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RADIOISOTOPE HEATER DEVELOPMENT PROGRAM
SUMMARY REPORT

by
M. W. HULIN

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by

Donald W. Douglas Laboratories, Richland, Washington
McDonnell Douglas Astronautics Company--Western Division

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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RADIOISOTOPE HEATER DEVELOPMENT PROGRAM

PHASE I STUDY SUMMARY REPORT *
(Contract No. NAS 9-8846)

By M. W. Hulin**

SUMMARY

The Donald W. Douglas Laboratories (DWDL), a directorate of the McDonnell Douglas Astronautics Company-Western Division, conducted a 5-month preliminary design and program planning study of a family of small (1- to 50-W) radioisotope heaters for manned spacecraft thermal control applications covering mission times of from 14 days to 5 years.

A survey of manned spacecraft programs was conducted within the McDonnell Douglas Astronautics Company and the NASA Manned Spacecraft Center to determine current and future thermal requirements for space components, and potential applications for radioisotope heaters. Approximately 37 applications were identified, requiring 180 to 300 heaters ranging in power from <1 to over 100W. Safety, design, and materials criteria were determined, and reference heater designs developed. Safety and optimization analyses were performed; manufacturing processes and quality assurance programs identified; and program plans and cost estimates formulated for phases II and III.

The primary objectives of the phase I study program were met: (1) Potential applications were identified for radioisotope heaters; (2) it was established that small radioisotope heaters can be made which meet the selected safety criteria and have a high probability of being safety- and flight-qualified; (3) an optimum group of radioisotope heaters was determined that would meet the requirement for a maximum number of applications and mission times of from 14 days to 5 years; and (4) program plans and budget estimates for phases II and III were developed. Results of the optimization analyses indicate that two heater sizes, 10 and 50 W, using two isotopic fuels, promethia and plutonia, will satisfy the majority of identified applications and missions.

Based on the phase I study, DWDL strongly recommends that phases II and III of this program be initiated without undue delay, and funded at a level required to produce flight-qualified hardware.

*MDAC/DWDL Report No. DAC 63371.

**Program Manager, Projects and Systems, Donald W. Douglas Laboratories, Richland, Washington.

INTRODUCTION

In September 1968, phase I of a three-phase program was undertaken by DWDL to develop a family of small radioisotope heaters for use in manned-spacecraft components. The technical portion of this program covered a period of 5 months. The primary objectives were to: Identify possible applications for small (1- to 50-W) radioisotope heaters in manned spacecraft systems; develop a radioisotope heater design to meet selected safety criteria with a high probability of being safety- and flight-qualified; develop an optimum group of radioisotope heaters that will satisfy the maximum number of applications and mission times of from 14 days to 5 years; develop program plans and budget estimates for phases II and III.

PROGRAM APPROACH

To accomplish the phase I study, the program was divided into 10 tasks:

1. Application studies - Review, investigate, and document potential radioisotope heater applications associated with crew system equipment.

2. Safety analysis - Establish safety criteria and constraints, using NASA/MSC and AEC inputs; and perform detailed safety analyses.

3. Design and analysis - Characterize heater configurations, temperatures, heat transfer modes, and power levels; and identify optimum sizes and power levels to span the 1- to 50-W range.

3a. Specific application - Apply an isotope heater design to a specific thermal control problem specified by NASA/MSC.

4. Reference designs - Produce reference heater designs for AEC and NASA/MSC review and selection prior to development.

5. Radioisotope fuels and encapsulating materials - Select fuels and materials that are compatible; meet all requirements for operational and environmental conditions; and are state-of-the-art or near term state-of-the-art.

6. Manufacturing processes and inspection techniques - Define processes and techniques required to manufacture radioisotope thermal heaters.

7. Coordination with AEC - Coordinate safety and design criteria and design approaches with AEC.

8. Program plans and budget estimates for phases II and III - Prepare program plans and budget estimates for phases II and III, and present program options for production of flight-qualified hardware.

9. Preliminary safety analysis report description - Prepare a preliminary description of a typical safety analysis report.

10. Program management and reports - Prepare monthly reports and presentation material on tasks 1 through 9; prepare a summary and a final report on the phase I study; and provide the direction required to achieve program objectives.

The interrelationship of these tasks is shown in figure 1. Applications studies, safety analysis, and radioisotope materials were inputs to the design and analysis task. Results of the design and analysis task were used to establish reference designs from which detailed specifications and final designs can be made. Data and results from tasks 1 through 5 were inputs to task 6, Manufacturing Processes and Inspection Techniques, and task 8, Program Plans and Budget Estimates for phases II and III. These later programs have an important bearing on phases II and III since they describe in detail the plan for developing and qualifying the radioisotope heaters. Task 7 provided for review and comment by the AEC concerning safety and design criteria, reference designs, materials selection, manufacturing program logic, and program plans and cost estimates for phases II and III.

TECHNICAL ACCOMPLISHMENTS

The program was initiated by discussing current and future requirements for thermal heaters in manned-spacecraft components with program personnel both within the McDonnell Douglas Astronautics Company and the NASA Manned Spacecraft Center on programs such as Space Laboratories, Saturn/Workshop, Launch Vehicles, Manned Orbital Laboratory, Advanced Manned Orbital Laboratory, Gemini, Big "G" (Gemini), Apollo, and AAP.

Approximately 37 applications were identified requiring from 180 to 300 heaters ranging in power from 1 to 50 W. Five representative applications are shown in table 1. The temperatures are typical--well below 500°F. Therefore, heater design requirements were somewhat less stringent because the only primary design problem was the thermal spike during launch abort and reentry.

Use of radioisotope heaters depends on their superior safety, performance, and engineering justifications. Recognition that the heaters must be designed to present an insignificant hazard in anticipated mission or credible abort environments led to the following guidelines: There must be no danger or special requirements imposed on astronauts performing their normal duties aboard a spacecraft; and the possibility of injurious radiation doses as a result of credible accidents or incorrect handling must be negligible.

Using these guidelines, the following safety criteria were generated:

- Design to allow industrial handling
- Survival in fireball, overpressure, and debris.
- Intact reentry from lunar return, earth orbit, and suborbital abort.

