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PARAMETRIC ANALYSES FOR A RADIOISOTOPE HEAT SOURCE FOR AN ARTIFICIAL HEART DEVICE

Prepared for
U.S. ATOMIC ENERGY COMMISSION

TRW
SYSTEMS GROUP

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PARAMETRIC ANALYSES
FOR A
RADIOISOTOPE HEAT SOURCE FOR AN
ARTIFICIAL HEART DEVICE

Contract AT(04-3)-858

January 31, 1972

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Prepared by:

T. H. Smith
Heat Source Development

H. Lurie, Manager
Artificial Heart
Heat Source

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ABSTRACT

Parametric analyses were performed to determine the optimum heat source configuration relative to previously determined 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.

Selective and nonselective vent systems were designed to vent the fuel-generated helium from the heat source 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.

Forty-three candidate designs were scored against the selection criteria. The recommended system, which is currently being fabricated, is a right-circular cylinder consisting of a Pt-20Rh liner, a T-111 strength member, a Pt-20Rh clad and a nonselective pressure relief device/capillary tube assembly. The liner and clad are interconnected to seal off the strength member from external contamination.

CONTENTS

	<u>Page</u>
1. INTRODUCTION	1
2. SUMMARY	2
3. SELECTION CRITERIA	7
3.1 Heat Source Characteristics	7
3.1.1 Volume and Weight	7
3.1.2 Environment	9
3.2 Compatibility	9
3.3 Thermal Converter Interfaces	9
3.3.1 Heat Flux	9
3.3.2 Gas Management	10
3.3.3 Mechanical Interfaces	10
3.4 Nuclear Safety	10
3.4.1 Impact	11
3.4.2 Fragmentation	12
3.4.3 Crushing	12
3.4.4 Fire	13
3.4.5 Oxidation/Corrosion	13
3.5 Cost	14
3.6 Reliability	14
3.7 Design Flexibility	14
3.8 Go/No-Go Criteria	15
4. CANDIDATE MATERIALS	16
5. ANALYSES	19
5.1 Fragment Resistance	22
5.1.1 Bullet Impact Tests	22
5.1.2 Interpretation of Data	31
5.2 Impact Resistance Analysis	32
5.3 Crushing Resistance Analysis	36
5.4 Material Interactions	45
5.4.1 Fuel/Liner Compatibility	45
5.4.2 Intermaterial Compatibility	50
5.5 Vent System Configurations	51
5.5.1 Selective Vent	53

CONTENTS (Continued)

	<u>Page</u>
5.5.2 Pressure Relief Device (PRD)	55
5.5.3 Capillary Tube	56
5.6 CREEP ANALYSES	59
5.6.1 Creep from Steady State Pressure	59
5.6.2 Void Volume versus Wall Thickness	65
5.6.3 Release of Stored Helium	68
5.7 Thickness Selection	69
5.8 Thermal Expansion and Gap Sizes	71
5.8.1 Heat Source Fueling	71
5.8.2 Cremation Fire	72
5.9 Minimizing Heat Source Volume and Weight	72
5.10 Costs	79
5.10.1 Materials	79
5.10.2 Tooling and Fabrication	85
5.10.3 Testing	86
5.10.4 Rejection Rates	86
5.10.5 Tooling Maintenance	87
5.10.6 Production Control	87
5.10.7 Packaging	87
5.10.8 Costing	87
6. SCORING OF HEAT SOURCE CANDIDATES	90
6.1 Scoring Technique	90
6.1.1 Heat Source Characteristics	90
6.1.2 Metallurgical Interactions	92
6.1.3 Thermal Converter Interfaces	92
6.1.4 Nuclear Safety	95
6.1.5 Cost	98
6.1.6 Reliability	98
6.1.7 Flexibility	102
6.2 Results	102
6.3 Sensitivity Analysis	107
7. CONCLUSIONS	113
8. RECOMMENDED DESIGN	114
8.1 Description	114
8.2 Material Compatibility	116
8.2.1 Fuel/Liner Compatibility	116
8.2.2 Intercomponent Compatibility	118

CONTENTS (Continued)

	<u>Page</u>
9. REFERENCES	120
APPENDIX	
CANDIDATE HEAT SOURCE VOLUME AND WEIGHT VERSUS DIAMETER FOR A 40-WATT THERMAL INVENTORY	122

1. INTRODUCTION

This report describes the Task 3 "Parametric Analyses" effort in the Radioisotope Heat Source Development for an Artificial Heart Device program. This program is being sponsored by the Atomic Energy Commission, Division of Applied Technology, under Contract AT(04-3)-858. This task was initiated in July, 1971, and was completed in December, 1971. Tasks 1 and 2, completed in June, 1971, delineated the design selection criteria and identified candidate materials for the designs (References 1 and 2, respectively). The purpose of Task 3 was to parametrically investigate candidate heat source designs and to arrive at a design recommendation that best satisfied all the selection criteria. Highlights of this task are summarized in Section 2 of this report, the selection criteria are enumerated in Section 3, and the candidate materials are identified in Section 4. A description of all the analyses and tests performed under this task are discussed in Section 5. Finally, the scoring procedure and the results of the parametric analyses are described in detail in Section 6, the conclusions in Section 7, and a description of the recommended design in Section 8.

This study was conducted under the direction of Dr. H. Lurie and the Task Engineer was Mr. T. H. Smith. Others who contributed significantly to the effort were Mr. A. J. Steinberger, Mr. S. E. Bramer, and Mrs. G. Gold.

2. SUMMARY

Under the Parametric Analysis Task of the Artificial Heart Heat Source Program, 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 for the artificial heart device. 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 as described in Section 3.

Previous analyses on both the current and other programs have indicated the vented heat source to be appreciably lower in both weight and volume than a nonvented design. The nonvented heat source must have heavier walls to resist the creep resulting from the constantly increasing internal pressure, and heavier walls are required to survive mechanical forces such as impact because of the high stress levels already existing in the heat source walls. Heat source analyses and design were therefore concentrated in this program on vented systems.

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 requirement to withstand bullet impact necessitated thicker strength member walls than would have been required in order to survive such environments as impact of the heat source into other media, crushing environments, fire, oxidation, or any other credible functional or accidental environment. The thicknesses of the candidate materials required to withstand the 30-06 bullet impact were experimentally determined and were found to be strongly dependent on both the material and capsule diameter. Since metallurgical interactions between different materials may also occur at elevated temperatures, strength member wall thicknesses had to be increased to account for such interactions. At

the higher temperatures (2000°F), metallurgical interactions could be severe enough to require the use of diffusion barrier coatings to reduce reaction rates to acceptable levels.

As expected, the minimum weight and volume designs were found to be spheres. However, only a minor volume and weight penalty is incurred if a short cylindrical section is provided between hemispherical ends to ease welding difficulties. Thus, the optimum design for a nonselectively-vented heat source was found to be a hemispherically-ended cylinder having a short cylindrical section, whereas the optimum design for a selectively-vented heat source was found to be a flat-ended cylinder. Moreover, a system that used a nonselective pressure relief device (PRD) and capillary tube was found to be more flexible than one utilizing selective vents, because the latter could only be installed into a flat surface of a noble metal whereas the nonselective vent could be installed into any material of any geometry. Neither vent system, however, requires internal void volume to provide a minimum weight and volume system. Although the PRD does not retain radon, a capillary tube, only a few inches long, was found to be adequate to limit the emissions to safe levels.

Candidate designs were finalized for both the 1350° and 2000°F applications. Analyses included single-layer, two-layer, and three-layer designs of all material combinations under consideration. The design containing each material combination was optimized in weight, volume, and ability to survive the various safety requirements for the two temperatures under consideration. There were originally 22 candidates for the 1350°F application and 17 for the 2000°F application. These candidates fell into eight configurations as shown in Figure 2-1. Configuration A is a single-layer configuration; configurations B, C, D, and E are two-layer configurations; and configurations F, G, and H are three-layer configurations. Each of these eight configurations may contain different material components. Four additional designs were subsequently analyzed. These were basically similar to design A (single-layer capsule with PRD) and to design F (three-layer capsule with PRD), but were flat-ended.

Both the 1350° and the 2000°F candidates were subsequently scored against the selection criteria. At both temperatures, the single-layer

**CONFIGURATION
A**

CONFIGURATION B

CONFIGURATION C

CONFIGURATION D

CONFIGURATION E

CONFIGURATION F

CONFIGURATION G

CONFIGURATION H

Figure 2-1. Artificial Heart Heat Source Candidate Configurations

Hafnialloy design containing a PRD and having hemispherical ends was the highest scoring candidate. The top six candidates are presented in Table 2-1. Sensitivity analyses indicated that even large changes in criteria weightings do not change the relative rankings of the top candidates.

Subsequent to these analyses, the AEC selected the Stirling mechanical thermal converter concept for the artificial heart device. The heat source power level would be 33 watts and the operating temperature in this system would be approximately 1600°F. Since the highest scoring designs were the same for both 1350° and 2000°F, it is most likely they will also be best for the 1600°F application.

Hafnialloy, which is the highest-rated system, is in an early stage of development and it is unlikely that Hafnialloy heat sources could be fabricated and fueled during the current program. The second-ranking candidate was therefore proposed for the current practicability demonstration. This system consists of a Pt-20Rh/T-111/Pt-20Rh design having a PRD/capillary system and hemispherical ends. More recent information has, however, indicated that a flat-ended heat source will result in a higher-efficiency thermal converter; hence, the recommended design is a flat-ended Pt-20Rh/T-111/Pt-20Rh heat source, 0.984 inch in diameter by 1.795 inches long.

Table 2-1. System Selection

<u>1350°F</u>			<u>2000°F</u>		
<u>System</u>	<u>Configuration</u>	<u>Score</u>	<u>System</u>	<u>Configuration</u>	<u>Score</u>
1. Hafn alloy	Hemispherical, PRD	86.5	1. Hafn alloy	Hemispherical, PRD	84.1
2. Pt-20Rh/T-111/Pt-20Rh	Hemispherical, PRD	84.5	2. Pt-20Rh/T-111/Pt-20Rh	Hemispherical, PRD	83.1
3. Hafn alloy	Flat-Ended, PRD	83.0	3. Hafn alloy	Flat-Ended, PRD	*
4. Pt-20Rh/T-111/Pt-20Rh	Flat-Ended, PRD	82.6	4. Pt-20Rh/T-111/Pt-20Rh	Flat-Ended, PRD	*
5. Mo/T-111/Pt-20Rh	Hemispherical, PRD	82.0	5. TZM/Pt-20Rh	Hemispherical, PRD	80.2
6. Mo-50Re/T-111/Pt-20Rh	Hemispherical, PRD	81.5	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.

3. SELECTION CRITERIA

To enable a comparison to be made between the various candidate design concepts, and to select a single concept for final design, selection criteria have been established (Reference 1). Each of the criteria, however, has 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 have, therefore, been established. The selection criteria may be grouped into seven categories. One-hundred weight points are distributed among these categories, which contain 17 criteria, as shown in Table 3-1.

3.1 HEAT SOURCE CHARACTERISTICS

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

3.1.1 Volume and Weight

Due to the limited volumes available for implantation, the Artificial Heart heat source must be as small as possible. Each candidate design will therefore be minimized in volume. A minimum volume baseline design will be defined, and it is this baseline design against which all other designs will be scored. Designs having large void volume will hence be heavily penalized by this criterion. 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 the extremely small volumes available for implantation in the human body and the critical interface with the recipient, the volume and weight criteria are given the highest weighting of 27 points. The weight of the heat source is directly additive to the overall thermal converter system weight. The volume of the heat source, however, is much more critical since it may result in a disproportionate increase in both the volume and weight of the total converter system. These considerations have led to the assignment of 17 points to the volume criterion and 10 points to the weight criterion.

Table 3-1. 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

3.1.2 Environment

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. The capability of a specific design to operate in either vacuum or inert gas environment and be handled in air will depend on the materials selected, the type of vent used, and the temperature capability of the components. Both of these criteria are equally important and have been assigned two points each.

3.2 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 (liner and vent) 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 have been evenly divided.

3.3 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 have been assigned to this category for that reason. The relative importance of the three criteria depends on the total converter system to be employed. Gas management, however, appears most important; hence, distribution of the 17 points in this category will consist of 4 for heat flux, 9 for gas management, and 4 for mechanical interfaces.

3.3.1 Heat Flux

The heat source heat flux may affect the thermal converter efficiency. Furthermore, the attainment of the desired heat flux may affect heat source temperatures and the operation of the heat source itself since the heat flux depends on the radioisotope inventory, geometry and on the distribution

of insulation required by the thermal converter design.

3.3.2 Gas Management

The disposal of the helium generated by the plutonium fuel, containment of radon and its decay products, and prevention of external contaminants from entering the heat source are the major considerations affecting the gas management criterion. The quantity of helium generated by 30 to 60 watts of Pu-238 in ten years is probably more than could be accommodated in the thermal converter system. Depending on the particular system chosen, the helium needs to be delivered directly, or indirectly via the working fluid, to the body or blood. The quantity of radon generated and its decay products (radioactive species of polonium, lead, bismuth, and thallium), if released from the heat source, may lead to exposures in excess of maximum permissible body (MPB) burdens. Complete retention of these radioactive species will obviously eliminate this potential hazard. Finally, minor amounts of contaminants, such as oxygen, nitrogen, or hydrogen, may be very detrimental to heat source integrity if allowed access to critical heat source components.

