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ABSTRACT

A joint U.S./Russia program has been conducted to design, develop, fabricate, launch, and operate the world's first space solar dynamic power system on the Russian Space Station Mir. The goal of the program was to demonstrate and confirm that solar dynamic power systems are viable for future space applications such as the International Space Station (ISS). The major components of the system include a solar receiver, a closed Brayton cycle power conversion unit, a power conditioning and control unit, a solar concentrator, a radiator, a thermal control system, and a Space Shuttle carrier. Unfortunately, the mission was demanifested from the ISS Phase 1 Space Shuttle Program in 1996. However, NASA Lewis is proposing to use the fabricated flight hardware as part of an all-American flight demonstration on the ISS in 2002.

The present paper concerns the design and analysis of the solar receiver aperture shield assembly. The aperture shield assembly comprises the front face of the cylindrical receiver and is located at the focal plane of the solar concentrator. The aperture shield assembly is a critical component that protects the solar receiver structure from highly concentrated solar fluxes during concentrator off-pointing events.

A full-size aperture shield assembly was fabricated. This unit was essentially identical to the flight configuration, with the exception of materials substitution. In addition, a thermal shock test aperture shield assembly was fabricated. This test article utilized the flight materials and was used for high-flux testing in the solar simulator test rig at NASA Lewis. This testing is described in a companion paper.

NOMENCLATURE

CBC	Closed Brayton Cycle
ISS	International Space Station
MLI	Multilayer Insulation
PGS	Power Generation System
SDFD	Solar Dynamic Flight Demonstration

INTRODUCTION

AlliedSignal Aerospace Equipment Systems, under NASA-Lewis Research Center Contract NAS3-26970, participated in a U.S./Russia program to design, fabricate, launch, and operate a joint solar dynamic flight experiment on Space Station Mir. The goal of the program was to demonstrate and confirm that solar dynamic power systems are viable for future space applications.

such as the International Space Station. AlliedSignal was 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, was responsible for the concentrator, radiator, thermal control system, and Space Shuttle carrier. System integration was performed jointly by NASA- Lewis and RSC-Energia.

The concentrator captures the solar rays and focuses the concentrated energy 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 concerns the design and analysis of the solar receiver aperture shield assembly. The aperture shield comprises the front face of the cylindrical receiver and is located at the focal plane of the solar concentrator. The aperture shield assembly is a critical component that protects the solar receiver structure from highly concentrated solar fluxes during concentrator off-pointing events.

The position of the aperture shield in the receiver is shown in Figure 1 (Strumpf, et al, 1996). The 9.45-in.-dia aperture of the receiver accepts the solar flux from the concentrator. In addition to defining the aperture position, the aperture shield assembly must accept the steady-state spillage from the concentrator, as well as any fluxes encountered during sun acquisition or emergency off-pointing events. The program requirement was to accommodate direct impingement of the full solar image for a one-hour period.

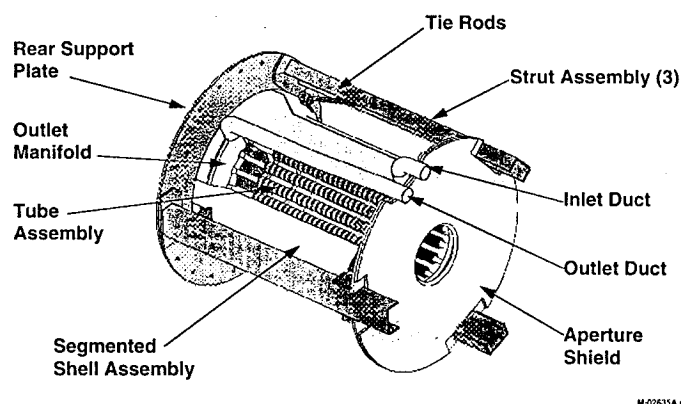


FIGURE 1. SOLAR RECEIVER ASSEMBLY

The solar dynamic flight demonstration (SDFD) program was to operate a system on Mir for a period of up to one year starting in late 1997 (Wanhainen and Tyburski, 1995). Unfortunately, the mission was demanifested from the ISS Phase I Space Shuttle program in 1996. However, substantial flight hardware, including the solar receiver, was fabricated. NASA Lewis is proposing to use the fabricated flight hardware as part of an all-American flight demonstration on the ISS in 2002.

