Unique Aspects Associated With the Design and Certification of a Radioisotope Thermoelectric Generator Transportation Package

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INTRODUCTION

Radioisotope Thermoelectric Generators (RTGs) are used as power or heat sources for space applications such as the Cassini Mission scheduled for 1997. Due to the radioactive material content of the RTGs, a certified, Type B(U) packaging is required for ground transportation. In addition, the RTGs typically contain plutonium in sufficient quantities to dictate the use of double containment per the requirements of 10 CFR 71.63(b) (10 CFR 71 1994). When this double containment requirement is coupled with a relatively high RTG internal heat load of up to 4,500 watts and a very demanding set of normal operating temperature limits for the RTG itself, a significant thermal design challenge exists.

In addition to the thermal design challenge, with the catastrophic impact of a malfunctioning RTG on a program such as the Cassini Mission, several other design constraints not commonly imposed on a radioactive materials transportation package development effort come into play. These added constraints are primarily directed at ensuring the operational integrity of the RTGs under all normal handling and transport conditions, thus ensuring proper function of the RTG once deployed in space. Included are rather restrictive normal operating condition shock and vibration limits and a requirement for continuous monitoring of the RTGs via electrical feed-through devices which penetrate both levels of containment. Structural design challenges are also created by rather restrictive, facility imposed size and weight constraints. The weight efficient nature of certain RTG payload designs also inherently leads to a potential for payload reconfiguration and payload/package interactions in the event of 10 CFR 71.73-defined accident conditions. Such reconfiguration also presents thermal and, to a lesser extent, shielding design challenges for the packaging subsequent to the accident sequence.

The remainder of this paper presents the specific design constraints which generally governed development of the packaging system and the specific thermal and structural features which were selected to accommodate those constraints. The electrical feed-through feature which allows monitoring of the payload temperatures during transportation while not compromising "leaktight," double containment is specifically discussed. Also included is a brief summary of the various test programs which were included as a part of the design development and certification processes.

GOVERNING DESIGN CONSTRAINTS

The most demanding constraint to be satisfied by the packaging design was a temperature limit imposed on the surface of the General Purpose Heat Source (GPHS) RTG during normal operation of the transportation system. During loading and unloading, a short term limit of 227 °C (440 °F) was established for the RTG. During actual transportation, a somewhat lower limit of 216 °C (420 °F) was imposed. With an internal heat load of up to 4,500 watts, these limits were found to be rather demanding. In addition, a design goal was established, which was to keep RTG temperatures, during transportation system operation, as close as possible to temperatures associated with storage of the RTGs in a free air environment, or approximately 177 °C (350 °F). Obviously, when loaded within two levels of "leaktight" containment, satisfaction of the prescribed temperature limits and the thermal design goal became particularly challenging. Adding to the challenge was the 10 CFR 71.51(b) requirement which does not allow reliance on a mechanical cooling system when addressing the activity release limits of 10 CFR 71.51(a). Use of an active cooling system to satisfy payload operational temperature limits was not precluded but if utilized was required to be fully redundant, highly reliable, and commercially available.

Other design constraints directed at preserving the operational integrity of the RTGs were a shock limit of 15 g and a vibration limit of 1.5 g during normal transportation. Finally, in order to confirm that operational integrity of the RTGs was not compromised during transport, payload temperatures were to be continuously monitored via the use of electrical feed-throughs which penetrated both levels of containment. These feed-throughs, plus other more traditional accelerometer and thermocouple instrumentation, were to be part of a trailer instrumentation and alarm system that would alert the driver to any abnormal events which, without corrective action, would potentially damage the RTGs.

As discussed above, the most significant regulatory constraints were the requirement for no reliance on active cooling, the double containment requirement, and a need to maintain "leaktight" containment boundaries during and subsequent to the hypothetical accident event.