3.3.3 Mechanical Interfaces

Most heat source concepts can be fitted with attachment lugs, ears, belly bands, etc., so that the heat source can be attached to the thermal converter. These types of mechanical interfaces will not produce a significant interface problem but must, of course, be evaluated for each heat source concept in light of specific thermal converter mechanical interface requirements. Depending on these requirements, for example, right circular cylinders may be appreciably simpler to attach than spheres.

3.4 NUCLEAR SAFETY

Nuclear Safety criteria include the ability of the heat source to survive impact, bullets or fragments, possible cremation environments, crushing, exposure to oxidizing environments, and exposure to air, body fluids and molten salts (in the event that the thermal converter utilizes molten salts for thermal energy storage). An artificial heart heat source must 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.

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

3.4.1 Impact

The impact environment associated with the crash of an airplane against a mountainside, head-on collision of fast moving trains, and automobile accidents were investigated. The environments associated with the airplane and train crashes are the most severe and were, therefore, investigated in detail.

The Boeing 747 was selected for analysis because the forward passengers probably have less material between them and the nose of the aircraft than in any other commercial jet in service today, and because of the expanding service of this aircraft. An analytical conversion was made from the impact velocity of the heart recipient (700 mph) against the aircraft materials backed by rock to the equivalent velocity against bare granite by comparing the dynamic stresses induced in the two impact modes. It was determined that an impact velocity of 210 ft/sec against granite is roughly equivalent to 1027 ft/sec (700 mph) against aluminum. At impact, some energy will be removed by the aluminum nose of the aircraft. In the case of the Boeing 747, however, this energy removal will be minimal since most of the material is already in sheet form, with the exception of the fiberglass honeycomb in the radome. Consequently, the reduction of heat source energy by intervening aircraft materials was neglected and the final equivalent impact velocity against granite is 210 ft/sec.

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.

Although some energy absorption can be expected by intervening materials on the train, by the body of the artificial heart recipient and by the

thermal converter itself, it is difficult to estimate this energy and it was therefore ignored. 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.

3.4.2 Fragmentation

The most severe fragmentation environments to which an artificial heart recipient may get 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 sold commercially in the United States. Although most shootings involve handguns, a considerable fraction does involve rifles, including all hunting accidents. 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-lb) and muzzle velocity (2700 ft/sec) of the commonly used high-powered rifles, and was therefore selected. The bullet is soft pointed and 95 percent jacketed; that is, all but 5 percent, the point, is encased in a copper jacket.

Data to evaluate the energy loss to the recipient's body and the thermal converter are not available. It was therefore assumed that 1000 ft-lb of energy are lost before impact with the heat source due to impact with the body and artificial heart system and due to frictional losses in the air.

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.

3.4.3 Crushing

Contact pressures generated by various vehicles and heavy excavating equipment were determined. The worst crushing environment is generated by

a track-type vehicle having grousers, or metal cleats, crushing the heat source on a hard surface such as concrete. If the heat source is stronger than the concrete it will be pressed into the concrete rather than be forced to bear a larger fraction of the vehicle weight. Consequently, the crushing environment was defined as a heat source design requirement, namely, a strength equal to or greater than the crush strength of concrete. In the size range under consideration, the heat source, lying on concrete must survive a 5000-lb static load.

Crushing environments such as being run over by automobiles, or collapsed-building rubble resting on the heat source, are less severe than the above requirement. 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.

3.4.4 Fire

The temperatures of building and gasoline fires have on rare occasion been measured as high as 2000°F. The National Fire Protection Association has defined a standard time-temperature fire curve which includes temperatures as high as 2300°F. Cremation temperatures have been measured as high as 2430°F for short durations. In view of the importance of not releasing radioactive fuel in a fire environment, a temperature of 2500°F for two hours has been selected for the fire-survival criterion. 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.

3.4.5 Oxidation/Corrosion

The heat source must survive in a post-accident oxidation or corrosion environment sufficiently long to permit retrieval. However, hunting accidents or airplane crashes in which affected persons are not located for several weeks, or even months, occur quite frequently. As a goal, therefore, the heat source, at its post-accident, steady-state temperature, should contain all the fuel in any post-accident environment for approximately 1000 years (10 half-lives).

3.5 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 will be stressed. Cost to be considered must include materials, special processing, forming, fueling, welding, assembling, and acceptance testing.

The cost category has been assigned 8 points. This point score reflects the importance of production costs on the success of an artificial heart device, although investigations to date indicate that heat source costs, in mass-production quantities, may not differ by much from one design to the next when compared to the cost of a total implanted heart device.

3.6 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.

Reliability is certainly as important as any of the first four categories. As mentioned above, however, some aspects of reliability have already received weights in the Compatibility and Nuclear Safety categories, and if separated would probably make Reliability the highest-weighted category of the seven. The remaining aspects of reliability (those specifically included in this category) will be given a total weighting of 8 points.

3.7 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 major impact of this criterion is in the areas of schedule and cost. Since cost has already been considered, and since schedule is not initially considered in the selection of a long-range optimum design, the design flexibility criterion has only been assigned three points.

3.8 GO/NO-GO CRITERIA

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

- 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 (in the event a TESM converter design is selected).

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

4. CANDIDATE MATERIALS

An analysis of the raw material availability, physical and mechanical property data, fuel compatibility, and material interaction data permitted initial selection of candidate material system combinations for the parametric study (Reference 2). 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 4-1. The following groundrules were used in deriving the candidate material systems:

- Iridium was eliminated as a clad candidate because of unavailability of the raw material for quantity production of 10,000 to 20,000 units/year.
- Palladium was eliminated as a clad candidate because no compatibility data with other materials are available, because its melting point is only 300°F above the anticipated cremation temperature, and because its stress-to-rupture is extremely low at the proposed operating temperatures.
- Pt-20Rh and palladium were eliminated from consideration for single-layered capsules because of their low relative strength and their susceptibility to grain growth at temperatures above 1200°F.
- W-25Re was 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, and because of difficulties in machining and fabricating this alloy.
- Ta-10W can be considered as a liner material only at 1350°F 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 reduce interaction with Pt-Rh alloys to acceptable levels.
- Mo and Mo-50Re are preferred as a liner over TZM because of their lower ductile/brittle transition temperatures and easier fabricability. These materials are proposed as liners only. In a two-layer system having a liner/strength member combination, TZM will be used because of its higher strength.
- A three-layer system of TZM or Mo/TZM/clad will not be considered since it has no advantages over a TZM/clad system.

Table 4-1. Candidate Material System Combinations for Parametric Study

Non-Selective Vent - 1350°F

<u>Single-Layer</u>	<u>Two-Layer</u>	<u>Three-Layer</u>
Hafn alloy	Ta-10W/Pt-20Rh	Ta-10W/T-111/Pt-20Rh
Oak Ridge Alloy	Ta-10W/Hafn alloy	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/Hafn alloy	Ta-10W/TZM/Pt-20Rh
	Mo/Oak Ridge Alloy	Mo-50Re/TZM/Pt-20Rh
	Mo-50Re/Hafn alloy	Pt-20Rh/TZM/Pt-20Rh
	Mo-50Re/Oak Ridge Alloy	
	Pt-20Rh/Hafn alloy	
	Pt-20Rh/Oak Ridge Alloy	

Selective Vent - 1350°F

<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/Hafn alloy	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

Non-Selective Vent - 2000°F

<u>Single-Layer</u>	<u>Two-Layer</u>	<u>Three-Layer</u>
Hafn alloy	TZM/Pt-20Rh	Mo/T-111/Pt-20Rh
Oak Ridge Alloy	Mo/Hafn alloy	Mo-50Re/T-111/Pt-20Rh
	Mo/Oak Ridge Alloy	Pt-20Rh/T-111/Pt-20Rh
	Mo-50Re/Hafn alloy	Mo-50Re/TZM/Pt-20Rh
	Mo-50Re/Oak Ridge Alloy	Pt-20Rh/TZM/Pt-20Rh
	Pt-20Rh/Hafn alloy	
	Pt-20Rh/Oak Ridge Alloy	

Selective Vent - 2000°F

<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/Hafn alloy	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

- Selective vent technology allows this vent to be welded into the noble metal alloys only (probably including the Oak Ridge Alloy). Thus one of the capsule members must be a Pt-Rh 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.

During the performance of the parametric study task, the list given in Table 4-1 was reduced further. The Oak Ridge Alloy was eliminated because there were insufficient design data available for this material and test samples could not be obtained. Candidates having a single component Ta-10W liner/strength member combination were eliminated because recent fuel compatibility data indicated questionable compatibility even at 1500°F. Although this material could be used as a liner, its performance as a structural heat source member is questionable.

5. ANALYSES

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. There were two baseline designs—one to operate at 1350°F and the other at 2000°F. The basic assumptions underlying the analyses are listed in Table 5-1. Table 5-2 identifies the analyses that were performed to enable a final heat source selection to be made, and the flow of the data from each analysis is shown in Figure 5-1. Analyses 1 through 6 all contribute to the selection of component thicknesses. Once component thicknesses have been selected, the detailed design of each concept can be undertaken.

Table 5-1. Basic Assumptions

- 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.
- The fuel shall be electrowrefined, 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 cremation 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.

Table 5-2. Analyses Required for Parametric Studies

<u>Purpose</u>	<u>Comments</u>
Satisfy Safety Requirements	Determine the minimum wall thicknesses required to survive impact, bullet impact, crushing, and creep due to internal pressure.
Determine Interaction Thickness	For those combinations of materials (including fuel) that interact, the interaction depths will be estimated and, for the purpose of structural analyses, will be subtracted from the thickness of the load carrying member.
Configure Vent System	Configure a vent system (selective or nonselective) for each design concept.
Select Component Wall Thicknesses	To be based on all the above analyses.
Design Weld Joints	Design joint areas to incorporate welds.
Determine Steady-State Temperatures	To be used in thermal expansion analyses and compatibility evaluation.
Determine Thermal Expansion	Use to size diameters and lengths to assure against interferences. Gaps must still be large enough to allow easy assembly.
Define Mechanical Interfaces with Converter	Incorporate an attachment method into each concept.
Minimize Volume and Weight	Using the above constraints, optimize diameters and lengths to minimize volume and weight of each heat source.
Finalize Dimensions	Make a design sketch of each concept.
Calculate Volume and Weight	Calculate the volume occupied by each heat source and the total weight.
Update Designs	If thermal converter inputs caused changes in design, calculate new volumes and weights.
Determine Cost, Failure Modes, and Design Flexibility	Determine concept fabrication cost, capital equipment for production quantities, potential design failure modes, and to what extent design modifications will affect the optimized design.

Figure 5-1. Design Procedure

5.1 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. Impact with a 30-06 rifle bullet (soft pointed and 95 percent jacketed) is a common accident among hunters, and also a realistic worst case. This bullet has a muzzle energy of approximately 3000 ft-lb. Data to evaluate the energy loss prior to actual heat source impact are not available, however. Assuming therefore that 1000 ft-lb (equivalent to the energy absorbed by approximately 0.060 inch of steel) are lost in the flesh surrounding the thermal converter, by impact of the thermal converter itself, and in frictional losses in the air, the heat source must withstand a bullet impact of approximately 2000 ft-lb.

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.

5.1.1 Bullet Impact Tests

A series of tests was performed on the candidate strength member materials Ta-10W, T-111, TZM, and Hafnallo. Oak Ridge National Laboratory was also contacted to obtain some of their alloy (Pt-Rh-W), but material was not available at the time. Due to the limited time and funding allowed for this test series, only a restricted number of tests could be performed on the above materials and the effects of the various variables (material, configuration, diameter, and temperature) could only be roughly obtained.

Tubular specimens of the four materials, having various wall thicknesses and diameters, were fabricated. A reference diameter of 0.35 inch O.D. was selected so that data generated in this test series could easily be compared with data generated in the PRHU program, thus minimizing the quantity of material and testing required. The specimens were tested at 1500°F in an argon atmosphere or at room temperature in air using pointed, 180-grain

bullets. Bullet energy was changed by offloading powder until a marginal specimen rupture was obtained. Thus, by changing the bullet energy and/or specimen wall thickness, the maximum survival energy per unit wall thickness was found for each candidate material.

5.1.1.1 Test Specimens

As mentioned above, to minimize material costs and to gain maximum benefit from the limited number of tests, the baseline specimen size was chosen to be the same as that of the Pioneer RHU. This permitted PRHU bullet test data to be used to supplement this set of test data. All test specimens consisted of open-ended tubes except one, which was an actual Pioneer test capsule. Half of the specimens contained 0.020-inch Ta-10W liners, and all contained alumina slugs to simulate the fuel in an actual heat source. The outside diameter of the Ta-10W liners was 0.250 inch, yielding a nominal diametral clearance between liner and strength member of 0.015 inch. Diameters and wall thicknesses of the test specimens are given in Table 5-3. Most of the specimens were 0.35 inch in diameter with wall thicknesses ranging from 0.040 to 0.056 inch, and were tested at 1500°F. To determine the effect of diameter on the impact resistance, additional Ta-10W specimens having diameters of 0.90 and 1.4 inches and flat sheet (diameter = ∞) were tested. All of these specimens had a wall thickness of $0.041 \pm .002$ inch and were tested at room temperature using the same type of bullet as described above. Ta-10W is relatively inexpensive and its ductility only varied from 30 to 42 percent from room temperature to 1500°F. All the specimens were 0.990 inch long.

Tantalum alloy and TZM specimens were machined from annealed and stress relieved bar stock, respectively. The Hafn alloy specimens were rolled from sheet stock, TIG welded, and then vacuum annealed (10^{-5} torr) at 1600°F for one-half hour. The Hafn alloy forming process was not nearly optimum, as evidenced by the longitudinal forming lines in the 48- and 50-mil thick specimens, and longitudinal hairline cracks in the 100-mil thick specimen. Because of the lack of annealing data for Hafn alloy, it was uncertain whether these specimens were fully annealed.

