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CONCEPTUAL DESIGN
OF AN
RTG SHIPPING AND RECEIVING FACILITY TRANSPORTATION SYSTEM*

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Abstract

The conceptual design of an RTG Facility Transportation System which is part of the overall RTG Transportation System has been completed and is described in detail. The Facility Transportation System serves to provide locomotion, cooling, shock protection and data acquisition for the RTG package during onloading and offloading sequences. The RTG Shipping & Receiving Facility Transportation System consists of a Transporter Subsystem, a Package Cooling Subsystem, and a Shock Limiting Transit Device Subsystem. The Transporter Subsystem is a custom designed welded steel cart combined with a pneumatically-driven hand tug for locomotion. The Package Cooling Subsystem provides five kilowatts of active liquid cooling via an on-board refrigeration system. The Shock Limiting Transit Device Subsystem consists of a consumable honeycomb anti-shock frame which provides shock protection for the 3855 kg (8500 LB) RTG package. These subsystems have been combined into an integrated system which will facilitate the offloading and onloading of the RTG Package into and out of the semitrailer as well as meet ALARA (as low as reasonably achievable) radiation exposure guidelines.

INTRODUCTION

A conceptual design effort was undertaken to develop a Facility Transportation System for the Radioisotope Thermoelectric Generator (RTG) Program. This system must provide adequate thermal control and shock protection for the RTG to ensure specified temperature and acceleration limits are not exceeded. The design utilizes off-the-shelf hardware wherever possible to meet performance requirements while minimizing cost.

The cart acts as the backbone to the Facility Transportation System (Figure 1). It provides the locomotion of the RTG, while in its containment vessel, between the semitrailer and several facilities. It also moves the package assembly within these facilities. It must be reliable and robust enough to withstand an inadvertent drop of the 3855 kg RTG package from a height of up to 457 mm (18 in). The cart is required to provide accessibility to the RTG containment vessel in order to function as an assembly/disassembly fixture.

FIGURE 1. RTG Facility Transporter Conceptual Design.

The 5 kW of waste heat dissipated by an RTG and transferred to the containment vessel must be removed by an active cooling loop provided by the Facility Transportation System.

The Shock Limiting Transit Device (or anti-shock frame) is used to limit the acceleration/deceleration of the RTG to 15G if the RTG/containment vessel package is dropped from a height of 457 mm (18 in) (Ard 1993). The types of drops it must protect against are defined by MIL-STD-810E (U.S. DOD 1989). The frame must protect the package both on and off of the facility cart and attach to the RTG package quickly in agreement with ALARA principles.

TRANSPORTER SUBSYSTEM

The primary function of the Transporter is to carry the 3855 kg RTG package into and out of several facilities as well as to and from the semitrailer. Transporter size is limited by the space available within the 14.6 m (48 feet) long semitrailer as well as within the most restrictive facility (the RTG fabrication facility at EG&G - Mound; Dayton, Ohio). The Transporter length is limited by a 2.49 m (98 in) width for a standard semitrailer. To fit within the hallways of the Mound Facility the Transporter width is limited by the minimum 1.58 m (62 in) hallway. The Transporter height is limited by an overall Transporter/anti-shock frame/RTG Package height restriction of a 2.13 m (84 in) Mound facility doorway. We have therefore, designed a Transporter whose overall dimensions leave adequate clearance between it and the limiting facility dimensions (Figure 2).

FIGURE 2. Transporter Subsystem Conceptual Design.

In order to operate the Transporter successfully both indoors and outdoors, we designed a cart which relies on large diameter casters which roll equally well on a soft asphalt surface as well as on hard concrete floors inside each facility. Swivel-type casters were selected to enable the cart to turn in tight hallways. The cart design includes four double-wheel 254 mm (10 in) diameter swivel casters. In addition we have selected casters which provide shock protection against normal handling loads.

Leveling feet have also been included. These feet are essential to the anti-shock protection function provided by the Shock Limiting Transit Device. They serve to short circuit the rest of the Transporter (such as the casters) during impact. The leveling feet will also make up for unevenness or slope in the parking lot surface.

FIGURE 3. Onloading & Offloading Transporter with Forklift.

Provisions have been included to fork the Transporter from either the side or the rear (Figure 3). Side forking is needed to load and unload the Transporter into the semitrailer and rear forking is required to load and unload the Transporter at the Mound Facility loading dock.

The design features a commercially-available pneumatically-driven hand tug for use once inside either facility (Figure 4). These hand tugs have been shown to work well with considerably larger objects (such as aircraft and heavy machinery) requiring towing. They work well with casters and can provide both tugging and steering inside

the tight confines of the Mound Facility. Travel speeds inside the facilities would be approximately 1.2 km/hr (0.75 mph). We have made provisions to be able to use such a hand tug at one or both ends of the Transporter. The conceptual design for locomotion out-of-doors is to tow the Transporter with the same large forklift that is used to remove the Transporter from the semitrailer.