APERTURE SHIELD DESIGN HISTORY AND CURRENT APPROACH

Previous designs for receiver aperture shield assemblies, such as for the solar dynamic ground test demonstration program, utilized a circumferentially segmented graphite aperture shield (Strumpf, et al, 1993). With the segmentation, low coefficient of thermal expansion, and high-temperature capability, the shield could accommodate the required thermal loads. However, the relatively low strength of the brittle graphite would result in significant problems during launch, requiring extremely complex design solutions.

For the SDFD system, a refractory metal configuration was used. A series of metallic foils, separated by spacers and tied together by refractory metal wire, provides the needed thermal and structural support. The shield resembles high-temperature multilayer insulation (MLI) and is indeed similar to the insulation system used on the receiver (Strumpf, et al, 1995). Design details are presented below.

DESIGN DESCRIPTION

The aperture shield assembly comprises a series of refractory metal foil layers separated by refractory metal screens in the hot-test region (closest to the concentrator) and ceramic spaces in the cooler regions. While the ceramic material is a better insulator than the screens, the temperature in the hottest regions is too high to use the ceramic. The foil layers (40 total) and screens are either tungsten or molybdenum, depending on the temperature requirement. A cross-section of the aperture shield is shown in Figure 2.

The foil stackup is mounted to a stainless steel backplate that provides assembly and structural support for launch loads. The backplate is shown in Figure 3. The machined pockets are designed to save weight and provide flexibility to accommodate thermal gradients in the plate.

The layers are stitched together and mounted to the support plate using tungsten attachment wire. A center refractory metal support ring adds structure to the foil stackup and defines the aperture opening for the receiver. The ring material is tungsten/25 percent rhenium. For thermal growth and fabrication ease, the ring is segmented into eight circumferential sections.

The top of the stackup is enclosed by a tungsten screen, which provides support for the attachment wires. This top screen is also segmented. The top foil layer, as well as the center support ring, is grit blasted to reduce reflectivity, especially specular reflectivity. Reflected concentrated sunlight could cause significant hot zones in the concentrator, and is undesirable. At the outer circumference, a stainless steel skirt encloses the outer edges of the foil layers.

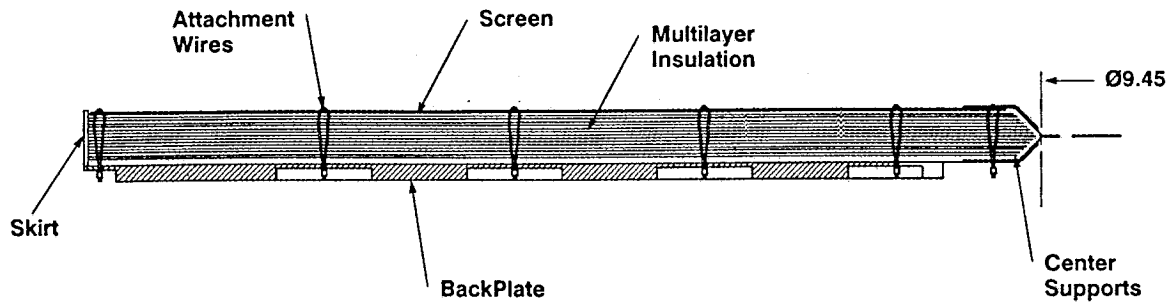


FIGURE 2. APERTURE SHIELD CROSS SECTION

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ON-ORBIT THERMAL ANALYSIS

Thermal models were created to predict the aperture shield temperatures in response to various scenarios. These include normal operation, emergency off-pointing for up to 60 min, and initial misalignment of the concentrator/receiver system after launch.

The models were run on the AlliedSignal Thermal Analyzer Program, a finite-difference in-house code similar to commercially available thermal analysis computer codes. A simplified schematic of the model is shown in Figure 6. Although there are many radial and circumferential nodes, to simplify the modeling effort, there are only two nodes in the foil stackup direction. Foil stackup conductances are derived from correlated data provided by Aerospace Design & Development, Inc., a subcontractor to AlliedSignal. The incident flux distribution on the aperture shield surface from the concentrator was derived for the various cases from calculations done at NASA Lewis (Kerslake and Fincannon, 1995).

