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DESIGN OF THE HEAT RECEIVER FOR THE U.S./RUSSIA SOLAR DYNAMIC POWER JOINT FLIGHT DEMONSTRATION

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ABSTRACT

A joint U.S./Russia program is being conducted to develop, fabricate, launch, and operate a solar dynamic demonstration system on Space Station Mir. The goal of the program is to demonstrate and confirm that solar dynamic power systems are viable for future space applications such as the International Space Station Alpha. The major components of the system include a heat receiver, a closed Brayton cycle power conversion unit, a power conditioning and control unit, a concentrator, a radiator, a thermal control system, and a Space Shuttle carrier.

This paper discusses the design of the heat receiver component. The receiver comprises a cylindrical cavity, the walls of which are lined with a series of tubes running the length of the cavity. The engine working fluid, a mixture of xenon and helium, is heated by the concentrated sunlight incident on these tubes. The receiver incorporates integral thermal storage, using a eutectic mixture of lithium fluoride and calcium difluoride as the thermal storage solid-to-liquid phase change material. This thermal storage is required to enable power production during eclipse. The phase change material is contained in a series of individual containment canisters

NOMENCLATURE

CBC	Closed Brayton cycle
GTD	Ground test demonstration
MLI	Multilayer insulation
PCM	Phase change material
PGS	Power generation system

INTRODUCTION

AlliedSignal Aerospace Equipment Systems, under contract to NASA-Lewis Research Center, Cleveland, Ohio, is participating in a U.S./Russia program to design, fabricate, launch, and operate a joint solar dynamic flight demonstration system on Space Station Mir. The goal of the program is to demonstrate and confirm that solar dynamic power systems are viable for future space applications such as the International Space Station Alpha. The expected launch date is September 1997 on STS87. AlliedSignal is responsible for the power generation system (PGS). The nominal PGS output power is 2 kW(e).

The PGS comprises a heat receiver, a closed Brayton cycle (CBC) power conversion unit, and a power conditioning and control unit. The Russian firm, RSC-Energia, is responsible for the concentrator, radiator, thermal control system, and the Space Shuttle carrier. System integration is performed jointly by NASA-Lewis and RSC-Energia.

The concentrator captures the solar rays and focuses the concentrated energy in through the receiver aperture and onto the inner surface of the receiver. This concentrated energy heats the CBC working fluid, an inert gas mixture of xenon and helium with a molecular weight of 83.8. The heated working fluid is expanded in a turbine, driving an electrical generator and a compressor that circulates the working fluid. Cycle waste heat is rejected to the radiator and ultimately to space. A recuperator increases thermal efficiency by recirculating thermal energy in the cycle.

The present paper describes the heat receiver component of the PGS. The heat receiver design is based on the receiver fabricated for the solar dynamic ground test demonstration (GTD) program (Strumpf, et al., 1993, 1994a). The GTD is presently under test at NASA-Lewis. The heritage of the heat receiver design goes back to the development work performed by AlliedSignal for Work Package 04 of Space Station Freedom (Strumpf, et al., 1988,

1994b). The Freedom receiver was a much larger unit, corresponding to an engine power output of over 30 kW (e). For the Freedom program, significant test and analysis support was provided by NASA-Lewis (Keislake and Ibrahim, 1990 and Whittenberger, 1992).

OVERALL RECEIVER DESCRIPTION AND OPERATION

The receiver design (shown in Figures 1 and 2) comprises a cylindrical receiver cavity, the walls of which are lined with a series of tubes running the length of the cavity. The receiver incorporates integral thermal storage, using a eutectic mixture of lithium fluoride and calcium difluoride as the thermal storage solid-to-liquid phase change material (PCM). This thermal storage is required in order to enable power production during the substantial eclipse period which accompanies the low-earth orbits of Mir. The eutectic has a melting point of 767°C (1413°F).

The CBC working fluid flows through a finned annular region in the tubes. The PCM is contained in a series of hermetically sealed metal containment canisters. The canisters are stacked and brazed to the working fluid tube.

The receiver cavity walls consist of a metallic shell with an inner ceramic cloth liner. The shell is externally insulated.

