refinement of the fine-grained alpha hafnium due to the spinning operation. Magnification = 200X.

Although the desired wall thicknesses and diameters could not be obtained for the Hafn alloy units, the resulting heat sources could still be used in the test program since the required wall thickness was only an estimate to begin with. As indicated in Section 6, the Hafn alloy units survived the impact and fire environments very well. Failures were obtained under ballistic impact similar to those obtained with the T-111 heat sources.

4.2 VENT FABRICATION

The Transit and Pioneer RTG type pressure relief device (PRD) was scaled down for use in the artificial heart heat source. The alumina in this PRD presents a very tortuous path for the venting gas and acts as an absolute filter for any fuel fines. To reduce the quantity of radon released from the heat source, a capillary tube was added to the PRD to complete the venting system. The quantity and type of vents required in the current program are listed in Table 4-5. Six vents were to be tested under the vent permeation tests. Fifteen additional vents were required to be inserted in heat source assemblies (12 test units plus three fueled units) and four vents were designated as contingency units, resulting in a total of 25 units. Weld development and example welds were to be performed using dummy vents which duplicated the material and size of the vents but did not contain other components.

Table 4-5. Vent Assembly Requirements

	Complete	Simulated
Test heat sources	12	
Fueled heat sources	3	
Vent development tests	6	
Weld development		20
Example welds		5
Contingency	<u>4</u>	<u>3</u>
Total	25	28

4.2.1 Pressure Relief Device

Figure 3-14 illustrates the PRD design. The PRD consists of a core, housing tube, two plugs, and a capillary tube. All of the metallic components were fabricated from Pt-20Rh material conforming to MRC Specification 1-13457 (see Section 4.1.1 above). The Pt-20Rh piece parts were machined and heat treated, and the inside surface of the tube was lapped. The alumina was plasma arc sprayed onto the cores, ground to final size, and the PRD's were assembled and welded. Both TIG and EB welding were used. Typical weld penetrations for the PRD are shown in Figure 4-8. The PRD's were then isostatically pressed to close any remaining gap between the PRD housing tube and the core. TRW quality assurance inspections were performed throughout the fabrication and assembly operations to ascertain that proper procedures were followed. Helium leak tests and dye penetrant inspections were performed on all welds to verify soundness. Photos of the PRD piece parts prior to assembly, and the completed assembly after it was welded into the liner end cap, are shown in Figures 4-9 and 4-10, respectively.

All of the completed PRD assemblies were given a room temperature helium permeation check to determine acceptability. The average helium generation rate (over 10 years) for the currently designed heat source is 1.3×10^{-6} cc/sec at STP conditions, with a resulting average pressure differential across the PRD of approximately 0.001 psi. Based on prior fabrication experience, the acceptable helium permeation range was set between 1.0×10^{-5} to 1.0×10^{-7} cc/sec (STP). The helium flow rates were measured utilizing a mass spectrometer type helium leak detector (see Section 5.2). Table 4-6 summarizes the results of these measurements taken at a pressure differential of 0.04 psi. The predicted flow rate under the same conditions is 5×10^{-5} std cc/sec. As can be seen, the agreement between the measured and theoretical flow rates is very good.

4.2.2 Capillary Assembly

The capillary tube subassembly consists of the 4-inch capillary tube coiled as a spiral and welded to the capillary cover. Special tooling was used to coil the tube to preclude closure of the 0.005 inch tube I.D. Precision machining was used to obtain the necessary tolerances in the capillary to cover weld joint.

PRD to Liner End Cap Weld

PRD Plug Weld #1

Capillary to PRD Weld

PRD Plug Weld #2

Figure 4-8. Weld Penetrations
for PRD

Figure 4-9. PRD Piece Parts

Figure 4-10. Assembled PRD's

Table 4-6. Room Temperature Helium Permeation Testing of Artificial Heart Heat Source PRD Assemblies (exhaust pressure = 10^{-5} torr)

S/N	Helium Permeation Rate (cc/sec @ STP) $\Delta P = 2 \text{ mm Hg}$	S/N	Helium Permeation Rate (cc/sec @ STP) $\Delta P = 2 \text{ mm Hg}$
003	8.1×10^{-5}	016	10.8×10^{-5}
004	8.1×10^{-5}	017	10.1×10^{-5}
005	8.4×10^{-5}	018	11.2×10^{-5}
006	9.3×10^{-5}	019	10.1×10^{-5}
007	11.4×10^{-5}	020	9.7×10^{-5}
008	9.0×10^{-5}	021	10.1×10^{-5}
009	9.3×10^{-5}	022	10.8×10^{-5}
010	8.1×10^{-5}	023	9.7×10^{-5}
011	8.7×10^{-5}	024	10.1×10^{-5}
012	9.6×10^{-5}	025	9.0×10^{-5}
013	8.1×10^{-5}	026	9.7×10^{-5}
014	10.1×10^{-5}	027	10.4×10^{-5}
015	8.8×10^{-5}	028	10.4×10^{-5}

As described in Section 4.4.1 below, the twelve assemblies for the test heat sources were TIG welded in order to seal the capillary tube. EB welding, using a variable frequency oscillator, was used to weld the capillary assemblies for the fueled units. Weld penetration is shown in Figure 4-11. Both helium leak tests and dye penetrant inspections were performed on all welds to verify weld quality. A photo of the capillary to cover weld is shown in Figure 4-12.

4.3 FUEL SIMULANT

As has been demonstrated in past heat source programs, specific fuel simulant properties become of utmost importance in certain heat source tests. Thus, strength and ductility are of importance in mechanical tests, whereas the thermal conductivity, or thermal diffusivity, become critical parameters in thermal tests. Therefore, the proper selection of a fuel simulant for the

Figure 4-11. Capillary to Cover Weld

Figure 4-12. Capillary Assembly

pressed and sintered PuO_2 fuel is extremely critical if representative results are to be obtained. However, it is not critical that the same simulant be used for all tests. The impact, fragmentation, and crush test heat sources should contain a simulant which simulates the density, strength, and other mechanical properties of the fuel. The fire test units, on the other hand, must contain a simulant which does not react in a non-representative manner with the heat source components at elevated temperatures and does not oxidize in an air environment if air enters the heat source during the test. These same requirements are imposed on the post-accident oxidation units, but since these units are drawn from previous impact and fragmentation test heat sources, the fuel simulant for the latter must not only match the density and the mechanical properties but also the chemical properties of the actual pressed and sintered PuO_2 .

A review of applicable fuel simulant materials was undertaken to evaluate the various candidate materials. Two categories of materials were investigated:

- 1) Actinide compounds which closely resemble the actual fuel, such as UO_2 and ThO_2 .
- 2) Other materials (metals or oxides) which can be mixed to yield desirable properties.

A review of the advantages and disadvantages of Mo, Ta, W, Al_2O_3 , CeO_3 , ThO_2 and UO_2 as fuel simulants, including the degree of mechanical, thermal, and chemical simulation, as well as fabrication, availability, and cost was performed. Of primary importance in most of the tests were the density and the mechanical properties of the simulant. Unfortunately, the mechanical properties of the fuel itself were, and still are, very poorly defined.

The choice of fuel simulant materials was narrowed to depleted UO_2 and ThO_2 . Both of these materials are actinide compounds which closely resemble the actual PuO_2 fuel in crystal structure and both have similar theoretical densities. In addition, the linear expansion properties of these materials are also similar. As mentioned above, the strength properties of PuO_2 were not well known and had to be estimated. A relationship exists between the elastic modulus, bond strength, and melting point for a number of different

oxide materials (Reference 17). These data do not include values for PuO_2 ; however, since all three oxides are actinide oxides it was assumed that the modulus versus melting point data lie on the same curve. As a result, UO_2 was estimated to more closely simulate the mechanical properties of PuO_2 , although the advantage over ThO_2 does not appear to be significant. ThO_2 has, however, been utilized successfully in the past during both the Transit and Pioneer heat source safety programs. Furthermore, thoria was more readily available and was considerably lower in cost than UO_2 . ThO_2 was, therefore, chosen as the fuel simulant for those heat sources subjected to mechanical tests. Since the post-accident oxidation tests were to be drawn from these units, they too would contain the thoria simulant. The heat sources to be used in fire tests, however, did not require a material which simulated the density, strength, and other mechanical properties of the fuel; therefore, to eliminate the presence of the slightly radioactive thoria, alumina was used. Neither thoria nor alumina react in a nonrepresentative manner with the heat source components and do not oxidize in an air environment.

A drawing of the fuel simulant is shown in Figure 4-13. The chamfers on each end were designed to allow clearance between the fuel simulant and the liner welds at each corner. The cavity in the one end allowed insertion of the PRD which protrudes into the fuel.

The thoria simulant was purchased from the Zirconium Corporation of America. The completed simulant pucks had a density of 85 to 95 percent of theoretical. A photo of the thoria simulant is shown in Figure 4-14. The alumina simulant pucks were fabricated at TRW. The alumina was machined in the "green" state, fired, and remachined to the final design dimensions.

4.4 HEAT SOURCE ASSEMBLY

4.4.1 Baseline Design

The baseline design heat sources were assembled and fueled by Mound Laboratory, Monsanto Research Corporation. An extensive weld development program was carried out by Mound Laboratory on the liner, strength member,

NOTES: UNLESS OTHERWISE SPECIFIED

1. PART IDENTIFICATION MARKING
TO BE DETERMINED

				-1		FUEL SIMULANT		PER COGNIZANT ENG									
		CODE IDENT NO.		PART OR IDENTIFYING NO.		NOMENCLATURE OR DESCRIPTION		WATERIAL		SPEC		REF DLS		ITEM NO.			
QTY REQD PER ASSY						PARTS LIST											
UNLESS OTHERWISE SPECIFIED						CONTRACT NO.											
1. DO NOT SCALE DRAWING. 2. INTERPRET PER M.L. LISTING. 3. DIMENSIONS ARE IN INCHES 125 4. SURFACE TEXTURE SHALL BE 5. REMOVE BURRS AND SHARP EDGES. 6. DIMENSIONS IN PARENTS FORM PLATING OR CONVERSION COATING. 7. PARENT IT CAL DATA IS FOR REFERENCE ONLY.						TOLERANCES ON ALL LINE DIMETERS UNDER .250 $\pm .005$.251 THRU .500 $\pm .010$.501 THRU 1.000 $\pm .015$ 1.001 THRU 2.000 $\pm .020$ 2.001 THRU 3.000 $\pm .025$ OVER 3.000 $\pm .030$ ON DECIMAL DIMENSIONS: .0001 $\pm .0002$.001 $\pm .002$.01 $\pm .003$.1 $\pm .005$ ON ANGULAR DIMENSIONS: MACHINED $\pm 0^{\circ}30'$ LOCATING $\pm 0^{\circ}30'$ FORMED $\pm 2^{\circ}$ CHAMFERS $\pm 5^{\circ}$						THE FOLLOWING EOS HAVE BEEN ATTACHED TO THIS PRINT ONE SPACE PARK 4410586'S BRASH, CALIFORNIA FUEL SIMULANT-AHHS					
FINISH PLAT TREAT						OTHER APPROVALS											
APPLICABLE SPECIFICATIONS THE ABOVE THW SYSTEMS GROUP						SCALE 2/1											
SHEET																	

Figure 4-13. Fuel Simulant

Figure 4-14. Fuel Simulant

and clad end cap welds using TIG welding on the liner and clad end caps and EB welding on the strength member end caps. The heavy wall of the T-111 strength member components precluded TIG welding. No difficulties were experienced with these end cap welds and good quality welds were obtained as verified by visual, dye penetrant, metallographic, and radiographic inspections of example welds. Visual, helium leak, and radiographic inspections of assembled units were performed (Reference 18).

Final closure of the heat source required welding of the capillary stub, which extends from the PRD to the clad end cap, followed by the capillary/clad cover weld. The former of these two welds presented great difficulty. The capillary tube was so small (0.025 inch O.D. by 0.005 inch I.D.) that acceptable welds were very difficult to obtain. In some cases the I.D. was completely closed; in most cases, insufficient weld penetration, weld cracking, or blowout in the weld zone resulted. Increasing the capillary O.D. would have alleviated the weld problems considerably, and any future design incorporating such a vent tube between the liner and clad should make use of a larger diameter tube.

To allow Mound Laboratory additional units for weld development, the requirement for acceptable welds at this joint was waived on the twelve test units. Since no helium was generated by the fuel simulant, no venting was necessary. On the other hand, if weld cracking or blowout on these units were to occur, contamination of the T-111 strength member by air entering through the open capillary coil was possible. Consequently, the capillary coils used in these test units were plugged prior to shipment to Mound Laboratory (Section 4.2.2 above). Such closure of the capillary completely sealed the heat source and prevented contamination of the T-111. Since the final closure weld on the heat source (capillary cover/clad weld) was an EB weld, no gas was sealed into the heat source. Trapped gas could have presented a problem upon heating of the units during the safety verification tests.

The fueled units were assembled by Mound Laboratory without difficulty. The capillary welds were very successful, as verified by visual observation of the weld through a Questar telescope and by inserting a 3-mil wire into

the capillary hole. One of the three fueled units was coated with platinized alumina high emissivity coating. The weights of the three fueled units were 279, 278, and 278 grams (0.62 lb). The power outputs were 33.0, 32.9, and 33.0 watts. The data package for the three fueled units is presented in Appendix B. An exploded view of a test heat source prior to assembly and three assembled test heat sources are shown in Figures 4-15 and 4-16, respectively.

4.4.2 Hafnialloy Design

The single-layer Hafnialloy heat sources were assembled at TRW Systems. Due to the thickness and size of the Hafnialloy members, EB welding was used.

Four welds (two for each end-cap thickness) were required to develop the weld schedules for the simulated PRD/End Cap welds and three welds (one for the thin-walled capsule and two for the thick-walled capsule) were required to develop the circumferential weld schedules. The simulated PRD rod was positioned in the end cap, extending 10 mils above the surface of the end cap. The electron beam was defocused and rotated at the edge of the PRD to affect a melt-down operation. Excess material acted as a filler and prevented the surface depression common in EB welds. Figure 4-17 is a photomicrograph of the example weld for the simulated PRD/end cap subassembly. The circumferential example weld for the end cap/tubular body assembly is shown in Figure 4-18. A photomicrograph of the area where the cap and tube join is shown in Figure 4-19. Note the high quality of the weldments.

Figure 4-20 shows two assembled Hafnialloy heat sources and an exploded view of a unit containing alumina fuel simulant. Weld quality of all heat sources was verified by visual examination, a surface penetrant nondestructive test using zyglo dye-penetrant per MIL-I-6866, and a helium leak check. Ten capsules (five of each wall thickness) were assembled. Eight of the assemblies (four of each wall thickness) contained a thorium simulant and two of the assemblies (one of each wall thickness) contained the alumina simulant.

Figure 4-15. Exploded View of Test Heat Source

Figure 4-16. Test Heat Sources

Figure 4-17. EB Example Weld of Simulated Pressure Relief Device in Hafnialloy Heat Source. Weld Penetration is Approximately 75%. Magnification = 8X.

Figure 4-18. EB Example Weld of End Cap in Hafnialloy Heat Source. Weld Penetration is greater than 100%. Magnification = 8X.

Figure 4-19. Photomicrograph of End Cap Example weld. Note that the weld zone has a fine-grained microstructure whose grain size is similar to that of the as-rolled and recrystallized end cap material. Magnification = 200X.