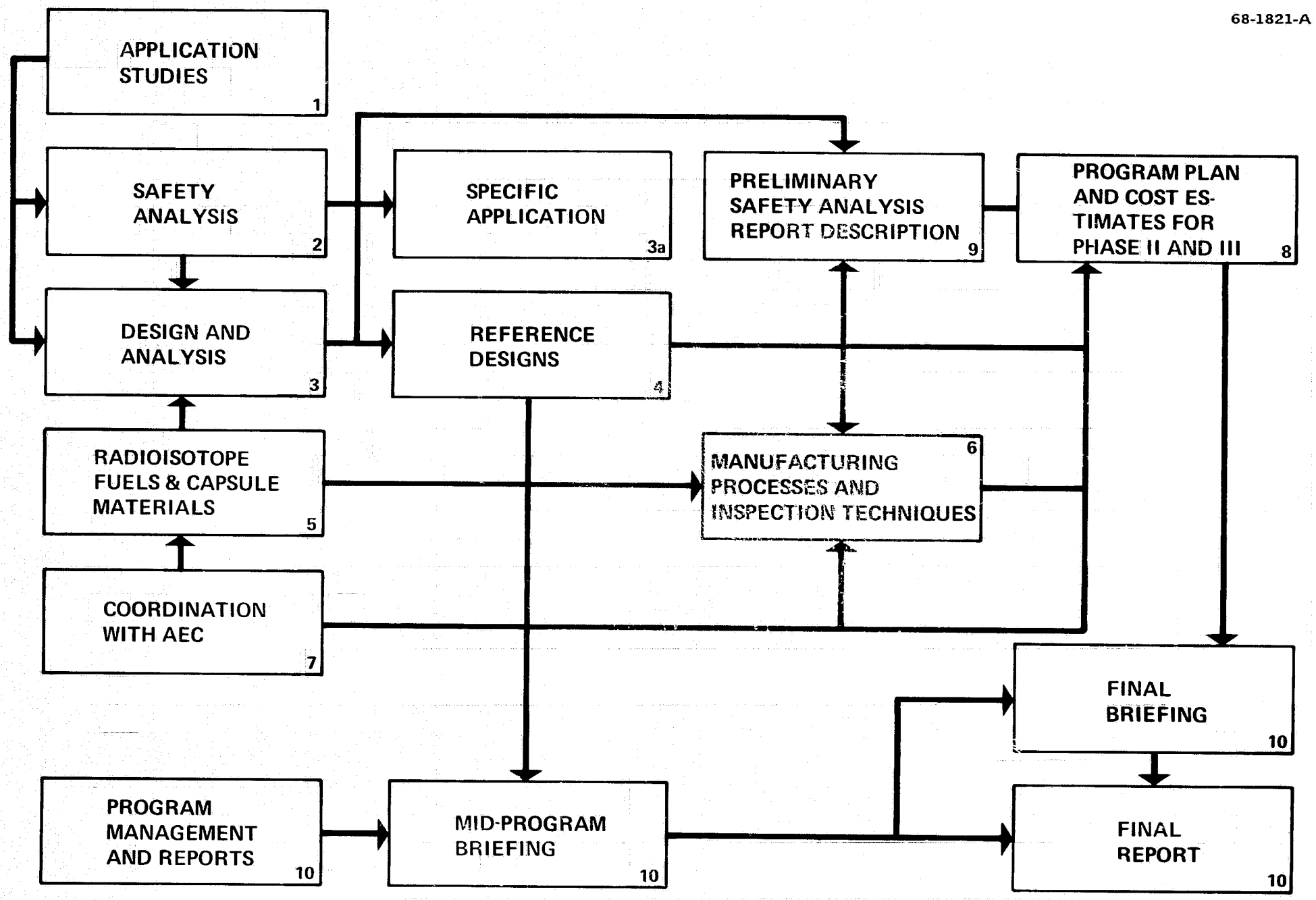


Figure 1. Phase I Program Tasks

TABLE 1

TYPICAL THERMAL CONTROL APPLICATIONS

Description	Power requirement (W)	Thermal requirement (°F)	No. per vehicle	Total required	Remarks
Waste water dump systems	3-1/2 to 10	50 to 100	3 to 5	9 to 15	Urine dump, fuel cell water dump, experiment effluent dump, (EOSL, MOL, Saturn/Workshop)
Standby fuel cell heat		70	3	3	Standby fuel cell must be available at all times (MOL)
Battery temperature control	~10 to 50	68 to 80	1 per battery	1 per battery	Heat required during standby mode; power required depends on battery size
Engine valve heater	< 50	40 to 140	4 to 8	12 to 24	Thermal profile is function of vehicle orientation, but cyclic operation is required (EOSL, MOL, Saturn/Workshop)
Structural cold spots	~ 40	60	2 to 4	4 to 8	Needed at interface between dome ends and cylindrical surface on crew compartment (EOSL, MOL)

- Ocean release resulting in less than 10^{-2} maximum permissible concentration (MPC) at the ocean surface.

- Intact impact at terminal velocities.

- Resistance to corrosion for 10 half-lives.

- Integral shielding to provide protection for astronauts, ground handling crews, and inexperienced persons.

Satisfactory industrial handling characteristics will be ensured by designing to ORNL Class C III structural and thermal test conditions. Intact reentry will be ensured by providing protection against reentry debris and ablation. Static pressure resistance will maintain capsule integrity to depths where isotope concentration at the ocean surface will be $<10^{-2}$ MPC. Heaters will be designed and tested for maximum assurance of intact impact on granite. Since it is desirable to limit astronaut dose rates to International Committee on Radiation Protection maximum occupational exposure (ICRP-MOE) levels, the integral shield is designed to limit the dose rate to 5 mr/hour at 1 meter. This also minimizes the need for ground handling procedures and equipment, and provides significant protection against injury in the event of incorrect handling.

Next, using the safety, environmental, and thermal requirements as guidelines, the following design criteria were established:

- Thermal output of 5 to 50 W at beginning of operational life.

- Mission times of from 14 days to 5 years.

- 20-year orbital life.

- Normal heater operating temperatures of <500°F.

- Intact reentry from lunar return, earth orbit, and suborbital abort.

- Launch pad abort survival from Titan IIIM, Saturn 1B, and Saturn V launch vehicles.

- Ten half-life corrosion lifetimes.

- Helium containment for 10 half-lives.

- Radiological dose rates of less than 5 mr/hour at 1 meter.

- Launch vibration load survival up to 44.9 g sinusoidal and 23.7 g random.

These criteria are translations of the safety and application requirements into workable quantities. They provided the framework for determining the analyses required to establish and verify radioisotope heater designs. Detailed analyses were completed in the following areas: Normal operation

thermal analysis; aerothermodynamic analysis, including reentry environment and thermal response; structural analysis (ocean burial), 20-year reentry, impact, corrosion, and oxidation; radiation shielding; accident and failure modes; and radiological hazards and consequences.

These data were used to develop the typical design shown in figure 2, and provided the necessary ground rules for selecting heater materials. Choices of fuel form and materials, and the reasons for these decisions, are briefly summarized below.

Fuel

The fuel forms chosen for detailed analysis (based on half-life, shielding, impact, availability, cost, compatibility, and state of development) were $^{147}Pm_2O_3$-W cermets, $^{238}PuO_2$ bare microspheres (plasma-fired or sol-gel), and $^{238}PuO_2$-Mo cermets. Final selection will depend on mission life and on the state-of-the-art in fuel development. A brief comparison of these fuel forms is presented in table 2.

Primary Containment Vessel

Arc-cast tantalum was chosen as the primary containment vessel material because of its high melting point, ease of fabrication, availability, and low cost. The only function of the primary containment vessel is to allow handling during heater fabrication.

Impact Energy Absorbent Layer

Tantalum foam was used as the energy absorber in development and analysis of reference designs. However, tantalum wool may be superior from impact and cost standpoints.

Structural Container

The choice for structural container material was T-111, primarily due to shielding considerations, strength in the 2000° to 2200°F temperature range anticipated during certain reentry trajectories, and high impact-energy absorption characteristics. Oxidation and sea water corrosion resistance of T-111 is also favorable.

Oxidation Barrier

Platinum was selected as the barrier because of its excellent resistance to sea water corrosion and oxidation, and its high melting point.