The receiver configuration combines three functional components—the heat receiver, the CBC heat source heat exchanger, and the thermal storage device—into a single unit. The CBC working fluid from the recuperator flows to a toroidal manifold at the aperture end of the receiver. The manifold distributes the fluid to the individual tubes. The flow is collected in the outlet manifold and sent to the turbine.

During sunlight periods, heat is transferred through the PCM to the CBC working fluid. The PCM is also melted and heated
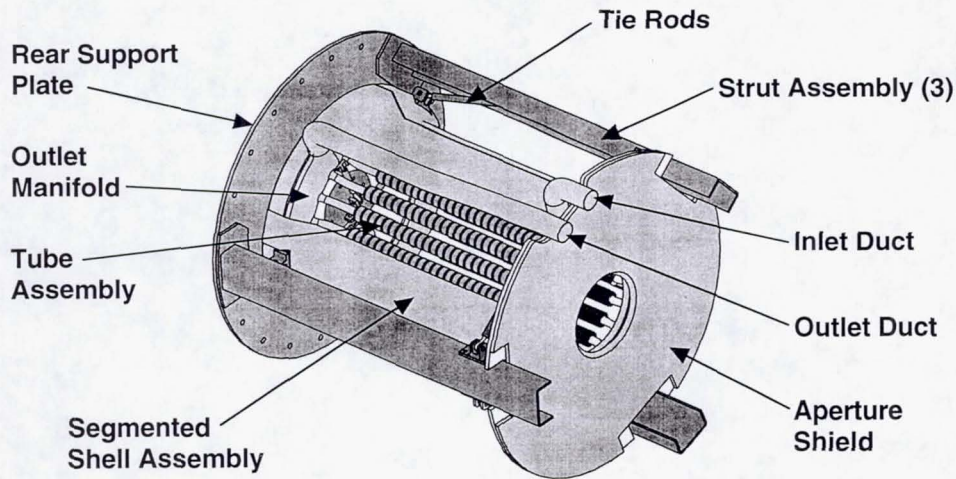
FIGURE 1. RECEIVER ASSEMBLY OVERVIEW
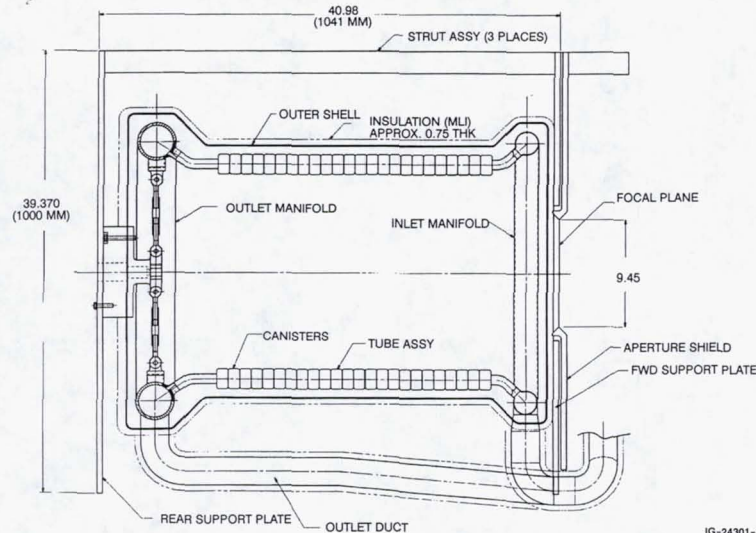
FIGURE 2. RECEIVER LAYOUT

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by the solar flux. During eclipse periods, the PCM transfers heat to the CBC working fluid and is frozen and cooled.

As shown in Figure 1, the receiver gas circuit, outer shell assembly, and aperture assembly are each independently mounted to the support structure, using tie rods. This approach minimizes launch load-induced and thermally induced stresses by off-loading weight from the gas circuit and allowing thermal growth.

The receiver design is summarized in Table 1.