Figure 4-20. Subassembly and Assemblies of Single-Layer Hafnialloy Heat Sources

5. VENT TESTING AND VERIFICATION

Since plutonium-238 is an alpha-emitting isotope, it is necessary to either fully contain the helium generated by isotopic decay, or allow it to escape from the capsule in a controlled manner so that the fuel is completely contained. By use of a pressure relief device, creep and eventual rupture of the capsule, caused by continual buildup of helium pressure, are eliminated.

One of the daughter products in the decay chains of plutonium isotopes is the radioactive gas radon. The quantity of radon or its daughter products released may be detrimental to the human body and must be investigated both in regards to its radiation effects and its chemical toxicity. By the use of a PRD and a capillary tube the release of the decay gases may be retarded for a period long enough to decrease the activity to a safe level before being released to the surroundings.

A series of design verification tests was performed to verify that the pressure relief device (PRD) will release the helium generated by radioisotope decay in a controlled fashion and at the same time will retain fuel particles for an extended period of time. Radon retention testing was also conducted to ascertain the degree of permeability of the vent system to radon.

5.1 ANALYSES OF GAS PERMEATION THROUGH CAPILLARY TUBES AND POROUS MEDIA

Analysis of the permeation of a gas through a porous medium or a capillary at relatively low pressures is complicated by the fact that the pore or tube diameters are often less than, or comparable with, the mean free path of the gas molecules. Under such conditions, the permeation rate in the pores will not follow that predicted by Poiseuille's Law which applies to viscous flow but will be somewhat higher. This is attributed to slippage along the boundary layer, and is called "slip flow" (Reference 19). Under this type of flow, viscosity has a diminished effect. If the pressure is further reduced until the mean free path is much greater than the pore size, viscosity plays no part at all in the flow since the molecules collide only with the walls and the transport mechanism is one of free molecular effusion, or Knudsen flow. The complete permeation equations will first be described

for circular capillaries and then be applied to a porous medium typical of the nonselective vents.

5.1.1 Flow in Capillaries

For the viscous flow of gases in a circular passage, Poiseuille's Law takes the form of:

$$\frac{u_1 P_1}{\Delta P} = \frac{D^2 P_m}{32 \mu L} \quad (5-1)$$

where

- u_1 = inlet velocity
- P_1 = inlet pressure
- ΔP = pressure drop
- D = effective diameter
- P_m = mean pressure in tube
- μ = absolute viscosity
- L = flow tube length

To account for the increased flow due to slip and/or molecular effusion, an extra term must be added:

$$\frac{u_1 P_1}{\Delta P} = \frac{D^2 P_m}{32 \mu L} + \frac{\delta}{3} \frac{D}{L} V_m \quad (5-2)$$

where

$$V_m = \text{mean molecular velocity} = \sqrt{\frac{8 RT}{\pi M}}$$

$$\left\{ \begin{array}{ll} \delta = \frac{2-f}{f} & D \ll \lambda \text{ (Knudsen flow)} \\ \delta = \frac{3\pi}{16} \left(\frac{2-f}{f} \right) & D > \lambda \text{ (slip flow)} \end{array} \right.$$

f = fraction of molecules undergoing diffusion reflection at the wall

$$\lambda = \frac{\mu}{P} \sqrt{\frac{\pi RT}{2M}} = \text{mean free path in gas}$$

R = Universal gas constant

T = absolute temperature

M = molecular weight

The parameter, δ , varies depending upon the flow regime and the surface conditions and is difficult to evaluate. Fortunately, it has been shown to have a fairly constant value in most media varying from 0.9 to 1.0 from the slip to the Knudsen flow regime, respectively. For noncircular capillaries, a shape factor, K , is introduced:

$$\frac{u_1 P_1}{\Delta P} = \frac{D^2 P_m}{16 K_v \mu L} + \frac{\delta}{3 K_k} \frac{D}{L} V_m \quad (5-3)$$

where

K = shape factor

subscript v refers to viscous flow ($K_v = 2$ for circular tube)

subscript k refers to slip and Knudsen flow ($K_k = 1.0$ for circular tube)

Applying continuity to obtain the volume flow:

$$Q_1 = \frac{D^2 A P_m \Delta P}{16 K_v \mu L P_1} + \frac{\delta D A \Delta P}{3 K_k L P_1} V_m \quad (5-4)$$

where

Q_1 = volume flow at inlet

To report the flow rate under standard conditions of temperature and pressure, the perfect gas law can be applied:

$$\frac{Q_1}{Q_o} = \frac{T_1}{T_o} \frac{P_o}{P_1}$$

where the subscript o applies to standard conditions. Substituting in equation 5-4, one obtains:

$$Q_o = \frac{D^2 A P_m \Delta P T_o}{16 K_v \mu L P_o T_1} + \frac{\delta A D \Delta P T_o}{3 K_k L P_o T_1} V_m \quad (5-5)$$

In equation 5-5 the first term represents the contribution from viscous type Poiseuille flow, whereas, the second term represents the flow resulting from free molecular diffusion through the capillary. As laminar flow is approached, the contribution of this second term is diminished.

5.1.2 Porous Media

The previous derivation was for single capillaries. In a porous medium, the flow path is more tortuous and the true flow path length may be appreciably longer than the specimen length. This introduces a new factor, the effective path length, L_{eff} , and a tortuosity function, q , defined as

$$\frac{L_{eff}}{L} = q$$

If porosity, ϵ , is defined as void volume divided by the total volume, then

$$\epsilon = \frac{\text{void volume}}{\text{total volume}} = \frac{L_{eff} A_{eff}}{L A} \quad \therefore \left(\frac{A}{L}\right)_{eff} = \frac{\epsilon}{q^2} \frac{A}{L}$$

where

A = cross section of porous medium

A_{eff} = effective cross sectional area of pores

Substituting in equation 5-5, one obtains

$$Q_o = \frac{A \Delta P T_o \epsilon}{L P_o T_1 q^2} \left[\frac{D^2 P_m}{16 K_v \mu} + \frac{D V_m \delta}{3 K_k} \right] \quad (5-6)$$

A second feature of a porous medium is the difficulty in defining its hydraulic radius or effective diameter, D . The hydraulic radius, m , is defined as (Reference 20):

$$\begin{aligned} m &= \frac{\text{volume filled with fluid}}{\text{wetted surface}} = \frac{\text{cross-sectional area}}{\text{wetted perimeter}} \\ &= \frac{\epsilon}{S'} = \frac{\epsilon}{S(1 - \epsilon)} \end{aligned} \quad (5-7a)$$

where

S' = internal surface area/unit volume of pores and solid

S = internal surface/unit volume of solid only

or

$$D = 4m = \frac{4\epsilon}{S(1 - \epsilon)} \quad (5-7b)$$

The preceding equations require several empirical constants to be used to predict the flow rate through a porous Al_2O_3 plug. These factors can be obtained either experimentally or by the use of the recommended values presented in the literature. The most difficult parameter to assess is the tortuosity factor, q , since appreciably different values are obtained depending upon the degree of consolidation of the ceramic. Values are presented in Table 5-1 for both the unconsolidated Al_2O_3 powder and for

consolidated and sintered Al_2O_3 . The PAS Al_2O_3 is expected to lie close to the value for consolidated Al_2O_3 . In addition, the materials of construction affect the values of some of the parameters. For example, the relative ductility of the Pt-20Rh alloy appears to effect a better metal-to-ceramic bond than does the Ta-10W alloy of the Transit PRD. The net result is that the artificial heart heat source PRD helium flow rate was approximately an order of magnitude less than that of a similarly constructed Transit PRD for the same pressure differential. The predicted flow rate for the artificial heart heat source PRD is shown in Figure 5-1.

Table 5-1. Constants Used in Flow Model

	Viscous	Slip
K_V (shape factor)	2.5	-
δ/K_K (shape and collision factor)	-	0.82
q (tortuosity)		
Unconsolidated	1.4	1.4
Consolidated	3.0	3.0

5.2 TECHNICAL APPROACH

To verify proper sizing of the pressure relief device and to demonstrate that the PRD maintains a stable helium permeation rate at a given pressure differential and retains fine fuel particles during either normal operation or transient accident environments, a series of flow tests was performed. Measurements of helium permeation rates through the PRD in the pressure and temperature ranges in which it will be required to operate were obtained. Under normal operating conditions the helium flow rate will be 1.3×10^{-6} cc/sec (STP), which is the generation rate of helium in the fuel and assumes 100% helium release. Helium flow rates of this magnitude are normally measured utilizing a mass spectrometer type helium leak detector capable of measuring flow rates in the range of

Figure 5-1. Predicted Helium Flow Rate of AHHS PRD at Room Temperature

1×10^{-10} to 1×10^{-2} cc/sec (STP) at a pressure of less than 10^{-4} mm Hg. If the system pressure were to be duplicated during the tests, however, the high back pressure would preclude the use of a helium leak detector type instrument. To overcome this difficulty, flow rates on the order of 10^{-6} cc/sec (STP) were measured with a low back pressure of 10^{-4} mm Hg. High back pressures, simulating the actual thermal converter system, were used when measuring high flow rates (greater than 10^{-2} cc/sec STP); under these conditions bubble meters or wet test meters can be used with high accuracy. All data were then compared to the theoretical predictions of flow for the PRD's and served to fully characterize each unit.

The PRD assembly test matrix is shown in Table 5-2. The key parameter measured in all cases was the helium permeability rate in cc/sec (STP), and was made at the pressure differential and temperature values indicated in the test matrix. Testing at 1565°F and 2500°F simulated steady-state and accident environments, respectively. Testing at 70°F resulted in room temperature versus elevated temperature data and verified the temperature effect on the helium flow rate.

5.2.1 Characterization Matrix

The flow characterization tests consisted of measuring helium flow rates through six test PRD's at temperatures of 70°, 1565°, and 2500°F with pressure differentials across the PRD's ranging from approximately 0.001 psi, simulating steady state operation, to 150 psi, simulating potential pressure transients expected in a fire environment. These tests were of short duration (one hour) but provided sufficient information to determine the flow characteristics of each PRD and allowed a comparison of the experimental flow data with theoretical predictions. The PRD's were then exposed to the environments listed in the remaining portion of Table 5-2 to obtain longer term data at the steady-state and accident conditions detailed below.

5.2.2 Flow Stability

After initial exposure to short-term testing to determine the helium permeation characteristics, one vent was subjected to a long-term test of 2,000 hours and two vents were subjected to 200-hour tests as defined in Table 5-2. Additional long-term tests were not required as maximum use has been made of currently available and applicable test data to minimize

Table 5-2. Pressure Relief Device Test Matrix

S/N	Characterization* Matrix			Temperature (°F)		Pressure Drop (psi)			Test Time (hrs)			Steady State	Transient	Capillary PRD Assembly**
	I	II	III	1565	2500	.001	105	150	2	200	2000			
001	X	X		X		X				X		X		
002	X	X		X			X			X		X		
003	X	X		X		X					X	X		
004	X		X		X			X	X				X	
005	X	X		X		X			X			X		X
006	X		X		X			X	X				X	X

*Characterization Matrix - I @ 70°F ΔP = 0.001, 105, 150 psi

II @ 1565°F ΔP = 0.001, 105 psi

III @ 2500°F ΔP = 0.001, 150 psi

Tests conducted according to the characterization matrix were of one-hour duration

**PRD's S/N 005 and 006 were tested for helium and radon permeation. Subsequently, the PRD's and two capillaries were joined and the test was repeated. The radon testing was done at room temperature.

duplication of testing which had been conducted in prior vented radioisotope heat source programs. The vent design is basically identical to that utilized in fabricating noble metal vents under the Vented Radioisotope Heat Source Program (Reference 21); these vents operated at TRW with a cumulative total test time of over 125,000 hours at 2000°F (average test time per vent was 20,000 hours). The new data verified the long term flow stability of the PRD's as already established in these earlier tests.

5.2.3 Fines Retention

Fines retention tests were conducted on all vents tested to verify that the vents will retain fuel particulate matter. Five mg of submicron thorium powder ($\text{Th}^{232}\text{O}_2$) were loaded on the fuel side of the vents prior to testing. Thorium was chosen as the simulated fuel tracer material because of its low cost, availability, relative ease of handling, chemical inertness, and compatibility with PRD components at elevated temperatures and because of the potential sensitivity in detecting small quantities of this material. The thorium powder consisted of particles whose average size was approximately 0.6 micron. Filter holders containing 0.3 μ filters were attached to each extension tube where the tubes enter the furnace chamber. Th^{232} has a relatively low specific nuclear radiation activity. Therefore, the absolute filters which were used in these tests were subjected to post-test neutron activation analyses. Following irradiation in a nuclear reactor, the samples were counted using scintillation or semiconductor detectors coupled to pulse height analyzers. The direct comparison of sample and standard count rates gave the initial thorium content. Thus, thorium, if present, could be detected in quantities as low as 0.4 microgram. This technique was previously proved to be very satisfactory in Transit PRD fines-retention tests.

5.2.4 Radon Retention

Radon retention within the heat source, or at least the reduction of radon release rates to acceptable levels, must be demonstrated to assure the adequacy of the design. An analysis was performed to determine the size of a capillary tube required to delay the emission of radon gases from the heat source long enough to hold the released activity below the maximum permissible body (MPB) burdens for radon as suggested by the International

Commission on Radiological Protection (Reference 4). The resultant capillary consisted of a 4-inch long tube having a 0.005 inch I.D. Testing of capillary assemblies was conducted to verify theoretical analyses of gas flow as a function of pressure and temperature. The permeability of radon through two PRD's was determined and then two PRD's were attached to capillary tubes and these complete venting systems were tested to determine helium and radon permeation rates.

A Th-228 source was used to simulate the fuel in these tests. The decay scheme of Th-228 includes radon-220, which constitutes the bulk of the radon released in an actual Pu-238 fueled heat source. A nuclear radiation detector was positioned directly in the downstream line leading from the vent. Since the decay products of radon emit their own characteristic radiations at various discrete energies, the detector in conjunction with a 400-channel pulse height analyzer was used to separate these energies and accurately determine the specific nuclides present.

Semiconductor radiation detectors are normally operated at 72°F. All warranty specifications are based on test results obtained at this temperature. The detectors may be operated at slightly higher temperatures (up to approximately 110°F) but a certain amount of degradation is experienced even at this relatively low temperature. Therefore, all radon retention tests were conducted at room temperature. Changes in PRD temperature affect the flow rate only (flow decreases with temperature) and do not have any effect on the disintegration rate of the radon.

5.3 TEST SPECIMENS AND EQUIPMENT

5.3.1 Test Specimens

Six test PRD's were fabricated to TRW Drawing D410571 shown in Figure 3-14. Pt-20Rh extension tubes (shown in Figure 5-2) were welded to each end of the PRD to facilitate flow testing at elevated temperatures. Two capillary assemblies, as shown in Figure 3-22, were used for the radon permeation tests.

5.3.2 Equipment and Instrumentation

All PRD/capillary tests were performed in the TRW Heat Source Laboratory. Schematic diagrams of the helium and radon test systems are shown

Figure 5-2. PRD in Brew Furnace

* $\text{Th}^{232}\text{O}_2$ POWDER AND ABSOLUTE FILTER
WILL BE USED IN ALL TESTS.

** THIS ABSOLUTE FILTER IS UTILIZED TO
MINIMIZE POSSIBLE MIGRATION OF THORIA
POWDER THROUGH THE PRESSURE SIDE OF
THE SYSTEM.