OVERVIEW OF RESULTANT DESIGN

An exploded view of the resultant design of the RTG Transportation Package is provided as Figure 1. As shown, each of the two containment vessels includes a structurally and

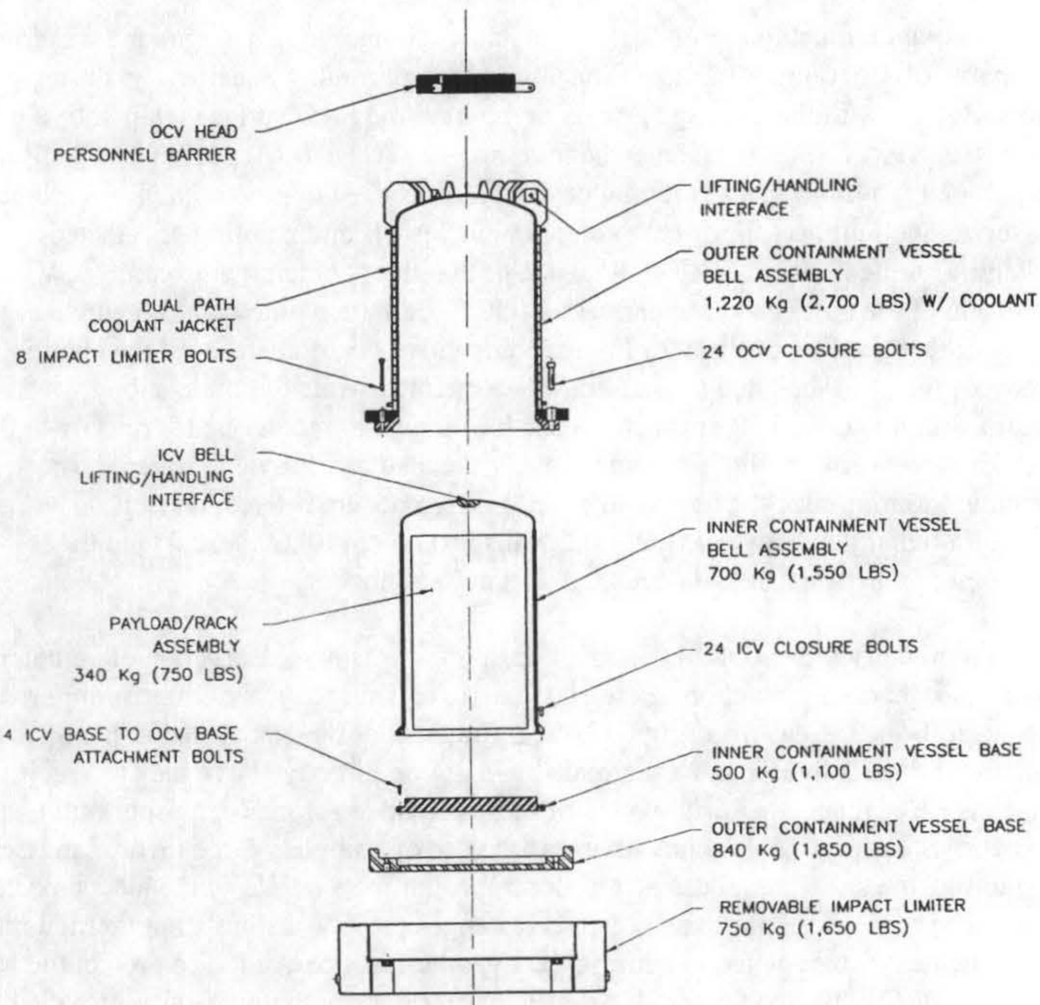

Figure 1. RTG Transportation Package.

thermally massive base plate, with a mating bell assembly. The outer bell assembly includes a dual flow path coolant jacket and top end fins, features which provide thermal and structural protection to the package and/or payload. Traditional bolted closures with elastomeric face seals are utilized for both vessels. The bottom end of the package is protected by a polyurethane foam filled impact limiter. Specific design features are presented and described in more detail in subsequent sections.

THERMAL DESIGN FEATURES

From an RTG operational integrity viewpoint, the most significant thermal design feature is the dual flow path coolant jacket which is integral to the outer containment vessel bell.

With a coolant temperature of 4 °C (40 °F), either coolant loop acting alone was found to be capable of satisfying RTG operational temperature limits. Specifically, during normal transportation, with the cooling system operational, the RTG surface temperature was found to be 193 °C (380 °F), somewhat over the 177 °C (350 °F) goal but well within the 216 °C (420 °F) limit. Other thermal design features used to protect the RTG include a pressurized helium backfill of both containment vessels and painting of selected packaging surfaces. The inside and outside of the inner containment vessel (ICV) bell and inside of the outer containment vessel (OCV) bell are painted black, using a high-temperature, baked-on coating for improved radiative heat transfer, and the external surface of the OCV bell and impact limiter are painted white to obtain a long wave radiation emittance of 0.80 or greater while limiting solar radiation absorptivity to 0.25 or less. The gaps between the ICV and the OCV are also carefully controlled during fabrication to minimize the temperature drop which occurs between vessels. The maximum radial gap between vessel sidewalls is 0.63 cm (0.25 inches), and the maximum gap between vessel heads is 1.27 cm (0.50 inches).