PACKAGE COOLING SUBSYSTEM

The basic requirement of the Package Cooling Subsystem is to remove the heat dissipated by the RTG (5 kW) prior to being loaded and after it has been unloaded from the semitrailer. This cooling is also to be provided while the package is being transported into and out of several facilities until the package is unloaded and the RTG is exposed to ambient conditions.

FIGURE 4. Hand Tug Attached to Transporter.

After considering several alternate concepts for providing this 5 kW of heat rejection, a conventional refrigerator (or chiller) was selected. Numerous such chillers are commercially available to suit our needs. The chiller will provide 45.4 L/min. (12 gal/min.) of water/propylene glycol mixture (60% water/40% propylene glycol) at or below 4.4°C (40°F) under a heat load of 6 kW. The heat absorbed by the coolant from the RTG plus the heat to operate the refrigerator are rejected to the surrounding air at a maximum temperature of 40.6°C (105°F).

After considering and rejecting both battery power and dedicated propane powered electrical generation, facility power was selected to run the chiller. The baseline chiller runs on 208/230 V, 60 Hz, 3Ø power and requires 22 Amps of service.

The chiller will continuously display both the supply and return coolant temperatures and incorporates a digital readout of chiller flowrate as well. A portable data logger was incorporated to monitor RTD's that are mounted inside the containment vessel, on the RTG itself. It will monitor these critical readings continuously during onloading and offloading as well as archiving the data back to the data acquisition system located on the semitrailer.

Rather than towing the chiller behind the Transporter, it will be mounted to the front deck of the Transporter (Figure 1). Critical time will be saved during both onloading and offloading since the chiller does not have to be loaded/tied down separately.

FIGURE 5. Chiller Mounting Provisions.

Vibration/shock isolation between the chiller and the Transporter is provided both during normal transportation as well as during a potential drop of the package. In addition to being mounted on helical isolators, the chiller mounting plate is attached to the Transporter on a slide system (Figure 5). These slides will allow the chiller to be located close to the RTG/containment vessel during movement in and around facilities and then easily moved forward to gain access during assembly/disassembly of the RTG Package.

We plan to incorporate features (such as coolant line quick-disconnects) during the preliminary design phase which will ensure that personnel exposure to radiation from the RTG meets ALARA radiation exposure guidelines.

SHOCK LIMITING TRANSIT DEVICE SUBSYSTEM

MIL-STD-810E defines the dynamic/shock environment the RTG may be exposed to. It defines two types of "drops" (flat and edge) which must be applied to the package. The Functions and Requirements Document (Ard 1993) limits the level of acceleration seen at the RTG center of gravity (cg) during these drops to 15G. The anti-shock frame acts as the cushion to limit this acceleration to acceptable levels. Designs were considered which either stored the energy in springs or dissipated it in plastically deforming honeycomb core material. This section presents a brief discussion of the derivations used to determine the viability of various anti-shock frame concepts.

Flat Drop

The flat drop of MIL-STD-810E defines a 457.2 mm (18 in) height from which the package must be dropped onto its bottom surface as shown in Figure 6.

Honeycomb material limits the acceleration to the RTG by converting the potential energy (E_p) into dissipated energy (E_D) by crushing core material in a uniform fashion. The acceleration is limited by the crush strength (f_{cr}) of the honeycomb material. The weight of the honeycomb material is neglected in this analysis.

$$E_p = E_D \quad (1)$$

$$W(y + \delta) = f_{cr} A \delta \quad (2)$$

Where: W = weight of RTG + containment vessel

y = drop height

δ = honeycomb deflection

A = Area of the honeycomb panel

The honeycomb deflection can be computed by rewriting equation 2:

$$\delta = (yW) / (f_{cr} A - W) \quad (3)$$

The acceleration (a) of the RTG can be computed by dividing the crushing force of the honeycomb panel by the weight of the containment vessel assembly.

$$a = f_{cr} A / W \quad (4)$$

The maximum deflection of the honeycomb panel beyond which the load increases above the desired uniform level is 70 percent of the original thickness (b) as shown in equation 5.

$$b_a = \delta = 0.7b \quad (5)$$

The thickness of the panel required to dissipate the potential energy is determined by combining equations 3 & 5.

$$b = (yW) / (0.7(f_{cr} A - W)) \quad (6)$$

Edge Drop

The edge drop defined by MIL-STD-810E is shown in Figure 7. During the drop, the RTG package sits with one edge on a curb and the other side lifted 457.2 mm (18 in) above the ground and released. The dynamic analysis shown below, which also utilizes the conservation of energy principle, depicts how the shock to the RTG cg is limited to 15 G. See Figure 7 and the Nomenclature Section for the definition of the derivation variables.

