Structural, Thermal, and Safety Analyses of Isotope Heat Source and Integrated Heat Exchangers for 6-kWe Dynamic Isotope Power System (DIPS)

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The design of a 30-kWt isotope heat source integrated with a Rankine boiler and a Brayton gas heater was subjected to structural, thermal, and safety analyses. Detailed structural analyses of the heat source integrated with the boiler and gas heater showed positive safety margins at all locations during launch. Detailed thermal analyses during assembly, transfer, and orbital operations showed acceptable temperatures at all locations. Reentry thermal analyses showed that the clads have acceptable peak and impact temperatures. Loss-of-cooling analyses indicated the feasibility of a passive safety concept for preventing overtemperatures. Static structural analysis showed positive safety margins at all locations, and dynamic analysis showed that there were no low-frequency resonances. Continuum-mechanics code analyses of the effects of the impact of Solid Rocket Booster (SRB) fragments on the heat source and of the very unlikely impact of the full heat source on concrete indicated relatively modest fuel clad deformations corresponding to little or no fuel release.

Introduction and Summary

The design of a 30-kWt isotope heat source integrated with a Rankine boiler and a Brayton gas heater, described in a separate paper (Schock 1991), was subjected to structural, thermal, and safety analyses. Detailed structural analyses using a 3276-node NASTRAN *rz*-model (MacNeal 1972 and MacNeal-Schwendler Corp. 1985) of the heat source integrated with the boiler and gas heater showed positive safety margins at all locations, for assumed launch loads of 40-G lateral and 30-G axial. Detailed thermal analyses showed acceptable temperatures at all locations, during assembly, transport, and flight operations. Reentry thermal analyses showed that the clads have acceptable peak and impact temperatures. Loss-of-cooling analyses indicated the feasibility of a passive safety concept for preventing overtemperatures. Continuum-mechanics code analyses of the effects of the side-on impact of Solid Rocket Booster (SRB) fragments on the heat source and of the impact of the full heat source on concrete indicated relatively modest fuel clad deformations corresponding to little or no fuel release.

Temperature Limits

Safety considerations require that the iridium capsules enclosing the fuel be ductile in the event of earth impact. Ductility requires that the capsules inside the impacting modules be above their ductile-to-brittle transition temperature (DBTT) for the iridium grain size at the time of impact.

Accidental reentry is assumed to occur either immediately after launch or within six months thereafter. The six-month limit represents the time for orbit decay after failure of the upper stage to ignite. Since ductility is a function of grain size, it is necessary to avoid excessive grain growth during the assumed six-month normal operation prior to reentry and during the few-minute reentry heat pulse.

In practice, this has implied an upper limit of 1600 K on the clad's normal operating temperature, and a limit of 1800 K on its peak reentry temperature. In addition, the ductility requirement imposes a lower limit of 1170 K on the iridium clad's impact temperature (Schock 1980).

Steady-State Temperatures

To determine the clad's normal operating temperatures, detailed thermal analyses were carried out for the heat source and the DIPS boiler or gas heater, for a variety of operating conditions. The analyses employed the 481-node two-dimensional (*rz*) model of the heat source and heat exchanger shown in Figure 1. The model is set up for two independent loops of the conversion system but can be operated with either one or both operating.

An axisymmetric *rz* model is a valid representation of the boiler and heat source, except for the internals of the heat source modules. These require the more detailed 3D model shown in Figure 2, which also displays typical operating temperatures.

Figure 3 shows the computed temperature distribution

(481-Node Model)

Figure 1 Axisymmetric Thermal Analysis Model of Rankine Heat Source and Boiler.

for the most severe case; that is, for the annular heat source coupled to the helical Brayton gas heater, only one of whose two loops is active (A) and the other inactive (I). As can be seen, the clad operating temperatures and all other temperatures are within acceptable limits for the respective ma-

terials. Figure 4 illustrates a corresponding solution for the Rankine system, which shows even more benign temperatures; and Figure 5 presents the temperature distribution for the thermoelectrically topped Rankine system, which approaches the clad temperature limit 1600 K.

Figure 2 Typical 3-D Temperature Distribution (in °C) within Heat Source Module. Local support shell temperature was 690°C. Similar results were obtained for a wide range of support shell temperatures.

Reentry and Impact Temperatures

In addition to the steady-state analyses discussed above, transient analyses were carried out to determine the clad's peak reentry temperature and impact temperature. The steep-descent case is generally most critical for the peak reentry temperature, and the orbital-decay case is most critical for the impact temperature. A wide range of cases was analyzed. Each case requires a combination of aerodynamic, aerothermodynamic, and thermal analyses. A typical solution for the orbital-decay case is depicted in Figure 6. It shows all three critical clad temperatures within acceptable limits.