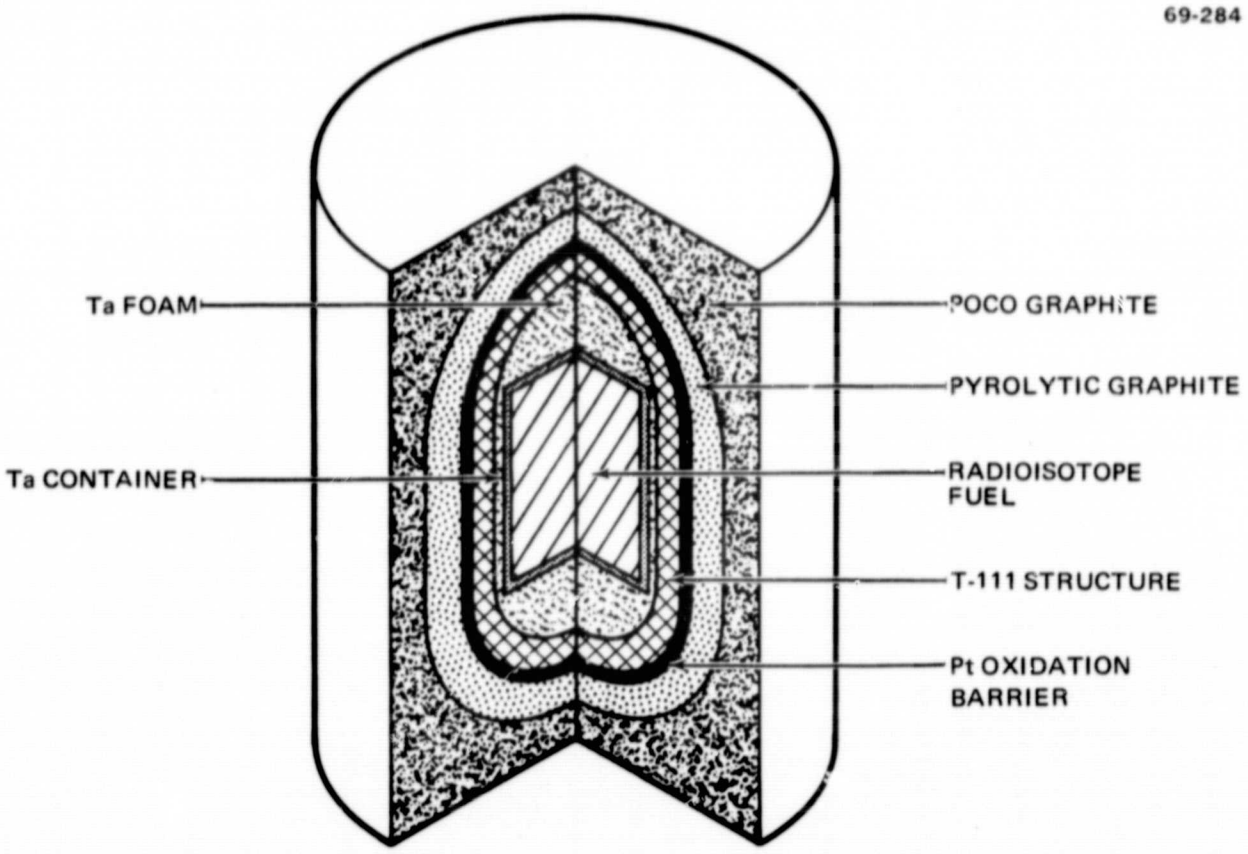


Figure 2. Typical Reference Heater Design

TABLE 2

FUEL FORM COMPARISON

	$^{147}Pm_2O_3$-20 v/o W cermet	$^{238}PuO_2$-20 v/o Mo cermet	$^{238}PuO_2$-20 m/o ZrO_2 solid solutions	$^{238}PuO_2$ bare microspheres (62.5% packing fraction-95% T. D.)
Power density (W/cc)	1.4	3.66	3.5	2.86
Specific gravity fuel form	9.13	10.12	9.65	6.31
Helium release	No He; β-emitter	Not known; estimate less than solid solution or microspheres	Estimated to be similar to microspheres	Estimated 5% to 20% at 2100°F for 5 min
Impact resistance	Superior	Superior results with W matrix	Poor	Poor
Half life	2.6 yr	87.4 yr	87.4 yr	87.4 yr

Thermal Insulation Layer

Pyrolytic graphite was chosen for thermal insulation because of its favorable values of thermal conductivity in both "a" and "c" directions. The material is also highly resistant to long term degradation at temperatures corresponding to normal heater operation.

Ablator Material

The prime candidate for ablative reentry protection is POCO graphite. Charring ablators such as carbon-fiber-reinforced phenolic are second choice because of possible degradation during normal heater operation.

Refractory Vs Superalloy

DWDL has investigated the use of a superalloy for a structural container and/or oxidation barrier. The superalloys are less expensive and perhaps more easily workable than are the refractories but they have some very significant disadvantages.

For shielding, the Pm 10-W heater requires a 0.060-in.-thick T-111 structural shell, while, to keep the dose rate under the design criteria of 5 mr/hour at 1 meter, 0.63 in. of Hastelloy-X is required. This gives a total heater weight of 4.059 lb for Hastelloy-X compared to 1.014 lb for the T-111 shell. For the 50-W heater, structural shell thicknesses are 0.120 in. for T-111 and 1.13 in. for Hastelloy-X; weights are 3.402 and 16.68 respectively. These weight differences more than offset the small savings in materials cost per capsule.

Strength of the superalloy is poor above 2000°F; typically, the yield strength of T-111 is 68×10^3 psi at 2000°F, while that of Hastelloy-X is about 7×10^3 psi. Reentry analyses indicate that the structural shell temperature will reach approximately 2100°F during an earth orbital decay trajectory. The superalloy would have to be kept below this temperature because of helium containment considerations; this would require an additional insulation material such as pyrolytic graphite. In a Saturn V launch pad abort environment, performance of superalloys would be questionable because of their relatively low melting points (2300° to 2600°F) compared to 3200°F for platinum.

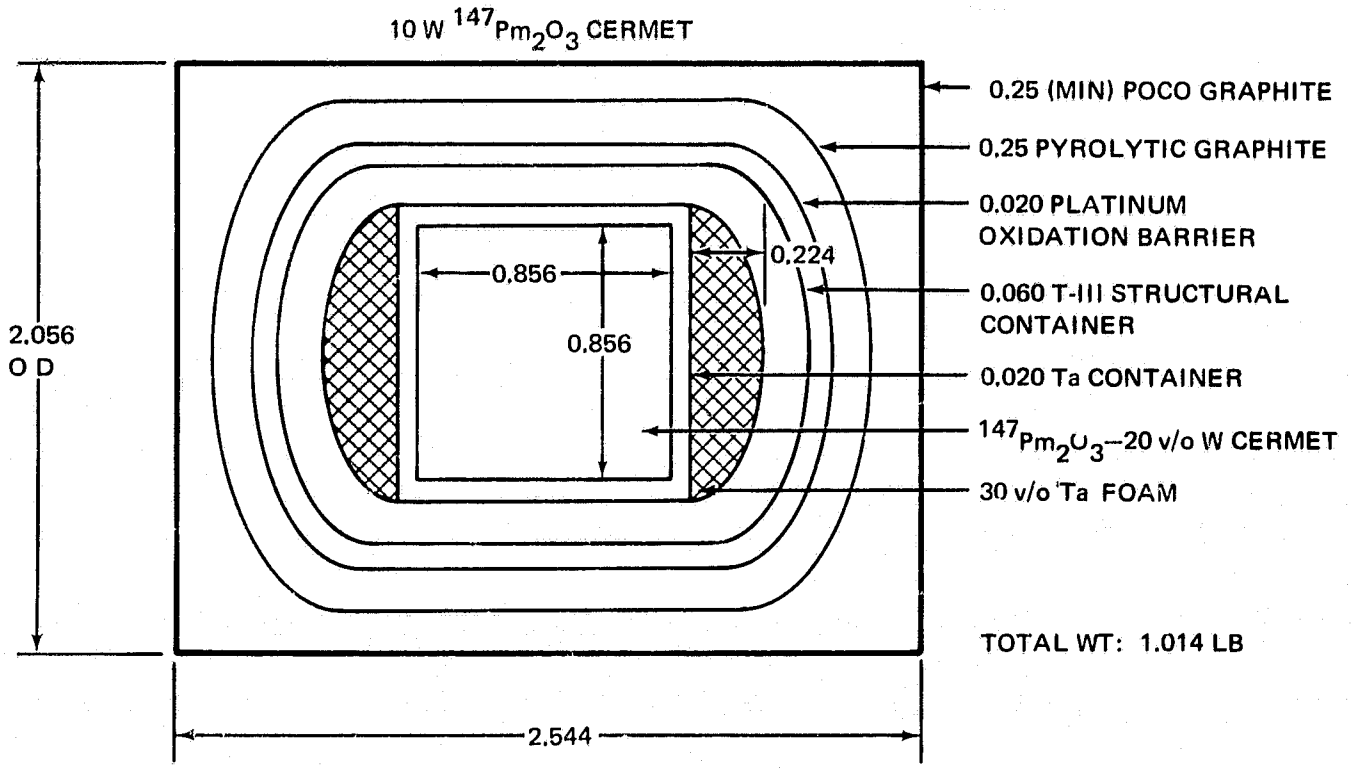
Based on these considerations, a superalloy would not appear to be a good choice.