Figure 5-3. Helium Flow Rate Test Setup

in Figures 5-3 and 5-4, respectively. A modified Brew vacuum system, shown in Figure 5-5, was used to heat the specimens to the highest test temperature of 2500°F. A second high temperature furnace, designed specifically for helium permeation testing of noble metal PRD's, was used for the long-term tests at 1565°F and is shown in Figure 5-6. A helium pressure manifold connected to both sides of the system allowed six test assemblies to be tested simultaneously or independently. The test units were placed in alumina tubes between two silicon carbide rod heating elements. A photograph of the radon permeation test system is shown in Figure 5-7.

A mass spectrometer-type helium leak detector capable of measuring helium flow rates in the 1×10^{-10} to 1×10^{-2} cc/sec (STP) range was utilized to monitor the PRD and capillary tube permeation rates. A standard helium leak with a leak rate of 2.8×10^{-8} cc/sec (STP) was used to calibrate the helium leak detector prior to each test. A bubble flow meter and wet test meter with accuracies of 1% were used to measure flow rates higher than those within the range of the leak detector.

The helium pressure differential across the PRD or capillary was measured with an MKS Baratron pressure indicator. This unit measures pressure differences to 0.05 percent accuracy of full-scale. A Leeds and Northrup optical pyrometer was used to monitor test specimen temperatures. This unit has a 0.3% accuracy at all temperatures measured during these tests.

Radon activity was determined by a semi-conductor alpha detector connected to a Victoreen 400-channel pulse height analyzer. Decay products of Th-228 emit their own characteristic γ , β , and α rays at various discrete energies. The detector was capable of separating these energies, and, therefore, an accurate determination of specific nuclides, including radon and its daughters, was made.

5.4 TEST PROCEDURE

5.4.1 Flow Characterization, Flow Stability, and Fines Retention Tests

The PRD assemblies, with a platinum extension tube welded to each end, were installed in a Brew vacuum furnace, using swagelok fittings in the top and bottom plates. Stainless steel tubing was used to connect the remainder of the external equipment.

Figure 5-4. Radon Detection Test Schematic

Figure 5-5. High Temperature Brew Vacuum Furnace

Figure 5-6. High Temperature Furnace for Helium Permeation Testing

Figure 5-7. Radon Test Facility

Five milligrams of thoria powder were loaded through the upper extension tube and the PRD assembly was vibrated to force the thoria to migrate to the upstream side of the PRD. Millipore filters were installed at each end of the platinum extension tubes. The system was evacuated and the vacuum integrity of the system was checked at room temperature utilizing a helium leak detector. After obtaining a vacuum of less than 1×10^{-5} torr in the furnace, the furnace temperature was raised to the temperature specified in the characterization matrix listed in Table 5-2. A helium gas supply was then used to maintain the required pressure differential across the PRD. The helium pressure differential was measured with an MKS Baratron pressure gauge, and the helium permeation rate was measured with a CEC or Veeco helium leak detector, bubble flow meter, or wet test meter, as required.

Subsequent to the characterization matrix testing, the PRD's were transferred to the flow stability test furnace and the required steady state temperature, vacuum, and pressure parameters for the long-term stability tests were established, as indicated in Table 5-2. For tests exceeding a two-hour duration, daily readings of the above parameters and helium permeation rates were recorded, except for the 2000-hour test for which weekly readings were taken. At the conclusion of each test, the thoria filters were removed and subjected to neutron activation analyses.

5.4.2 Transient Tests

PRD's S/N 004 and 006 were tested in transient temperature environments at temperatures up to 2500°F for 2-hour durations. Subsequent to the characterization matrix testing, each PRD was maintained at a temperature of 1565°F and ΔP of 1×10^{-3} psi for 1 hour to maintain steady state equilibrium. The temperature was increased from 1565°F to 2500°F and the pressure from 10^{-3} to 150 psi at a linear rate over a 30-minute period and maintained for 2-hour duration to simulate the fire environment. Temperature, pressure differential, and helium flow rates were continually monitored during this test.

5.4.3 Radon Attenuation Tests

Two PRD's and two PRD/capillary assemblies were assembled and tested for radon attenuation. The extension tubes and Th^{232} powder were removed from the PRD's. In turn each PRD and assembly were installed in the radon attenuation testing facility, shown schematically in Figure 5-4. The vacuum integrity of the system was verified each time and the required

helium flow rate was established. The radon count rate for each test unit was then compared to the radon count rate obtained for the same helium flow rate but without the test unit in the line. Ratio of the two radon activities yielded the attenuation by the test specimen.

5.5 TEST RESULTS

5.5.1 Flow Characterization Tests

As mentioned above, helium permeation data were recorded both at room and at elevated temperatures to characterize the PRD's. The data obtained are shown in Table 5-3. The room temperature test data are compared with theoretical predictions for this type PRD in Figure 5-8. Although some variation in flow from PRD to PRD existed under all test conditions, the average flow at a particular pressure differential compared very well with theory. The slight variation in flow can be attributed to some variability in the fit between the PRD core and its housing. Although it was attempted to minimize the size of this gap, it could not be totally eliminated. It has been shown analytically that a gap a few microns wide will result in a noticeable variability in the flow rate from PRD to PRD.

Helium permeability data for the PRD's at the normal heat source operating temperature of 1565°F and at a fire temperature of 2500°F are shown in Figures 5-9 and 5-10, respectively. Again, there is very good correlation between predicted and recorded data. It can be noted, however, that the discrepancy between theory and experimental data is slightly higher at 2500°F. It is suspected that differential expansion between the metal and the alumina may have resulted in a slight increase in the flow cross sectional area at the higher temperatures. As mentioned above, at the low permeation rates experienced by these vents, a very slight area change is sufficient to affect the flow rate significantly.

5.5.2 Flow Stability

After initial exposure to short term tests to determine the helium permeation characteristics, two vents (S/N 001 and 002) were subjected to 200-hour tests and one vent (S/N 003) was subjected to a long-term test of 2000 hours. The flow rates, as expected, remained basically unchanged. Figure 5-11 shows the long-term steady-state performance of PRD S/N 003

Table 5-3. PRD Characterization Test Data

PRD S/N	Helium Permeation Rate std cc/sec						
	70°F			1565°F		2500°F	
	.001 psi	105 psi	150 psi	.001 psi	105 psi	.001 psi	150 psi
001	1.4×10^{-6}	2.7×10^{-1}	5.7×10^{-1}	1.7×10^{-6}	7.1×10^{-2}	NA*	NA
002	1.4×10^{-6}	3.8×10^{-1}	5.0×10^{-1}	2.2×10^{-6}	1.5×10^{-2}	NA	NA
003	1.3×10^{-6}	2.0×10^{-1}	3.3×10^{-1}	1.9×10^{-6}	1.2×10^{-2}	NA	NA
004	1.2×10^{-6}	1.3×10^{-1}	2.4×10^{-1}	NA	NA	1.4×10^{-6}	5.0×10^{-1}
005	1.4×10^{-6}	1.0×10^{-1}	1.8×10^{-1}	1.0×10^{-6}	3.7×10^{-2}	NA	NA
006	1.6×10^{-6}	1.9×10^{-1}	4.0×10^{-1}	NA	NA	1.2×10^{-6}	6.6×10^{-1}

*NA: Test data not required as defined in Table 5-2.

Figure 5-8. Correlation between Predicted and Experimental Helium Flow Rate of Artificial Heart Heat Source PRD's at Room Temperature

Figure 5-9. Experimental Helium Permeation Data at 1565°F

Figure 5-10. PRD Helium Permeation Test Data at 2500°F

Figure 5-11. Long-Term Helium Permeation Test History for Vent S/N 003

during the 2000-hour test at the nominal operating temperature of 1565°F. The helium flow, at a constant pressure, remained remarkably stable during the duration of the test and compares very well with theoretical predictions.

5.5.3 Fines Retention Tests

After completion of the six fines retention tests, the absolute filters were removed and placed in separate polyethylene vials and subjected to neutron activation analyses. Neutron activation analysis is an elemental method of analysis based on the quantitative measurement of radioactivity produced in a sample by neutron irradiation.

The millipore filter samples and thorium comparator standards were simultaneously irradiated for 30 minutes each in a rotating rack of the TRIGA Mark I nuclear reactor, at a thermal neutron flux of 1.8×10^{12} n/cm²-sec. Following the irradiation, time was allowed for the decay of shorter-lived radioisotopes present in the filters and polyethylene vials. The samples and standards were then counted, either in a 3-inch x 3-inch

NaI (Tl) well-type scintillation detector coupled to a 400-channel pulse height analyzer, or on a 35 cc lithium drifted germanium semiconductor detector coupled to a 4096-channel analyzer.

The direct comparison of sample and standard count rates gave the initial thorium content or the lower limit of detectability. The lower limit is defined as that quantity of an element that would have to be present in the particular sample in order to be detected.

The analytical results are listed in Table 5-4. In each case the quantity of thorium present was lower than the limit of detectability indicating complete fuel retention by the PRD.

Table 5-4. Millipore Filter Analyses

PRD S/N	Microgram, Thorium
001	≤ 0.13
002	≤ 0.19
003	≤ 0.15
004	≤ 0.36
005	≤ 0.20
006	≤ 0.21

5.5.4 Radon Attenuation Tests

The initial portion of the radon attenuation tests was conducted without any restriction in the flow system. An open tube was placed in series with the radon source and radiation detector, in place of the PRD or capillary system, as shown in Figure 5-4.

Subsequently, PRD's S/N 005 and S/N 006 were installed separately into the test setup to determine their helium and radon flow characteristics. A typical trace of the measured activity of radon and its daughter products is shown in Figure 5-12. Three hundred and fifty-seven microcuries of Rn-220 are generated in 10 years from 33.1 watts of Pu-238. The maximum permissible amount of Rn-220 allowed to the artificial heart recipient during the 10-year design life is 0.01 microcurie. A total radon attenuation of 3×10^{-5} is therefore required.

Figure 5-12. Typical Radon Activity Trace

Test data indicated that PRD S/N 005 and S/N 006 attenuated radon by 99.82% and 95.90%, respectively. This variation in attenuation is not surprising in view of the fact that the two PRD's had undergone different severe thermal environments prior to the tests. PRD S/N 005 had been heated to 1565°F and PRD S/N 006 had been heated to 2500°F. Based on all previous data obtained for this type of PRD, exposure to temperatures above 2000°F tends to make the PRD slightly more permeable to gas flow.

It is interesting to note that the variation of helium flow through the test system at low pressures did not affect the permeation rate of the radon. This can be attributed to the fact that the mean free path of the radon atoms was much greater than the tube diameters and the atoms collided primarily with the tube walls rather than helium atoms. The introduction of a steady state flow of helium into this system at approximately 1×10^{-6} cc/sec (STP) did not effectively raise the density of the gases in the system enough to change the mechanism of free molecular effusion.

PRD S/N 005 was subsequently connected in series with a capillary assembly, as shown in Figure 5-13, and tested to determine the total radon attenuation by the heat source venting system. The total attenuation of radon was only 99.92%, as shown in Figure 5-14. The helium flow data obtained for the capillary indicated that its resistance to flow was much lower than that of the PRD. Therefore, the 4-inch long capillary tube also had a much lower resistance to radon permeation than did the PRD and did not effectively reduce the overall radon permeation rates of the PRD/capillary system. The overall attenuation was only 8×10^{-4} .

To investigate the effect of a smaller capillary, a 0.005-inch I.D. tube was crimped along its length to effectively yield a capillary of reduced cross sectional area. The effective inside diameter of the capillary tube was reduced from 0.005 inch to approximately 0.001 inch. The crimped capillary tube separately reduced the radon permeation by 99.95%, as shown in Figure 5-15. Subsequently, PRD S/N 006 and the crimped capillary tube were tested together in series, resulting in a total radon attenuation by the total venting system of 99.987%, or 1.3×10^{-4} . As can be seen from this test, the effectiveness of the capillary can be increased appreciably by the crimping process, or by reducing the I.D. of the tube.

Figure 5-13. PRD S/N 005 and Capillary Assembly

Figure 5-14. Radon Attenuation Data for PRD S/N 005 and Capillary Assembly

Figure 5-15. Radon Attenuation Data for PRD S/N 006 and Capillary Assembly

It is of interest to note that the Bi-212 peak is visible in Figure 5-14 but not in Figure 5-15. This is due to the fact that some of the daughter products of the radon accumulated on the detector surface during long tests. Prior to each test this activity was usually allowed to decay to a low enough level so as not to interfere with the Rn-220 peak. In Figure 5-15 the Bi-212 background had decayed sufficiently so as to be obscured by the Rn-220 peak. On the other hand, the Bi-212 background was sufficiently high so as to be discernible in Figure 5-14. The appearance of a discrete peak in the channel 301 position of Figures 5-14 and 5-15 is also of interest. This peak does not fall in the decay chain of Rn-220. It is suspected that a second radioactive gas, such as Rn-219, may have permeated through the absolute filter between the test source holder and the surface barrier detector. Rn-219 would be present as a result of some Th-227 impurity in the Th-228 fuel simulant. Rn-219 itself was not detected because its low activity was probably obscured by the higher activity of Rn-220. However, the daughter product of Rn-219 (Po-215) would be observed at channel 301, as noted above.

5.6 CONCLUSIONS

- The helium permeation rates of all PRD assemblies tested remained stable not only through short-term testing, but also during long-term, high temperature operation.
- Experimental testing during this program has demonstrated the ability of the artificial heart heat source PRD to retain submicron fuel simulant while passing helium under all test conditions.
- Post-test visual examination of specimens revealed no major change in appearance attributable to exposure environments.
- There is good correlation between the experimental helium permeation data and the theoretical equations for both slip and viscous flow in a porous medium. Still better correlation could be obtained by empirically determining the constants in the theoretical equations specifically for the artificial heart heat source PRD's.
- The greatest spread between predicted and actual helium permeation rates, at a constant pressure, occurred at the highest test temperatures of 2500°F. It is suspected that differential expansion between the metal and the alumina may have resulted in an increase of the flow area at the higher temperatures. At the low permeation rates experienced by these vents, a very slight area change would be sufficient to affect the flow rate.
- The helium permeation rate through the PRD's was relatively independent of temperature.

- At high pressure differentials, relative to the normal operating conditions, the permeation mechanism of non-selective vents changes from slip flow to viscous laminar flow. During this change, the effect of the pressure gradient on the permeation rate changes from a first order dependency (proportional to ΔP) to a second order dependency (proportional to $(\Delta P)^2$).
- Radon attenuation by the PRD's varies depending on the thermal history of the PRD. For units not heated above 2000°F, attenuation in excess of 99% can be expected; for units heated above 2000°F, attenuations of 95% or better can be obtained.
- The 0.005-inch I.D. capillary was not sufficient to further reduce radon permeation appreciably. A smaller diameter capillary, or a crimped tube is, however, very effective.
- Under normal use, the PRD's are not heated to temperatures above 2000°F. Using a small diameter capillary, total radon attenuations of 10^{-6} are, therefore, obtainable with the current venting system (99.82% by the PRD and 99.95% by the capillary). Since an attenuation of 3×10^{-5} is required, a safety margin of 30 is available.