Loss of Cooling

Another safety-related analysis concerned the effect of loss-of-cooling. The heat source of the dynamic isotope power system (DIPS), unlike that of a radioisotope thermoelectric generator (RTG), is cooled by active fluid loops. If

both of the two loops stopped operating, the isotope heat source temperatures would rise. Because of the system's high heat capacity, the rate of temperature rise is slow. But without special cooling provisions, it would eventually compromise fuel containment. To avoid that, the design uses a temperature-limiting passive cooling scheme. It consists of thermally insulating the outside of the annular heat source with multifoil materials that melt about 200 to 300 K above their normal operating temperature. Either single materials or alternating foils that form low-melting eutectics may be used. The feasibility of this concept was demonstrated analytically and experimentally on earlier programs (Darooka and Loughheed 1977).

Transient analysis of the uncooled heat source in Fairchild's present study yielded the results shown in Figures 7 and 8. Figure 7 shows that the temperature rise of the heat source is relatively slow, because of its high heat capacity. The results show that foil melting should commence within about 40 minutes after loss-of-cooling, to avoid excessive clad temperatures.

Figure 3 Orbital Operating Temperatures (in °C) of Brayton Heat Source and Gas Heater, with One Loop Active (A), One Inactive (I), and a -40°C Heat Sink.

Figure 4 Orbital Operating Temperatures (in °C) of Rankine Heat Source and Boiler, with One Loop Active, One Inactive, and a -40°C Heat Sink.

Figure 5 Orbital Operating Temperatures (in °C) of Thermoelectrically Topped Rankine System.

Figure 6 Temperature History of Heat Source Module Components after Orbital-Decay Reentry of Module.

(Without Melting of Foil Insulation)

Figure 7 Temperature Rise of Brayton Heat Source after Active System Stops Operating.

(Without Melting of Foil Insulation)

Figure 8 Temperature Rise of Individual Insulating Foils after Brayton System Stops Operating.

(Decomposed View)

Figure 9 Model for Structural-Dynamic (NASTRAN) Analysis of Rankine Heat Source and Boiler Assembly during Launch.

Figure 10 Critical Launch Stresses in Rankine System, Results of 3276-Node NASTRAN Analysis (40-G Lateral + 30-G Axial).

Table 1 Summary of Safety Margins at Critical Locations of the Rankine System. Results of 3276-Node NASTRAN Analysis (40-g Lateral + 30-G Axial).^a

Stress	Boiler	Inner Can	Outer Can		
			Base	Cylinder	Cap
Buckling (S.F. = 1.5):					
Compression	>1.0	>1.0	>1.0	>1.0	>1.0
Shear	>1.0	>1.0	>1.0	>1.0	>1.0
Ultimate (S.F. = 1.5):					
Tension	0.26	>1.0	0.89	0.65	0.83
Compression	0.26	>1.0	1.0	0.65	0.83
Shear	0.04	0.44	0.19	0.14	0.21
Yield (S.F. = 1.25):					
Tension	0.41	>1.0	0.91	10.67	0.85
Compression	0.41	>1.0	>1.0	0.67	0.85
Shear	0.16	0.44	0.20	0.15	0.23

$$\text{Safety Margin} = \frac{\text{Allowable Stress}}{\text{Actual Stress} \times \text{Safety Factor}} - 1$$

As seen in Figure 8, the foil temperatures at that time range from 1570 K for the inner foils to 670 K for the outer foils. A variety of suitable metals and eutectics melting in that range is available. Lower-melting materials would be used for the outer foils. Once the inner foils melt, adjoining layers heat up and propagate the foil meltdown. After the foils have melted or self-brazed, the heat source will cool off rapidly.

Structural Analyses

The heat source and heat exchangers were subjected to static and dynamic structural (NASTRAN) analyses. Figure 9 shows a decomposed view of the model of the boiler support shell and the heat source inner and outer cans. Initial analyses revealed excessive local stresses which required some modification of the structure.

As shown in Figure 10, the boiler support can and the

- Relatively stiff structure avoids low resonant frequencies.

Figure 11 Lowest Resonant Modes of Rankine Heat Source and Boiler.

heat source outer can were strengthened at the base of the assembly, and the heat source's inner and outer cans and cover were strengthened at the top of the assembly. These changes resulted in the stresses shown in the figure, for an assumed 40-G lateral load and a 30-G axial load at launch. As shown in Table 1, the modified design yielded positive launch margins at all locations.

The design was also subjected to structural dynamic analysis. Figure 11 shows the resonant frequencies and (exaggerated) deformations for the four lowest resonances. As can be seen, the structure is stiff enough to avoid low resonant frequencies. Table 2 summarizes the dynamic response of the structure, for a 1-G input at the base of the assembly. Once the actual inputs at the base of the assembly are known, they can be combined with the amplifications shown in the table to compute the dynamic launch loads on the inner and outer cans.