TABLE 1	
RECEIVER DESIGN SUMMARY	
Active tube length, m (ft)	0.61 (2.0)
Number of tubes	20
Number of containment canisters	24 per tube
Fluid tube OD, cm (in.)	2.22 (0.875)
Tube wall thickness, cm (in.)	0.089 (0.035)
Containment canister inner wall thickness, cm (in.)	0.081 (0.032)
Containment canister outer wall thickness, cm (in.)	0.152 (0.060)
Containment canister sidewall thickness, cm (in.)	0.152 (0.060)
Containment canister OD, cm (in.)	4.52 (1.78)
Containment canister length, cm (in.)	2.54 (1.00)
Tube spacing, center-to-center, cm (in.)	6.60 (2.60)
Aperture diameter, cm (in.)	24.0 (9.45)

COMPONENT DESCRIPTIONS

The following paragraphs contain descriptions of the various components of the heat receiver.

Containment Canister

The containment canisters are individual compartments that contain the PCM. The canister material is the cobalt-base super-alloy Haynes 188. The canisters are sealed by vacuum electron beam welding after filling with the PCM through a small fill-hole. A fabricated containment canister is shown in Figure 3.

The canisters are stacked and brazed to the working fluid tube as shown in Figure 4. The canisters are not brazed to each other, but are separated by amorphous silica spacers.

The use of individual containment canisters for the PCM is a key attribute of the receiver design. This configuration affords a readily fabricable and highly reliable design. Failure of a canister would affect only that individual canister, and have minimal impact on receiver operation. The compartmentalization also reduces the chance of failure by localizing the void formation upon freezing (due to the lower density of the liquid as compared to the solid), minimizing the likelihood of high stress buildup.

The thick-walled canisters are very durable and afford adequate resistance to long-term space exposure considerations
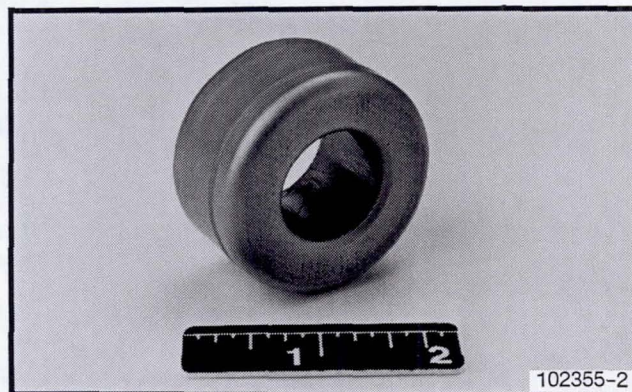

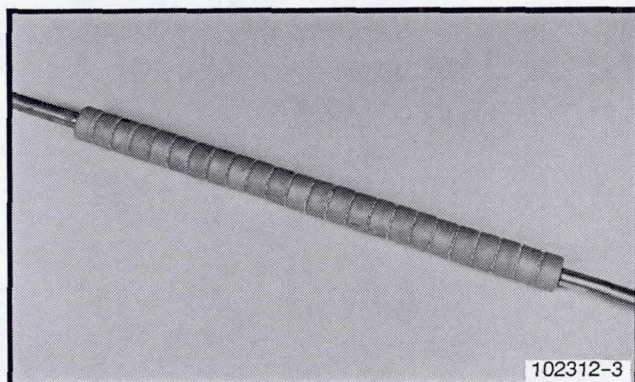FIGURE 3. CONTAINMENT CANISTER

FIGURE 4. CANISTERS BRAZED TO WORKING FLUID TUBE

such as sublimation and atomic oxygen attack. In addition, the canister sidewalls provide adequate heat transfer paths, thus obviating the need for PCM thermal conductivity enhancement.

The canisters are designed to avoid thermal ratcheting. Heat is added at the outer surface and removed at the inner surface. This allows for void formation at the hot face during freezing, such that liquid formed during melting can expand into the void.

Gas Circuit

The gas circuit consists of the working fluid tubes and the manifolds. The entire gas circuit is made of Haynes 188. Fluid flows through the tubes via a finned annular region, as shown in Figure 5. The center of the tube is blocked to increase the flow velocity. The fin is brazed to the tube inner wall and the outer wall of the centerbody blockage. The fins form 20 flow passages. To prevent fluid channeling in the event of a poor braze between the fins and the tube wall, the fins are installed in 7.6-cm (3-in.)-long sections. Adjacent sections are slightly offset, allowing flow redistribution.