6. SAFETY TESTS

A series of design verification tests was performed to verify that the artificial heart heat source will survive various accident environments as delineated by the safety criteria. Tests subjected the heat source to impact, fragmentation, crush, fire, and post-accident oxidation environments under conditions delineated in Section 3.1:

- Impact against granite simulated the crash of an airplane or the head-on collision of fast moving trains, conditions which are of approximately equal severity. The equivalent heat source impact velocity against granite was calculated to be 216 ft/sec.
- The most severe credible fragmentation environment was determined to be impact by a 30-06 rifle bullet. Assuming some energy loss during air travel and in the human body prior to actual impact of the heat source, a bullet energy of 2000 ft-lb has been assumed. Tests using a 45-caliber hand gun were also performed.
- The worst credible static crushing environment to which the artificial heart recipient may be subjected is generated by a track-type vehicle having metal cleats. In the size range under consideration, the heat source, lying on concrete, was required to survive a 5000-lb static load.
- Although cremation of the recipient of an artificial heart device is highly unlikely, such an environment is somewhat less severe than that which might be encountered in a long duration warehouse fire (which represents the most severe credible temperature to which the heat source may be subjected). In view of the importance of not releasing radioactive fuel in a fire environment, the heat source was required to survive a temperature of 2500°F for two hours.
- Finally, since fuel containment must be achieved for extended durations following any of the above accidents, tests were performed to verify capsule integrity in an oxidizing environment at the post-accident, steady-state heat source temperature.

A total of 12 baseline design heat sources and 10 Hafnialloy heat sources were used for safety testing. Of the 12 three-layer units, three were tested in impact, five were tested in bullet impact, and two each were tested in crushing and fire. One additional bullet impact test was performed on a unit previously tested in the fire environment, and two-post accident oxidation tests were performed on units previously tested in impact

and bullet impact. The Hafn alloy test units were of two thicknesses. Two of each thickness were tested in impact, two in bullet impact, and one in fire. In addition, one of the thin-walled Hafn alloy impact units was tested in the post-accident oxidation environment.

6.1 IMPACT TESTS

Impact tests were performed to demonstrate the fuel containment capability of the heat source during an accident such as an airplane or a train crash. Numerous theoretical analyses of the response of radioisotope heat sources to impact against an unyielding surface such as granite have been performed over the last few years (Reference 4). The problem of predicting the failure of a fueled cylindrical or spherical capsule remains unsolved, and must be treated experimentally. Thus, all heat source development programs include a series of tests in which actual heat sources, fueled with a fuel simulant, are impacted against granite at the anticipated impact velocity to verify the adequacy of the design.

During the current test series the heat sources were impacted against granite at a velocity of 216 ft/sec (Section 3.1.1) and a temperature of 1565°F, the operating temperature of the heat source under actual operating conditions in the artificial heart device.

6.1.1 Test Specimen and Equipment

6.1.1.1 Test Specimen

A total of seven heat sources was tested, as shown in Table 6-1. Three heat sources were of the baseline design (AHT series) and consisted of the three-layer Pt-20Rh/T-111/Pt-20Rh design; the remaining four heat sources were of the single-layer Hafn alloy design (Hf series).

A larger variation in wall thickness had originally been planned for the Hafn alloy units. As described in Section 4.4.2, however, fabrication difficulties prevented the spinning of thicker Hafn alloy components. In addition, five baseline design heat sources were originally scheduled to be impacted. However, due to the success of the first three tests and the complete fuel containment by the heat sources, it was decided to relegate

Table 6-1. Impact Test Matrix

Unit	Strength Member Thickness (in)	Orientation
AHT-5	0.095	End-on/PRD
AHT-10	0.095	45°/PRD
AHT-11	0.095	Side-on
Hf-14B	0.118	End-on/PRD
Hf-16B	0.110	End-on/PRD
Hf-17A	0.119	45°/PRD
Hf-18A	0.110	45°/PRD

the two remaining heat sources to bullet impact testing (see Section 6.2 below).

6.1.1.2 Equipment and Instrumentation

TRW's impact gun facility was utilized to conduct the heat source impact tests. The gun facility consists of a pneumatic gun, triggering mechanism, fire control console, furnace, and a granite block target with padded rebound chamber (Figure 6-1). The pneumatic gun will propel capsules weighing up to 2 pounds at velocities up to 300 ft/sec. A clam-shell resistance-type heater was used to raise the temperature of the heat source prior to impact. A chromel-alumel thermocouple, in contact with the heat source, was connected to a Leeds and Northrup potentiometer thus permitting temperature measurements to an accuracy of $\pm 10^{\circ}\text{F}$. As a capsule left the gun, its velocity was experimentally determined by measuring the time of flight between two photomultiplier tube sensing devices accurately spaced a known distance apart. Impact velocity was measured to ± 5 ft/sec. Heat source impact orientation (i.e., impact angle) was varied by changing the orientation of the granite target block and/or the orientation of the heat source in the gun. Impact angles of 0° to 90° were thus possible.

Figure 6-1. Impact Gun

6.1.2 Test Procedure

Several mass models, simulating the mass properties and physical dimensions of the actual heat source, were used to verify the operation of the system. The impact gun air pressure/heat source velocity correlation was verified, and the operation of the clam-shell heater and of the complete system at various impact angles was checked out.

Prior to each test, the heat sources were weighed. Each heat source was in turn placed in the impact gun, and both the heat source and the target were aligned for the proper impact angle. After proper orientation of the heat source, a chromel-alumel thermocouple was placed in contact with the heat source and the heater was lowered into position. The heat source temperature was slowly raised to 1600°F and maintained at this temperature to allow the entire heat source to reach thermal equilibrium. When a steady-state temperature was achieved, as indicated by a Leeds and Northrup potentiometer, the heater was removed and the heat source was impacted against the granite block at 216 ft/sec. In each case the impacted heat source rebounded into the adjacent catcher box. The temperature of the heat source dropped approximately 35°F when the heater was removed, resulting in an impact temperature of 1565°F. When cool enough to handle, the heat source was retrieved from the catcher box and checked for fuel simulant release by taking a swipe of the external surface of the unit.

6.1.3 Test Results

The results of the heat source impact tests are summarized in Table 6-2. All of the heat sources tested survived impact and remained integral, resulting in complete fuel containment. Immediately after impact, the heat sources were examined visually, and a radiological survey was made to determine if any thorium fuel simulant had been released. Surface swipes were made of the entire heat source and were measured with an alpha counter. All of the smears taken of the heat sources were below or equal to the background of the instrument utilized. Although deformed and flattened at the impact zones, none of the heat sources had visible breaches of the external surfaces. However, post-test helium leak tests indicated that heat sources AHT-10 and AHT-11 had minute breaches of the clad surface in the area of impact. These leak tests were performed by the "bomb" technique. The heat source was placed in a small pressure chamber which was first evacuated for several

Table 6-2. Impact Test Results

Unit	Orientation	Results
AHT-5	End-on/PRD	Completely intact. Slightly foreshortened.
AHT-10	45°/PRD	Deformed at 45°. Clad completely intact except for minute helium leak in impact area.
AHT-11	Side-on	Flattened along its length. Clad completely intact except for minute helium leak in impact area.
Hf-14B	End-on/PRD	Completely intact. Slightly foreshortened.
Hf-16B	End-on/PRD	Completely intact. Slightly foreshortened.
Hf-17A	45°/PRD	Completely intact. Deformed at 45°.
Hf-18A	45°/PRD	Completely intact. Deformed at 45°.

hours and then pressurized overnight with 50 psig of helium. The heat source was subsequently removed and placed in a small calibrated chamber connected to a leak detector. The rate at which this chamber could be evacuated while containing a test specimen indicated the presence or absence of a leak.

Heat source AHT-5 impacted at approximately 10° instead of the planned end-on, or 0° angle of impact. This slight deviation in impact angle occurred due to a slight rotation of the heat source in flight. This unit is shown in Figure 6-2 after impact. The heat source was foreshortened in overall length and the outer diameter at the impacted end had increased appreciably. Very little abrasion of the Pt-20Rh clad was noted.

Figure 6-2. Heat Source AHT-5 After End-On Impact

This unit was sectioned circumferentially approximately 1/2-inch from the impacted end, as shown in Figure 6-3. The thoria was fractured although still integral. Some loose thoria powder was observed which probably resulted from the sectioning operation. The thoria was removed from the impacted end containing the PRD, as shown in Figure 6-4. The PRD was intact and appeared to have survived remarkably well, although it was bent approximately ten degrees. The inlet hole of the PRD was clear and not obstructed with any fuel simulant. Figure 6-4 also shows a shear type displacement on the inner surface of the welding shim which appears to have resulted from the force of the fuel simulant during impact. However, the liner, and this area of the liner end cap in particular, were not breached.

Test unit AHT-10, as it appeared after impact, is shown in Figure 6-5. Based on past impact tests of similar radioisotope heat sources, impact at 45° is the most severe, especially in regards to abrasion of the outer member. The deformation of unit AHT-10 appeared to be localized in the area of impact with a slight folding over of the relatively ductile Pt-20Rh clad in the area of impact. A slight amount of abrasion of the clad occurred at the opposite end to that impacted, which appears to be a typical occurrence for units impacted at 45°. This abrasion results from a "slapdown" of the trailing end of the unit subsequent to the initial impact.

Test unit AHT-10 was also sectioned circumferentially approximately 1/2-inch from the impacted end, as shown in Figure 6-6. The PRD was bent approximately ten degrees. The inlet hole of the PRD was clear and did not contain any traces of fuel simulant. The relatively ductile Pt-20Rh folded over in the area directly behind the impact area and remained integral. Except for a few minor hairline cracks in the Pt-20Rh welding shim, this area showed very little damage.

A post-impact view of heat source AHT-11 is shown in Figure 6-5. The rough texture of the clad at one end of the impacted surface resulted from impacting on a portion of the granite block which had been chipped slightly during previous testing. This phenomenon occurred on portions of the impacted surfaces of several of the test capsules. The deformation of heat source AHT-11 appeared to be very symmetric, including the slight folding over of the clad at each end. Except for a minute helium leak in the impact

Figure 6-3. Heat Source AHT-5 Upon Sectioning

Figure 6-4. Impacted End of Heat Source AHT-5

Figure 6-5. Heat Sources AHT-10 and AHT-11 After Impact

Figure 6-6. Heat Source AHT-10 After Sectioning

area, the heat source appeared in excellent condition. This unit was selected for post-impact oxidation tests (Section 6.5).

Test units Hf-14B and Hf-16B, impacted end-on, are shown in Figures 6-7 and 6-8, respectively. Both of these heat sources impacted at approximately 10° instead of the planned end-on, or 0° angle, originally planned. These units appeared to have suffered the least damage of all those tested. The heat sources were foreshortened slightly and the outer diameter at the impacted end increased by approximately 0.1 inch. These units, together with heat source AHT-5, also suffered the least abrasion damage to the impacted surfaces.

Figures 6-7 and 6-8 also show a post-impact view of test units Hf-17A and Hf-18A, respectively. These units, impacted at 45° , also survived remarkably well and suffered only a very slight amount of surface abrasion at the end opposite to impact. As mentioned above, this type of abrasion is the result of "slapdown" of the heat source onto the granite block.

Test units Hf-14B and Hf-18A were sectioned circumferentially approximately 1/2-inch from the impacted end, as shown in Figures 6-9 and 6-10, respectively. The solid PRD in each unit was bent approximately five degrees but remained intact. Examination of the two units revealed very little damage to the inner surface of the sectioned portions. Some hairline cracks were visible on the inner surfaces of the end caps at the impacted end of each unit; a shear type displacement, similar to that noticed in unit AHT-5, was observed extending from the base of the PRD across the inner surface of the end cap of unit Hf-14B; and a slight gap was visible between the end cap and the body behind the point of impact of unit Hf-18A. This gap in unit Hf-18A extended circumferentially around the end cap for approximately 45 degrees, with the maximum width approximately 0.020 inch. The gap appeared to be between 0.015 to 0.020-inch deep and was probably due to the lack of penetration of the end cap weld. None of these defects penetrated the end cap, and complete fuel simulant containment was achieved. The thorium fuel simulant in both of these units was heavily fractured especially in unit Hf-18A (Figure 6-10). Although fractured, only a slight amount of loose powder was observed.

Figure 6-7. Heat Sources Hf-17A and Hf-14B After Impact

Figure 6-8. Heat Sources Hf-16B and Hf-18A After Impact

Figure 6-9. Heat Source Hf-14B After Sectioning

Figure 6-10. Heat Source Hf-18A After Sectioning

6.1.4 Conclusions

Both the three-layered Pt-20Rh/T-111/Pt-20Rh and single-layered Hafn alloy heat sources survived granite impact very well with no release of fuel simulant. The T-111 strength member thickness of 0.095 inch and Hafn alloy thickness of 0.110 to 0.120 inch were obviously more than adequate for this accident environment. Furthermore, the ductile Pt-20Rh clad was also able to absorb and/or transmit the impact energy without a major breach. Only a minute helium leak was found in two of the three-layered units. Heating of the heat sources in air during the tests obviously had no detrimental effects on any of the units, and all inner surfaces were bright and clean and appeared to be in the as-assembled condition.

6.2 FRAGMENTATION TESTS

Fragment-impact, or fragmentation tests, are required to evaluate the capability of the heat source to withstand the impact of high velocity fragments which may result from an explosion of a shell or from a high velocity bullet. Heat sources were impacted by 30-06 rifle bullets and by 45-caliber hand gun bullets. In each case, the heat source temperature was 1565°F, the normal operating temperature of the heat source in the human body.

6.2.1 Test Specimens and Equipment

6.2.1.1 Test Specimens

Six baseline Pt-20Rh/T-111/Pt-20Rh heat sources and four single-layer Hafn alloy heat sources were tested at various bullet energies. Initially, only three of the baseline design units were to be tested, but due to the excellent survivability of the heat sources in other environments and their questionable survivability in 30-06 bullet impact, the number of baseline test units was increased to six.

In addition to these simulant-fueled heat sources, numerous T-111 and Hafn alloy dummy units were used to calibrate the facility and validate the 2000 ft-lb design capability prior to expending real test hardware. The configurations of the Hafn alloy units differed only in wall thickness whereas the T-111 units differed in wall thickness, number of T-111 layers used, existence or omission of strength member end-caps, existence or omission of liner and clad, existence or omission of fuel simulant, and type of simulant

material used. The T-111 and Hafnialloy test units are described in Tables 6-3 and 6-4, respectively.

6.2.1.2 Equipment and Instrumentation

The tests were conducted at the TRW Systems rifle test facility. The equipment for the 30-06 tests consisted of a fixed 30-caliber machine gun, an electric chronograph, heater, and firing panel. The test cell consisted of a 7-foot long by 3-foot diameter vacuum chamber, capable of being pumped down to less than 5 mm of mercury and being back-filled with argon or helium. For these tests argon was used. A 30-caliber machine gun was hard mounted at one end of the test chamber and a chronograph at the other end. The chamber was fitted with wooden rebound panels, a specimen holder, and an electrical heater assembly. The latter consisted of a clam-shell type heater attached to pulleys. Just before firing of the gun, the heater assembly was removed from the test specimen. The facility is shown in Figures 6-11 to 6-13.

The 30-06 bullets used in these tests were 180-grain (0.026 pound), 0.308-inch diameter (30-caliber), soft pointed bullets. The bullets were 95 percent copper jacketed; that is, all but 5 percent, the point, was encased in a copper jacket. The normal muzzle energy of these bullets is approximately 2900 ft-lb, with a velocity of 2700 ft/sec. By offloading the powder, the velocity, and hence the energy, was varied. Assuming 900 ft-lb of energy are lost due to frictional losses in the air and due to impact with the body and thermal converter system, an impact energy of 2000 ft-lb was originally specified.