Reference Design Details

Figures 3 and 4 are typical of the family of isotope heaters developed during the phase I study. Design details for 10- and 50-W promethia and plutonia heaters are shown. A nominal 1- to 1 void volume to fuel volume ratio is incorporated in the plutonia heater designs. Specific powers for the promethia 10- and 50-W heaters are 9.9 and 14.7 W/lb respectively; and for plutonia 10- and 50-W heaters, 13.6 and 20.6 W/lb respectively.

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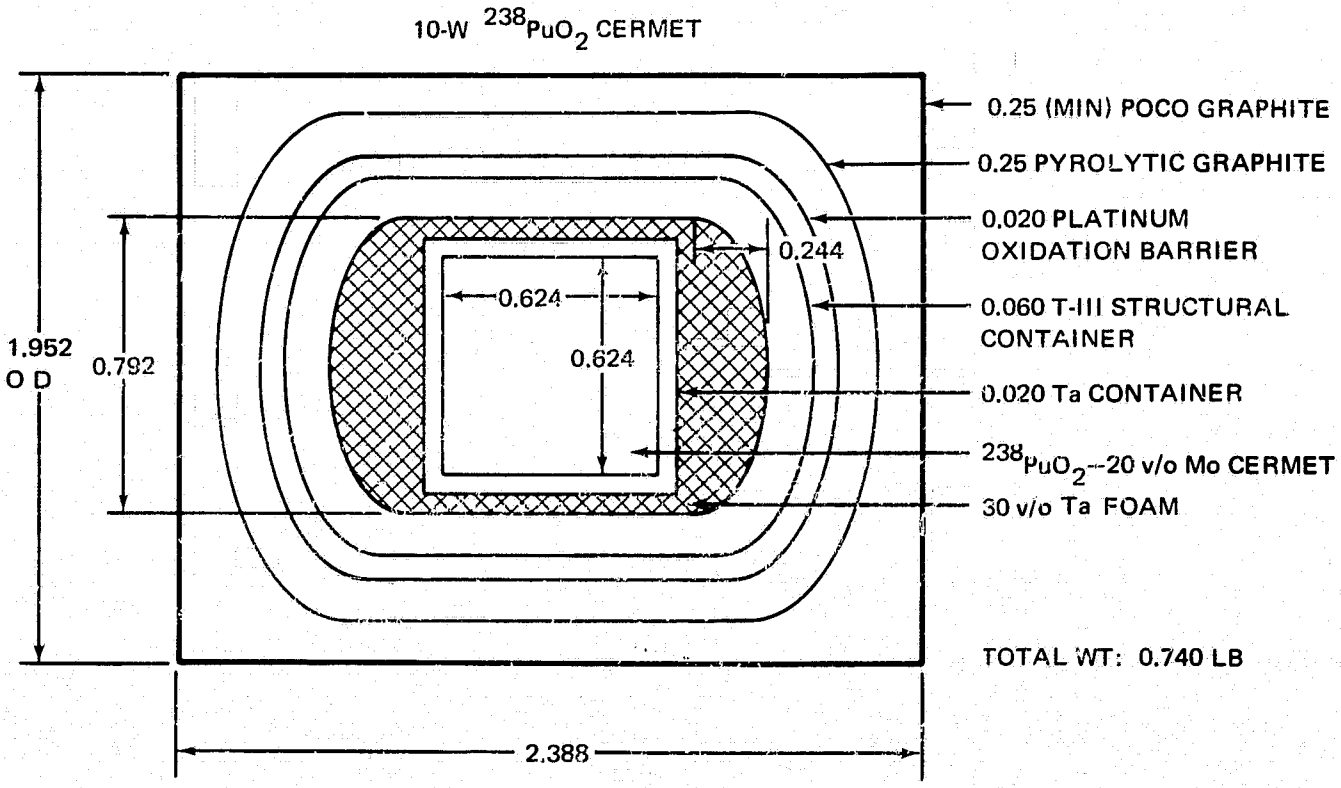
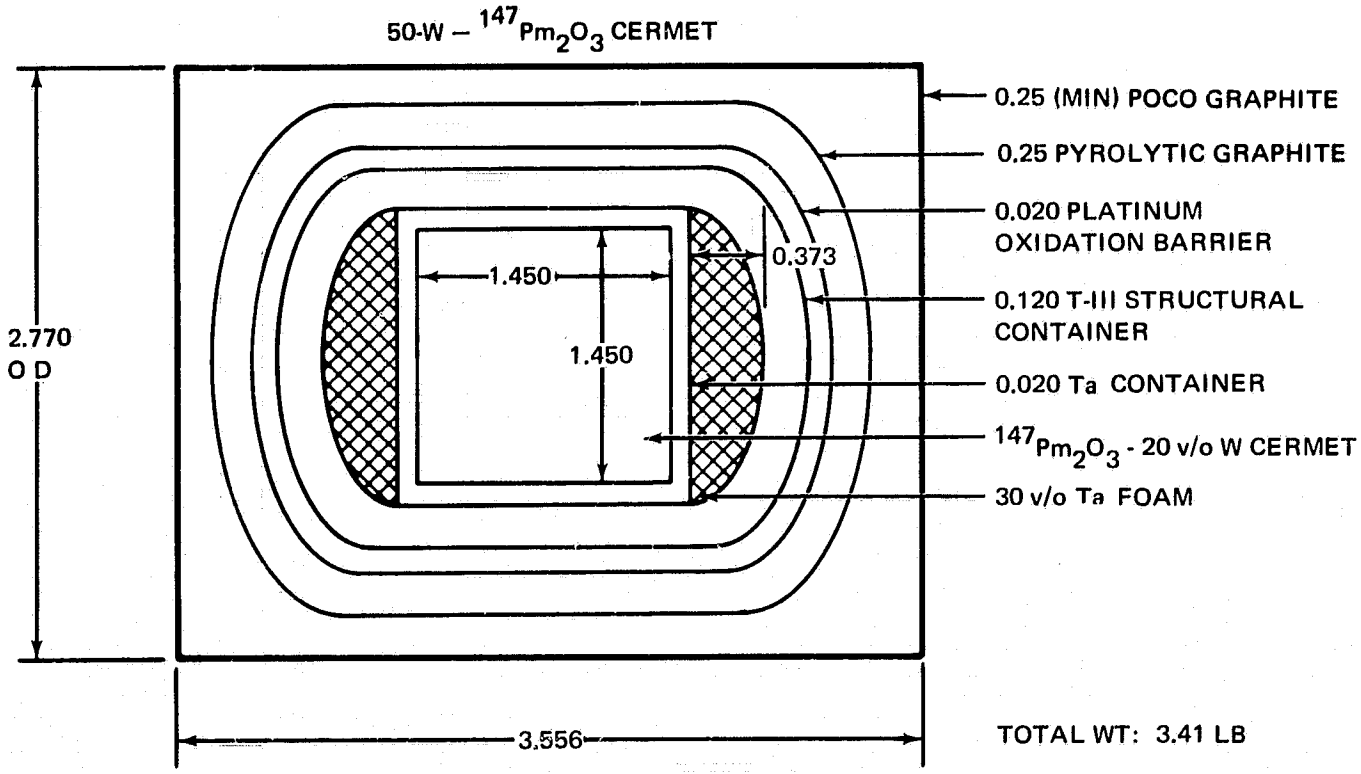