The fins act to decrease the hydraulic radius of the flow passages. This results in an increased heat transfer coefficient. Along with the increase in heat transfer surface, a significant enhancement in heat transfer rate is afforded by the configuration.
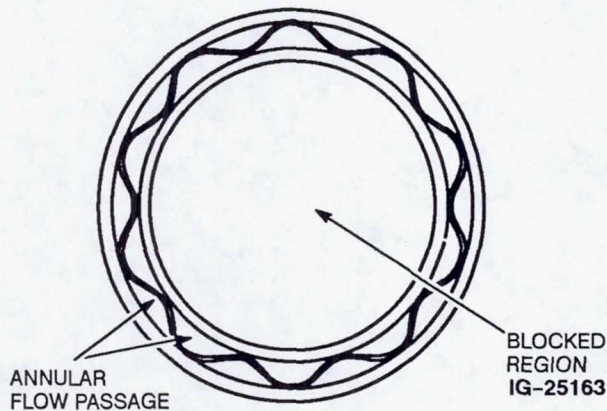
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FIGURE 5. TUBE CROSS SECTION

As shown in Figure 2, both the inlet and outlet ends of each tube are bent. The bending accommodates differential tube-to-tube thermal expansion and reduces thermal stresses. The differential thermal expansion is due to the circumferentially asymmetric incident flux arising from concentrator shadowing by Mir. There are no fins in the bent tube ends.

The tubes are connected to toroidal manifolds. The outlet manifold connections use a nipple to transition from the thick-walled manifold to the thin-walled tube (see Figure 6). No nipple is needed for the thin-walled inlet manifold connections. The large difference in manifold wall thickness is driven by stress considerations. It is desirable to reduce the outlet manifold stress at the expense of the inlet manifold stress, since the high temperature at the outlet end results in creep damage. The inlet end temperatures are below the creep threshold for Haynes 188.

The gas circuit assembly is shown in Figures 7 and 8. It can be seen that three receiver tubes are missing, resulting in a total of 20 tubes. The missing tubes are at locations opposite to the support strut locations. The support struts would completely block these tubes from receiving any incident solar flux from the concentrator. This would result in unacceptably high thermal stresses during receiver heatup periods. Removal of the tubes eliminates this potential problem.

Outer Shell Assembly

The outer shell assembly comprises an inner liner, a metallic shell (including an aperture cone), and external insulation. The assembly is shown in Figures 9 and 10 (without insulation for clarity). The inner liner, which defines the cavity walls, consists of layers of silicon carbide cloth stitched together, with silicon carbide fiber in between the layers. The liner assembly sections are attached to the metallic shell with wire fasteners, as shown in Figure 11.

Since there is a reasonably large gap between tubes, some of the radiation entering the receiver through the aperture will impinge directly on the walls. The walls act to reradiate the incoming flux to the back side of the tubes and aid in providing a relatively uniform flux circumferentially around the tubes.

The outer shell consists of eight segmented cylindrical pieces attached to end caps. The outer shell provides the support structure for the inner liner, a mandrel for the outer insulation, and an attachment structure for the aperture cone. The aperture cone is configured to represent the envelope of the incoming light rays from the concentrator, while protecting the manifold from cavity reradiation. The outer shell assembly is attached to the support frame tie rods. The outer shell mounting is totally independent of the gas circuit mounting.

The receiver insulation comprises high-temperature multilayer insulation (MLI) wrapped around the outer shell. The MLI consists of alternating layers of metallic foil and amorphous silica cloth. Fifty foil layers are used. The total insulation thickness is 2.5 cm (1 in.).