The 45-caliber bullet tests were conducted in air, with the gun hard mounted at a distance of 12 inches from the test specimen. The same clam-shell heater used for the 30-06 rifle tests was used to heat the test specimens to 1565°F. The bullets used were standard 45-caliber bullets, 230 grains, 0.45 inch in diameter, and unjacketed. The 45-caliber bullet test facility is shown in Figure 6-14.

The temperature of the heat source was monitored in each case using Pt/Pt-Rh thermocouples attached to the heat source. Temperature at impact was 1565°F $\pm$ 10°F. The bullet velocity was accurate to $\pm$ 2%.

Table 6-3. T-111 Fragmentation Test Units

Specimen No.	Strength Member O.D. x Wall Thickness, inch	Description
1	0.940 Dia x 0.095 $\pm$.005 ↓	Single-layer strength member - no end caps and no simulant.
2		Single-layer strength member - no end caps and no simulant.
3		Single-layer strength member with Pt-20Rh liner - no end caps - Thoria simulant.
4		Single-layer strength member with Pt-20Rh liner - no end caps - Thoria simulant.
5		Single-layer strength member with Pt-20Rh liner - no end caps - Al ₂ O ₃ simulant.
6		Single-layer strength member with Pt-20Rh liner - no end caps - Al ₂ O ₃ simulant.
7		Single-layer strength member with Pt-20Rh liner - no end caps - Al ₂ O ₃ simulant.
8		Single-layer strength member with Pt-20Rh liner - no end caps - Al ₂ O ₃ simulant.
9		Single-layer strength member with Pt-20Rh liner - no end caps - Al ₂ O ₃ simulant.
10		Single-layer strength member with Pt-20Rh liner - no end caps - Al ₂ O ₃ simulant.
11	↓	Single-layer strength member with Pt-20Rh liner and clad - welded end caps on S.M. only - Al ₂ O ₃ simulant.
12		Single-layer strength member with Pt-20Rh liner and clad - welded end caps on S.M. only - Al ₂ O ₃ simulant.
13		Single-layer strength member with Pt-20Rh liner and clad - welded end caps on S.M. only - Al ₂ O ₃ simulant.
21	0.940 Outside Diameter	Two-layer laminated S.M. (30 mil - 9 mil gap - 55 mil) - Pt-20Rh liner - no end caps - Thoria simulant.
22	0.940 Outside Diameter	Two-layer laminated S.M. (30 mil - 9 mil gap - 55 mil) - Pt-20Rh liner - no end caps - Thoria simulant.
AHT-1 AHT-3 AHT-4 AHT-6 AHT-8 AHT-9	0.940 Dia x 0.095 $\pm$.005 ↓	Actual simulant-fueled heat source per Figure 3-23. ↓

Table 6-4. Hafnialloy Fragmentation Test Units

Specimen No.	Strength Member I.D. x Wall Thickness, inch	Description
Hf-101	0.750 x 0.087	Single-layer S.M. - No end caps - Al_2O_3 Simulant
Hf-102	0.750 x 0.097	Single-layer S.M. - No end caps - Al_2O_3 Simulant
Hf-17B	0.750 x 0.110	Actual simulant - fueled heat source per Figure 3-26.
Hf-15A	0.750 x 0.110	Actual simulant - fueled heat source per Figure 3-26.
Hf-12A	0.750 x 0.127	Actual simulant - fueled heat source per Figure 3-26.
Hf-12B	0.750 x 0.127	Actual simulant - fueled heat source per Figure 3-26.

6.2.2 Procedure

6.2.2.1 30-06 Rifle Tests

IMR 4198 powder was used in all the 30-06 rifle tests. This powder was different from that used in previous tests (Reference 4) and was chosen to obtain more reproducible velocities in the velocity range of interest. A set of calibration tests was performed. In calibrating the facility, each round was fired through the vacuum chamber and chronograph assembly, and the time of flight through the chronograph was measured. The velocities at a distance of approximately 10 feet from the end of the gun varied from 1200 ft/sec to 2410 ft/sec for charges of 14 grains to 38 grains, respectively. Duplicate shots varied by less than ± 15 ft/sec throughout this range, and the velocity was linear with charge size, as shown in Figure 6-15. This velocity/charge correlation was then used in the actual heat source tests; that is, the velocity was determined by weighing the powder charge and using the calibration curve of Figure 6-15. Aiming accuracy was found to be quite good. The 0.308-inch diameter bullets repeatedly fired to impact within a 1/2-inch diameter area.

Figure 6-11. Ballistic Impact Test Cell

Figure 6-12. Ballistic Impact Test Instrumentation

Figure 6-13. Ballistic Impact Heater Assembly

Figure 6-14. 45-Caliber Test Facility

Figure 6-15. 30-06 Bullet Velocity and Energy vs. Powder Charge

In performing the ballistic impact tests, the test specimen was located in the specimen holder, a thermocouple was attached to it, the electrical heater was placed around the specimen, and the test cell was sealed. To avoid oxidation of the specimens at elevated temperatures, an inert cell atmosphere was introduced prior to heating the specimens to the final test temperature. The test chamber was evacuated to less than 5 mm of mercury and electrical power was supplied to the heater. When the specimen temperature reached between 200° and 450°F, the cell was flooded with argon to approximately 770 mm of mercury, and the heater power was slowly increased until the specimen temperature reached 1650°F. The heater was then moved aside by a pull wire, and within 3 seconds the gun was fired. At the time of firing the specimen temperature was approximately 1565°F. Automatic ejection of the spent shell caused the argon pressure in the test cell to decay to 760 mm, and eventually air back-diffused through the gun into the test cell. In most tests, the cell door was opened before the specimen completely cooled and some oxidation of the specimens occurred. The small amount of oxidation, however, had no effect on the specimens except for surface discoloration.

6.2.2.2 45-Caliber Tests

No velocity calibration for the 45-caliber tests was required since standard bullets were fired at the heat sources point blank. The heat source was located in the specimen holder and heated in air using the same heater as used in the 30-06 tests. Although some slight oxidation of the T-111 and Hafnialloy components could occur when tested in air, this oxidation was negligible and did not affect the results of the tests. Again, the heater was remotely removed and the gun was fired (also remotely). Temperature of the test units at time of firing was 1565°F $\pm$ 10°F.

6.2.3 Results

6.2.3.1 30-06 Rifle Tests

The results of the 30-06 rifle bullet tests are summarized in Tables 6-5 to 6-7. Table 6-5 contains checkout test data generated prior to committing heat sources to test. These units, as indicated above, were not test heat sources but rather simple dummies configured to simulate the heat sources.

Table 6-5. 30-06 Fragmentation Checkout Tests

Specimen No.	Bullet Energy ft-lb	Velocity ft/sec	Orientation	Remarks
1	1950	2180	Side-On	Failed
2	1950	2180	Side-On	Room Temperature test - Failed
3	1950	2180	Side-On	Failed
4	1300	1790	Side-On	Failed
5	1300	1790	Side-On	Failed
6	1300	1790	Side-On	Room Temperature test - Passed
7	580	1190	Side-On	Passed
8	580	1190	Side-On	Passed
9	680	1300	Side-On	Passed
10	780	1400	Side-On	Marginal
11	1000	1550	Side-On	Failed
12	900	1500	Side-On	Failed
13	780	1400	Side-On	Failed but marginal
Hf-101	680	1300	Side-On	Failed
Hf-102	580	1190	Side-On	Passed

Table 6-6. 30-06 Fragmentation Tests

Specimen No.	Bullet Energy ft-lb	Velocity ft/sec	Orientation	Results
AHT-8	1000	1600	Side-On	Failed
AHT-9	780	1400	Side-On	Passed
AHT-3	1950	2180	Side-On @ 45° to Axis	Failed
AHT-6	1950	2180	Side-On 1/4" off G (glancing blow)	Failed
AHT-4	2900	2700	Side-On	Mock-up of body and engine using beef steak and 40-mil stainless steel sheet. Heat source failed.
Hf-17B	680	1300	Side-On	Failed - marginal
Hf-12A	680	1300	Side-On	Passed
Hf-12A-R	780	1400	Side-On	Retest of above item - rotated test item 90° - failed - not a valid test
Hf-15A	680	1300	End-On direct hit on PRD	Failed - sheared through thin section at PRD weld

Table 6-7. Supplemental 30-06 Tests

Speciment No.	Type	Bullet Energy ft-lb	Velocity ft/sec	Orientation	Results
21	2-layer	680	1300	Side-On	Inner layer of S.M. survived
22	2-layer	1000	1550	Side-On	Both S.M. layers failed

Impact of these dummy units with 30-06 bullets immediately indicated that the 2000 ft-lb survivability criterion established for the heat sources would not be met. Failures of these units at 1565°F occurred at energies as low as 800 ft-lb (1400 ft/sec). At room temperature, however, a T-111 strength member containing a liner and alumina simulant survived a 1300 ft-lb (1790 ft/sec) impact. A Hafnialloy dummy unit failed on side-on bullet impact at 680 ft-lb (1300 ft/sec).

Baseline Design Tests - Based on the above results it was decided to modify the original test plan and test some of the heat sources at lower energy levels to determine what energy they could actually survive. Heat source failure was obtained at an impact energy of 1000 ft-lb (1550 ft/sec), as seen in Figure 6-16 for unit AHT-8. The clad peeled back from the impact point and the bullet penetrated all three heat source layers. No great deformation of the heat source occurred, however. Some of the fuel simulant was shattered and spilled out of the heat source. Impact of unit AHT-9 at 780 ft-lb (1400 ft/sec) caused the clad to be ripped off the heat source, but the strength member remained intact (Figure 6-17). Some small surface cracks were noticed in the dent of the strength member, but a helium leak check indicated the unit to be intact. This heat source (AHT-9) was subsequently tested in the post-accident oxidation environment, as described in Section 6.5.

Since most accident situations will lead to impact at an angle or to a glancing-blow impact, two additional heat sources were tested under such conditions at the energy level prescribed by the fragmentation criterion. Heat sources AHT-3 and AHT-6 were impacted at 1950 ft-lb (2180 ft/sec) at 45° to the heat source axis and with a glancing blow 1/4 inch off the center-line, respectively. Again, the bullets penetrated all three heat source layers crushing and spilling the fuel simulant. The hole in unit AHT-6

AHT-8

Figure 6-16. Unit AHT-8 following 30-06 bullet
Impact at 1000 ft-lb (1550 ft/sec)

Figure 6-17. Unit AHT-9 following 30-06 bullet
Impact at 780 ft-lb (1400 ft/sec)

(glancing blow off center) was considerably larger and more oval than the hole in unit AHT-3 (45° impact). Consequently most of the fuel simulant spilled from unit AHT-6. These two units are shown in Figures 6-18 and 6-19, respectively.

Finally, to determine the effect of the human body and the thermal converter system on heat source survivability, one heat source was tested in a simulated body/converter system at full bullet energy - 2900 ft-lb (2700 ft/sec). Since heat source failure was already known to occur at energy levels as low as 1000 ft-lb (1550 ft/sec), failure in this case was probable, though the extent was unknown. A one-inch thick beef steak and a 0.040-inch thick stainless steel sheet were used in the mock-up. Heat source AHT-4 and the body/converter mock-up are shown in Figure 6-20 in the post-test condition. Failure of the heat source was similar to that of unit AHT-6. A large oval hole was created through all three layers of the heat source, the heat source bulged appreciably in the failure zone, and most of the fuel simulant spilled out of the unit.

Hafnialloy Tests. Three side-on 30-06 bullet impact tests were performed on two Hafnialloy heat sources. Unit Hf-17B, 0.110-inch thick, was impacted at 680 ft-lb (1300 ft/sec). Although the heat source failed, the failure was considered marginal. Penetration of the Hafnialloy occurred, as seen in Figure 6-21, but the penetrating hole was small and very little thorium fuel simulant was lost. Unit Hf-12A, which was 0.127-inch thick, was impacted at the same energy and passed. Slight surface cracks were noted in the impact area, Figure 6-22, but these did not penetrate into the interior of the heat source. The same unit was turned 90° and impacted again at 780 ft-lb (1400 ft/sec). Failure occurred. Since the fuel simulant had been crushed in the first test and since deformation of the Hafnialloy had already occurred, this test is considered questionable.

The last 30-06 heat source bullet test was conducted on unit Hf-15A, end-on, at 680 ft-lb (1300 ft/sec). The wall thickness of this unit was 0.110 inch. Impact occurred dead center on the PRD. The bullet sheared the PRD weld and drove the PRD into the fuel simulant, as shown in Figure 6-23. As discussed in Section 4.4.2, the PRD/end cap weld had a penetration of approximately 75%. Thus the weld wall thickness was effectively only 0.75×0.110 or 0.082 inch.

Figure 6-18. 30-06 Bullet Impact at 45° to Axis

Figure 6-19. Glancing Blow Off-Center by 30-06 Bullet

Figure 6-20. Simulated Body/Converter Test

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Figure 6-21. Unit Hf-17B following 30-06 Bullet Impact at 680 ft-lb (1300 ft/sec)

Figure 6-22. Unit Hf-12A following 30-06 Bullet Impact at 680 ft-lb (1300 ft/sec)

Figure 6-23. Unit Hf-15A following End-On Bullet Impact at 680 ft-lb (1300 ft/sec)

Supplemental Tests. Two additional tests were conducted in an attempt to determine how the heat source could be modified to survive higher energy bullet impact and meet the 2000 ft-lb fragmentation criterion. Military armament studies have shown that the penetrating ability of bullets can be reduced by using laminated materials. Such construction allows succeeding layers to flatten the bullet core and distributes the energy over a larger target area. An attempt was made to study this phenomenon using a two-layer T-111 strength member (specimens 21 and 22). In these units the total material wall thickness was reduced by approximately 10 percent from the thickness used in the baseline design. The results are given in Table 6-7. Only the outer 0.030-inch member failed on 680 ft-lb (1300 ft/sec) impact, but both inner and outer layers failed on 1000 ft-lb (1550 ft/sec) impact. A comparison of the failure of unit 22 with the failures experienced in units 11 and AHT-8, all tested at 1000 ft-lb energy, indicates the severity of the failure to have been reduced by the laminated construction. Further tests are, of course, required to establish the usefulness of such layered construction in improving ballistic impact resistance.

6.2.3.2 45-Caliber Tests

Test unit AHT-1 was tested point-blank with a 45-caliber bullet. This heat source was fueled with alumina simulant and had previously been tested for two hours in a 2500°F fire. The heat source appeared to be in excellent condition at the end of the fire test (Section 6.4). The heat source following the 45-caliber impact test is shown in Figure 6-24. Although dented, the heat source was intact. Not even the clad was penetrated. A standard 45-caliber shot has an energy of 370 ft-lb. Based on the results of the 30-06 rifle tests, a high margin of survivability was expected in this test.

Hafnialloy test unit Hf-12B was tested in a similar manner. The heat source following the test is shown in Figure 6-25. This unit was 0.127 inch thick and, as seen in the figure, sustained very little damage. Oxidation of the unit occurred since it was heated in air, but the material remained ductile.

6.2.4 Conclusions

The requirement for the test heat source to survive ballistic impact of a 30-06 bullet at an energy of 2000 ft-lb (2210 ft/sec), cannot

Figure 6-24. Heat Source AHT-1 following a 45-caliber Impact Test

Figure 6-25. Hafnialloy Heat Source Hf-12B following 45-caliber Test

be met without design modification. The maximum survival energy for the baseline design was found to be approximately 900 ft-lb (1500 ft/sec). The Hafnialloy test units had a wall thickness somewhat thinner than desired and consequently the survival energy was lower. The survival energies for the Hafnialloy units were 650 ft-lb (1270 ft/sec) and 800 ft-lb (1420 ft/sec) for the 0.110- and 0.127-inch wall thicknesses, respectively. Excellent survivability of both designs was demonstrated for the 45-caliber impact.