Figure 3. 10-W Reference Heater Designs

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DIMENSIONS
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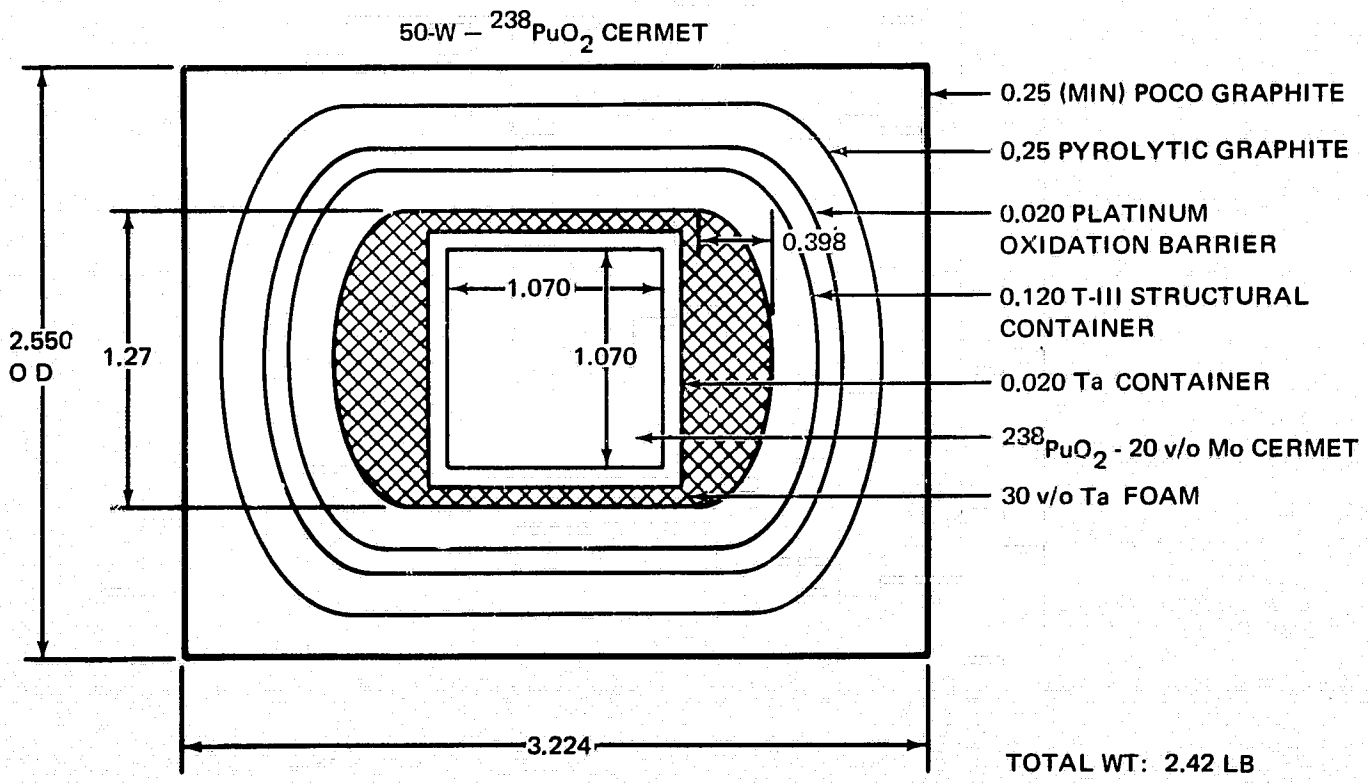


Figure 4. 50-W Reference Heater Designs

Table 3 gives the weights of 5-, 10-, 25-, and 50-W Pu and Pm cermet heaters. Figure 5 presents a weight-vs-power curve for combinations of the same and different heater sizes. This curve is based on Pm heater weights but the same conclusions are valid for Pu. The number(s) in each power level interval represents the lightest heater or combination of heaters that satisfies the power requirements of that interval.

Figure 5 shows that weight differences between the lightest and next heaviest heaters or combinations of heaters are small (generally <1 lb). The important point is that all applications can be satisfied (without incurring a significant weight penalty) by using 10- and 50-W heaters either individually or stacked and/or diluted.

Pm and Pu heaters of the same uniform size have identical outer dimensions and all material thicknesses are the same from the structural shell outward. The power density of PuO_2 is more than twice that of Pm_2O_3, and even with the nominal 1-to-1 void/fuel volume ratio, the Pu uniform-size heater is somewhat lighter than its Pm counterpart. Note (table 3) that the 10-W Pu cermet minimal heater size is 0.224 lb lighter than the uniform size, while the 50-W Pu heater is 0.781 lb lighter.

Again, the weight penalty is small compared to the additional cost of fabricating and qualifying two heater sizes for one power level. Many of the qualification tests such as ablation, impact, vibration, and launch abort debris could be performed with one heater size for each power level selected. Engineering analyses and manufacturing development costs would also be reduced by a uniform heater size approach. Due to the small weight differences (0.224 and 0.781lb), it would be difficult to justify the minimal size approach, considering that a great number of heaters per mission would be required to amortize the cost of two heater-sizes for one power level. In addition, the uniform size approach permits interchangeability of Pm and Pu heaters, since only one mounting arrangement is required for each power level. These are only reference designs; the final design will be selected early in the phase II program.

Alternate Design Comparisons

Six radioisotope heater concepts considered during the phase I study are shown in table 4. Design and safety analyses identified the relative weight and safety characteristics for different structural and ablator shapes. Improved structural characteristics were obtained by avoiding sharp corners and small radii. The sphere concept, while offering attractive weight and safety advantages, suffers from lack of fuel fabrication state-of-the-art experience. Analysis showed that there is a distinct safety advantage, from the standpoint of reentry and impact, in heater shapes having high drag coefficients. This results in lower heating and lower impact velocities upon reentry. The table shows that flat-faced configurations have reentry impact velocities significantly lower than other shapes.

TABLE 3

HEATER WEIGHTS

Pm_2O_3 cermet	Weight (lb)
PMC-5-1	0.697
PMC-10-2	1.014
PMC-25-1	2.036
PMC-50-2	3.410
PuO_2 cermet (Minimum size)	
PUC-5-1	0.530
PUC-10-3	0.740
PUC-25-1	1.524
PUC-50-3	2.423
PuO_2 cermet (Uniform size)*	
PUC-10-4	0.964
PUC-50-4	3.205
* All dimensions and material thicknesses of structural shell out to and including POCO graphite ablator are identical for the Pm and Pu heater designs.	