From a regulatory viewpoint, the thermal design focus is on preservation of containment. To this end, thermal protection of the elastomeric closure seals is of utmost importance. To protect the seal areas from a hypothetical fire, insulation is provided in the form of the foam-filled impact limiter and a thermal shield region directly above the OCV bell seal flange. Such features are fairly typical of those provided for many transportation packages. Somewhat more innovative was the use of relatively large thermal masses surrounding the seals (e.g., base plates alone account for over 1/3 of the loaded package mass). The heavy base plates and thick bell flanges provide a significant thermal mass to absorb the heat fluxes generated during the hypothetical fire event. To protect the seals from the hot RTG payload, an RTG specific barrier plate assembly is also provided. This assembly was designed to isolate effectively the RTG and its heat sources from the seals even if the RTG was assumed to "break up" during an accident condition, thus allowing the internal heat sources to reconfigure in a worst-case fashion. Important structural features associated with this barrier assembly are discussed below. Figure 2, which presents the GPHS RTG and its barrier plate assembly mounted within the transportation packaging, shows all significant thermal design features discussed above.

Recalling that active cooling cannot be counted on when addressing regulatory normal conditions of transport, it became necessary to assume that the coolant jacket would be drained and dry; in effect, becoming another insulating boundary. A careful balancing of heat paths between the seal area and the exterior of the package was therefore required to adequately insulate the seals from the effects of a fire while not "over-insulating" and causing excessive seal temperatures for normal conditions of transport. The thick base plates and bell flanges, coupled with other design features such as the closure bolt access tubes, provide the heat transfer paths under normal conditions of transport necessary to maintain desired seal temperatures. The barrier plate assembly also helps minimize normal condition seal temperatures by elevating the "hot" RTG above the closure seals.