The results of the thermal analysis for the three operational scenarios are summarized in Table 1. The parameters given are peak incident flux, equivalent peak flux in number of suns (at an average low earth orbit solar constant of 0.1417 w/sq cm), maximum temperature of the top (exposed) tungsten foil layer, maximum backplate temperature, and maximum center ring temperature.

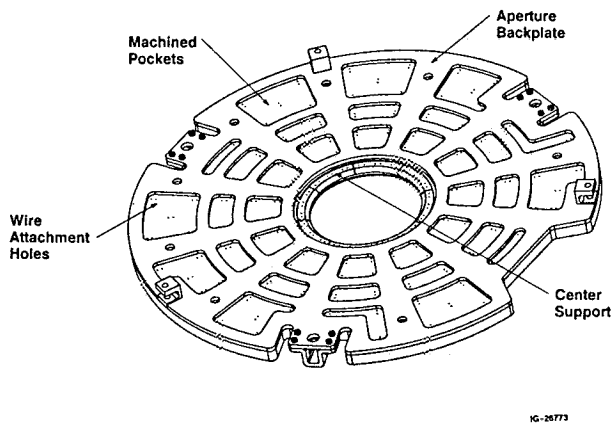


FIGURE 3. APERTURE SHIELD BACK VIEW

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A section of the aperture assembly is shown in Figure 4. A front view of the assembly is shown in Figure 5. The mounting links (three axial and three tangential) provide independent mounting to the PGS support structure. The shield diameter is approximately 1 m.

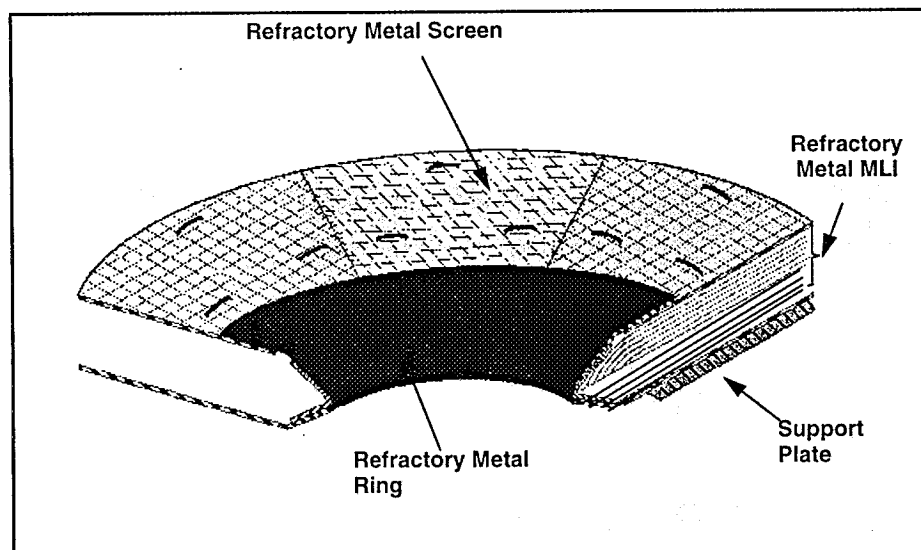


FIGURE 4. APERTURE ASSEMBLY

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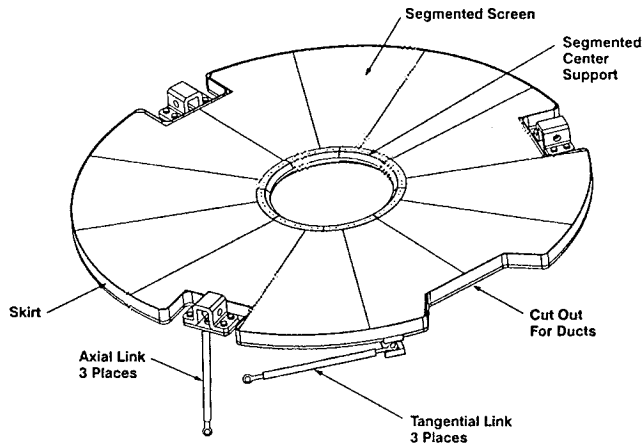


FIGURE 5. APERTURE SHIELD FRONT VIEW

During normal operation, around 2.0 kw (out of 16.8 kw) spills onto the aperture shield.