5.1.1.2 Test Facility

The tests were conducted at the TRW Systems rifle test facility. The

Table 5-3. Bullet Specimen Summary

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

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 either argon or air 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 heater assembly 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 gun, the heater assembly, and specimen, thermocouple, and holder are shown in Figures 5-2, 5-3 and 5-4, respectively.

5.1.1.3 Bullet Energy Calibration

The 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 jacketed; that is, all but 5 percent, the point, was encased in a copper jacket. The normal muzzle energy of these bullets is approximately 3000 ft-lb, with a velocity of 2700 ft/sec. By offloading the powder, the velocity, and hence the energy, may be varied.

Approximately 30 rounds were offloaded with powder charges ranging from 12 to 45 grains. Each 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 705 ft/sec to 2450 ft/sec with charges of 12 to 45 grains, respectively. The variation of velocity with powder weight was linear from 2450 ft/sec to 1200 ft/sec, with a data scatter from the straight line of less than 40 ft/sec. From 1200 ft/sec down to 700 ft/sec the variation was non-linear indicating that the powder burning was less efficient. Prediction of bullet energy from the velocity versus powder weight plot was calculated to be accurate to within $\pm 25\%$ at 700 ft/sec, $\pm 7\%$ at 1600 ft/sec, and $\pm 2\%$ at 2450 ft/sec.

Above a bullet velocity of 1300 ft/sec, the bullet impact point was extremely reproducible at six feet from the gun. Below this velocity, however, the bullet dropped rapidly. Since the specimen holder did not allow for much altitude adjustment, it had to be moved to within three feet of the gun for low velocity tests.

Figure 5-2. 30-Caliber Machine Gun

Figure 5-3. Heater Assembly

5.1.1.4 Test Procedure

Tests were conducted in air at room temperature and in argon at 1500°F. For the room temperature tests, the specimens were simply placed in the holder, the cell door was closed and the gun was fired. These specimens were all slightly heated by the bullet's impact, but only very slight surface discoloration was observed. For the 1500°F tests, the test specimens were located in the specimen holder, a thermocouple was attached to the specimens, the electrical heater was placed around the specimens, and the test cell was sealed. To avoid oxidation of the specimens at elevated temperatures, an inert cell atmosphere was introduced prior to heating of the specimens. 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 increased until the specimen reached 1500°F. The heater was then moved aside by a pull wire and within 3 seconds the gun was fired. 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.

5.1.1.5 Test Results

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. For convenience the results are all reported in terms of ft-lbs/milli-inch.

In the first set of tests, five baseline specimens were tested in argon at 1500°F to determine the bullet energy required to produce a marginal failure in T-111. All specimens included 0.020-inch Ta-10W liners and alumina fuel simulant. The five specimens, designated 1B-1 to 1B-5, are shown in Figure 5-5. There was no fracture at a bullet energy/mil of strength member wall thickness of 26.5 ft-lb/mil, but a marginal fracture occurred at 29.8 ft-lb/mil. This concluded this set of tests. On the

Figure 5-4. Specimen, Thermocouple and Holder

1B-2 -- 1600 ft/sec
26.5 ft-lb/mil

1B-4 -- 1800 ft/sec
33.5 ft-lb/mil

1B-1 -- 1200 ft/sec
14.5 ft-lb/mil

1B-5 -- 1700 ft/sec
29.8 ft-lb/mil

1B-3 -- 2000 ft/sec
40.2 ft-lb/mil

PRHU -- 1700 ft/sec
29.8 ft-lb/mil

Figure 5-5. T-111 Bullet Impact Specimens

basis of these data it was decided to begin the second set of tests at an energy of 29.8 ft-lb/mil wall or 1700 ft/sec for 40-mil specimens.

In the second set of tests Ta-10W, TZM, and Hafnialloy specimens were tested in argon at 1500°F. The Ta-10W and TZM specimens had 20-mil Ta-10W liners and alumina simulant, but the Hafnialloy specimens contained alumina without the liners. Liners were omitted from the Hafnialloy specimens because the specimens were not truly circular and the weld that was made to join the two ends of the rolled sheet did not permit liners to be inserted. These specimens are shown in Figure 5-6. Two Ta-10W specimens were tested. The 29.8 ft-lb/mil specimen (1A-1) failed badly and the 14.5 ft-lb/mil specimen (2A-2) barely survived. Three TZM specimens were tested. The 29.8 ft-lb/mil specimen (1C-1) failed badly, the 23.2 ft-lb/mil specimen (1C-2) also failed, but the 16.6 ft-lb/mil specimen (2C-3) survived with a large margin. Finally, two Hafnialloy specimens were tested. Specimen 1D-1 failed at 24.8 ft-lb/mil in the impact area, the weld zone and in one of the forming lines (see Section 5.1.1.1 above). Specimen 1D-2 failed at 18.6 ft-lb/mil in the impact area and in the weld zone. Based on these results it was decided not to test the 100-mil thick specimen (2D-1) since it had far more pronounced longitudinal discontinuities.

In the third set of tests, 8 Ta-10W specimens were tested. The first two (1A-3 and 6A-1) were tested in argon at 1500°F, without liners. The remaining six specimens (1A-2, 1A-4, 2A-1, 6A-2, 7A-1, and flat sheet) were tested in air at room temperature, also without liners. These specimens all had wall thicknesses of approximately 40 mils and the purpose of the tests was to determine the effect of diameter on the bullet resistance of the specimens. These specimens are shown in Figure 5-7.

In the fourth and final set of tests, one Pioneer RHU without clad but containing a liner and alumina fuel simulant was tested in argon at 1500°F. The PRHU was tested at 29.8 ft-lb/mil and fractured just as did the specimen without welded end caps (1B-5). Thus, at elevated temperature the effect of welded end caps is negligible. The PRHU, following disassembly, is shown in Figure 5-5.

1A-1 Ta-10W -- 1700 ft/sec
29.8 ft-lb/mil

2A-2 Ta-10W -- 1400 ft/sec
14.5 ft-lb/mil

1C-1 TZM -- 1700 ft/sec
29.8 ft-lb/mil

1C-2 TZM -- 1500 ft/sec
23.2 ft-lb/mil

2C-3 TZM -- 1500 ft/sec
16.6 ft-lb/mil

1D-1 Hafnialloy -- 1700 ft/sec
24.8 ft-lb/mil

1D-2 Hafnialloy -- 1500 ft/sec
18.6 ft-lb/mil

1A-3 -- 1200 ft/sec
13.8 ft-lb/mil

6A-1 -- 1200 ft/sec
14.1 ft-lb/mil

1A-2 -- 1200 ft/sec
14.5 ft-lb/mil

1A-4 -- 1400 ft/sec
18.8 ft-lb/mil

2A-1 -- 1500 ft/sec
16.5 ft-lb/mil

6A-2 -- 1175 ft/sec
13.6 ft-lb/mil

7A-1 -- 1175 ft/sec
14.6 ft-lb/mil

FLAT SHEET -- 705 ft/sec
5.2 ft-lb/mil

Figure 5-6. Ta-10W, TZM and Hafnialloy Specimens

Figure 5-7. Ta-10W Specimens

5.1.2 Interpretation of Data

5.1.2.1 Material Survivability

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 is 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. The 24.8 ft-lb/mil specimen failed most distinctly in a forming line and the weld. The front side of the specimen exhibited a ductile type failure but the failure on the back-side near the forming line and weld was brittle. The 18.6 ft-lb/mil specimen also exhibited a ductile type failure on the front side, but on the back side, where the failure ran along the weld for half its length, it appeared very brittle. If this brittle failure zone along the weld, which was probably caused by poor control of the welding atmosphere, is ignored, the remainder of the specimen looked much like the 33.5 ft-lb/mil (1800 ft/sec) T-111 specimen. If it is assumed that the 18.6 ft-lb/mil Hafnialloy specimen was overstressed by the same factor as the 33.5 ft-lb/mil T-111 specimen, a tentative maximum survival energy for Hafnialloy 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.

5.1.2.2 Diameter and Temperature Effects

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. The results of the six room-temperature tests are shown in Figure 5-8. Damage to the flat sheet was minimal and it was estimated that the specimen could have survived about twice the test energy. The curve fitted between these points represents the energy that one mil of Ta-10W will marginally survive at room temperature versus diameter.

In order to apply the above data to different materials and at elevated temperature, several assumptions must be made. R_D is defined as the ratio of the Ta-10W failure energies at two diameters, that is,

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

It is 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 Hafnialloy 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 strength member thicknesses required to survive bullet impact at an energy of 2000 ft-lb are shown in Figure 5-9 for the four materials investigated as a function of capsule diameter. Curves for both the 1350° and 2000°F application are shown. The four candidate strength member materials rank in the order of T-111, TZM, Hafnialloy, and Ta-10W, with T-111 requiring the minimum thickness.

5.2 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, notably by Sandia Corporation (References 3 and 4). The problem of predicting the failure velocity of a fueled cylindrical or spherical capsule remains unsolved, and must be treated

Figure 5-8. Ta-10W Bullet Energy/Wall Thickness Vs Diameter @ R. T.

Figure 5-9. Strength Member Design Wall Thickness Vs Diameter

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, and the adequacy of the design is verified.

As mentioned in the previous section, impact by a rifle bullet is considered to be the most severe accident environment to which the Artificial Heart heat source will be exposed. Thus it is 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 is not possible, the various heat source designs were compared to an empirical correlation of the available impact data.

During high velocity impact of a shell against a flat unyielding surface (granite), most of the deformation occurs in a localized region of the shell. At some velocity, the critical velocity, failure of the shell will occur. Assuming the basic factors involved in impact failure are dynamic stress at impact, strength of the shell, momentum at impact, and the capacity to absorb the impact, a dimensionless stress ratio, S , and an impact momentum ratio, M , can be derived (Reference 5):

$$S = \frac{R}{t} \frac{V}{\sigma_u} \sqrt{E\rho}$$

$$M = t^2 V \sqrt{\rho/2 (\sigma_y + \sigma_u) \epsilon_f}$$

and

$$S = f(M)$$

where

R = mean shell radius

t = wall thickness

V = shell velocity

E = modulus of elasticity

ρ = density

σ_u = ultimate tensile strength

σ_y = yield strength

ϵ_f = strain to failure

The parameters S and M were calculated for the available impact data and are shown in Tables 5-4 and 5-5 for T-111 and TZM, respectively. Plots of these data are shown in Figures 5-10 and 5-11 and the curves representing the impact failure criterion are drawn. Although some slight scatter in the data exists, points to the left of the curve represent impact in which the capsules survived; points to the right of the curve 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 required to survive bullet impact were calculated (Table 5-6) and are also shown in Figures 5-10 and 5-11. 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.

5.3 CRUSHING RESISTANCE ANALYSIS

A rigorous theoretical analysis of a capsule under a crushing load was beyond the scope of this program. Simplified conservative analyses of a spherical shell and an infinite cylinder were, however, performed to again verify that a capsule designed to survive bullet impact will survive the required crush environment. The crushing criterion, discussed in Section 3, requires that the heat source crush strength be greater than that of concrete.

The cross sectional view of a long cylinder before and after application of a load is shown in Figure 5-12. Assuming that the volume of the fuel within the capsule does not change as a result of the deformation, and that the fuel pulverizes and transmits the load uniformly to the capsule wall like a fluid under pressure, the following relationships can be established:

Table 5-4. Available T-111 Impact Data

Reference	Radius (in)	Thickness (in)	Temperature (°F)	Velocity (ft/sec)	S	M (in ²)	Comments
Transit (6)	1.15	0.090	2400	330	262	0.0122	Survived
	1.15	0.090	2400	325	257	0.0120	Survived
	1.15	0.090	1987	338	158	0.0140	Survived
	1.15	0.090	2410	332	264	0.0123	Failed
	1.15	0.090	2405	287	228	0.0106	Survived
	1.15	0.090	1995	329	155	0.0136	Survived
	1.15	0.090	2435	325	264	0.0121	Failed
	1.15	0.090	2070	340	178	0.0140	Survived
	1.15	0.090	1998	331	155	0.0137	Failed
	1.15	0.090	2380	324	257	0.0120	Survived
	1.15	0.090	2410	327	257	0.0120	Survived
	1.15	0.090	1990	338	158	0.0140	Survived
LRHSC (7)	0.765	0.090	1200	355	94.4	0.0145	Survived
	0.759	0.082	1200	353	101	0.0119	Survived
	0.750	0.060	1200	357	139	0.0065	Survived
	0.759	0.082	1200	400	115	0.0136	Failed
	0.759	0.082	1200	450	130	0.0153	Failed
	0.781	0.127	1200	346	66.4	0.0281	Survived
	0.770	0.100	1200	260	62.5	0.0131	Survived
	0.770	0.100	1200	240	57.6	0.0121	Survived
	0.781	0.127	1200	230	44.2	0.0187	Survived
	0.781	0.127	1200	260	49.8	0.0211	Survived
	0.781	0.127	1200	250	48.0	0.0203	Survived
	0.781	0.127	1200	250	48.0	0.0203	Survived
	0.781	0.127	1200	250	48.0	0.0203	Survived
PRHU (8)	0.153	0.040	400	163	23.0	0.00099	Survived
	0.153	0.040	400	163	23.0	0.00099	Survived
	0.153	0.040	400	218	31.0	0.00133	Survived