The discrepancy between the expected wall thickness required to survive 30-06 impact at 2000 ft-lb and the actual thickness required is obviously due to the oversimplifying assumptions made in correlating earlier ballistic impact data (Section 3.3.2). It had been assumed that survival energy varies linearly with wall thickness and that the variation of the survival energy with diameter is independent of temperature and material. One or more of these assumptions may be in error. Further testing is required to enable prediction of ballistic impact survivability.

The requirement to survive a direct hit by a 180-grain, 30-06 rifle bullet travelling with an energy of 2000 ft-lb must also be reviewed. A redesign of the heat source to survive bullet impact may be required. As has been amply demonstrated in the design of armor plate, a multi-layered material withstands bullet impact more readily than a single-layered material of the same thickness. Multi-layered designs incorporating metallic and ceramic structures should therefore be further investigated.

6.3 CRUSH TESTS

The purpose of this test series was to determine the survivability of the artificial heart heat source while resting on concrete under a 5000-pound crushing load. Two tests were performed with the load applied in the axial direction (end-on) and in the radial direction (side-on), respectively.

6.3.1 Test Specimens and Equipment

6.3.1.1 Test Specimens

There were two types of test specimens used in this test series: checkout specimens and test heat sources. The checkout specimens were merely steel bars of the same length and diameter as the heat sources. The test units were simulant fueled (thoria) baseline design heat sources.

6.3.1.2 Equipment and Instrumentation

The heat source crush tests were performed on a Research Incorporated programmable universal testing machine, shown in Figure 6-26. This machine is capable of operating under loads up to 40,000 pounds applied at loading rates ranging from 500 lb/min to 25,000 lb/sec or strain rates ranging from 0.050 inch/min to 5 inches/sec. The applied load was measured to ± 0.2 percent.

A concrete block was mounted to the upper platten of the test machine, and the test item was pressed against it. The concrete block, 12 by 18 by 18 inches, was constructed to simulate a typical freeway roadbed. The ASTM specifications for concrete construction were extremely difficult to interpret and did not specify what ingredients to use. The composition and construction details were, therefore, obtained from the California Department of Highways' Materials Laboratory. Table 6-8 lists the recommended and actual compositions of the concrete block estimated to have a compressive strength of 4000 psi. Two days after the concrete was poured, the plywood form was removed. The top and four sides of the block were kept moist for 10 days after pouring, as recommended by the California Department of Highways' Materials Laboratory. The slight variation between the recommended and actual composition of the concrete block is well within construction tolerances to provide the 4000 psi compressive strength of a freeway roadbed.

The heat sources were heated to the test temperature using a clamshell heater. Each specimen was located in a hollowed-out firebrick which held the specimen and positioned the clamshell heater around it. The insulation surrounding the heat sources prevented them from cooling off too rapidly after removal of the heater. The insulation did not interfere with the test since it broke and fell away as soon as contact with the concrete was made. Each sample had a Pt-10Rh thermocouple welded to it which was attached to a strip chart recorder. Compressive loads were also recorded on a recorder.

6.3.2 Test Procedure

The checkout specimens were used in the initial tests to check fits, handling sequences, heating procedures, and load programs prior to testing

Figure 6-26. Crush Test Set-Up

Figure 6-27. Crush Test - Heater Installed

Table 6-8. Concrete Block Composition

Item	Description (Mesh Size)	Composition Weight (lbs)		Remarks
		Recommended	Actual	
#2 Aggregate	1-1/2 inch $\rightarrow$ 1 inch	154	132	Ingredients obtained from California Highway Department Materials Laboratory
#3 Aggregate	1 inch $\rightarrow$ 1/2 inch	76	76	
Sand	1/4 inch $\rightarrow$ Fines	154	142	
Cement		50 - 60	51	Commercial purchase of Type II, low alkali cement
Water		50 - 50	50	

test units. The two heat source tests were conducted in the same manner, one in the end-on and the other in the side-on mode.

Each test unit, with thermocouple attached, was placed in the firebrick holder located on the lower platten of the test machine. The lower platten was raised until the test unit made light contact with the concrete block. Caution was taken to ensure that the test unit did not make contact in a region of the concrete block damaged by previous tests. The position of the lower platten was nulled out on the console, so that the loading program would begin when the unit was returned to this height. The lower platten was then lowered and the heater was placed around the test unit (see Figure 6-27). Electrical power was provided to the heater and the test unit temperature was monitored. The temperature was maintained between 1700° and 1750°F to allow internal components of the heat source to reach temperature. When a temperature of 1760°F was reached, the heater was removed, the lower platten was brought up to its nulled position, at which time the test unit made contact with the concrete block, and the load of 5000 pounds was applied. From the time the heater was removed until the full load of 5000 pounds was reached, the elapsed time was 15 ± 2 seconds. Test unit temperature was $1600 \pm 20^\circ\text{F}$ at the time of initial loading, and $1560 \pm 20^\circ\text{F}$ when the load reached 5000 pounds 7.5 seconds later. The load was maintained at 5000 pounds for three minutes and then reduced to zero. The test unit was then removed and examined.

6.3.3 Results

Typical temperature and load-time profiles are shown in Figures 6-28 and 6-29, respectively. Photographs of unit AHT-12 just before testing and of unit AHT-7 just after testing are shown in Figures 6-30 and 6-31, respectively. As can be seen in Figure 6-31, the porous firebrick crushed under the applied load and fell away, allowing the heat source to bear the full 5000-lb load. A post-test photograph of the two test units is presented in Figure 6-32. Both units were in excellent condition at the end of the test. Very slight deformation in the clad could be seen in the areas of contact, but no visible breaches occurred. Upon helium leak checking these units, it was determined that unit AHT-7 had a very small leak at one end of the crushed clad. In this area the outline of the strength member could be barely ascertained. The sharp corner of the strength member end cap had obviously penetrated the thin clad under the 5000-lb crushing load.

6.3.4 Conclusions

The crush tests indicated that the heat source is capable of surviving end-on and side-on crushing loads in excess of 5000 pounds. Due to the excellent condition of the units following the tests it was decided not to section them but rather to use them at some later date for additional static crush or dynamic crush tests. As indicated in Section 4.1.2 above, no Hafnialloy heat sources were tested under crushing loads. Based on the excellent results obtained for the baseline design, however, it is believed that the Hafnialloy units would survive a similar environment.

6.4 FIRE TESTS

Fire tests were conducted to demonstrate the capability of the heat source to withstand a severe fire environment. As indicated in Section 3.1.4 above, the National Fire Protection Association has defined a standard time-temperature fire curve which includes temperatures as high as 2300°F (Reference 22). The standard fire curve is shown in Figure 6-33. In view of the importance of not releasing radioactive fuel in a fire environment, however, a temperature of 2500°F for two hours had been selected for the fire-survival criterion. Four heat sources (two baseline design and two Hafnialloy units) were tested. One each of the baseline and Hafnialloy

Figure 6-28. Crush Test Specimen Temperature Vs Time

Figure 6-29. Crush Test Load Vs Time

Figure 6-30. Unit AHT-12 before Crush Test

Figure 6-31. Unit AHT-7 after Crush Test

Figure 6-32. Crush Test Units After Test

Figure 6-33. Standard Time - Temperature Fire Curve

units was quenched in water following the 2-hour, 2500°F exposure. All of the heat sources survived remarkably well.

6.4.1 Test Specimens and Equipment

Four simulant fueled heat sources were fire tested as noted in Table 6-9. Since there was no need to simulate the mechanical properties of the fuel in these tests, alumina simulant was used in both the baseline and Hafnialloy heat sources.

Table 6-9. Fire Test Matrix

Heat Source S/N	Temperature		Quench 70°F Water	Orientation
	1565°F/1 hr.	2500°F/2 hrs.		
AHT-1	X	X		Vertical
AHT-2	X	X	X	Horizontal
Hf-5B	X	X		Horizontal
Hf-18B	X	X	X	Horizontal

The heat sources were tested in a Keith high temperature gas furnace having a capability of 3000°F operation in a furnace hot zone of 14 x 14 x 14 inches. For redundancy, two sets of Pt-10Rh thermocouples were attached to each heat source tested. A Leeds and Northrup and a Hewlett-Packard recorder were used to monitor the temperature of the heat sources. The test facility is shown in Figure 6-34.

6.4.2 Test Procedure

Operation of the furnace and temperature monitoring instrumentation was checked out prior to testing of actual test items. Two sets of Pt-10Rh thermocouples were attached to each heat source and connected to the recorders. Each test heat source was in turn placed on a high purity alumina fire brick within the furnace hot zone. Orientation of the heat sources in the four tests is noted in Table 6-9. The front opening of furnace was partially covered with fire bricks and the furnace was started. The temperature of the test unit was raised to 1565°F and maintained for one hour. The front of the furnace was then completely closed off to prevent excessive

Figure 6-34. Fire Test Facility

heat losses, and the temperature was raised to 2500°F and maintained for two hours. The furnace was then shut off. Two of the units were removed and quenched in 70°F water. The recorder chart speed was increased prior to quenching to more readily record transient temperature data. When cool, the test units were removed from the test area, weighed, and visually inspected, and one unit of each design was disassembled for inspection.

6.4.3 Results

Heat source AHT-1 was placed in the furnace in a vertical position. One hour after the furnace was shut off, the heat source was removed and allowed to cool to room temperature. The heat source survived the fire test without any visible damage or discoloration, as shown in Figure 6-35. Movement of internal components indicated that no internal damage had occurred either. Since no damage had occurred and since a second unit was available for detailed disassembly and analysis, it was decided to relegate this unit to the 45-caliber ballistic impact tests described above.

The second baseline design heat source (AHT-2) was placed in the furnace in a horizontal position. Upon removal from the furnace after cooldown the heat source showed no damage or discoloration. To determine the effect of quenching the heat source from a high temperature, the heat source was reheated to 2500°F in a Burrell resistance furnace, removed while hot, and quenched in a bucket of water. The temperature at which the capsule entered the water was approximately 1900°F. The capsule surface temperature, as indicated by a Pt-10Rh thermocouple attached to the outer surface, immediately dropped to the temperature of the water. Heat source internal temperatures could not be monitored during the quenching sequence. The heat source sustained absolutely no visible damage. Heat source AHT-2 was sectioned circumferentially at the midplane and disassembled without any difficulty. Visual examination of the internal surfaces did not reveal any damage. All of the external and internal surfaces appeared to be in the as-assembled condition and did not appear to have been affected by the high temperature fire or quenching environments. A post-test photo is shown in Figure 6-36.

Testing of the first Hafnialloy heat source (Hf-5B) under the same fire conditions resulted in the deformation of the heat source wall onto the alumina fuel simulant, as shown in Figure 6-37. The final assembly weld on all of

Figure 6-35. Heat Source AHT-1 After Fire Test

Figure 6-36. Heat Source AHT-2 Disassembly

Figure 6-37. Deformed Heat Source Hf-5B

Figure 6-38. Heat Source Hf-5B Disassembled

the test heat sources was performed by an electron beam welder, thus resulting in a vacuum within the capsule. At the maximum test temperature of 2500°F the atmospheric pressure differential was sufficient to deform the heat source as noted above. Although the surface of the unit was blackened due to slight oxidation, the heat source was completely intact. This heat source was also sectioned circumferentially at the midplane. Visual examination confirmed that the heat source wall had deformed around the fuel simulant. The area of contact was over approximately 180° of the circumference of the fuel simulant, as shown in Figure 6-38.

A 0.040-inch diameter hole was drilled through one end cap of the second Hafnialloy heat source tested (Hf-18B) to eliminate the pressure differential during the test. This hole simulated the PRD which in a real heat source would allow pressures to equalize. This heat source is shown in Figure 6-39 prior to the test. The two Pt-Rh thermocouples were held in position by the Pt-Rh straps as shown to facilitate handling of the capsule in transferring it from the furnace to the water container during the quenching operation. Following the 2500°F exposure, this unit was removed from the furnace at a temperature of approximately 1800°F and quenched in water. As with unit Hf-5B, this unit was blackened due to slight oxidation, but remained completely intact as shown in Figure 6-40. The heat source wall did not deform during this test.

6.4.4 Conclusions

All of the tested heat sources survived the fire environment very well. The baseline design units appeared to be in the as-assembled condition after the test. The Hafnialloy units were slightly oxidized but totally integral. The test series revealed that the severe fire environment at temperatures of 2500°F and the subsequent thermal shock encountered during the quenching operation had no deleterious effects on the fuel retention capability of the heat sources.

6.5 POST-ACCIDENT OXIDATION TESTS

The purpose of the post-accident oxidation tests was to evaluate the fuel containment capability of the heat source in post-accident environments. The steady state heat source temperature in such an environment depends on the heat source power loading and size and on the particular environment in

Figure 6-39. Fire Unit Hf-18B Prior to Test

Figure 6-40. Hafn alloy Unit Hf-18B After Test

which it is placed. Analyses have indicated that the temperature of the artificial heart heat source suspended in still air would be approximately 800°F. When placed on the ground, the insulation afforded by the soil would raise the heat source temperature to approximately 900°F. The most severe thermal environment would result when the heat source is partially, or fully, buried in low conductivity soil. Since the temperature of the heat source is directly proportional to the conductivity of the soil, and since the latter varies by an order of magnitude depending on the type of soil in question,* burial temperatures are extremely difficult to predict. Based on the abundance of the various soils over the world, a value of 0.32 Btu/hr-ft°F was arbitrarily selected for the thermal conductivity. Two different analyses for the temperature of a heat source buried to a depth of 6 inches in such soil resulted in heat source surface temperatures of 600°F and 1300°F (Appendix D). Since neither of the analyses was precise for the small artificial heart heat source, conservative values of 1000° and 1300°F were selected for the post-accident oxidation test temperatures.

Three heat sources were heated to the above temperatures and held in a slow moving stream of air for a period of 60 days. The test units were partially buried in Ottawa sand which is essentially pure quartz and constitutes 60 percent of the earth's crust.

6.5.1 Test Specimens and Equipment

6.5.1.1 Test Specimens

Three heat sources were used in these tests. Two of the heat sources (AHT-9 and AHT-11) were of the baseline design and had previously been subjected to fragmentation and impact testing, respectively; the third heat source was of the Hafn alloy design (Hf-16B) and had previously been subjected to impact testing. Heat source AHT-9 survived bullet impact at 1400 ft/sec. The clad was ripped off by the impact of the bullet as described in Section 6.2 and shown in Figure 6-17. Heat sources AHT-11 and Hf-16B had been impacted, broadside and end-on, respectively, at 1565°F against granite,

*At 1200°F, the conductivities for diatomaceous earth and granitic detrital soils are 0.0465 and 0.465 Btu/hr ft°F, respectively.

as described in Section 6.1. Post-impact views of these units are shown in Figures 6-41 and 6-42, respectively. Since heat source AHT-11 survived the previous impact test intact, a 0.040-inch diameter hole was drilled through the clad to simulate a post-impact breach, as shown in Figure 6-41. A similar hole was drilled in the end cap of the Hafnialloy unit to simulate the PRD and allow pressure equilization.