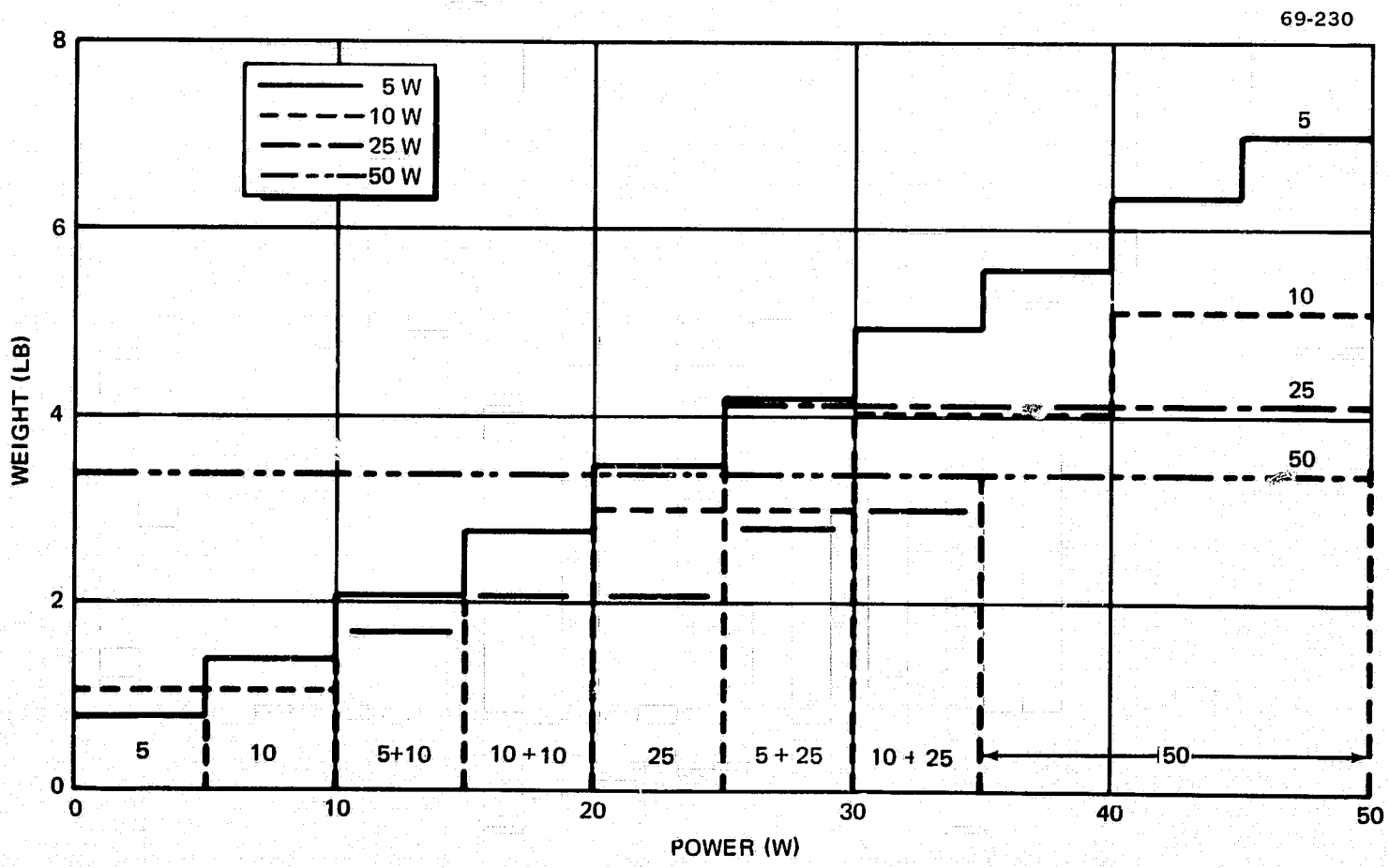


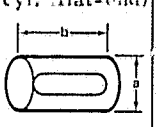
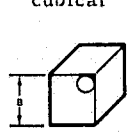
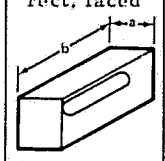
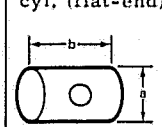
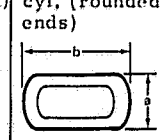
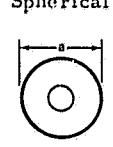
Figure 5. Heater Weight Vs Power Comparison

Table 4 also shows an overall weight and volume summary for the six concepts. For the same outer ablator shape--whether a parallelepiped or cylinder--overall weights for spherical inner capsule designs are about 10% lower than for cylindrical inner capsule designs.

The cubic or rectangular heater shape results in the heaviest ablator, while the spherical or cylindrical heater with rounded ends corresponds to the lightest. The reference flat-ended cylinder is in between.

TABLE 4

HEATER CONCEPT COMPARISON FOR PROMETHIUM FUEL

Capsule shape Ablator shape	Cylindrical cyl. (flat-end)  Reference design		Spherical cubical  Alternate A		Cylindrical rect. faced  Alternate B		Cylindrical cyl. (flat-end)  Alternate C		Cylindrical cyl. (rounded ends)  Alternate D		Spherical Spherical  Alternate E	
Weight summary (lb)	10W	50W	10W	50W	10W	50W	10W	50W	10W	50W	10W	50W
Bare capsule	0.49	2.26	0.40	1.84	0.49	2.26	0.40	1.84	0.49	2.26	0.40	1.84
Pyro graphite	0.14	0.34	0.11	0.28	0.14	0.34	0.11	0.28	0.14	0.34	0.11	0.28
POCO graphite	0.36	0.81	0.58	1.36	0.55	1.24	0.42	0.94	0.25	0.51	0.22	0.43
Total wt	1.01	3.41	1.09	3.48	1.18	3.84	0.93	3.06	0.88	3.11	0.73	2.55
Dimensions (in.)												
a	2.06	2.77	2.18	2.98	2.06	2.77	2.18	2.98	2.06	2.77	2.18	2.98
b	2.54	3.56	---	---	2.50	3.52	2.18	2.98	2.50	3.52	---	---
Total vol (in.^{3})	8.70	21.41	10.36	26.46	10.57	26.97	8.14	20.78	6.53	17.11	5.43	13.86
Impact velocity (ft/sec)												
End-on	245	333	178	232	196	262	221	293	382	532	423	578
Edge or side on	329	438	131	171	178	233	328	435	330	448		
W/A (lb/ft^2)												
End-on	44.0	81.5	33.2	56.4	40.2	72.1	35.9	63.2	38.3	74.3	28.2	52.6
Edge or side on	27.9	49.9	23.5	39.9	33.2	56.7	28.2	49.6	28.7	52.5		

The flat-ended cylindrical heater configuration with a cylindrical fuel container was selected on the basis of state-of-the-art fabrication technology and ability to survive reentry heating and impact. Flat-faced configurations, while having lower heating rates and impact velocities, incur weight, volume, and surface-area penalties. Also, more analyses and tests are required to determine the stability of these shapes under all phases of mission operations and environments, and credible accidents.