Mounts/Tie Rods

Tie rods with spherical rod ends are used to transfer receiver loads to the support structure. The gas circuit and outer shell are independently supported. As shown in Figure 12, the tie rods are attached to the structure through a clevis mount, mount base, and pin. The clevis mounts (see Figure 13) are oriented on the mount base such that no bending moments are induced in the mounts.
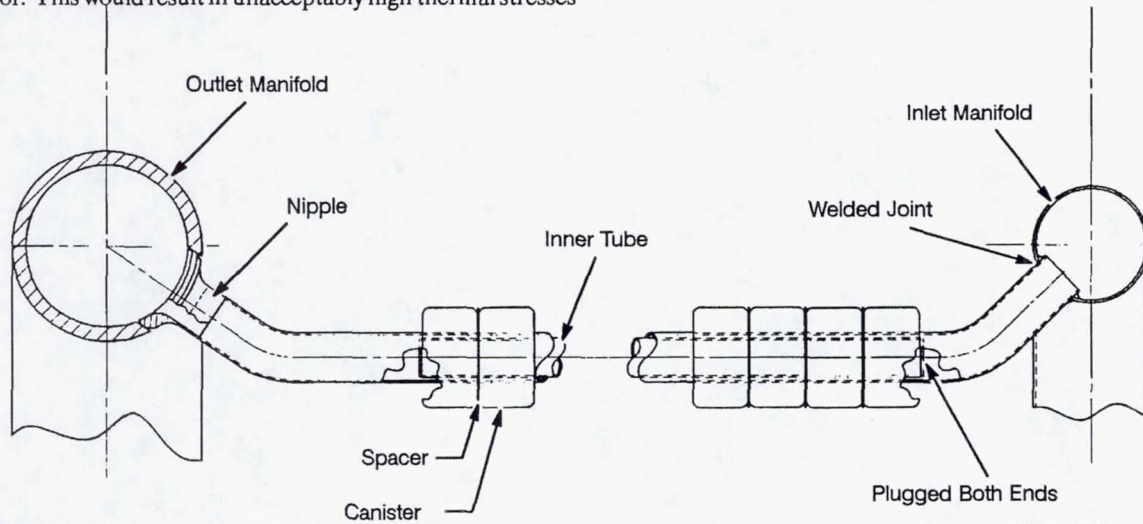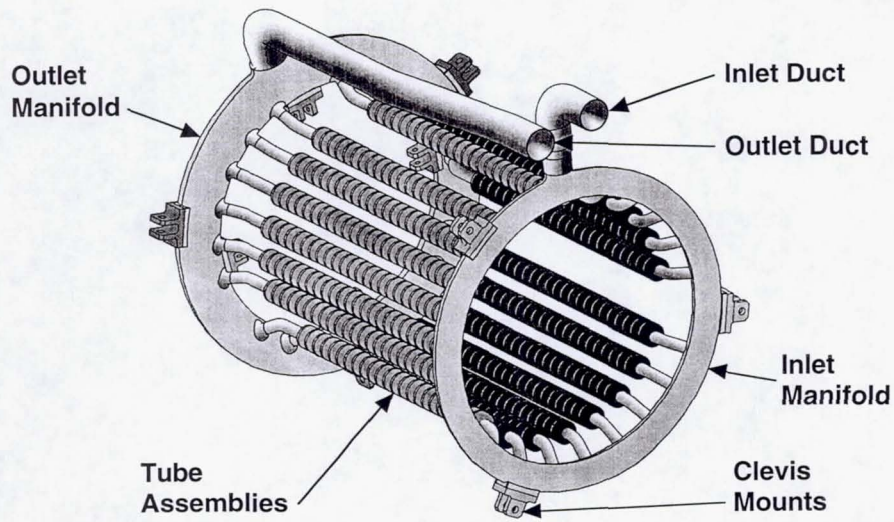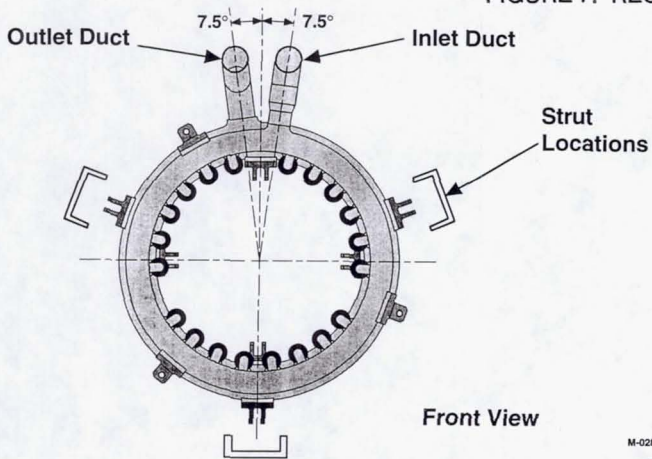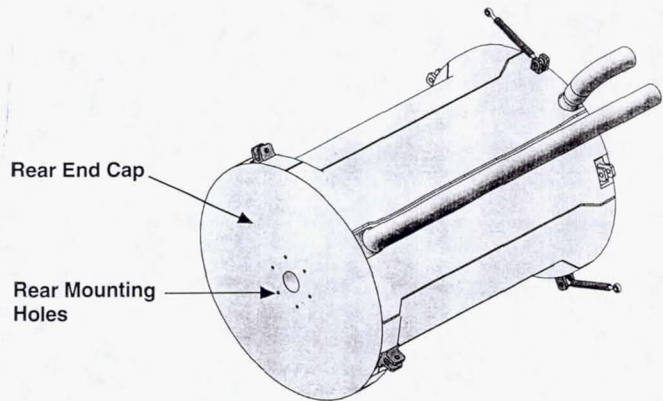