Table 5-5. Available TZM Impact Data

Reference	Radius (in)	Thickness (in)	Temperature (°F)	Velocity (ft/sec)	S	M (in ²)	Comments
TRW DART (9)	0.667	0.114	2000	220	38.5	0.0121	Marginal
	0.667	0.114	2000	200	35.1	0.0110	Survived
	0.667	0.114	2000	200	35.1	0.0110	Marginal
	0.667	0.114	2000	220	38.5	0.0121	Marginal
	0.667	0.114	2000	196	34.3	0.0107	Survived
	0.655	0.090	2000	201	43.7	0.00686	Survived
	0.655	0.090	2000	201	43.7	0.00686	Survived
	0.655	0.090	2000	199	43.4	0.00679	Marginal
	0.689	0.090	2000	197	45.2	0.00672	Failed
	0.689	0.090	2000	212	48.6	0.00723	Survived
	0.689	0.090	2000	207	47.4	0.00707	Survived
	0.689	0.090	2000	212	48.6	0.00723	Survived
	0.689	0.090	2000	195	44.7	0.00665	Survived
	0.689	0.090	1600	204	44.1	0.00690	Survived
	0.689	0.090	2000	209	47.9	0.00713	Survived
	0.689	0.090	1350	176	38.2	0.00578	Marginal
	0.345	0.060	1920	110	18.1	0.00168	Survived
	0.345	0.060	1800	180	29.5	0.00278	Survived
	0.345	0.060	1320	215	34.6	0.00311	Survived
	0.345	0.060	2000	170	29.2	0.00258	Survived
Vented Capsule (10)	0.600	0.050	1400	239	79.8	0.00242	Survived

Figure 5-10. Impact Correlation for T-111 Capsules

Figure 5-11. Impact Correlation for TZM Capsules

Table 5-6. Impact Correlation for Artificial Heart Heat Source

Material	Temperature (°F)	Radius (in)	Thickness (in)	Velocity (ft/sec)	S	M (in ²)
T-111	1350	0.630	0.100	216	40.2	0.0099
	2000	0.630	0.120	216	41.6	0.0152
TZM	1350	0.625	0.126	216	30.4	0.0145
	2000	0.625	0.137	216	29.6	0.0170

Figure 5-12. Cylinder Cross Section

$$\text{Volume} = \pi r_o^2 \ell = (4akr_o + \pi(kr_o)^2) \ell$$

$$a = \frac{\pi r_o (1-k^2)}{4k}$$

$$c = 4a + 2\pi kr_o = \pi r_o \frac{(1-k^2)}{k} + \frac{2\pi k^2 r_o}{k}$$

$$c = \pi r_o \frac{(1+k^2)}{k}$$

$$\epsilon = \frac{c-c_o}{c_o} = \frac{(1-k^2)}{2k^2}$$

$$p = \frac{P}{2a\ell}$$

$$\sigma = \frac{pr}{t} = \frac{Pkr_o}{2a\ell t} = \frac{Pr_o}{2\ell t} \frac{4k^2}{\pi r_o (1-k^2)}$$

$$\sigma = \frac{2P k^2}{\pi \ell t (1-k^2)}$$

where

- r = radius
- r_o = original radius
- t = wall thickness
- a = half-width flattened area (see Figure 5-12)
- ℓ = cylinder length
- c = cylinder circumference
- k = radius reduction ratio
- p = internal pressure
- P = load
- σ = wall stress
- ϵ = elongation

A similar analysis was performed for the sphere. A cross-sectional area of a sphere under load is shown in Figure 5-13. Using the same assumptions applied above:

$$\text{Volume} = \text{Vol}_{\text{Cyl}} + \text{Vol}_{\text{Half Toroid}}$$

$$\text{Vol}_{\text{Half Toroid}} = \text{Area} \cdot 2\pi \cdot \text{Radius}_{\text{c.g.}} = \frac{\pi(kr_o)^2}{2} \left(a + \frac{4 kr_o}{3\pi} \right) 2\pi$$

$$\text{Volume} = \frac{4}{3} \pi r_o^3 = 2\pi a^2 kr_o + \pi^2 a^2 k^2 r_o^2 + \frac{4}{3} \pi k^3 r_o^3$$

$$a^2 + \frac{\pi kr_o a}{2} + \frac{2}{3} r_o^2 \left(\frac{k^3 - 1}{k} \right) = 0$$

Figure 5-13. Sphere Cross Sectional Area

$$a = \frac{-\pi k r_o}{4} + \sqrt{\frac{\pi^2 k^2 r_o^2}{16} - \frac{2}{3} r_o^2 \frac{(k^3-1)}{k}}$$

$$= r_o \left[\sqrt{\frac{\pi^2 k^2}{16} - \frac{2}{3} \frac{(k^3-1)}{k}} - \frac{\pi k}{4} \right] = \beta r_o$$

$$c_1 = 4a + 2\pi k r_o = (4\beta + 2\pi k) r_o$$

$$c_2 = 2\pi (a + k r_o) = 2\pi r_o (\beta + k)$$

$$p = \frac{P}{\pi a^2} = \frac{P}{\pi \beta^2 r_o^2}$$

$$\sigma_1 = p \frac{(a + k r_o)}{2t} = \frac{P}{2\pi \beta^2 r_o^2 t} (\beta + k) r_o = \frac{P (\beta + k)}{2\pi r_o t \beta^2}$$

$$\sigma_2 = p \frac{(a + k r_o)}{2t} \left(2 - \frac{a + k r_o}{k r_o} \right)$$

$$= p \frac{(a + k r_o)}{2t} \left(\frac{k r_o - a}{k r_o} \right) = p \frac{(k^2 r_o^2 - a^2)}{2t k r_o}$$

$$\sigma_2 = \frac{P (k^2 - \beta^2) r_o^2}{2\pi \beta^2 r_o^3 t k} = \frac{P (k^2 - \beta^2)}{2\pi \beta^2 r_o t k}$$

where

- r_o = original radius
- t = wall thickness
- a = half-radius flattened area
- c_1 = circumference in plane of load
- c_2 = circumference normal to load
- k = radius reduction ratio
- p = internal pressure

P = load
 σ_1 = stress parallel to load
 σ_2 = stress normal to load

The stress σ and elongation ($\epsilon = \frac{c-c_0}{c_0}$) are shown plotted in Figures 5-14 and 5-15 against the deformation (1-k) for the cylinder and sphere under load, respectively. For a given elongation to failure, allowable stress, and capsule dimensions, Figures 5-14 and 5-15 allow easy calculation of the required shell thickness for a given load or the allowable load for a given shell thickness. Table 5-7 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 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.

5.4 MATERIAL INTERACTIONS

5.4.1 Fuel/Liner Compatibility

No fuel/liner compatibility data are available for the very high purity (0.005% or 500 ppm total impurity content) electrorefined pressed and sintered PuO_2 . 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 refractory metals. The fuel forms used were $^{238}\text{PuO}_2$ microspheres, plutonia/molybdenum cermet (PMC), 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° to 2000°F operating range of the heart heat source. These data do include an evaluation of stoichiometric versus substoichiometric PuO_2 fuel (PuO_{2-x} , where $x \leq 0.2$). In addition,

Figure 5-14. Cylinder Lateral Crushing Load

Figure 5-15. Sphere Crushing Load

Table 5-7. 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
Hafn alloy	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 Hafn alloy at 2000°F is not well known.

the data may have been obtained for test specimens having fuel volume/container area ratios or fuel volume/container volume ratios appreciably different from the actual hardware system. This would affect the extent of interaction; i.e., the greater the ratio, the greater the extent of interaction. 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 reliable for predicting results at 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 provide an insight as to fuel/liner response and justification as to candidate fuel containment materials recommended for the parametric study. Detailed compatibility data between PuO_2 and Ta-10W, unalloyed molybdenum, TZM, Mo-50Re, Pt-20Rh, and Hafn alloy are given in the Materials Survey Topical Report (Reference 2) and will not be repeated here.

Based on these data, estimates were made of the expected interaction depths between electrorefined PuO_2 and the candidate liner materials over a ten-year period. These estimated values are given in Table 5-8 for the 1350° and 2000°F applications.

Table 5-8. 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

5.4.2 Intermaterial Compatibility

Contact between dissimilar materials in multilayered radioisotope heat sources raises a question of compatibility between adjacent components. The data reported in Reference 2 are based on compatibility testing performed under closely-controlled conditions and predictions based on analyses of phase diagrams. The compatibility data for the following material combinations are presented in the reference and will not be repeated here: Ta-10W/Pt-20Rh, Ta-10W/T-111, Ta-10W/TZM, TZM/T-111, Mo-50Re/T-111, Mo-50Re/TZM, Pt-20Rh/T-111, and Pt-20Rh/TZM.

Diffusion barriers may be required at the liner/strength member and strength member/clad interfaces to minimize deleterious chemical interactions. If materials compatibility data show or predict the formation of extensive brittle intermetallics at the interface, or extensive solid solution between the metal heat source components, such a diffusion barrier is required. The presence of these brittle intermetallics and new solid solutions at material interfaces will modify the physical and chemical behavior of the system. A system without the required diffusion barriers becomes more unpredictable with time at a rate strongly dependent on temperature. However, the use of diffusion barriers can also create chemical compatibility problems within a system since each time a diffusion barrier is used, two new material interfaces are created. Data on alumina, platinized alumina, zirconia, tantalum carbide, and zirconium carbide are also presented in Reference 2.

Additional data have recently been generated at TRW on IR&D funds for the following material combinations: Ta-10W/Hafnialloy, Ta-10W/oxidized Hafnialloy, T-111/oxidized Hafnialloy, T-111/Mo-50Re, Mo-50Re/Hafnialloy, TZM/Hafnialloy, and T-111/plasma arc sprayed (PAS). HfO_2 /Pt-20Rh. The results of these tests are given in Table 5-9.

As described in Reference 2, a parabolic relationship can be used to extrapolate data in time, and a Larson-Miller type relationship can be used to correlate the thickness of the interaction zone with temperature and time. Where adequate data were available, ten-year compatibility estimates were then made on the basis of these correlations. The combinations include: Ta-10W/Pt-20Rh, Ta-10W/T-111, Pt-20Rh/T-111, and Pt-20Rh/TZM. Although no

Table 5-9. Recent IR&D Compatibility Data

Interface	Time at Temperature Days	Temperature °F	Reaction Depth Inch
Ta-10W/Hafn alloy	40	1550	No interaction
Ta-10W/oxidized Hafn alloy	40	1550	No interaction
T-111/oxidized Hafn alloy	40	1550	No interaction
Mo-50Re/Hafn alloy	40	2000	0.0002
TZM/Hafn alloy	40	2000	0.004
T-111/Mo-50Re	40	2000	No interaction
T-111/PAS HfO ₂ /Pt-20Rh	40	2000	No interaction

specific correlations were available for the interaction depths obtained with Ta-10W/TZM, Mo-50Re/T-111, Mo-50Re/TZM, and Mo-50Re/Hafn alloy, these interaction depths could be estimated from available data. Since no data were available for the remaining material combinations, it was assumed that Ta-10W/Hafn alloy reacts in the same manner as Ta-10W/T-111, since data indicate that the hafnium contained in T-111 diffuses into the Ta-10W, and that Mo reacts similarly to TZM or Mo-50Re. Finally, it was assumed that no incompatibility exists between Pt-20Rh and Hafn alloy. No data on this material combination are available, but since Hafn alloy contains platinum, and since the Hafn alloy surface may already be rich in platinum, this assumption is considered valid. A summary of all the estimated interaction depths is given in Table 5-10.

5.5 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

Table 5-10. 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	2000	0.002	Available Correlation*
Pt-20Rh/TZM		0.005	Available Correlation*
Pt-20Rh/Hafn alloy		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

*Materials Survey Topical, Reference 2.

tube. These components were sized to minimize heat source volume and weight.

5.5.1 Selective Vent

The selective vent permeates helium only. In the temperature range of interest, however, it has been successfully fabricated of noble metals only. The selective vent consists of mullite fibers properly aligned in a platinum 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. The pressure drop across a selective vent can be determined from the equation:

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

where

- ΔP = pressure differential (psi)
- t = thickness (in)
- Q = flow rate (cc/sec)
- K = diffusivity constant (cc-in/sec-in²/atm)
- A = area (in²)

The diffusivity is a function of temperature and for a 20 v/o zircon mullite vent is equal to 1.45×10^{-7} , 3.2×10^{-7} and 4.6×10^{-7} cc-in/sec-in²-atm at 1350°, 2000° and 2500°F, respectively (Reference 11). Figure 5-16 illustrates the ΔP required as a function of surface area, flow rate (power), and operating temperature for a minimum thickness vent (0.040 inch). The flow rates selected correspond to the steady state helium production rates of Pu-238 at the powers indicated, and equal to 1.6×10^{-6} , 2.0×10^{-6} , and 2.4×10^{-6} std cc/sec at 40, 50 and 60 watts, respectively. The pressure differential at 2500°F can be calculated by multiplying the value at 2000°F by 0.695 (ratio of the diffusivities).

Figure 5-16. Pressure Drop Vs Vent Area

Since for this temperature range 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. This would minimize the vent area required for a given thickness of 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. Thus, a heat source with clad diameter of 1.25 inches could have a maximum selective vent area of approximately 0.8 inch^2 if a vent is used at the one end of the cylindrical heat source, or 1.6 inch^2 if vents are put into both ends. For a 0.040-inch-thick vent, a 40-watt heat source, and an operating temperature of 1350°F , the ΔP 's are 8.2 and 4.1 psid, respectively. Using a factor of safety of 1.5 the clad must withstand ΔP 's of 12.3 and 6.2 psid, respectively. The clad must thus have a thickness of approximately 0.050 inch if one vent is used or 0.034 inch if vents are installed in both ends. The difference in these wall thicknesses represents approximately 5 percent of the heat source volume. The decision was therefore made to put selective vents into both ends of the clad and thus minimize the clad required thickness.