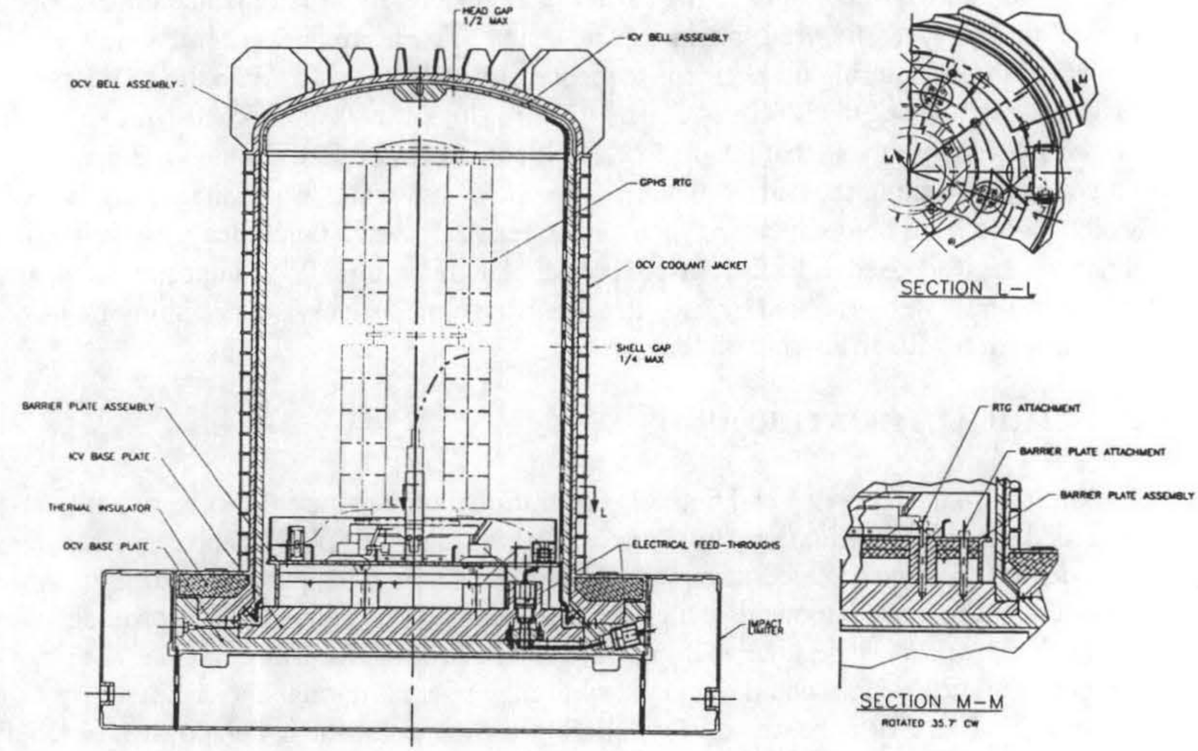

Figure 2. RTG Transportation Package With GPHS Payload.

STRUCTURAL DESIGN FEATURES

One of the more significant structural design approaches was selected early on in the design development process. This was a decision to utilize rather "robust," essentially nonyielding, seal flanges and base plates while allowing the containment boundary to deform outboard of the seal regions. This approach allowed system weight limits to be satisfied without compromising seal area performance. The use of heavy base plates and thick seal flanges also provided thermal benefits as discussed above. As ultimately demonstrated during full scale structural testing, although containment boundary deformations were allowed to occur outboard of the seals, seal area deformations were limited to approximately .013 cm (.005 inches) as a result of free drop and puncture tests. Such magnitudes are easily shown to be within the capabilities of the elastomeric sealing elements.

Due to the thermal importance of the barrier plate feature, its structural attachment was critical to the successful performance of the design. To ensure the barrier assembly remained in place during the accident sequence, it was bolted directly to the ICV base plate, independent of the RTG itself. The RTG payload was then attached "through" the barrier plate assembly so that the payload itself could break free without loading and potentially separating the barrier plate from the ICV base plate. Long attachment bolts, which would bend before breaking, and design features, which precluded their failure in direct shear, were used to further ensure barrier plate retention. RTG-imposed shock and vibration limits were satisfied by use of specially designed shock-isolated shipping skids in conjunction with an air-ride trailer.

ELECTRICAL FEED-THROUGHS

To confirm on the receiving end that RTG operational temperature limits were not exceeded during transportation, thus further ensuring that the RTG will properly function once deployed, electrical feed-throughs are incorporated into the packaging design. An overview of the key components which make up the feed-through feature is provided as Figure 3. The primary design development challenge for the feed-through was to arrive at a configuration which would remain "leaktight" under all normal and accident conditions. This challenge was met by utilizing components which were known to satisfy rather stringent Military Specifications covering issues such as structural shock and thermal cycling (e.g., MIL-C-24217A and MIL-STD-202, Method 207). These same standards are utilized for components such as deep submergence electrical connectors in submarine applications. The containment portion of the feed-through (virtually identical for both ICV and OCV) consists of a D. G. O'Brien 107 Series receptacle welded to a support sleeve which in turn is welded to the corresponding base plate. Internal to each D. G. O'Brien connector are nine individually sealed electrical conductors which have been shown via extensive testing to remain leaktight under extreme thermal and structural shock conditions.

TEST PROGRAMS

The RTG Transportation Package design development and design demonstration efforts required several testing programs to be executed. During development of the design, half-scale testing was used to confirm impact limiter design configurations and attachment details. That testing also provided early confirmation of OCV seal flange sizing. Full scale thermal feasibility tests were also performed as a means to convince the RTG user community that the design concept being pursued could indeed thermally protect the RTG payloads and satisfy specification requirements. Heated mockups of the GPHS RTG were developed and placed within a single bell assembly to establish that convective heat transfer mechanisms between finned RTGs and the ICV were properly understood and modeled.