Summary of Trajectory Calculations

Reentry trajectory calculations for both earth and lunar return were made, using an improved version of the RESTORE computer code originally developed at Atomics International. A summary of lunar return trajectory

quantities for promethia cermet reference heater designs is presented in table 5. Extreme reentry angle conditions are -5.2° and -90°, the minimum and maximum for an Apollo mission. In the cases studied, maximum integrated heating and ablation occur at -6.25° side-on, nonspinning; the peak heating rate occurs at -90° side-on, nonspinning; and the maximum T-111 temperature occurs with the -5.2° lunar return.

PHASES II AND III PROGRAM PLAN

Phase I program tasks were structured to cover major technical areas of design and safety analysis, materials selection, manufacturing, and quality assurance. One output of these individual tasks was a detailed description and statement of the phase II and phase III work required to successfully fabricate and qualify the heaters. Phase II will be initiated by performing a detailed analysis and evaluation of the reference designs, selected materials, and development test program. Based on this information, Manufacturing and Quality Assurance will prepare plans and estimates for heater fabrication and inspection. Similarly, Test Engineering will determine the needed development and qualification test programs. Identified tasks and a proposed schedule for phases II and III are shown in table 6.

A detailed plan for development and testing of heater hardware and prototype heaters has been developed. Each component will be tested alone and/or in combination with related components. Development testing and design will be an iterative process and progress in stages.

The interrelationship and sequence of the development tests are shown in figure 6. Rectangular blocks represent identified tests. This diagram shows that some tests can be conducted independently, while other tests are dependent on the results from a number of preceding tests.

Close liaison with AEC concerning definition of the required safety test program will further enhance the probability of expedited interagency Safety Panel and Space Council approval for ultimate flight application. Fuel delivery requirements and lead times are established to ensure availability of the radioisotopes when needed. Coordination of the planning activity with AEC, and NASA inputs and agreement, will minimize the elapsed time between phase I completion and initiation of subsequent phases.

A number of program options were prepared for development of flight-qualified radioisotope heaters. The programs are presented in the order recommended. All except option 2 have an 18-month schedule for completion.

Option 1 - A program for development, testing, and qualification of a complete set of heaters consisting of two sizes, 10 W and 50 W, and two fuels, $^{147}Pm_2O_3$ cermet and $^{238}PuO_2$ microspheres. Industrial test facilities would be used.

TABLE 5

SUMMARY OF REENTRY QUANTITIES FOR LUNAR RETURN

Heater and Trajectory	Flight Orientation	T_{111} Max Temp (°F)	Peak Heating Rate (Btu/ft²-sec)	Time to Peak Heating Rate (sec)	Integrated Heating (Btu/ft²)	Time to Impact (sec)	Impact Velocity (ft/sec)	Ablator Thickness (in.)
50-W Pm_2O_3								
6-1/4°	End-on	1645	888*	75	53 045*	308	333	0.11*
6-1/4°	Side-on nonspinning	1574	1140*	70	63 430*	350	438	0.22*
6-1/4°	Side-on spinning	1683	411	70	22 800	350	438	0.04
90°	End-on	797	4355*	8	14 532*	88	333	0.03*
90°	Side-on nonspinning	826	5040*	7	15 960*	136	438	0.06*
90°	Side-on spinning	947	1810	7	5470	136	438	0.02
5.2°	Side-on spinning	2496	273	90	41 200	587	438	0.06
10-W Pm_2O_3								
5.2°	Side-on spinning	2315	270	90	26 500	497	329	0.04

*At stagnation point

Option 2 - The same as option 1 except that the program would be conducted in increments and spread over 28 months or 3 fiscal years. Industrial test facilities would be used.

Option 3 - Identical to option 1 except that major tests would be performed at government test facilities.

Option 4 - A minimum-cost version of option 3; government test facilities would be used for a minimum development test program.

Option 5, 6, 7, and 8 - Programs to develop a single-size single-fuel heater under a minimum development test program, using government test facilities.

All options include a complete series of qualification tests.

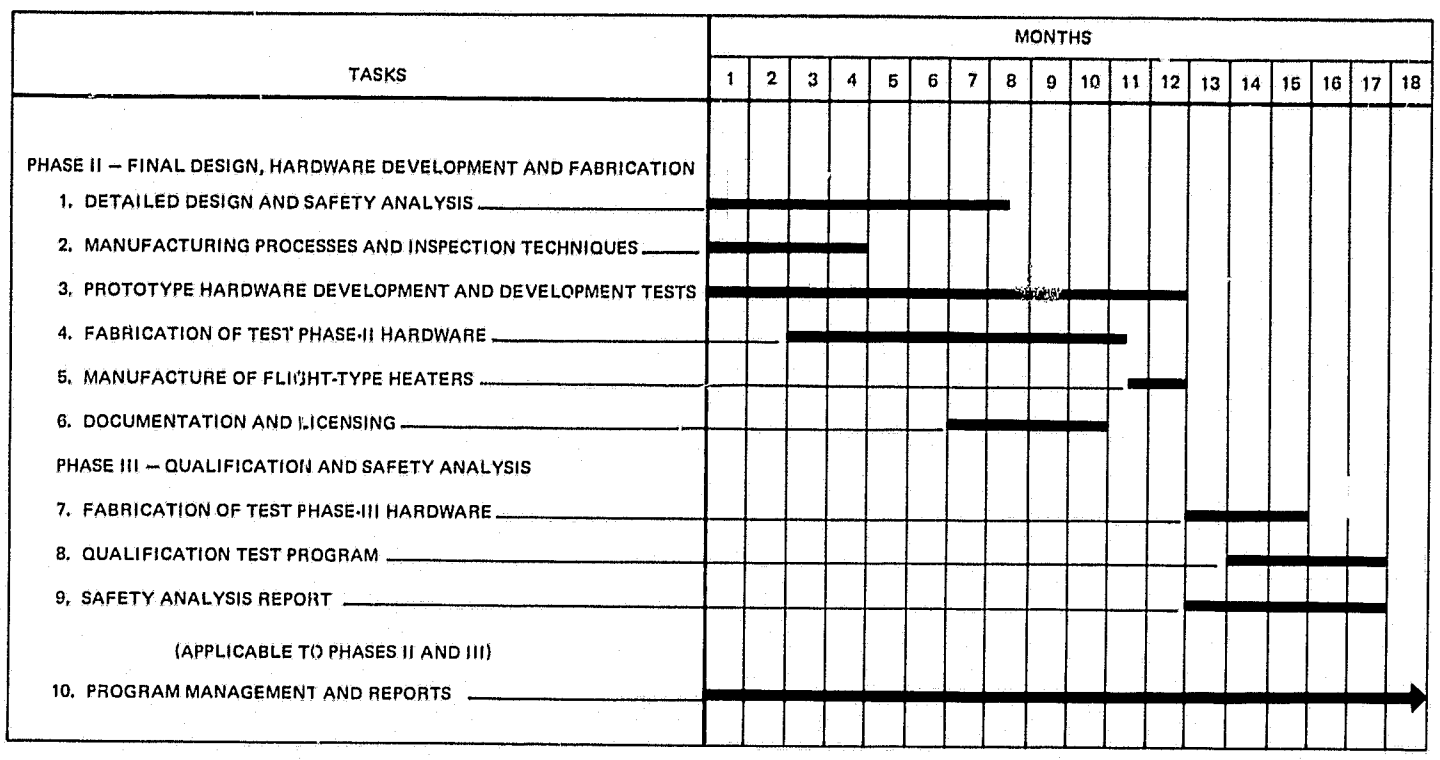
CONCLUSIONS

Results of the phase I study program show that the four primary objectives of the study were met:

1. Identify potential applications for small (1- to 50-W) radioisotope heaters in manned-spacecraft systems - The survey of manned spacecraft and launch vehicles identified more than 37 areas of application requiring 180 to 300 heaters ranging in power from 1 to 100 W. Radioisotope heaters would not be considered for all of these applications either because electric

TABLE 6

PHASES II AND III TASK SCHEDULE



heaters would perform as well or because of complexity and/or size. However, many of the identified applications such as viewports, base thermal requirements, structural cold spots, and standby fuel cells would benefit by use of radioisotope heaters--if they were available.