5.5.2 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. 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 reduce the quantity of radon released from the heat source, a capillary tube may need to be used, as explained in Section 5.5.3 below.

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

A pressure drop/flow correlation for a typical PRD is shown in Figure 5-17. As can be seen, the pressure differentials for the range of flow rates under consideration (1.2×10^{-6} to 2.4×10^{-6} cc/sec) are very low. Creep resulting from such low pressures is inconsequential.

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

5.5.3 Capillary Tube

To reduce the quantity of radon released from the heat source, a capillary tube may need to be used. Flow through the capillary is sufficiently slow that the discharge of undecayed radon gas will be effectively eliminated. In addition, use of a capillary will result 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 12). 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. Reference 5 gives an MPB of 0.03 μCi for Rn-220.

An analysis containing a considerable amount of conservatism 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 . The amount of Rn-220 present increases with time and climbs to a value of approximately 432 μCi at the end of ten years. This activity was estimated using the following radioisotopic contaminants for pressed and sintered $^{238}\text{PuO}_2$ (Reference 13):

Figure 5-17. Correlation between Predicted and Experimental Flow Rate of Transit PRD's at 2700°F

<u>Isotope</u>	<u>Parts per million</u>
Am-241	133
Np-237	269
U-232	0.05
U-234	3870
Pu-236	0.25
Pu-238	86.96%
Pu-239	10.63%
Pu-240	19,400
Pu-241	4,060
Pu-242	< 5

To decay 432 μCi of Rn-220 to 0.01 μCi requires a delay time of approximately 15 half-lives, or $54.5 \text{ sec} \times 15 = 817.5 \text{ seconds}$. Due to its larger atomic weight, radon will diffuse through the capillary at a lower rate than helium. For conservatism, however, it was assumed that the radon will be vented with the helium gas, which must then be delayed by 817.5 seconds. The tube length required for an 817.5-second dwell time in the capillary may be approximated from the following equation:

$$L = \frac{\theta \dot{q}}{A}$$

where

- L = capillary length, inch
- θ = dwell time (817.5 seconds)
- $\dot{q}$ = helium generation rate ($1 \times 10^{-7} \text{ in}^3/\text{sec}$)
- A = capillary cross sectional area ($19.7 \times 10^{-6} \text{ in}^2$ for a 0.005 - inch diameter tube)

The length must be approximately 4 inches, or approximately 0.27 inch per half life. Thus, for every three half-life-lengths, the Rn-220 will be decayed by about an order of magnitude. Therefore, if an additional order of magnitude reduction in released Rn-220 is desired, the tube need only be lengthened by approximately an inch.

The above calculation is conservative for four reasons. First, it was assumed that none of the Rn-220 released from the heat source would

escape from the body. Second, it was assumed that all the Rn-220 would enter the capillary tube as soon as it was produced and that therefore none would decay within the capsule. Third, it was assumed that the radon diffusion rate through the capillary is equal to that of helium. Finally, the capillary was sized to yield a radon emission rate equal to the MPB at the end of 10 years, resulting in considerably lower rates during the 10-year life of the artificial heart device.

The production of Rn-222 also increases with time, but even after 10 years is less than 0.0024 μCi which is well below the MPB of 0.03 μCi .

5.6 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 (Section 5.5). 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. As mentioned in Section 5.5, the highest ΔP 's are obtained across a selective vent, and worst-case creep is obtained when this 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.

5.6.1 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 cremation 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.

Two phenomena occur when the temperature of the heat source increases from the steady state operating temperature to the 2500°F cremation 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 cremation 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.

In determining the creep life of the heat source, the following assumptions were made:

- The effective stress causing creep is the maximum elastic stress in the clad

$$\sigma = K \frac{Pr}{t}$$

where

- σ = stress
- K = stress concentration factor for a flat-ended capsule
- P = pressure
- r = radius
- t = wall thickness

- The effective stress is correlated by the Larson-Miller parameter

*The capsule internal pressure can further increase if some of the helium has been retained in the fuel at the normal operating temperature. This subject is discussed separately in Section 5.6.3.

$$\sigma = f(P)$$

where

$$P = T (C + \log_{10} t)$$

T = absolute temperature
C = constant
t = time

The Larson-Miller correlation for Pt-20Rh is shown in Figure 5-18.

- Failure is defined as the time when the clad will creep to rupture. For the constant pressure and temperature case, time-to-rupture can be directly obtained from the Larson-Miller parameter. If the pressure and/or temperature vary, the "fraction of life" correlation is assumed to hold. That is

$$\sum_i \frac{t_i}{\tau_i} = 1 \quad \text{at failure}$$

where

t = time under condition i
 τ = time to rupture under condition i.

Capsule radioisotope inventory, diameters, wall thicknesses, temperature histories, and material properties versus temperature were used as input to the TRW computer program STRCRP (STress and Resulting CReep in a Pressure vessel), and the computer iterated to find the initial pressure which would expend 100 percent of the heat source clad creep life. The computer output was that constant pressure which would expend exactly 100% of the capsule creep life when subjected to either 1350° or 2000°F for 10 years and 2500°F* for 2 hours. The results for initial temperatures of 1350° and 2000°F are shown in Figures 5-19 and 5-20, respectively. Note that the pressure is the value at the initial normal operating temperature and not at 2500°F.

*Allowing for the pressure increase due to the perfect gas law.

Figure 5-18. Stress Rupture of Refractory Metal Alloys

Figure 5-19. Maximum Permissible Pressure in a 1350/2500°F Environment

Figure 5-20. Maximum Permissible Pressure in a 2000/2500°F Environment

For a given clad diameter and wall thickness, the maximum permissible 10-year pressure may thus be determined. The vent must then be sized to operate at a pressure lower than this value. This is usually an iterative process for which the proper match between clad diameter, wall thickness, and vent area must be found.

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

5.6.2 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. The assumptions made were:

- The ΔP is that required by the selective vent installed in the Pt-20Rh clad member
- This member must not creep to failure.
- The minimum void volume is that required for component clearances only

A typical design was selected for analysis:

Fuel inventory:	40 watts
Design:	liner/strength member/clad
Clad:	Pt-20Rh
Clad I.D.	0.943 inch
Fuel volume:	0.568 in ³
Temperature:	2000°F

A selective vent having a diameter of 0.75 inch was assumed to be installed in the clad member. The internal pressure history was determined by the perfect gas law, so that

$$P = \frac{P_0 T}{T_0},$$

where

P = pressure

T = absolute temperature

and the temperature was assumed to have a step function, $T = 2460^\circ\text{R}$ (2000°F) for ten years and 2960°R (2500°F) for two hours.

Three cases were analyzed. In the first case, a 0.030-inch-thick clad and minimum clearance volume (0.073 in^3), resulting in a total heat source volume of 1.555 in^3 , were assumed. Analyses showed that the clad failed due to creep before the end of the 10-year/ 2000°F plus 2-hour/ 2500°F life requirement.

In the second case, the void volume was increased by lengthening the heat source until the clad wall did not fail due to creep. The heat source volume for this case was found to be 2.11 in^3 . The existence of a large void volume necessitated a departure from the step function pressure history approach used in all prior analyses. Instead, the pressure was a function of time and void volume. Two typical pressure/time plots are shown in Figure 5-21. The first curve, having a sharp rise rate, corresponds to a void volume equivalent to the minimum clearance volume. The second curve corresponds to a void volume ten times the minimum clearance volume. Note that even such a large void volume will lead to 90% of the steady-state ΔP in only 21 days. Since the required design life is in excess of 3650 days, void volume must be very large to extend creep life significantly.

In the third case, the baseline design was modified by merely increasing the clad thickness until the clad did not fail due to creep. This required less than 1 mil additional thickness or less than 0.006 in^3 .

Summarizing, the baseline design failed due to creep, but Cases 2 and 3 survived. The impact the design modifications had on the heat source volume is shown below:

Figure 5-21. Transient Pressure Response

$$\begin{aligned} V_{\text{Case 1}} &= 1.555 \text{ in}^3 \text{ (minimum possible volume)} \\ V_{\text{Case 2}} &= 2.11 \text{ in}^3 \\ V_{\text{Case 3}} &= 1.561 \text{ in}^3 \end{aligned}$$

As can be seen, the most volume effective method of prolonging creep life of a selectively-vented heat source in this size range is to increase the wall thickness rather than increasing void volume.

5.6.3 Release of Stored Helium

The two 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.

An attempt was made to derive an approximation of the potential pressure spike curve for a 1350°F heat source suddenly exposed to a 2500°F cremation environment. Several contacts were made with LASL and MRC personnel but it was learned that there are no helium release rate data available for electrorefined fuel. The data for SSC and PMC, moreover, were insufficient to determine the shape of the release curve or the quantity of helium that the specimen contained, since neither the size of the sample was available nor was there assurance that all the helium had been collected.

Purely analytical techniques met with the same lack of success. 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 6.0). Inclusion of this factor could only make the selective vent design even less attractive by requiring larger vents or heavier-walled clads.

5.7 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 material thickness required to withstand such bullet impact is not only dependent on the material and temperature, but also on the heat source diameter. The total design thicknesses used to size the candidate heat sources, including both structural and material interaction considerations, are presented in Figure 5-22.

Figure 5-22. Strength Member Design Wall Thickness Vs Diameter

The required clad thickness again depended on the type of vent used. As indicated in Section 5.5.1, 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.

5.8 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 cremation 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 cremation 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.

5.8.1 Heat Source Fueling

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 emissivity and thermal expansion rates used are shown in Figures 5-23 and 5-24. The analyses were performed for a 40-watt heat source, and the resulting required gap sizes are shown in Table 5-11.

5.8.2 Cremation Fire

During cremation of the artificial heart recipient, 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 in Table 5-11 are also adequate to prevent interference during the cremation environment. Expansion differentials during cremation were not nearly as large as during welding; hence, there will be no damage to the heat source components.

5.9 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 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, ASCAP-2, was developed that used as input the material choices, vent type (flow characteristics), material densities, member thicknesses in accordance with Section 5.7, gap sizes in accordance with Section 5.8, 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 5-25. The plots of all the volume and weight versus diameter calculations are presented in Appendix A. The following conclusions were drawn from these analyses:

Fuel: Average value estimated

Mo-50Re: Data not available.
Assumed to be the same as Mo

Pt-20Rh: Data for pure Pt used from
200° to 1600°F, then blended
into Pt-20Rh data.

Figure 5-23. Emissivity Vs Temperature

Figure 5-24. Thermal Expansion Vs Temperature
(References 2 and 14)

Table 5-11. Assembly Gap Diametral and Length Clearances

Material System	Fuel/Liner Gap	Liner/Strength Member Gap	Strength Member/Clad Gap
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	-

Figure 5-25. Total Heat Source Volume and Weight Vs Outside Diameter

- The sphere has the smallest volume and weight
- There is little difference in volume and weight of a sphere and hemispherically-ended cylinders having short cylindrical sections 0.1 to 0.4 inch in lengths. (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 PRDs, 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. A very small volume and weight penalty was imposed on the design by using a short hemispherically-ended cylinder rather than a sphere as can be seen in Figure 5-25. 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. A sample set of results is shown in Table 5-12. This sample table lists the volumes and weights of all the heat source components and their sums.

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 6.0. 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 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 6.0.

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

Table 5-12. Sample Analysis

DESIGN F4 1350F
HEMISPHERICAL SHAPED ENDS

----- D(N)= 1.3

CAPSULE LENGTH= 1.39903, L/D= 1.07618, CAPSULE WEIGHT= .59284 lb
TOTAL VOLUME= 1.2850491 in³

	AREA	DIAMETER	LENGTH	VOLUME	WEIGHT	
0	.33211E+01	.98548E+00	.10845E+01	.57666E+00	.22050E+00	FUEL
1	.34890E+01	.10055E+01	.11045E+01	.34231E-01	.00000E+00	GAP
2	.37591E+01	.10455E+01	.11445E+01	.72464E-01	.49058E-01	LINER
3	.39050E+01	.10665E+01	.11655E+01	.40234E-01	.00000E+00	GAP
4	.54208E+01	.12650E+01	.13640E+01	.46078E+00	.27831E+00	STRENGTH MEMBER
5	.55454E+01	.12800E+01	.13790E+01	.41122E-01	.00000E+00	GAP
6	.57137E+01	.13000E+01	.13990E+01	.56294E-01	.38111E-01	CLAD

THICKNESS

1 .1E-01	2 .2E-01	3 .105E-01	4 .99258333E-01
5 .75E-02	6 .1E-01	7 .1E-01	8 .2E-01
10 .99258333E-01	11 .75E-02	12 .1E-01	9 .105E-01
DENSITY			
2 .677E+00	4 .604E+00	6 .677E+00	8 .677E+00
12 .677E+00	10 .604E+00		

FUEL POWER DENSITY = 4.3 WATTS/CC
FUEL SPECIFIC POWER = .44E+00 WATTS/GM
CAPSULE POWER = 40 WATTS
FUEL VOID FRACTION = .9E-02 GAP AROUND PRD

in Figures 5-26 and 5-27 for flat-ended and hemispherically-ended geometries, respectively. These 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 (see Figures 5-28 and 5-29).