Impact Analyses

The final set of safety analyses carried out dealt with the effect of impacts on the assembled annular heat source. Two cases are of principal interest: The first concerns the impact on the heat source of shrapnel generated by the accidental or deliberate explosion of the Shuttle's solid-rocket booster, (Eck and Mukunda 1989a), as in the Challenger accident. The second case concerns the ground impact of the assembled heat source. Although the heat source is designed to disassemble during reentry, it could remain intact in the event of a suborbital abort in which the booster and the spacecraft break up or burn away but the free heat source is released at an altitude which is too low to burn away the aluminum housing and release the heat source modules. In that very unlikely case, the intact heat source would impact the Earth at a substantially higher terminal velocity (87 m/s) than the free heat source modules (49 m/s).

Impact analyses of the above two cases were carried out

Table 2 Dynamic Response (Force Multiplication Factors) of the Rankine Heat Source.

Mode	Direction	Input at Base	Response	
			Middle of Inner Can	Top Cap of Outer Can
	X	1.0	6.0	9.0
	Y	—	0.7	0.6
	Z	—	1.2	3.4
	X	—	1.0	0.8
	Y	—	0.5	0.8
	Z	1.0	10.0	13.3
	X	1.0	1.7	2.6
	Y	—	0.1	0.3
	Z	1.0	0.4	1.2
	X	—	0.2	0.2
	Y	—	0.2	0.2
	Z	1.0	3.1	3.6

by means of the two-dimensional microsecond-scale continuum-mechanics code PISCES (Pohl et al. 1984). This code has both Eulerian and Lagrangian options, and the two options can be combined within the same problem. Thus, the code can be used to analyze an explosion-initiated shock wave and the effects of the impact of that shock wave on deformable bodies. Because of its power and versatility, the code has been used by Fairchild for analyzing a variety of safety problems for more than a decade. Over that period, much progress has been made in generating materials models that yielded good agreement between analytical and experimental results (Eck and Mukunda 1991).

Figure 12 depicts the 2D model of the heat source module used in the impact analyses. The model includes the iridium-clad fuel capsule and the carbon-carbon impact shell and aeroshell. The carbon fiber insulator has been omitted, because its density is too low for it to have any significant effect.

Figure 13 depicts the model of the heat source assembly at its terminal velocity of 86.6 m/s, about to impact a 3"-thick concrete slab. As shown, only the three modules at the impact face are modeled in detail. The other nine modules are represented by solid graphite blocks. The heat source model also includes the Inconel inner can and the multifoil-insulated aluminum outer can.

Figure 14 depicts the progressive deformation of the heat source's leading modules for 600 μ s after its side-on impact on concrete at its terminal velocity. Extended analyses for a variety of cases have shown that most of the fuel capsule deformation occurs in that time period.

Figure 12 2-D Impact Analysis Model of GPHS Heat Source Module.

Figure 13 Side-On Impact of Heat Source on Concrete Slab.

Figure 15 presents close-ups of the leading heat source module and its two fuel capsules showing their progressive deformation after impact. The capsule deformation is quantified in terms of the ellipticity ϵ , which is defined as the ratio of maximum to minimum diameter minus one. The final ellipticities can be compared with experimentally obtained results to calibrate the analyses and interpret the significance of the results (Eck and Mukunda 1991).

Similar analyses were performed for the impact of SRB fragments on the heat source. Figure 16 illustrates the deformation of the leading heat source modules 600 μ s after the heat source is impacted by an SRB fragment at 100 m/s. The SRB shrapnel used in the analyses consisted of a 1.27 cm-thick steel shell segment, extending over 90 degrees of the circumference of the 3.66-meter-diameter SRB. Although almost all of the fuel capsule deformation has taken place at 600 μ s, the figure shows that the back side of the heat source is still unaffected by the impact.

Figure 17 depicts the progressive deformation of the leading heat source module and the resultant fuel capsule deformation, for a fragment impact velocity of 100 m/s. Similar analyses were performed for impact velocities of 150 and 200 m/s, which spans the range of interest.

Finally, the leading-fuel-capsule ellipticities resulting from the impact of the intact heat source on concrete and of the SRB fragments on the heat source are depicted in Figure 18 as a function of time. To help interpret these results, the two scales at the right of the figure depict experimental results from a broad range of bare-capsule and GPHS module impact tests, respectively. The position of each tick mark denotes the experimentally observed ellipticity after the test. The number alongside each tick mark shows the measured fuel release as a fraction of the capsule's inventory. As can be seen, even the low-probability cases analyzed above lead to deformations that correspond to either no fuel release or only minor fuel release ($<0.1\%$).

Figure 14 Deformation of Forward Side of Heat Source after its Impact on Concrete.

Figure 15a Progressive Deformation of Leading Module After Impact of Heat Source on Concrete.

Figure 15b Progressive Deformation of Leading Fuel Capsules after Impact of Heat Source on Concrete at 87 m/s.

- Back side of heat source unaffected by impact

Figure 16 Heat Source Deformation 600 μ s after Impact of SRB Segment at 100 m/s.

Figure 17 *Progressive Deformation of Leading Module after Impact of SRB Segment on Heat Source.*

Figure 18 Deformation of Leading Fuel Capsules and Effect on Fuel Containment.

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