6.5.1.2 Equipment and Instrumentation

The tests were conducted in the TRW Heat Source Laboratory. The test setup is shown schematically and pictorially in Figures 6-43 and 6-44, respectively. All units were tested at the same time.

The soil and the heat sources were placed inside stainless steel pipes, which in turn were enclosed by clamshell heaters and insulating bricks. Two 3-inch diameter pipes were fitted with flanged view ports at each end to facilitate sighting of the test units. An air inlet tube was welded to one end of the pipe and an air exhaust tube leading to a hood was welded to the other end. Absolute filters were placed in each of the lines to assure personnel safety should the thoria fuel simulant be released within the test tube. Air flow meters were also installed in each of the lines to monitor the air flow rate. The entire assembly was placed in a hood for additional safety in case of failure and release of thoria.

A chromel/alumel thermocouple was inserted through the center of each stainless tube immediately adjacent to each test unit. Temperature readings were continually monitored and controlled with Hewlett Packard recorders. In addition, a secondary check was made daily utilizing a Leeds and Northrup potentiometer. Temperatures were measured to $\pm 10^{\circ}\text{F}$.

6.5.2 Test Procedure

The front flanged view port of each tube was initially removed and the bottom of each tube was filled to approximately a 1-inch depth with Ottawa sand. The test units were partially buried in the sand and the view ports replaced and sealed with a high temperature gasket. Air flow was set at $60 \text{ ft}^3/\text{hr}$.

Heat sources AHT-11 and Hf-16B were placed in a single furnace tube and heated to 1300°F . Heat source AHT-9 was placed in a separate furnace

Figure 6-41. Heat Source AHT-11 Following Granite Impact Test

Figure 6-42. Heat Source Hf-16B Following Granite Impact Test

Figure 6-43. Schematic of Test Set-up

Figure 6-44. Post-Accident Oxidation Test Equipment

tube and heated to 1000°F. The Hewlett Packard recorder/controllers were used to continuously monitor and control the two temperatures.

6.5.3 Test Results

6.5.3.1 Heat Source Oxidation

Due to equipment malfunction, the 1300°F furnace operated at 1550°F for several hours during the first night of operation. The equipment was repaired and the temperature readjusted to 1300°F. During the first 24 hours of operation heat source AHT-11 in this furnace oxidized extensively. Within a 72-hour period the heat source continued to oxidize and the volumetric expansion of the refractory metal oxide caused the heat source clad to burst allowing the oxide to spill over the sides and ends of the heat source as shown in Figure 6-45. After seven days of operation all of the refractory metal within this heat source appeared to have been completely oxidized.

Heat source AHT-9, operating at 1000°F, did not show any significant signs of oxidation until after approximately 80 hours of testing. The oxidation increased until gross volumetric expansion occurred on the 12th day of testing, causing the oxide to spill over the sides of the heat source. After 21 days of testing the refractory metal member seemed to be completely oxidized. No pictures of this unit were taken during the actual test due to the low test temperature and the resulting poor lighting conditions within the test tube.

Due to the extensive and rapid oxidation of unit AHT-11, all view of the Hafn alloy unit behind it was obscured. Since the tantalum strength member of the baseline design unit seemed to be completely oxidized it was decided to reverse the tube so as to bring the Hafn alloy unit into view. The test furnace was shut down after 31 days of operation and allowed to cool. The tube containing the two heat sources was then reversed so that the Hafn alloy unit came into view, and the temperature was returned back to 1300°F. At this time the Hafn alloy heat source appeared to be in a remarkably good condition as there appeared to be only a slight oxide film on the surface.

A photograph was taken of heat sources Hf-16B and AHT-11 on the 59th day of testing, as shown in Figure 6-46. Heat source Hf-16B in the foreground appeared to be integral and in excellent condition as noted

Figure 6-45. Heat Source AHT-11 After Two Days at 1300°F

Figure 6-46. Hafnialloy Heat Source Hf-16B (front) and Heat Source AHT-11 (back) after 59 days at 1300°F

above. The clad of heat source AHT-11, which had expanded and subsequently burst as a result of the volumetric expansion of the T-111 oxide, is shown in the rear of this photo. The chromel-alumel thermocouple is also shown in this photo as indicated.

After sixty days of testing the test furnaces were shut down and allowed to cool.

6.5.3.2 Post-Test Examination

A radiological check of the capsule surfaces and the inside of the furnace tubes subsequent to termination of the post-accident oxidation test revealed that there had been no detectable fuel simulant release.

Heat source Hf-16B survived the post-accident environment in excellent condition, as seen in Figure 6-47. The impacted end appeared to have an oxide scale approximately 0.002-inch thick. In addition, the two cracks observed in Figure 6-42 in the area of the PRD, increased in size slightly to approximately 1/4-inch and 3/8-inch long by 0.010 inch deep. Some scale was also evident in the cylindrical portion adjacent to the impacted end, but the rest of the heat source outer surface was relatively free of any oxide scale. The 0.040-inch hole in the end cap was intentionally plugged and the heat source was helium leak checked. The Hafnialloy heat source was completely integral and indicated no helium leaks.

Heat source AHT-11, when removed from the test furnace, revealed the ruptured clad, the completely oxidized strength member, and the liner (Figure 6-48). The liner was completely integral, as verified by a helium leak test, but the impacted surface had a pronounced deformation, as seen in Figure 6-48. Since the original heat source (Figure 6-41) did not have a similar deformation, the bulge along the impacted surface could not have been caused by an imperfection in the granite impact surface. It is postulated that the liner deformation occurred when the fractured, hard, and relatively rigid, fuel simulant reacted against the ductile liner during the granite impact test. The heat source was disassembled to examine the inside of the liner and the fuel simulant in the impacted area. The end of the liner was first sectioned circumferentially approximately 1/2-inch from the end to reveal the PRD. The remainder of the unit was then sectioned longitudinally so as to reveal the inside area of the impacted liner. This

Figure 6-47. Hafnialloy Heat Source Hf-16B After 60 Days at 1300°F

unit is shown in Figure 6-49. The PRD showed very little damage and the inlet hole was clear of any fuel simulant. The deformation of the liner which resulted from the ballistic impact test can be seen.

Heat source AHT-9 is shown in Figure 6-50 after removal from the test furnace. The photos reveal the heat source as removed and also the liner after its removal from the ruptured clad. The deformation of the liner, which resulted in the ballistic impact test, can be seen. Integrity of the liner was verified by helium leak checking it using the bomb technique.

6.5.4 Conclusions

The rate of oxidation of the T-111 strength member within the baseline design heat source is a very strong function of temperature. Although the T-111 strength member of heat source AHT-9 was greatly exposed (Figure 6-17) as a result of the fragmentation test, it oxidized much more slowly at 1000°F than did the strength member of heat source AHT-11 which only had an area 0.040 inch in diameter exposed to air at a higher temperature.

(a) As removed from furnace

(b) Heat source liner

Figure 6-48. Heat Source AHT-11 After 60 Days at 1300°F

Figure 6-49. AHT-11 Liner Following Disassembly

Figure 6-50. Heat Source AHT-9 After 60 Days at 1000°F

The volumetric expansion of the T-111 upon oxidation is so great that the stress generated in the Pt-20Rh clad exceeds the ultimate strength of the material and failure of the clad occurs. This is the phenomenon previously observed in similar tests of the Transit heat source. To avoid release of the radioactive fuel in a post-accident environment using a refractory alloy strength member/noble metal clad system, a liner which will remain integral in an oxidizing environment must be used.

The Hafnialloy heat source demonstrated excellent resistance to oxidation in surviving the test. It was noted that the oxidation of the outer surfaces was slightly greater at the impacted end. This was probably due to the microcracks and stress areas generated in this area as a result of the impact forces. These small cracks would have allowed the flowing air to penetrate slightly deeper than in other areas. However, after 60 days at 1300°F the single-layer heat source was completely integral and in excellent condition.

7. CONCLUSIONS

Early analyses had indicated that a vented radioisotope heat source was considerably smaller and lighter than a non-vented one. Detailed parametric analyses of vented heat sources were therefore performed to arrive at a heat source optimized in weight, volume, and safety. The top rated system was determined to be a single-layer Hafn alloy heat source. Due to the limited mechanical property, compatibility, and heat source test data available for Hafn alloy, however, this system was not selected as the baseline design. Hafn alloy heat sources were, however, fabricated and tested in order to evaluate this alloy for future application. The baseline design was a three-layer system having a Pt-20Rh liner, T-111 strength member, and a Pt-20Rh clad. A pressure relief device/capillary assembly was connected between the noble metal liner and clad to allow venting of the helium gas generated by fuel decay and also allow decay of the generated radon-220 gas to acceptable levels.

In this design, the only component subject to contamination was the T-111 strength member. Since this component was sealed within the liner/clad assembly, contamination by either the fuel or external atmosphere was not possible. Should rupture of the clad occur during an abort environment, oxidation of the T-111 strength member would occur rapidly but fuel containment would be assured by the noble metal liner. Some interactions between the liner and the fuel, T-111, and air may follow eventually. The temperature of the heat source in air is approximately 800°F. Assuming partial burial, heat source temperatures of 1000 to 1300°F are reasonable. At these temperatures, interactions of Pt-20Rh with other materials and oxidation are so slow that a 0.020-inch liner will contain the fuel for at least 1000 years (in excess of ten half-lives). It is important to note, though, that the temperature of the heat source will drop with time as the power of the fuel diminishes due to decay. Since oxidation and material interactions are extremely sensitive to temperature, a considerable amount of conservatism is built into the design.

Safety design verification tests indicated both the baseline and Hafn alloy designs survive all accident environments except one with

containment of the fuel simulant in at least one totally integral capsule component. Neither design was capable of containing the fuel simulant under a 2000 ft-lb 30-06 rifle bullet impact. Data available on the design of armor plate indicate that laminated or multi-layered materials, consisting of either metal-metal or metal-ceramic layers, have vastly improved ballistic impact properties. Further studies in this area as related to heat source design are required.

The following areas relating to the design of the radioisotope heat source for an artificial heart device are recommended for further study:

- The requirement to survive a 2000 ft-lb impact by a 30-06 rifle bullet must be reviewed. If found applicable the design of the heat source must be modified to meet this requirement. As mentioned above, data obtained in the design of armor plate indicate that multi-layered construction improves the properties of a structure in ballistic impact. Further study in this area, as it relates to heat source design, is required.
- Static crush tests have indicated the heat source to survive a 5000-lb crushing load while resting on concrete. The behavior of the heat source under dynamic crush environments, such as being hit by a large heavy object or by a slow-moving sharp, heavy object, needs to be investigated.
- No data exist on the compatibility of electrorefined plutonium-238 oxide with Pt-20Rh. The data generated with production grade stoichiometric fuel, however, indicate no interactions at temperatures up to 2190°F and times up to 360 days. No extrapolation to very long times is currently possible and should be deferred until additional long term compatibility data become available. Similar data for Hafn alloy are required.
- No data for the rates of helium and radon release from pressed and sintered PuO₂ are available. One hundred percent release of the generated gases has been assumed in the design of the heat source. Due to the very short half life of radon-220, it is especially important to determine the release rates of this gas. If sufficient decay of radon occurs within the fuel matrix, a capillary tube may not be required in the heat source.
- Some aging of T-111 at elevated temperatures has been observed under tests run for 1000 and 10,000 hours. The strength of the material has been observed to increase somewhat and its ductility to decrease. Longer term data are required to allow extrapolation to service lives in excess of 10 years, but no drastic deterioration of the properties is expected.

- The following three minor modifications are recommended for the baseline design: reduce clearances between components to eliminate or reduce rattle; increase the diameter of the tube connecting the liner to the clad to simplify final clad closure; and extend the capillary out of the heat source to enable the heat source to remain sealed until actual insertion into the artificial heart device when the capillary can be cut flush with the heat source end cap.
- Additional safety verification tests of Hafn alloy heat sources, using the improved Hafn alloy formulations, should be performed to further evaluate this alloy for artificial heart heat source applications.

8. REFERENCES

1. Part 37.150 of Federal Aviation Regulations, Volume II, "Aircraft Flight Recorder Technical Standard Order C51a".
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APPENDIX A
UPDATED HAFNALLOY PROPERTY DATA

Based on the results of the Phase I effort of the Hafnialloy Development Program,* Hf-1%Pt-0.5%Pd (Hf-105) and Hf-1.5%Pt-1.5%Pd (Hf-150) were selected for further study. Scale-up operations consisted of producing 30-to 70-pound, consumable electrode, arc-melted ingots. A total of 250 pounds of each alloy was produced. The ingots were forged at elevated temperatures to 1-1/2- to 2-inch thick sheet bars which were then rolled at elevated temperatures to sheet which ranged in thickness from 0.015 to 0.160 inch. One hundred and seventy-five pounds of Hf-105 and 170 pounds of Hf-150 high quality sheet were produced.

Elevated temperature mechanical and physical property data were generated utilizing the sheet material. These data included tensile, thermal expansion, and hemispherical emittance properties. Table A-1 summarizes the tensile properties of Hf-105 and Hf-150 alloys. The following conclusions can be drawn:

- 30-mil thick Hf-105 and Hf-150 specimens, in the as-rolled, recrystallized, and TIG welded conditions, have slightly lower yield and tensile strengths, but the same elongation, as 90-mil thick material. In addition, recrystallized Hf-105 and Hf-150 has greater ductility than as-rolled material. The ductility of Hf-105 is greater than that of Hf-150 at the lower temperatures, but the yield and ultimate tensile strengths of Hf-150 are greater than those of Hf-105.
- Above 2400°F, the alloys exhibited erratic behavior in that some samples had low strengths with high elongations, whereas others failed abruptly under no applied load as the temperature was increased. Micro-structural analyses of these specimens indicated that a hot-short behavior existed; the second phase, hafnium-noble metal inter-metallic, formed a low melting eutectic as the temperature rose above 2200 to 2400°F. This condition had not been readily foreseen because the hafnium-noble metal phase diagram had not existed.**

*"Oxidation Resistant Refractory Alloys for RTG Applications," Phase I Summary Report, TRW-A-11069-0060, October 1971.

**A reduction in the noble metal content of the alloy was found to alleviate this situation. Also the addition of small quantities of tin to the lean alloys was found to result in improved oxidation properties, as described in Section 3.5.2 of the report.

Table A-1. Tensile Properties of Hafnialloy

Alloy	Test Temp (°F)	Sample Thickness (in)	Metallurgical Condition	Yield Strength (psi)	Ultimate Tensile Strength (psi)	Elongation (%)
Hf-105	RT	0.030	As-rolled, Recrystallized and Weld Bead-on-Plate	41,800 - 49,300	62,100 - 68,200	13 - 31
		0.090	As-rolled, Recrystallized and Weld Bead-on-Plate	46,100 - 66,600	63,200 - 79,000	11 - 28
Hf-150		0.030	As-rolled, Recrystallized and Weld Bead-on-Plate	66,000 - 76,800	77,800 - 101,900	2 - 9
		0.090	As-rolled, Recrystallized and Weld Bead-on-Plate	37,900 - 89,300	65,700 - 104,100	2 - 12
Hf-105	1400	0.030	As-rolled, Recrystallized and Weld Bead-on-Plate	17,400 - 20,600	18,850 - 22,100	25 - 32
		0.090	As-rolled	28,100	31,600	33
Hf-150		0.030	As-rolled, Recrystallized and Weld Bead-on-Plate	23,700 - 26,800	27,550 - 29,400	26 - 33
Hf-150	2200	0.090	Recrystallized	2,400	5,900	63
Hf-150	2400	0.090	As-rolled and Recrystallized	875 - 1,800	1,310 - 4,100	42 - 69
Hf-105	2600	0.090	As-rolled	*	*	0
Hf-150	2600	0.090	Recrystallized	480-1120	1,800 - **	67 - **
Hf-150	2640	0.090	As-rolled	860	1,370***	56***

*Samples failed abruptly as temperature rapidly approached 2600 ± 200°F.