The emergency off-pointing requirement is for full sun on the shield for 60 min (16.8 kw). Thermal analysis was conducted at an off-pointing location of 3.0 deg. This location contains the incident energy on the shield, minimizing leakage into the aperture or outside the shield boundaries.

The initial alignment case could occur when the system is first activated after launch. The assumed off-pointing angle of 1.7 deg locates the peak flux on the center ring. Total power on the shield is 10.9 kw (there is significant leakage into the aperture). It is assumed that the maximum time required to move away from the off-point spot is 5 min.

All predicted temperatures (see Table 1) are well within the capability of the materials used.

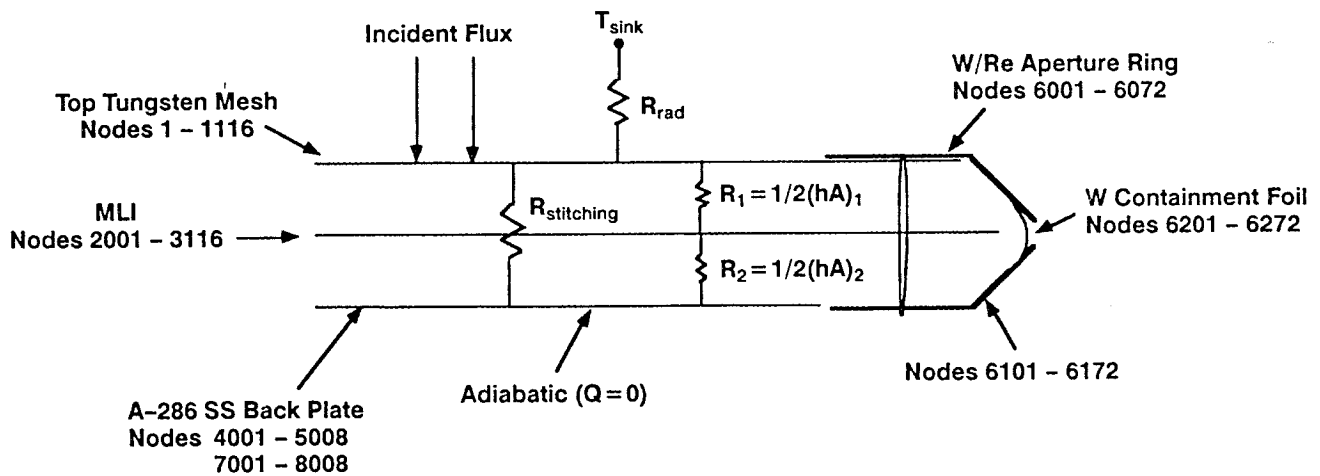


FIGURE 6. APERTURE ASSEMBLY THERMAL MODEL

TABLE 1					
SUMMARY OF APERTURE ASSEMBLY THERMAL ANALYSIS					
Flux Case	Peak Flux		Max. Top Layer Temp., °F	Max. Backplate Temp., °F	Max. Center Ring Temp., °F
	w/cm ²	Suns			
Normal operation	9.49	67.0	1312	684	1318
Initial alignment at 1.7 deg off-point	82.23	580.3			
15 sec			3184	16	3064
5 min			3288	99	3399
Emergency off-point at 3.0 deg (60 min)	79.23	559.1	3455	1026	2505

ON-ORBIT STRESS ANALYSIS

The on-orbit stresses for the aperture shield assembly are primarily thermal, although there are some low-level vibration stresses. Structural models were prepared for the center ring and backplate support using the ANSYS computer code. The flexible foils were not specifically analyzed, but there should not be any significant thermal stress problems within the foils as they are thin and quite compliant. In addition, the foils are not structural members. The inputs to the stress analysis were the predicted on-orbit temperatures.