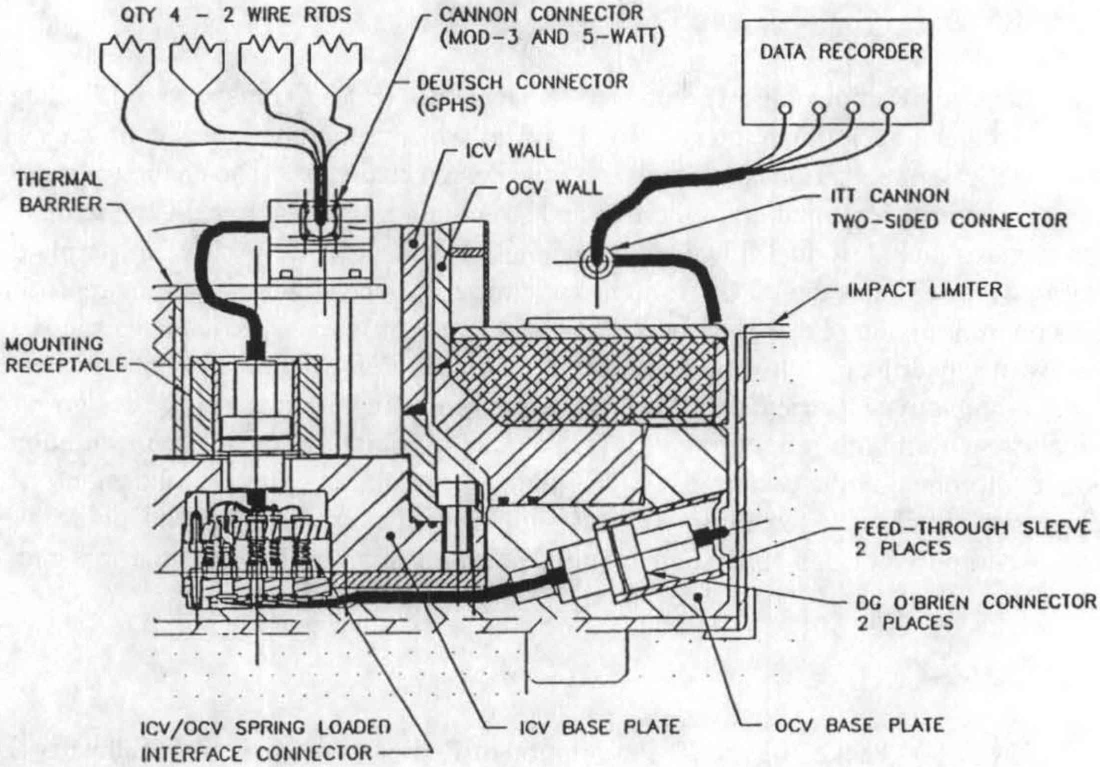

Figure 3. Electrical Feed-Through Design Feature.

These early stage design development/feasibility tests were followed by thermal qualification and, ultimately, structural certification test programs. The thermal qualification test programs were used primarily to demonstrate that the final design would thermally protect the RTG payloads under all normal operating conditions. This included a complete simulation of a loading, transport, and unloading sequence. The testing was also used to establish time lines for corrective actions should abnormal events occur. Certification testing involved full scale prototypes subjected to free drop and puncture events. A total of 10 normal condition free drops, 10 accident condition free drops, and 15 puncture tests were performed, with damage distributed between 2 complete test articles. Testing was particularly aggressive due to the early adoption of the design approach which allowed containment boundary yielding to occur. With yielding being allowed, it was recognized that a design demonstration approach which relied on analysis alone would be difficult to defend. In fact, in many cases, extensive testing was used in lieu of performing detailed analyses.

SUMMARY

Development of a Radioisotope Thermoelectric Generator (RTG) Transportation Package which protects the operational integrity of the RTGs while remaining in full compliance with all applicable regulations presented a unique design challenge. The challenge was met using a careful combination of thermal and structural design features. Key thermal design features include a dual flow path coolant jacket and an RTG specific barrier plate assembly which isolates the RTGs from the closure seals. The structural design approach focuses on minimizing seal area deformations via the use of "robust" base plates and seal flanges while specifically allowing containment boundary deformation outboard of the seals. An innovative electrical feed-through design is also incorporated in the design which allows continuous monitoring of RTG payload temperatures during transportation without compromising the two levels of "leaktight" containment. Successful design development and proof of the ability of the design to satisfy key RTG payload and Regulatory-imposed design constraints required several test programs, both thermal and structural.

REFERENCES

10 CFR 71 (1994) "Packaging and Transportation of Radioactive Materials," Subparts E and F, *Code of Federal Regulations*, as amended.