5.10 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. That is, hard tooling will be utilized extensively, lot-sampling inspection techniques will be used, piece part machining operations will be limited to weld joint preparations, welding fixtures will accommodate multiple heat sources, and fuel will be pressed and sintered to the final configuration. These costs do not include the cost of fuel or its forming, but do include material, piece part fabrication, loading of fuel, all subassembly and assembly welding, acceptance testing, scrappage, tool maintenance, production control, and packaging estimates. These elements are illustrated in the sample cost sheet shown in Figure 5-30.

Prior to a large production effort, there must be a preproduction study effort to devise meaningful, low cost, inspection techniques and to determine the reproducibility of any one production operation and the effects of fabrication tolerance variations on the end requirements. Investment in such a study could reduce production program costs by an order of magnitude.

Many candidate fabrication procedures were reviewed to arrive at the lowest cost manufacturing method for each candidate design. The fabrication approaches finally selected for the various designs were basically the same, and are outlined in the following discussion.

5.10.1 Materials

All materials will be purchased from material suppliers to the thicknesses and diameters required to produce finished parts (except weld joints).

Figure 5-26. Total Heat Source Volume and Weight Vs Heat Source Diameter - Flat Ends

Figure 5-27. Total Heat Source Volume and Weight Vs Heat Source Diameter - Hemispherical Ends

Figure 5-28. Minimum Total Volume and Weight Vs Power - Flat Ends

Figure 5-29. Minimum Total Volume and Weight Vs Power - Hemispherical Ends

DESIGN #F4-1350 (Pt-20Rh/T-111/Pt-20Rh)

ASSEMBLY UNIT COST

COMPONENT UNIT COST*	Number/ Assy	Cost/Assembly (\$)		
		Material	Piece Part Fabrication	Total
Vent-Internal PRD	1	-	300	300
Liner	2	103	91	194
Coating	0	-	-	-
Strength Member	2	32	76	108
Coating	0	-	-	-
Clad	2	122	64	186
Coating	0	-	-	-
Vent-External	0	-	-	-
SUM				788 = 788

SUB-ASSEMBLY SCRAP**

Liner	- 15%	\$ 74	
Strength Member	- 15%	\$ 91	
Clad	- 15%	\$ 29	
SUM		\$ 194	= 194

TOOLING MAINTENANCE/1000 UNITS

Comments: 540 HRS/1000 = \$4/UNIT

PRODUCTION CONTROL/1000 UNITS

Comments: 540 HRS/1000 = \$4/UNIT

PACKAGING

Comments: \$50 = 58

TOTAL COST/UNIT

\$1040

1,040

*includes individual scrap rates per Table 5-14

**See Table 5-15

Figure 5-30. Sample Cost Sheet

Non-recoverable scrappage of expensive raw stock materials (Pt-20Rh in particular) will be minimized in this manner. During the preproduction program the dimensions of stock required to produce a part will be determined, and the tools will be modified to comply. This will eliminate the necessity to perform expensive surface machining operations. Raw material costs used in this analysis are summarized in Table 5-13.

Table 5-13. Candidate Material Costs

Material	Form	Approximate Cost* (\$/lb)
Ta-10W	0.030 Sheet	47
Ta-10W	0.020 Wall Tube	180
T-111	0.090 Sheet	52
T-111	0.080 Wall Tube	320
Mo	0.030 Sheet	32
Mo	0.020 Wall Tube	190
TZM	0.090 Sheet	40
TZM	0.080 Wall Tube	180
Mo-50Re	0.030 Sheet	1420
Mo-50Re	0.020 Wall Tube	8000
Pt-20Rh	0.030 Sheet	2200
Pt-20Rh	0.020 Wall Tube	2500
Hafn alloy	0.125 Sheet	200
Hafn alloy	0.125 Wall Tube	1000

*Inspection costs not included

5.10.2 Tooling and Fabrication

All tooling will be production grade (hard) tooling that will accommodate multiple units, where practical. Hemispherical domes will be punched. For flat-ended cylindrical designs, the tube stock will be cut to length using jigs and fixtures that insure precise cutoff length and a minimum of operator time. Discs for the flat ends will be punched to final diameter. Where required and practical, step weld joints will be machined in single pass operations using preformed grinding wheels or parting tools that form

all surfaces of the step joint in one pass. Rotating welding fixtures that accommodate a dozen or more assemblies will be used to minimize EB welding pump-down time per unit.

5.10.3 Testing

With hard tooling it should only be necessary to conduct inspection of the first article, a lot sample inspection of one part per hundred, and a final acceptance test on each lot of approximately ten per hundred. Welds may require more extensive inspection of perhaps 25 per hundred.

5.10.4 Rejection Rates

Parts and subassembly rejection rates will be somewhat material-dependent. The Ta-10W, T-111, and Pt-20Rh components may be formed at room temperature and a scrap rate of approximately 10% is anticipated. Mo-50Re parts may also be fabricated at room temperature but past experience indicates that a higher scrap rate occurs due to cracking. Approximate 15% scrap is anticipated. Mo, TZM, and Hafn alloy parts are typically formed at elevated temperature (the Hafn alloy processing has not yet been fully developed; hence, a worst-case situation is assumed) and higher scrap rates are anticipated (20, 25, and 20 percent, respectively). These fabrication scrap rates were used in the costing and are summarized in Table 5-14.

Table 5-14. Component Scrap Rates

<u>Component Material</u>	<u>Component Scrap Rate</u>
Ta-10W	10%
T-111	10%
Pt-20Rh	10%
Mo-50Re	15%
Mo	20%
TZM	25%
Hafn alloy	20%

During welding, additional scrappage will occur. For instance, TZM weldments have suffered high mortality rates in the past, whereas materials such as T-111 have exhibited low weld scrappage rates. Initially, these costs were to include such elements as Material Review Board costs and other repair work. It was noted, however, that rework costs were a significant portion of the unit investment at the early stages of assembly, and hence it was more economical to scrap the units rather than to rework them. Hence, in the final cost estimates it was assumed that if a liner or strength member weldment is discrepant, all components would be destroyed to salvage the fuel. In the case of a clad discrepancy, however, it is more cost-effective to strip the clad off, thus losing the clad and vent (if the vent is in the clad), and employing a new clad. The welding scrap rates used for costing purposes are presented in Table 5-15.

5.10.5 Tooling Maintenance

To estimate tooling maintenance costs, it was assumed that three tool maintenance men would be required full-time for a facility producing 10,000 units per year. This translates into a cost of approximately \$4 per unit.

5.10.6 Production Control

Production control was also estimated on an annual basis as three men per year for a production rate of 10,000 units per year. This cost was also approximately \$4 per unit.

5.10.7 Packaging

A special shipping container will be required for the fueled heat source. If multiple heat sources are shipped together, active cooling may be required. Based on the packaging required for the Pioneer RHU, this cost is estimated at \$50 per unit.

5.10.8 Costing

Material supplier cost data (\$/pound for the configuration desired) were applied to the heat source component weights to estimate material costs. Fabrication labor costs were determined from estimates of the time required to form a part and the labor rate costs consistent with the type of operation. These fabrication costs were checked by comparing them with costs incurred

Table 5-15. Welding Scrap Rates

Design		Scrap Rate		
Strength Member Material	Liner Material	Liner Weld ⁽¹⁾ (%)	Strength Member Weld ⁽²⁾ (%)	Clad Weld ⁽³⁾ (%)
T-111	Ta-10W	15	15	15
	Mo	25	15	15
	Mo-50Re	15	15	15
	Pt-20Rh	15	15	15
TZM	Ta-10W	15	40	15
	Mo-50Re	15	40	15
	Pt-20Rh	15	40	15
Hafn alloy	Ta-10W	15	15	
	Mo	25	15	
	Mo-50Re	15	15	
	Pt-20Rh	15	15	

(1) These rates are applied to all costs through liner welding

(2) These rates are applied to all costs through strength member welding

(3) These rates are applied to components in clad only.

on the Pioneer RHU program and with vendor quotes to assure consistency. PRD costs were estimated by assuming a streamlined Transit PRD production plan; an estimate of \$300 per PRD was obtained. Detailed costs for a selective vent are not available. For purposes of these analyses a cost of \$200 per vent was assumed.

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 are not included but will be almost totally independent of the design candidate. The costs are summarized in Section 6.0.

6. SCORING OF HEAT SOURCE CANDIDATES

Based on the analyses presented above, each of the 43 candidate designs was scored against each of the selection criteria discussed in Section 3. Due to the varying relative importance of each of the criteria, weighting factors were assigned to each. The method of scoring the candidate designs against the criteria, a summary of the results, and sensitivity of the results to the weighting factors are described below.

6.1 SCORING TECHNIQUE

One hundred weight points were distributed among the 17 selection criteria, as described in Section 3. The method of applying these points to the candidate designs is summarized in Table 6-1, and described in detail below. The 1350° and 2000°F designs were scored independently.

6.1.1 Heat Source Characteristics

6.1.1.1 Volume and Weight

The baseline volume is the smallest possible volume attainable (zero excess void and smallest overall heat source volume) and therefore received 17 points. Designs having volumes nearly equal to the baseline volume received nearly 17 points each. Designs considerably larger received nearly zero points each. The following equation was used.

$$\text{Score} = 17 \left(\frac{V_0}{V} \right)^2$$

where

V_0 = lowest volume candidate

V = volume of the candidate being scored

17 = the maximum permissible number of points

A design 10% larger than the baseline would receive 14.1 points for the volume criterion. A design 50% larger than the baseline would receive 7.5 points, and a design 100% larger would receive only 3.4 points.

The weight scores were calculated in a similar manner. The equation used was

$$\text{Score} = 10 \left(\frac{W_0}{W} \right)^2$$

Table 6-1. Scoring Techniques

Volume	Score = $17 \left(\frac{V_0}{V} \right)^2$	V_0 = minimum volume system
Weight	Score = $10 \left(\frac{W_0}{W} \right)^2$	W_0 = 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	

where

W_0 = lowest weight candidate

W = weight of candidate being scored

10 = maximum permissible number of points

6.1.1.2 Operability in Gas and Vacuum

A design was given the full two points if it could be operated in both an inert gas environment and a vacuum without degradation of any of its components. The design received zero points if it could only be operated in one of the two environments. All designs analyzed could operate in both environments; hence all designs received two points.

6.1.1.3 Handling in Air

If a design could be handled in air without any component degradation, it received two points. If it could not be handled in air, it received zero points. All designs could be handled in air; hence all designs received two points.

6.1.2 Metallurgical Interactions

Contamination of the liner by either oxygen or impurities from the fuel generally leads to embrittlement and loss of impact resistance. Similarly, the properties of all material interaction zones degrade due to the diffusion of one metal, or alloying elements, from one component into the other. Elimination of such incompatibility is thus extremely important in the design of radioisotope heat sources. For this reason, material combinations undergoing severe interaction should be heavily penalized. The square correlation was therefore assumed.

$$\text{Score} = 9 \left(\frac{\text{Unaffected thickness remaining after 10 years}}{\text{original thickness}} \right)^2$$

6.1.3 Thermal Converter Interfaces

The effect each of the thermal converter interface criteria (heat flux, gas management, and mechanical interfaces) has on the integration of the heat source into the thermal converter system depends on the system selected. Definition of the scoring techniques for these criteria had, therefore, been deferred until recently when a system selection took place.

6.1.3.1 Heat Flux

As discussed in Section 3.0, the heat source heat flux may affect the thermal converter efficiency and may also dictate the design of the thermal insulation. For the Stirling mechanical thermal converter concept selected for the Artificial Heart device, however, this criterion is not very relevant. For this reason all designs were given the maximum score of 4.0 points.

6.1.3.2 Gas Management

The optimum heat source vent system will release helium, retain radon, and prevent contaminants outside the heat source from reaching critical heat source components. Both the selective and nonselective vents will release helium, but only the former will retain radon within the heat source and prevent back-diffusion of external contaminants. If the selective vent, however, is placed in the heat source liner, contaminants may still affect the outer heat source components. Thus, scoring of the various designs against the gas management criterion depended not only on the type of vent used, but also on its location and the susceptibility of the heat source components to attack by contaminants. It should be pointed out that although the PRD does not retain radon, a capillary tube may readily be used to limit the release of radon to acceptable levels. Nonetheless, designs using a PRD were penalized for their lack of absolute radon retention. A summary of the scoring technique and associated rationale are given in Table 6-2.

6.1.3.3 Mechanical Interfaces

The current thermal converter system requires the heat source to be located within the engine cylinder. Maximum converter efficiencies are obtained with minimum dead space between the heat source and the cylinder walls and between the heat source and the displacer piston adjacent to it. The optimum heat source resulting in minimum dead space is a right circular cylinder. Hemispherically-ended cylinders or spheres would require a shaped cylinder head and complicated piston design. Furthermore, attachment of the heat source to the cylinder walls is simplified with a right-circular cylindrical construction.

Flat-ended cylinders thus scored 4 points, whereas hemispherically-ended ones scored only 2 points.

Table 6-2. Gas Management Scores

System	Score	Comments
Selective vent in Pt-20Rh/Hafnalloys	9.0	Retains radon; both Pt-20Rh and Hafnalloys oxidation resistant
Selective vent in noble metal clad (all systems)	9.0	Retains radon; excludes external atmosphere from refractory metal components
PRD in Pt-20Rh/Strength Member/Pt-20Rh	7.0	Does not retain radon; liner and clad interconnected to prevent contamination of strength member
PRD in single layer Hafnalloys	7.0	Does not retain radon; Hafnalloys oxidation resistant
PRD in Pt-20Rh/Hafnalloys	7.0	Does not retain radon; both Pt-20Rh and Hafnalloys oxidation resistant
Selective vent in liner (with exception of Pt-20Rh/Hafnalloys system)	5.0	Retains radon; refractory metal components susceptible to oxidation
PRD in liner in all other systems	4.0	Does not retain radon; refractory metal components susceptible to oxidation

6.1.4 Nuclear Safety

6.1.4.1 Impact

Analyses indicated that all T-111 and TZM candidates would survive impact (see Section 5.2). No significant data are, unfortunately, available for Hafnialloy, but the impact survivability requirement is believed to be less severe than the bullet impact requirements for which data have been obtained. The analyses performed were crude and could only convey a rough approximation of design adequacy. The degree of optimism in the design adequacy is reflected in the scoring, where a candidate is assigned a maximum score if there is a considerable amount of data to confirm the engineering estimate, and a low score if little or no data are available to form an engineering judgment of adequacy.