For the backplate, the maximum stresses occur for emergency off-point at 60 min. The maximum predicted thermal stress is 43.1 ksi. Since the vibration-induced stress is less than 1 ksi, the total stress is well below the material yield strength of 78 ksi (at operating temperature).

For the center ring, the maximum stress occurs during the initial alignment period. The peak stress is at 15 sec (not maximum temperature), when the thermal gradients are quite large (see Figure 7). With very low vibration-induced stress, the total stress of about 10 ksi is well below the material yield strength of 14.5 ksi (taken, for conservatism, at the maximum predicted temperature).

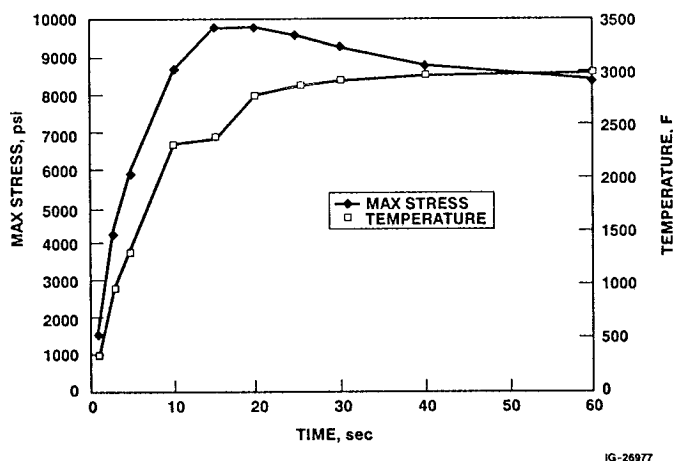


FIGURE 7. CENTER RING MAXIMUM STRESS VERSUS TIME, PSI

LAUNCH LOAD ANALYSIS

Launch loads were analyzed for the backplate support, attachment wires, and center ring. The ANSYS models were used for the support plate and center ring. Hand calculations were performed for the wire. The components are at ambient temperature during launch. The stress results are summarized in Table 2. All predicted stresses are below allowables.

Component	Maximum Predicted Stress, ksi	Yield Strength, ksi
Support plate	68.6	95
Attachment wire	97.3	160
Center ring	10	249

CONCLUSION

A full-size aperture shield assembly for the heat receiver component of the joint U.S./Russia SDFD program was fabricated. This unit was essentially identical to the flight configuration, with the exception that nickel foils were substituted for the refractory metal foils required for the flight unit. In addition, a thermal shock test aperture shield assembly was fabricated. This unit is shown in Figures 8 and 9. This test article utilized the flight refractory metals and was subjected to high-flux testing in the solar simulator test rig at NASA Lewis. This testing is described in a companion paper (Kerslake, et al, 1997).

The aperture shield assembly was designed to accommodate all on-orbit and launch loads. Detailed analysis has indicated that all loads can be comfortably accommodated.

The SDFD mission was demanifested from the ISS Phase 1 Space Shuttle Program. NASA Lewis is proposing to use the fabricated flight hardware as part of an all-American flight demonstration on the ISS in 2002.