**Sample never failed, test halted at limit of machine cross-head travel.

***Machine cross-head traveled ~ 0.5 inch when test was terminated.

Table A-2 presents the thermal expansion data for the Hf-150 alloy. The thermal expansion of Hf-150 is lower than that of Ta-10W, T-111, Mo, TZM, Mo-50Re, and Pt-20Rh from room temperature to 1500°F, but is higher from 1500° to 2560°F. No explanation can be given at this time for the sudden significant increase in the thermal expansion of the alloy at temperatures above 1500°F.

Table A-3 gives the hemispherical emittance of Hf-105 and Hf-150 specimens whose surfaces were in the as-processed and pre-oxidized conditions. As expected, the pre-oxidized surfaces had higher hemispherical emittance values than the as-processed samples.

Table A-2. Thermal Expansion Data for Hf-150

Temperature (°F)	ΔT $T - T_0$ (°F)	Length, L_0 (inch)	$\Delta L = L - L_0$ (inch)	Thermal Expansion $\frac{\Delta L}{L_0}$ (inch $\times 10^{-3}$)	Coefficient of Thermal Expansion = in/in/°F $\times 10^{-6}$
68	0	0.50412	0	0	0
600	532	0.50473	0.00061	1.21	2.26
1200	1132	0.50551	0.00139	2.76	2.44
1500	1432	0.50587	0.00175	3.47	2.42
1800	1732	0.50923	0.00511	10.14	5.85
2100	2032	0.51155	0.00743	14.74	7.25
2400	2332	0.51235	0.00823	16.32	7.00
2560	2492	0.51235	0.00823	16.32	6.55

Table A-3. Emittance Data for Hf-105 and Hf-150

Hf-105 (As Processed)		Hf-150 (As Processed)	
Temperature (°F)	Hemispherical Emittance	Temperature (°F)	Hemispherical Emittance
1399	0.44	1401	0.57
1708	0.44	1705	0.56
2000	0.42	2000	0.53
2387	0.37		
1994	0.36		
1715	0.34		
1399	0.32		
2980	0.42		

Hf-105 (Pre-Oxidized)		Hf-150 (Pre-Oxidized)	
Temperature (°F)	Hemispherical Emittance	Temperature (°F)	Hemispherical Emittance
1387	0.79	1398	0.84
1714	0.68	1701	0.83
2019	0.64	2000	0.73
2285	0.61		
2610	0.50		

APPENDIX B

ARTIFICIAL HEART HEAT SOURCE DATA PACKAGE

For heat source assemblies HF-1, HF-2, and HF-3.

Shipping Date - January 4, 1973

1. Serial numbers of the capsule components used

<u>Component</u>	<u>Capsule Number</u>		
	<u>HF-1</u>	<u>HF-2</u>	<u>HF-3</u>
Weld Reflector Ring	10	11	12
Liner Tube	38	39	43
Liner End Cap (plain)	31	33	38
Liner End Cap (vent)	9	10	11
S.M. Tube	102	103	105
S.M. End Cap (plain)	40	41	42
S.M. End Cap (vent)	27	28	29
Clad Tube	35	44	41
Clad End Cap (plain)	41	46	43
Clad End Cap (vent)	22	41	39
Clad Capillary Assembly	16	21	20

2. Deviations were covered by the following MRB actions N001AH72 - Pt-20% Rh alloy grain size and hardness - TRW acceptance - TWX, 8/9/72.

N002AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N003AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N004AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N005AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N006AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N007AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N008AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N009AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N010AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N011AH72 - Component dimensions - TRW acceptance - TWX 10/19/72
 N012AH72 - Weld Box atmosphere - TRW acceptance - TWX 10/30/72
 N013AH72 - Capillary tube example weld - TRW acceptance - 10/25/72

3. Weight of Fueled Heat Sources.

<u>Assembly No.</u>	<u>Weight</u>
HF-1	279 grams
HF-2	278 grams
HF-3	278 grams

4. Thermal Output

<u>Assembly No.</u>	<u>Power</u>
HF-1	33.04 watts
HF-2	32.87 watts
HF-3	33.02 watts

5. Total Neutron Emission Rate

<u>Assembly No.</u>	<u>Emission Rate</u>
HF-1	2.15×10^5 n/sec
HF-2	2.16×10^5 n/sec
HF-3	2.08×10^5 n/sec

6. Gamma and Neutron Spectra

The gamma spectrum for assembly HF-2 is given in Figure 1 and the neutron spectrum in Figure 2.

7. Neutron and Gamma Dose Rates

See attached table.

8. Helium Leak Rate

The helium leak rate of each of the three fueled liner assemblies prior to breaking the sealed tip of the capillary tube was $<1 \times 10^{-6}$ std cc He/sec.

9. Contamination Survey of Heat Sources

<u>Assembly No.</u>	<u>Wipe (d/m)</u>
HF-1	6
HF-2	6

10. Contamination Survey of Shipping Containers

<u>Container No.</u>	<u>Wipe (d/m)</u>			
	<u>Inner</u>	<u>Top</u>	<u>Bottom</u>	<u>Side</u>
1	18	-0-	-0-	-0-
2	18	4	6	-0-

FIGURE 1

Neutron Energy Spectrum for Artificial Heart Capsule HF-2

7. Neutron and Gamma Dose Rates

Assembly No.	Distance cm ^a	Side (mrem/hr)			Top (mrem/hr)			Bottom (mrem/hr)		
		Neutron	Gamma	Total	Neutron	Gamma	Total	Neutron	Gamma	Total
HF-1	20	6.7	2.0	8.7	2.3	.4	2.7	9.3	1.7	11.0
	25	4.3	1.4	5.7	1.2	.3	1.5	5.1	1.1	6.2
	30	3.1	1.0	4.1	.9	.25	1.15	3.4	.7	4.1
	40	1.9	.7	2.6	.6	.2	.8	1.7	.4	2.1
	50	1.1	.4	1.5	.35	.15	.5	1.0	.3	1.3
	100	.4	.2	.6	.15	.1	.25	.4	.2	.6
HF-2	20	7.3	2.0	9.3	1.9	.35	2.25	10.5	1.8	12.3
	25	4.8	1.3	6.1	1.2	.3	1.5	5.0	1.0	6.0
	30	3.3	1.0	4.3	.7	.25	.95	3.7	.6	4.3
	40	1.9	.5	2.4	.5	.2	.7	1.9	.4	2.3
	50	1.2	.3	1.5	.3	.15	.45	1.1	.25	1.35
	100	.3	.1	.4	.2	.1	.3	.3	.1	.4
HF-3	20	7.0	2.0	9.0	2.2	.3	2.5	9.6	1.8	11.4
	25	4.1	1.3	5.4	1.4	.2	1.6	5.1	1.1	6.2
	30	3.0	1.0	4.0	.95	.15	1.1	3.4	.7	4.1
	40	1.8	.6	2.4	.6	.1	.7	1.8	.4	2.2
	50	1.2	.4	1.6	.4	.05	.45	1.1	.3	1.4
	100	.3	.2	.5	.09	.01	.1	.3	.2	.5

^aReadings are from center of source to the center of detector.

APPENDIX C
EQUIPMENT SPECIFICATION
FOR THE
ARTIFICIAL HEART HEAT SOURCE

1. SCOPE

This specification establishes the performance, design, fabrication and test requirements for the radioisotope heat source for an Artificial Heart Device.

2. APPLICABLE DOCUMENTS

The following documents of the latest issue form a part of this specification to the extent indicated herein:

SPECIFICATIONS

TRW Systems

PR3-1	TIG Welding
PR3-13A	EB Welding
PR12-6	Marking and Identification of Parts, Equipment, Subassemblies and Assemblies
AS1-15	Assembly Specification Plasma-Arc Spraying of Parts for the RTG Program

Monsanto Research Corporation

MD1-13457	Pt-20Rh Specification
MD1-13458	T-111 Specification
Dwg. 1-14839	MRC Heat Source Acceptance Specification

Los Alamos Scientific Laboratory

TBD	Medical Grade Plutonium-238 Oxide Specification.
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DRAWINGS

TRW Systems

C410628	Clad Assembly, AHHS
D410647	Capillary Clad Assembly, AHHS
D410585	Clad Components, AHHS
C410587	Strength Member Assembly, AHHS
D410584	Strength Member Components, AHHS
C410586	Liner Assembly, AHHS
D410646	Liner End Cap Assembly, AHHS
D410583	Liner Components, AHHS
D410571	Pressure Relief Device Assembly
D410581	Welding Reflector Ring, AHHS
D410582	Fuel - AHHS
D410816	Fuel Simulant - AHHS

OTHER PUBLICATIONS

TRW Systems

SAN-858-9	Radioisotope Heat Source Development for an Artificial Heart Device Interface Agreement Between MRC and TRW Systems
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Monsanto Research Corporation

MD-10058	Mound Laboratory Quality Control Policy
MD-10095	Engineering Change Notice Preparation Instruction
MD1-11583	Procedure for Non-Conforming Material Request
MD-70149	Heat Source Identification System
MD1-14709	Procedure for Steel Impression Stamping Serial Numbers and Other Markings

Atomic Energy Commission

AEC-MC-0529	Safety Standards for the Packaging of Radioactive and Fissile Materials
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3. FUNCTIONAL AND PERFORMANCE REQUIREMENTS

3.1 Design and Construction. The design, fabrication, and assembly of the fueled and simulant-fueled heat source shall conform to TRW Systems Drawing C410628 and all subassemblies thereto. Materials, processes, and procedures for fabrication and assembly shall conform to the documents listed in Section 2 herein.

3.1.1 Fabrication of Piece Parts. The heat source piece parts shall be fabricated by TRW Systems or TRW-approved subcontractors in accordance with TRW drawings and applicable specifications listed in Section 2. These piece parts will be furnished to MRC for assembly of the heat source.

The radioisotope fuel (Medical Grade, Plutonium-238 Oxide) shall be fabricated by LASL in accordance with TRW Systems Drawing D410582 and applicable LASL specifications.

3.1.2 Heat Source Assembly. The assembly and quality control of the fueled and simulant-fueled heat source shall be in accordance with this specification and the MRC Heat Source Acceptance Specification 1-14839.

3.2 Weight. The weight of the fueled or simulant-fueled heat source shall not exceed 0.65 lb.

3.3 Power. The power output of the fueled heat source shall be 33.1 ± 0.2 watts at the time of encapsulation.

3.4 Ground Handling and Storage. The heat source shall not release fuel at any time during handling operations. Fuel containment shall be assured in all normal and accident environments associated with extended storage of the unit up to 15 years and shall meet the requirements of AEC-MC-0529.

3.5 Transportability. The heat source, or the heat source in conjunction with the shipping container, shall not release fuel during normal transportation or potential accident environments associated with such transportation.

3.6 Safety. The heat source shall be designed and fabricated in such a manner that all hazards associated with the unit are eliminated or minimized. Safety of the heat source under accident environments shall be demonstrated through testing.

4. QUALITY ASSURANCE

4.1 Verification of Compliance. Compliance with the requirements of Section 3 shall be verified by either inspection, analysis, or test. The responsibility for the inspections and tests shall be in accordance with the TRW/MRC Interface Agreement, as indicated below. The responsibility for the analyses shall reside with TRW.

<u>Section</u>	<u>Verification by</u>
3.1 Design and Construction	Inspection
3.2 Weight	Test
3.3 Power	Test
3.4 Ground Handling and Storage	Analyses
3.5 Transportability	Analyses
3.6 Safety	Analyses and Tests

4.2 Acceptance Inspections and Tests. Each deliverable heat source shall be subjected to acceptance inspections and tests.

4.2.1 Dimensional Inspections. TRW shall be responsible for all tests and inspections required to certify conformance of the capsule piece parts to the requirements of the drawings. In addition, MRC may perform dimensional inspections as required in their assembly procedures.

LASL shall be responsible for all the tests and inspections required to certify that the fuel disc(s) conform(s) to the requirements of the drawing.

4.2.2 Weight. The weights of all the heat source components, except the fuel, shall be determined by TRW prior to shipment to MRC. The weight of

the fuel shall be determined by LASL prior to shipment to MRC. The weight of the assembled unit shall be verified by MRC.

4.2.3 Power. The power output shall be determined by calorimetry techniques by LASL prior to heat source assembly.

4.2.4 Contamination. Each unit shall be tested by MRC by means of a smear test to determine the presence of removable contamination. Less than 0.005 microcurie of contamination shall be present.

4.3 Heat Source Acceptance. Final inspection of the heat source shall be performed by MRC to assure conformance to the MRC heat source specification. All inspection data and the quality control report shall be available to TRW Systems for review prior to shipment of the heat sources.

Final acceptance of all units shall be performed by AEC/DAO. In addition, TRW shall perform receiving inspection on all simulant-fueled and fueled heat sources.

4.4 Functional and Performance Testing. TRW Systems is responsible for all test requirements and the performance of all functional and safety testing. Testing will be performed on simulant-fueled units at TRW Systems or other locations designated by TRW.

5. PREPARATION FOR DELIVERY AND SHIPMENT

5.1 Marking. The serial number of each unit shall be legibly marked on each unit.

5.2 Shipping. The shipping containers shall be provided by MRC and shall satisfy the requirements set forth in AEC-MC-0529 and the Department of Transportation regulations, as applicable.

APPENDIX D

BURIAL TEMPERATURES

A rigorous analysis of the temperature of a partially buried heat source was beyond the scope of this program. A conservative value of this temperature can, however, be obtained from well established conduction equations for fully buried heat sources in a semi-infinite medium.

For a horizontal cylinder of length L and diameter D , buried with its axis at a distance Z below the surface*:

$$T - T_s = \frac{Q}{2\pi Lk} \ln \frac{4Z}{D} \quad D \ll Z, Z \ll L$$

where

T = heat source surface temperature

T_s = ground surface temperature

Q = heat source power

k = soil conductivity

The thermal conductivity of soils varies from 0.0465 to 0.465 Btu/hr ft°F depending on the soil composition. Assuming a conductivity of 0.32 Btu/hr ft°F and a burial depth of 6 inches, the temperature of the artificial heart heat source generating 33.1 watts was calculated to be 1300°F.

Since the requirements that $D \ll Z$ and $Z \ll L$ are not satisfied for the short artificial heart heat source, a second analysis assuming the heat source to be a sphere was performed. For a sphere of diameter D with its center at a distance Z below the surface*:

$$T - T_s = \frac{Q}{2\pi Dk} \left(1 - \frac{D}{4Z}\right).$$

*W. H. McAdams, Heat Transmission, Third Edition, McGraw Hill Book Co., 1954, p. 25.

Assuming a sphere having a volume equal to that of the cylindrical heat source, $D = 1.38$ inches and the heat source temperature is 600°F .

Since neither of the above analyses is precise for the small artificial heart heat source, it is estimated that the heat source temperature is actually between the two extremes. For the purpose of determining the ability of the heat source to survive in a post-accident oxidation environment, temperature values of 1000° and 1300°F were selected.