Two prime variables affected design confidence: the material of the strength member and the type and location of the vent. There is a considerable amount of favorable impact data on heat sources with T-111 strength members, and there is little doubt that the designs containing strength members of the thicknesses selected are capable of withstanding impact, if the vent does not fail. There is also a considerable amount of data on TZM strength members, but there are a considerable number of failures among the data. It is realized that many of these failures were caused by the capsule design rather than by weakness of the material, but nevertheless, the failures do exist. Therefore, there is slightly less confidence in the TZM designs than in the T-111 designs. As mentioned above, there are no impact data available for Hafnialloy capsules. The confidence in the thickness selection for this material is therefore correspondingly low.

The prime vent parameter affecting the vent survivability under impact is its location. Vents located in the liner are protected during impact; vents in the clad, on the other hand, are susceptible to damage. Thus there is considerably more confidence in internal vents. These considerations were used to establish the following scoring table. The score is dependent on strength member material, type of vent, and vent location.

Strength Member Material	Vent Outside	Selective Vent Inside	PRD Inside
T-111	2.8	3.0	3.0
TZM	2.4	2.6	2.6
Hafnallo	1.0	1.2	1.2

6.1.4.2 Fragmentation

All of the candidate heat sources were designed using strength member wall thicknesses selected to resist bullet impact. These thickness requirements were determined by actual tests. There was a considerable number of tests of T-111 and TZM parts, but the Hafnallo testing was quite limited. The scoring is thus somewhat proportional to the number of tests performed.

As in the case of impact, described above, the weak point in the design could again be the vent. If the vent is on the outside, it is susceptible to rupture (particularly the selective vent which is made of a weak noble metal). The more layers that back up a selective vent, however, the more confident one can be that the design will survive bullet impact and that no fuel will be released even if vent rupture occurs. The scoring system used was based on these considerations and is shown in the following table.

Strength Member Material	Vent Outside 3-Layer	Vent Outside 2-Layer	Vent Inside
Hafnallo	-	1.0	1.2
TZM or T-111	3.0	2.8	3.0

6.1.4.3 Fire

Analyses of various fire environments have indicated that the worst potential fire would have a temperature of 2400° to 2500°F. Maximum heat source temperature under such environments will be 2500°F. There are adequate data to insure that all the candidate designs will survive a 2500°F fire exposure for several hours. Hence, all designs received 3 points for fire resistance.

6.1.4.4 Crushing

There is a considerable level of confidence that the TZM and T-111 designs will survive crushing (see Section 5.3), but sharp corners and external vents somewhat reduce this confidence. Due to the developmental nature of Hafnalloys and the lack of extensive property data, there is less confidence in these designs. The degree of design confidence is reflected in the following scoring system that was used.

Strength Member	Hemispherical Ends		Flat Ends	
	Internal Vent	External Vent	Internal Vent	External Vent
T-111	3	2.8	2.8	2.6
TZM	3	2.8	2.8	2.6
Hafnalloys	2	1.8	1.8	1.6

6.1.4.5 Oxidation

To protect the primary structural member and/or contain the fuel, all heat source designs have an external member that provides oxidation resistance. In all designs, except Hafnalloys, however, this member is relatively weak and may be breached by impact, crushing action, or bullet impact. When this member is breached, the T-111 or TZM strength member will be oxidized severely, and eventually will not provide any encapsulation capability. If the heat source design contains a liner, and it is made of any of the candidate liner materials except Pt-20Rh, it too will oxidize and the fuel may eventually be released. The following scoring procedure was thus devised:

Strength Member Material	Liner Material				
	Pt-20Rh	Ta-10W	Mo	Mo-50Re	No Liner
Hafnalloys	3	3	3	3	3
T-111 or TZM	2.4	1.2	1.4	1.4	1.0

Designs with Mo or Mo-50Re liners receive more points than designs with Ta-10W liners because at the exposure temperature under consideration Mo

and Mo-50Re oxidize at a slower rate than Ta-10W.

6.1.5 Cost

Scores for cost were calculated using the equation

$$\text{Score} = 8 \left(\frac{\text{Minimum Cost Candidate}}{\text{Cost of Candidate Scored}} \right)$$

where 8 is the maximum number of points for the cost criterion. Such a linear relationship with cost is used, as opposed to the square-relationship used for volume, weight, and compatibility, because added cost is considered less critical than these other criteria.

6.1.6 Reliability

In addition to the criteria already identified above, there are three additional potential failure modes for the heat source. They may be identified as:

- Vent failure
- Lack of structural soundness at various stages of assembly including installation into the thermal converter
- Lack of weld joint reproducibility

The candidate heat source designs were ranked relative to their reliability in these three failure modes. One hundred points were equally divided among these three categories, each design was evaluated against the failure modes, and the total score was used to rank the various candidate heat source designs.

6.1.6.1 Vent Failure

The PRD is a proven design which is part of a heat source flight-qualified for the Transit and Pioneer RTG missions. Hence, designs that use PRDs received 33-1/3 points in this category. The selective vent, however, has not been developed to the same level as the PRD, and hence, designs using selective vents were penalized 5 points.

6.1.6.2 Structural Soundness

Components made of TZM and Mo have exhibited some brittle characteristics, particularly at intermediate and lower temperatures (below 1000°F). This characteristic is not always apparent during inspection and its criticality

depends on the number of encapsulation layers in the capsule and which layer is potentially brittle.

The only single-layer candidate is the Hafn alloy design. It does not possess this brittle quality in the parent material, and should therefore have a high structural soundness reliability score.

There are two types of two-layer candidates: a Hafn alloy strength member containing a liner, and a TZM strength member with a Pt-20Rh clad. For the Hafn alloy designs, all the liner candidate materials are reliably sound materials except for Mo. The latter design is thus penalized half the available structural soundness points. In the TZM designs, the clad is a sound material but the TZM is potentially unsound. Since in this case the unsound material is the strength member, the design should be penalized more severely (25 points).

The three layer designs have either T-111 or a TZM strength member. The clad is always Pt-20Rh and hence sound. The only unsound liner material is Mo which is only used with the T-111 strength member. This design is penalized 6 points. All the TZM designs are penalized 17 points due to the brittle nature of the strength member. A heavier penalty is not enforced since there are two additional sound encapsulating members in the heat source.

These point penalties are summarized below.

Strength Member Material	Liner Material	Point Penalty		
		One-Layer Design	Two-Layer Design	Three-Layer Design
Hafn alloy	None	0	-	X
	Ta-10W	-	0	
	Mo	-	17	
	Mo-50Re	-	0	
	Pt-20Rh	-	0	
T-111	Ta-10W	X	X	0
	Mo			6
	Mo-50Re			0
	Pt-20Rh			0
TZM	None	X	25	-
	Ta-10W		-	17
	Mo-50Re		-	17
	Pt-20Rh		-	17

6.1.6.3 Weld Joint Reproducibility

As mentioned above under the fabrication costs, some of the candidate materials are easier to weld than others. Materials that may be reproducibly welded produce less scrapage. In addition to cost implications, this non-reproducibility has reliability implications. TZM components will produce the most variant quality weld of the candidate materials. Mo components will be slightly less variant. With proper weld development, Hafn alloy is expected to produce very reproducible welds. Due to the small data base, however, components of this material must also be scored low, but not as low as Mo components. Ta-10W, Mo-50Re, and Pt-20Rh all produce reproducible weldments.

The score must also reflect the function of the component in question. For instance, if the component having poor weld reproducibility is the strength member, it should be scored lower than if it were the liner. Hence, the following point reduction scoring scheme was devised and used:

Strength Member Material	Liner Material	Point Penalty		
		One-Layer Design	Two-Layer Design	Three-Layer Design
Hafn alloy	None	17	-	
	Ta-10W	-	17	
	Mo	-	33-1/3	
	Mo-50Re	-	17	
	Pt-20Rh	-	17	
T-111	Ta-10W			0
	Mo			6
	Mo-50Re			0
	Pt-20Rh			0
TZM	None		33-1/3	-
	Ta-10W		-	30
	Mo-50Re		-	30
	Pt-20Rh		-	30

6.1.6.4 Ranking for Reliability

A sample score sheet is shown in Figure 6-1. Note the negative scores were summed and deducted from 100% to get a total score of 53%. These evaluations were conducted for all the designs at both 1350° and 2000°F, and produced ratings of 37% to 100%. This spread was divided into 9 grade levels, and the 8 points in the reliability category were distributed as follows:

% Range		Score (Points)
High	Low	
100	93	8
92	86	7
85	79	6
78	72	5
71	65	4
64	58	3
57	51	2
50	44	1
43	37	0

DESIGN #F4-2000 (Mo-50Re/TZM/Pt-20Rh)

FAILURE MODES

VENT OPERATION

PRD is proven

STRUCTURAL SOUNDNESS IN ALL ASSY.
ENVIRONMENTS

*TZM strength member may be
brittle*

- 17%

WELD JOINT REPRODUCIBILITY

*TZM strength member may not be
highly reproducible*

- 30%

EVALUATION OF RELIABILITY

53%

RANKED SCORES (0 to 8)

2

Figure 6-1. Sample Reliability Sheet

6.1.7 Flexibility

Four equally-important qualities were considered in the design flexibility criterion. The heat source should have the capability to accept a change in power loading, provide a rigid interface for the thermal converter, accept a change in geometry and have the ability to be mass-produced without necessitating a change in the basic design concept. If all of these requirements were satisfied, the design was scored high in flexibility. Conversely, lack of flexibility was scored low. For example, if a design requires a selective vent, and selective vents can only be installed into a flat-ended cylinder, it has no "geometrical change" capability, and hence should be ranked low.

Each design was graded in each quality. If it was excellent, it received 25%, good: 20%, fair: 15%, and poor: 5%. The grades ranged from 100% to 65%. The designs were scored on the following basis.

% Range		Score (Points)
High	Low	
100	94	3.0
93	88	2.5
87	82	2.0
81	76	1.5
75	71	1.0
70	66	0.5
65	0	0

6.2 RESULTS

As already mentioned in Section 4.0, all the designs using the Oak Ridge Alloy were omitted because there were not enough data available for the design of these candidates. Forty-three designs were analyzed in detail. The twenty-six 1350°F candidate designs were scored separately from the seventeen 2000°F designs. These candidates are listed in Tables 6-3 and 6-4, respectively. Note the design numbers assigned to each candidate in the tables. The letter in the design number indicates the general configuration as shown in Figure 6-2; the number following the letter indicates the material combination. The lower case letter, when used, indicates a difference only in end-cap configuration as described below. There are

Table 6-3. 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 6-4. Candidate Design Identification -
2000°F Candidates

Design Number*	Materials	Geometry	Type Vent
A1	Hafnalloys	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.

Figure 6-2. Candidate Configurations

eight candidate configurations for the 1350° and 2000°F optimized heat source designs. Variations on each configuration are 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: Hafnalloys.
- 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 Hafnalloys 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 Hafnalloys 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.
- 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 Hafnalloys 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.

Four additional candidates are listed in Table 6-3 which are not shown in Figure 6-2. These designs (designated by letter a) are basically similar to designs A and F but are flat-ended. These designs were not originally analyzed because they are not optimum designs, but were added when it was learned that flat-ended designs may be preferable for the selected thermal converter design.

The candidates were scored in accordance with the procedures described in Section 6.1 using the data discussed in Section 5. The scores were entered on the score sheets shown in Tables 6-5 and 6-6 for 1350° and 2000°F designs. For each candidate the scores in all the criteria were summed. The 1350° and 2000°F candidates were ranked separately. The system 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 6-7. Note that the top two designs are the same for both temperatures.