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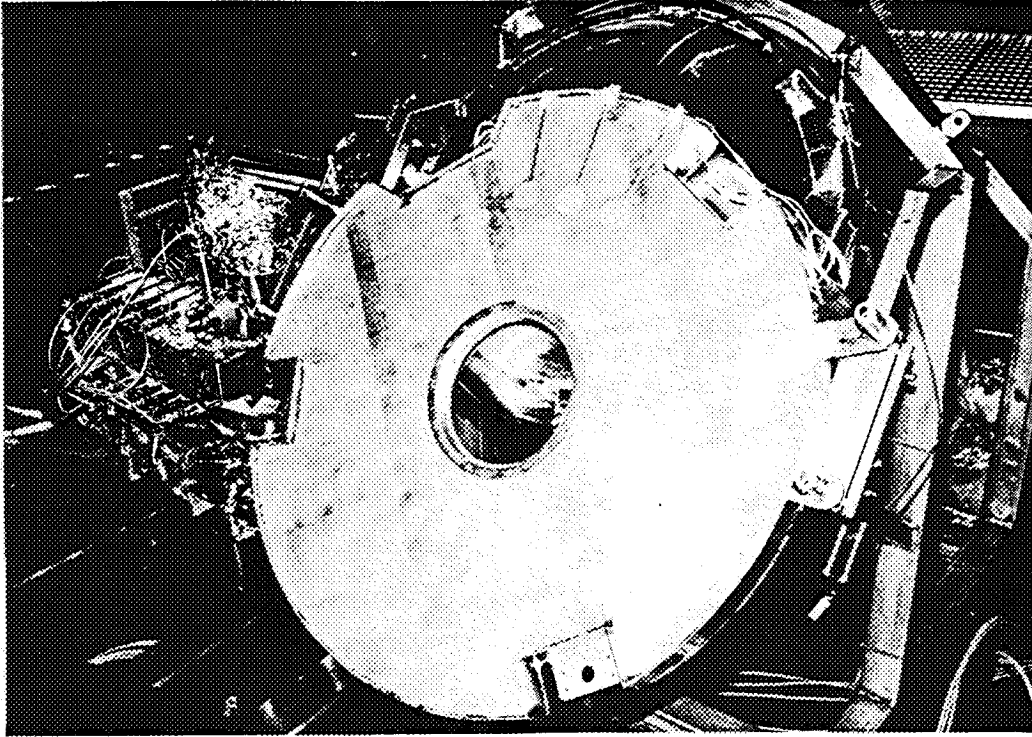


FIGURE 8. APERTURE SHIELD TEST ARTICLE

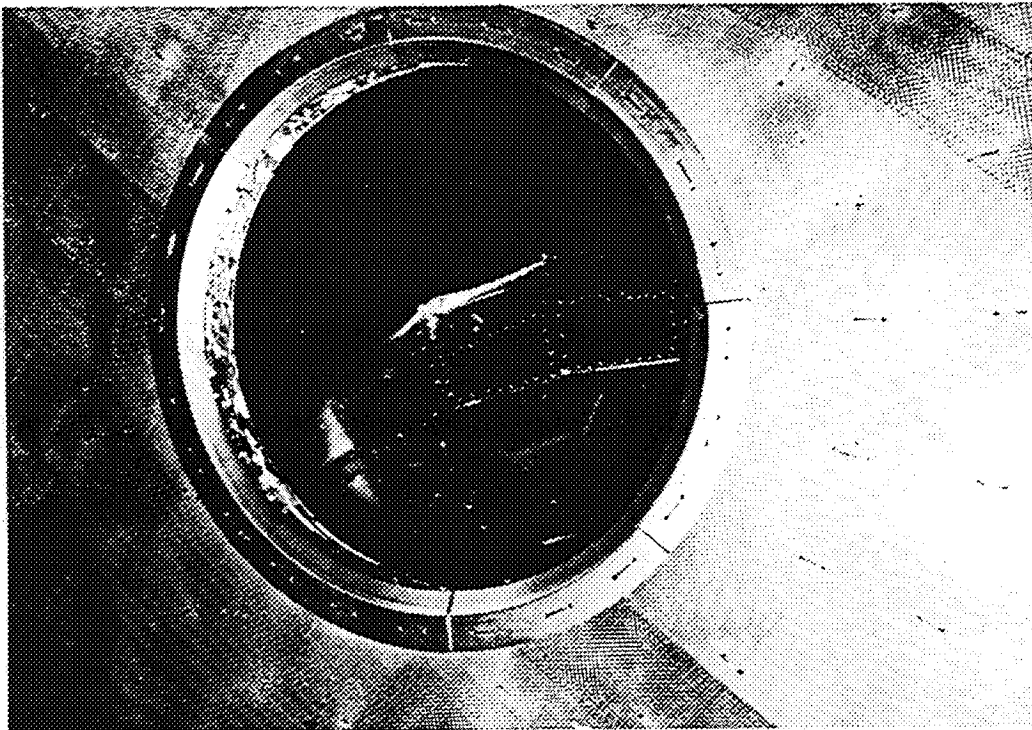


FIGURE 9. TEST ARTICLE APERTURE RING DETAILS

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