The total energy within the system is equal to the sum of the kinetic, potential, dissipated and stored energies:

$$E_T = E_K + E_p + E_D + E_S \quad (7)$$

Rewritten in terms of E_K , Equation 2 becomes:

$$E_K = E_T - (E_p + E_D + E_S) \quad (8)$$

In the edge drop case, the RTG containment vessel is rotating about one edge. Therefore the kinetic energy is equal to one half the product of the mass moment inertia and the square of the rotational velocity:

FIGURE 6. RTG Flat Drop Configuration.

$$E_K = \left(\frac{1}{2}\right) I (d\theta / dt)^2 \quad (9)$$

Rewriting Equation 9 and solving for $d\theta / dt$:

$$(d\theta / dt) = \sqrt{2E_K / I} \quad (10)$$

Taking the derivative of equation 10 with respect to time (t):

$$(d^2\theta / dt^2) = \left(\frac{1}{2}\right) \sqrt{2 / I E_K} (dE_K / d\theta) (d\theta / dt) \quad (11)$$

Combining equations 10 & 11:

$$(d^2\theta / dt^2) = (1 / I) (dE_K / d\theta) \quad (12)$$

The acceleration (a) at the RTG cg can be written:

$$a = R' (d^2\theta / dt^2) \quad (13)$$

To satisfy the FRD requirements, the acceleration at the RTG cg must not exceed 15G; therefore, this limit and equations 12 & 13 can be incorporated to yield:

$$(R' / I) (dE_K / d\theta) \leq 15G \quad (14)$$

In order to ensure that potential designs did not "bottom out" we had to determine the maximum deflection of the anti-shock frame (through an iterative process).

$$\delta = \theta_{\max} (\pi / 180) (x) \text{ when } (d\theta / dt) = 0 \quad (15)$$

Where x is the distance ($2r$) from the supported edge of the anti-shock frame to the outer edge of the honeycomb panel (or to the outermost spring in a spring design).

The formulas developed above were used to evaluate the various design options (both spring designs and crushable designs were considered).

Our current baseline is a "donut" style honeycomb panel as shown in Figure 8. This design also requires significantly less vertical space than spring designs and is very light weight. The honeycomb panel design can be easily handled and installed onto the RTG package. The baseline design consists of:

Outside Diameter = 1.17 m
 Inside Diameter = 0.923 m
 Honeycomb Crush Strength (f_{cr}) = 1.17 MPa
 Thickness = 127 mm

Referring to equations 3, 4, & 6 for the flat drop and equations 14 & 15 for the edge drop, the calculation values for the required deflection to absorb the impact load and the acceleration seen by the RTG during each type of drop are presented in Table 1.

FIGURE 7. RTG Edge Drop Configuration.

FIGURE 8. RTG Shock Limiting Transit Device Concept.

Table 1 - Calculated Performance of Honeycomb "Donut" Anti-shock Frame.

Type of Drop	Flat Drop	Edge Drop
Deflection (δ) (mm)	38.6	82.8
Acceleration (G's)	12.85	4.79
Min. Panel Thickness (mm)	55.1	118.4

The donut design fulfills the requirements of both the flat and edge drops since it concentrates the deformable material near the outer edge of the anti-shock frame (so that a large percentage of the total amount of honeycomb becomes available during the edge drop). This design is tolerant of variations of weight of the RTG package (in contrast with spring designs).

Honeycomb is limited in its ability to absorb small shock loads without plastically deforming. The honeycomb panel can withstand a crane lowering the RTG package onto the ground with a hook speed of just over 6 in/s without crushing. If a thin layer of energy absorbing material such as an elastomeric pad could be bonded to the bottom side of the panel, the crushing threshold would be increased significantly. This concept has been incorporated into our current baseline design.

CONCLUSION

The conceptual design of an RTG Facility Transportation System has been successfully completed which meets or exceeds all of the stated requirements. It meets the demanding space limitations of the existing facilities it must service, it functions well both outdoors and indoors, and it will facilitate onloading and offloading of the RTG Package as part of the overall RTG Transportation System.

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-----Nomenclature-----

English

A : Area of honeycomb panel
a : Acceleration
b : Thickness of crushable material
E : Energy
I : Polar mass moment of inertia at edge of anti-shock frame
r : Radius of Anti-shock frame
R : Distance from Anti-shock frame lower corner to the Containment Vessel/RTG/Anti-shock frame cg
R' : Distance from Anti-shock frame lower corner to the RTG center of gravity (cg)
t : Time
W : Weight of RTG and containment vessel
y : Drop height

Greek

δ : honeycomb deflection
 θ : Angle the RTG/Containment Vessel will rotate through after the anti-shock frame touches the ground

Subscript

a : Allowable
D : Dissipated
K : Kinetic
P : Potential
S : Stored
T : Total