6.3 SENSITIVITY ANALYSIS

The sensitivity of the scores and relative rankings of the various designs to changes in criteria weightings was analyzed. Three specific

Table 6-5. 1350°F Design Candidates

Design Number	Characteristics							Criteria																			
	Volume 3 (in ³)	Weight (lb)	Liner Thickness (in)	Un-affected Thickness (in)	Critical Member Thickness (in)	Un-affected Thickness (in)	Cost \$	17 (V ₀ /V) ²	10 (W ₀ /W) ²	Oper Gas/Vac	Hand in Air	9 (Rem Lin Lin Th) ²	9 (Rem Th Th) ²	Heat Flux	Gas Mgmt	Mech Interface	Imp	Frag	Fire	Crush	Oxid	8 Min Cost Cost	Reliab	Flex	Total	Rank	
								17	10	2	2	9	9	4	9	4	3	3	3	3	3	8	8	3	100		
A1	1 241*	0 529	0 139	0 137	0 139	0 139	580*	17 0	7 6	2	2	8 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 1	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 6-6. 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 \$	$17\left(\frac{V_0}{V}\right)^2$	$10\left(\frac{W_0}{W}\right)^2$	Oper Gas/Vac	Hand in 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	$8\frac{\text{Min Cost}}{\text{Cost}}$	Reliab	Flex	Total	Rank
								17	10	2	2	9	9	4	9	4	3	3	3	3	3	8	8	3	100	
A1	1 387	0 601	0 164	0 159	0 164	0 164	640*	15 8	6 5	2	2	8 4	9 0	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 9	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 0	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 6-7. 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.

cases were investigated. In each case, the most heavily weighted criterion (volume) was reduced from 17 points to 10 and the seven points given to other criteria. In the first case the weight criterion was increased from 10 to 17 points; in the second case the cost criterion was increased from 8 to 12 points and the safety criteria were increased from 15 to 18 points; in the last case all seven points were assigned to the safety criteria making the safety criteria worth 22 points. The same general groundrules as described previously were used in scoring all the 1350°F designs against these new criteria. The results are shown in Table 6-8. As can be seen, the top six designs have remained at the top. With only two minor exceptions, the relative ranking of these six designs has remained unchanged. The two exceptions occur with the volume weighting at 10 points and the safety weighting at 22 points. In this case, the first- and second-ranked designs (hemispherically-ended Hafn alloy and Pt-20Rh/T-111/Pt-20Rh capsules, respectively) changed position and the third- and fourth-ranked designs (flat-ended Hafn alloy and Pt-20Rh/T-111/Pt-20Rh capsules, respectively) changed position. Due to the lack of safety data for Hafn alloy, the Hafn alloy designs suffered heavy penalties when the safety criteria weighting was increased to 22 points.

Obviously, many more changes to the weightings and scoring technique are possible. However, the changes in the weightings discussed above are fairly severe and as seen did not affect the ranking of the top designs. It is thus concluded that the rankings of the top designs are not very sensitive to the criteria weightings.

Table 6-8. Sensitivity Analysis

Pressure Relief Device Designs

System	Configuration	Baseline		Volume = 10, Weight = 17		Volume = 10 Cost = 12, Safety = 18		Volume = 10, Safety = 22	
		Score	Rank*	Score	Rank*	Score	Rank*	Score	Rank*
Hafn alloy	Hemispherical	86.5	1	84.8	1	85.6	1	84.4	2
Hafn alloy	Flat	83.0	3	81.6	3	82.3	3	81.8	4
Ta-10W/Hafn alloy	Hemispherical	73.8		72.5		73.6		73.3	
Mo/Hafn alloy	Hemispherical	70.9		69.8		70.6		70.4	
Mo-50Re/Hafn alloy	Hemispherical	74.3		73.1		73.3		73.8	
Pt-20Rh/Hafn alloy	Hemispherical	76.7		75.3		75.8		76.3	
TZM/Pt-20Rh	Hemispherical	78.0		78.3		77.0		77.2	
Ta-10W/T-111/Pt-20Rh	Hemispherical	80.7		78.3		79.5		80.1	
Mo/T-111/Pt-20Rh	Hemispherical	82.0	5	80.0	5	80.7	5	81.4	5
Mo/T-111/Pt-20Rh	Flat	79.6		77.8		79.3		80.1	
Mo-50Re/T-111/Pt-20Rh	Hemispherical	81.5	6	79.3	6	79.6	6	80.9	6
Mo-50Re/T-111/Pt-20Rh	Flat	79.4		77.5		78.5		79.9	
Pt-20Rh/T-111/Pt-20Rh	Hemispherical	84.5	2	82.2	2	83.1	2	84.8	1
Pt-20Rh/T-111/Pt-20Rh	Flat	82.6	4	80.7	4	82.2	4	83.8	3
Ta-10W/TZM/Pt-20Rh	Hemispherical	70.9		70.9		70.7		71.7	
Mo-50Re/TZM/Pt-20Rh	Hemispherical	71.9		72.1		71.0		72.7	
Pt-20Rh/TZM/Pt-20Rh	Hemispherical	74.4		74.3		73.9		75.8	

Selective Vent Designs

System	Configuration	Baseline		Volume = 10, Weight = 17		Volume = 10 Cost = 12, Safety = 18		Volume = 10, Safety = 22	
		Score	Rank*	Score	Rank*	Score	Rank*	Score	Rank*
TZM/Pt-20Rh	Flat	69.5		68.7		69.6		70.9	
Pt-20Rh/Hafn alloy	Flat	76.7		74.4		76.1		77.8	
Pt-20Rh/T-111/Pt-20Rh	Flat	78.1		76.2		77.8		79.4	
Pt-20Rh/TZM/Pt-20Rh	Flat	67.6		67.5		67.0		70.0	
Ta-10W/T-111/Pt-20Rh	Flat	73.5		71.6		73.5		75.2	
Mo/T-111/Pt-20Rh	Flat	73.9		72.1		73.9		75.8	
Mo-50Re/T-111/Pt-20Rh	Flat	75.6		73.8		75.5		77.5	
Ta-10W/TZM/Pt-20Rh	Flat	64.0		63.5		64.9		66.4	
Mo-50Re/TZM/Pt-20Rh	Flat	65.5		65.0		66.2		68.2	

*Sensitivity analysis was applied to all designs, but for clarity, only the top six designs were ranked.

7. CONCLUSIONS

The top-rated heat source for both the 1350° and 2000°F applications is a single-layer Hafn alloy heat source with a PRD and hemispherical ends. This system, however, is not recommended for the current practicability demonstration due to the limited compatibility and fabrication data available for this alloy. It is recommended that the Hafn alloy system be again reviewed and considered for future use in the Heart Program at the end of the current Hafn alloy Development Program. At that time a considerable amount of fabrication experience and compatibility data (both with the fuel and with other materials) will be available, and a new evaluation of the applicability of Hafn alloy to the Artificial Heart heat source can be made.

The next-highest-rated system, and the one recommended for fabrication in the current program, is the Pt-20Rh/T-111/Pt-20Rh design having a non-selective PRD. As can be seen in Table 6-7, 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.

As a result of the Parametric Analysis study, the following additional recommendations are made:

- Additional bullet impact tests should be performed, especially for Hafn alloy, since bullet impact resistance is the controlling design criterion for the strength member.
- Compatibility of the liner with electrorefined PuO_2 must be established.
- Helium release rates from electrorefined PuO_2 fuel should be obtained to verify the safety of the heat source under cremation environments.

8. RECOMMENDED DESIGN

8.1 DESCRIPTION

Requirements imposed on the Artificial Heart heat source by the thermal converter have recently been established by the AEC, as follows:

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

Based on the results of the parametric analyses discussed above, a three-layer, flat-ended heat source, consisting of a Pt-20Rh liner, a nonselective PRD, a T-111 strength member, a Pt-20Rh clad, and a short capillary tube, has been selected. To minimize the "dead" space around it, and thus improve the overall system thermal efficiency, the heat source will have square corners and no protrusions. The heat source will be 0.984 inch in diameter, 1.795 inches long, and will weigh 0.62 lb. A schematic of the heat source is shown in Figure 8-1.

The clearances between, and the thicknesses of, the encapsulating members were determined and optimized by the parametric analyses described above. The Pt-20Rh liner is 0.020 inch thick. Each end cap has a 0.010-inch step to facilitate positioning during the welding operation. One of these caps accommodates the PRD, a shortened and simplified version of the Transit PRD, which extends into a recess in the fuel and is welded flush with the liner cap. The T-111 strength member, sized to survive a 30-06 rifle bullet impact, is 0.095 inch thick. Each end cap includes a 0.040 inch step for positioning and ease of welding. 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. The requirement to minimize external "dead" space, imposed by the thermal converter system, precludes positioning the capillary externally to the heat source. Clad weld joints are similar to those described above.

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

Figure 8-1. Recommended Artificial Heart Heat Source

The capillary is 4 inches long and has an ID of 0.005 inch. One portion of the 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. In addition, the capillary tube reduces the levels of Radon-220 emitted from the heat source to acceptable levels (Section 5.5.3) and minimizes the amount of contaminants entering the interior of the liner.

8.2 MATERIAL COMPATIBILITY

As mentioned in Section 5.4, completely compatible materials do not interact to form new materials whose physical properties differ from those of the original materials in the system. Incompatibility usually results in a system having degraded properties.

8.2.1 Fuel/Liner Compatibility

The fuel to be used in the Artificial Heart heat source is electro-refined (very high purity), oxygen-16 enriched, pressed and sintered plutonium-238 oxide. Unfortunately, no data exist for the compatibility of this 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. These impurities in the 98-percent pure production grade material definitely contribute to the chemical interactions. Electro-refined PuO_2 will have an impurity level of less than 0.05 percent (550 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} where $x \leq 0.2$, is desirable in the case of refractory metal liners since there would be no source of 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 15 and 16). 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 17).

Based on conversations with AEC/DAT and LASL (Reference 18), the fuel to be used for the Artificial Heart application will be 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} .

8.2.2 Intercomponent Compatibility

Since the proposed liner and clad materials are the same, the only other material interface of concern in the proposed design is the Pt-20Rh/T-111 interface. A considerable amount of data has been collected for these materials, as shown in Table 8-1. 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 0.007 inch at

Table 8-1. 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
19	3.0	0.0001	0.0004	0.0012			
20	3.1						0.0049
20	4.2				0.0016		
20	16.8				0.0025	0.0028	
19	30.0	0.0002	0.0007	0.0030			
20	42.0					0.0072	
21	271		0.0021	0.0070			

1900°F. As indicated in Section 5.4 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 8-2 taken from Reference 2. 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 (total thickness equals the thickness required to survive bullet impact plus thickness of interaction zones). The thicknesses of the liner and clad are also larger than the thickness of the interaction depth. Thus the design is considered acceptable.

Figure 8-2. Pt-20Rh/T-111 Interaction

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APPENDIX
CANDIDATE HEAT SOURCE VOLUME AND WEIGHT
VERSUS DIAMETER FOR A 40-WATT THERMAL INVENTORY

Analyses were carried out to determine the effects of heat source diameter and geometry (hemispherically- and flat-ended cylinders) on the candidate heat source volume and weight. This appendix presents the data generated, in graphical form, for the two geometries considered and for diameters ranging from 0.8 to 2.0 inches. The radioisotope thermal inventory was 40 watts. The volumes and weights include fuel, voids, liners, strength members, and clads, where applicable. For this round of calculations fine design details such as coatings, PRDs, and capillary tubes were omitted since they had not yet been defined at the time of the analysis and since they do not have a significant effect on the total heat source volume or weight. The distinction made between PRD and selective vent designs refers instead to component thicknesses required to make the candidate design compatible with that type of vent. Each of these figures was used to choose the optimum configuration (geometry and diameter) of the candidate design. Once these were selected, a detailed weight and volume calculation was made for each component including the vent, capillary tube, and coatings (if required).

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. A1

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. B1

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. B2

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350⁰F Design

PRD Type Vent

Candidate Materials

Liner: Mo-50Re
S. M.: Hafn alloy
Clad :

Legend:

--- Flat Shaped Ends
— Hemispherically Shaped Ends

DESIGN NO. B3

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. B4

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. C1

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

Selective Type Vent

DESIGN NO. D1

Heat Source Volume & Weight at Source Outside Diameter

1350°F Design

Selective Type Vent

VOLUME IN³

3.2

Pt-20Rh
Hafn alloy

Flat Ends
Conically Shaped Ends

1.4 1.8 1.9 2.0

DESIGN NO. E1

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. F1

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. F2

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. F3

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. F4

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. F5

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

Candidate Materials

Liner: Mo-50Re
S. M.: TZM
Clad: Pt-20Rh

Legend:

--- Flat Shaped Ends
— Hemispherically Shaped Ends

DESIGN NO. F6

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

PRD Type Vent

DESIGN NO. F7

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

Selective Type Vent

DESIGN NO. G1

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

Selective Type Vent

DESIGN NO. G2

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

Selective Type Vent

DESIGN NO. H1

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

Selective Type Vent

DESIGN NO. H2

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

Selective Type Vent

DESIGN NO. H3

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

Selective Type Vent

DESIGN NO. H4

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 1350°F Design

Selective Type Vent

DESIGN NO. H5

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

PRD Type Vent

DESIGN NO. A1

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

PRD Type Vent

DESIGN NO. B2

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

PRD Type Vent

DESIGN NO. B3

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 2000⁰F Design

PRD Type Vent

DESIGN NO. B4

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

PRD Type Vent

Candidate Materials

Liner:
S. M.: TZM
Clad : Pt-20Rh

Legend:
--- Flat Shaped Ends
— Hemispherically Shaped Ends

DESIGN NO. C1

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

Selective Type Vent

Candidate Materials

Liner:

S. M.: TZM

Clad : Pt-20Rh

Legend:

--- Flat Shaped Ends

— Hemispherically Shaped Ends

DESIGN NO. D1

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

Selective Type Vent

DESIGN NO. E1

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

PRD Type Vent

DESIGN NO. F2

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

PRD Type Vent

Candidate Materials

Liner: Mo-50Re
S. M.: T-111
Clad : Pt-20Rh

Legend:

--- Flat Shaped Ends
— Hemispherically Shaped Ends

DESIGN NO. F3

Total Heat Source Volume & Weight
Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

PRD Type Vent

DESIGN NO. F4

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

PRD Type Vent

DESIGN NO. F6

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

PRD Type Vent

DESIGN NO. F7

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

Selective Type Vent

DESIGN NO. G1

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

Selective Type Vent

DESIGN NO. G2

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

Selective Type Vent

DESIGN NO. H2

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

Selective Type Vent

DESIGN NO. H3

Total Heat Source Volume & Weight Vs. Heat Source Outside Diameter

40 Watts, 2000°F Design

Selective Type Vent

DESIGN NO. H5