FIGURE 6. TUBE/MANIFOLD DETAILS

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Outlet
Manifold

Inlet Duct

Outlet Duct

Inlet
Manifold

Tube
Assemblies

Clevis
Mounts

M-02823

FIGURE 7. RECEIVER GAS CIRCUIT

Outlet Duct

7.5°   7.5°

Inlet Duct

Strut
Locations

Front View

M-02824

FIGURE 8. GAS CIRCUIT END VIEW

Rear End Cap

Rear Mounting
Holes

M-02636

FIGURE 10. RECEIVER SHELL ASSEMBLY (REAR VIEW)

Cut Outs
For Mounts/
Ducts

Segmented
Pieces

Tie Rods
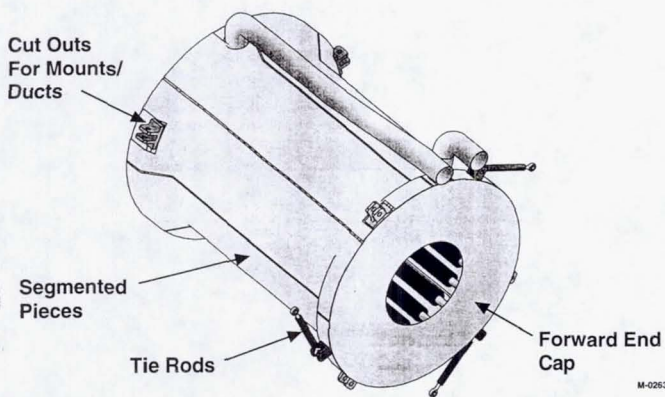
Forward End
Cap

M-02634

FIGURE 9. RECEIVER SHELL ASSEMBLY
(FORWARD VIEW)

NICHROME WIRE
FASTENERS

SEWN MULTILAYER
INNER LINER
(SILICON CARBIDE)

HAYNES 188
RECEIVER
SHELL
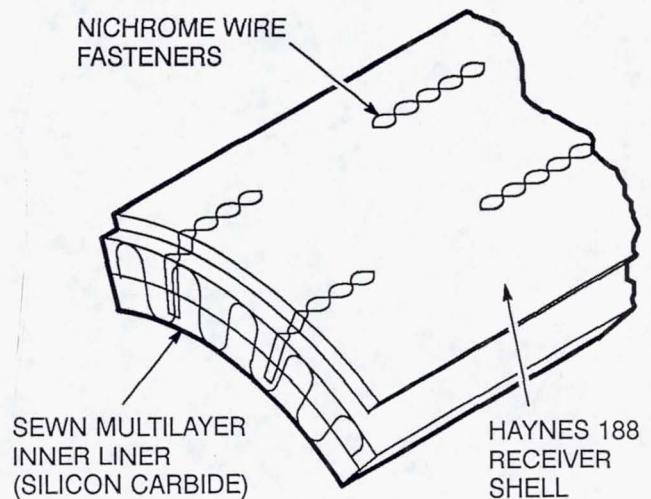
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FIGURE 11. INNER LINER ATTACHMENT