2. Develop a radioisotope heater design to meet selected safety criteria with a high probability of being safety- and flight-qualified - Detailed safety and design analyses of the reference designs show that they will meet established safety criteria, and that they have a high probability of surviving all mission phases, operations, and environments. Materials, configurations, and fabrication techniques selected are--or are near--the state of the art. The heaters have been designed for safe handling by both experienced and inexperienced personnel, and impose no special requirements on astronauts during performance of their normal duties. Also, the heaters have been designed to present an insignificant probability of injurious radiation dose as a result of a credible accident or incorrect handling.

3. Develop an optimum group of radioisotope heaters to meet requirements of a maximum number of applications and mission times of from 14 days to 5 years - Results of the optimization studies completed for the phase I study show that two heater-sizes, 10 and 50 W, using two types of radioisotope fuels, promethia and plutonia, will meet identified applications and mission requirements. These optimization analyses further show that only a small weight penalty is incurred by using uniform heaters having the same

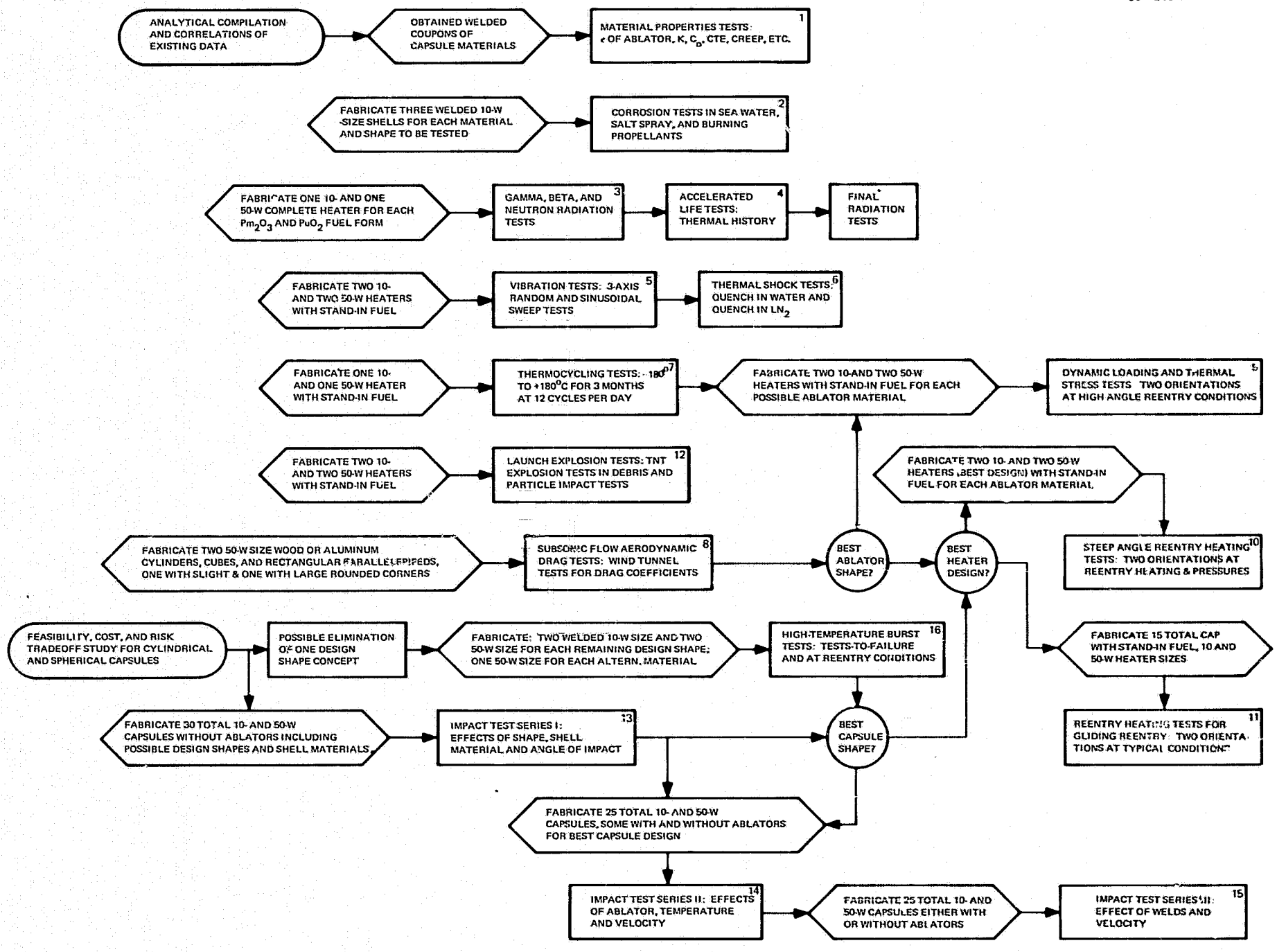
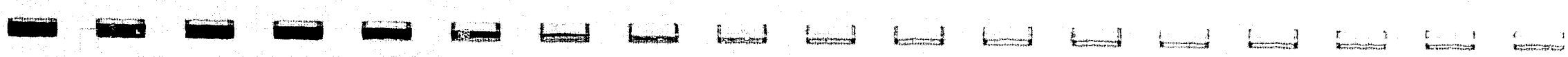


Figure 6. Test Specimen Fabrication and History Chart for Phase II Development Tests



dimensions for both promethia and plutonia fuels. Weight penalties are small when compared to the additional cost of fabricating and qualifying two different heater sizes for one power level. Another important consideration is the interchangeability of promethia and plutonia heaters that the uniform heater size permits, since only one mounting arrangement is required for each power level.

4. Develop program plans and budget estimates for phases II and III - Major tasks were established, schedules prepared, and development and qualification tests identified for the development, test, fabrication, and qualification of flight-type radioisotope heaters. Several plans were prepared for accomplishing these tasks, depending on availability of funds, schedule, and/or identified requirements. Selection of any of the proposed options would result in safety-qualified radioisotope heaters.

DWDL concludes that it is entirely feasible to develop a group of small radioisotope heaters that will meet a large number of manned-spacecraft component applications. Completion of a development program will greatly reduce the time between identification of requirements and ultimate mission qualification. Also, availability of flight-qualified radioisotope heaters will enable systems engineers to consider their use with the same degree of confidence as for electrical heaters. This will provide a degree of flexibility in design and selection that is not now available.

RECOMMENDATIONS

Radioisotope heaters would have been considered for many space applications in recent years--had they been available. In fact, the NASA/MSC heater requirement for the EASEP seismic experiment package was firmed up immediately subsequent to the start of the present study; the heater is being developed by AEC/DID for an early Apollo mission. The reliability of radioisotope heaters is recognized, and the feasibility of designs to meet stringent safety criteria has been shown. DWDL recommends that phases II and III of the Radioisotope Heater Development Program be initiated without delay and funded at the level required to produce flight-qualified heaters. Any one of the eight program options will result in flight- and safety-qualified radioisotope heaters. But DWDL believes that option 1 would prove most cost-effective and have the lowest risk factor.