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The mount structure and tie rods are Haynes 188 with the exception of the spherical rod ends, which are Haynes 25.
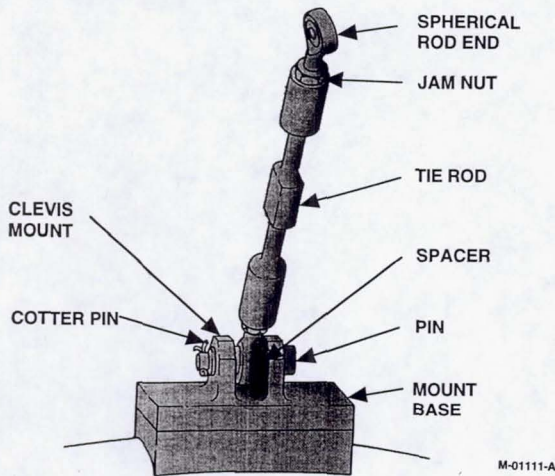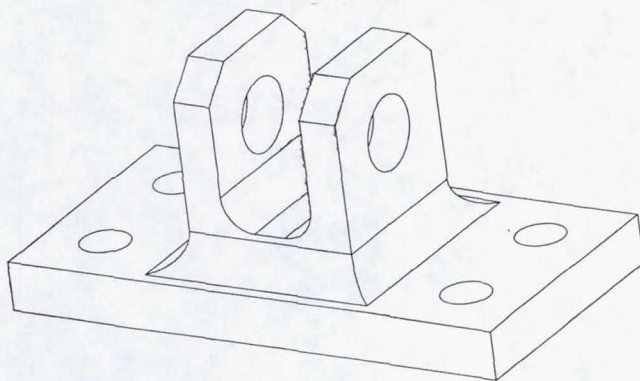

FIGURE 12. MOUNT CONFIGURATION

Labels: SPHERICAL ROD END, JAM NUT, TIE ROD, SPACER, PIN, MOUNT BASE, CLEVIS MOUNT, COTTER PIN

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FIGURE 13. CLEVIS MOUNT

Aperture Assembly

The receiver aperture accepts the solar flux from the concentrator. The aperture is 24.0 cm (9.45 in.) in dia. The aperture position is defined by the aperture assembly, which must accept the steady-state spillage from the concentrator as well as any transient flux during sun acquisition or emergency off-pointing of the concentrator. The aperture assembly comprises a graphite aperture shield, refractory metal MLI, and a metallic support plate.

Struts and Supports

The receiver support structure is shown in Figure 14. This structure comprises three struts, with rear and forward support plates. The strut assembly is connected to struts supporting the

Labels: Rear Support Plate, Strut Assembly, Tie Rod Mounts, Forward Support Plate
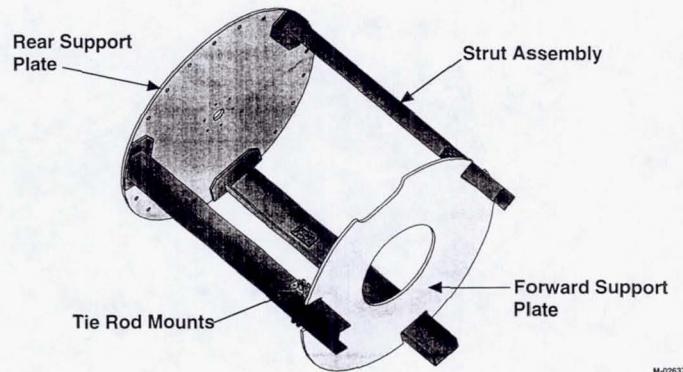
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FIGURE 14. RECEIVER STRUTS AND SUPPORT

other PGS components. The gas circuit, outer shell, and aperture assembly are independently mounted to the structure using tie rods.

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