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The design and mounting of the gratings for the Far Ultraviolet Spectroscopic Explorer (FUSE)

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ABSTRACT

The Far Ultraviolet Spectroscopic Explorer grating mechanical design and analysis are discussed. These gratings are large (266mm X 275mm), and unique design constraints were imposed to maintain optical performance. FEM results of deflection and stress are presented. Requirements driving the unconventional grating design and its mount are addressed, including the plan to accommodate remote vacuum alignment in multiple degrees of freedom.

Keywords: bonded mount, FUSE, FUVS, grating, holographic, lightweighting

1. INTRODUCTION

The Far Ultraviolet Spectroscopic Explorer (FUSE) is a NASA sponsored low earth orbiting astrophysical observatory designed to provide high spectral resolution observations within the 905Å to 1195Å bandpass. FUSE is designed for a three year mission and is scheduled to launch on a NASA Med-Lite Expendable Launch Vehicle in October 1998. Production of the flight mission elements is to begin in November 1995. The mission's development efforts are constrained to a fixed cost cap and a three year schedule to launch.

The FUSE instrument primary science requirements include achieving 30,000 spectral resolution ($\lambda/\Delta\lambda$) while maximizing effective area across the bandpass.[1] The normal incidence optical system has an off-axis parabolic mirror feeding a slitted Rowland circle spectrograph with a double delay line photon counting detector. The system is replicated four times (except the detectors) to achieve the effective area requirement and a level of redundancy. Figure 1 shows the optical system layout.

2. THE FAR ULTRAVIOLET SPECTROGRAPH GRATINGS

The grating blanks and Grating Mount Assemblies (GMAs) are designed and developed by the University of Colorado's Center for Astrophysics and Space Astronomy. The Far Ultraviolet Spectrograph employs four gratings: two with SiC coatings and two with LiF coatings. Each grating has holographically recorded rulings on a spherical optical surface. Ruling densities are 5767 grooves/mm for SiC channels and 5350 grooves/mm for LiF channels. The rulings will be holographically recorded in France by Jobin-Yvon (J-Y) in collaboration with the Laboratorie D'Astronomie Spatiale (LAS).

2.1 Grating Blank Design

Optical surface distortion of each grating blank is integrally tied to maintaining the instrument resolution requirement. Any distortion induced by the grating mount, 1g release, thermal environment, or hysteresis must not reduce the instrument resolution below 30,000. The launch vehicle was not defined during the design phase of the FUSE structure and gratings, so Delta II launch loads were assumed in the structure design. Estimated loads were extrapolated for the gratings based on their mounting location to the instrument's graphite-epoxy structure. Consequently, the gratings have been designed to withstand loads of 15g simultaneously in 3 axes. Standard aerospace factors of safety are used at 1.25 x limit load for test verification, 1.4 for ultimate stress, and 1.25 for yield stress (minimum). The spectrograph's on orbit thermal operating range is 15° to 25°C and survival range is -10° to 40°C. The grating blank shape and figure are a result of the optical design resolution, active area, and holographic recording requirements. Optical design parameters are described in Green and Wilkinson[1].

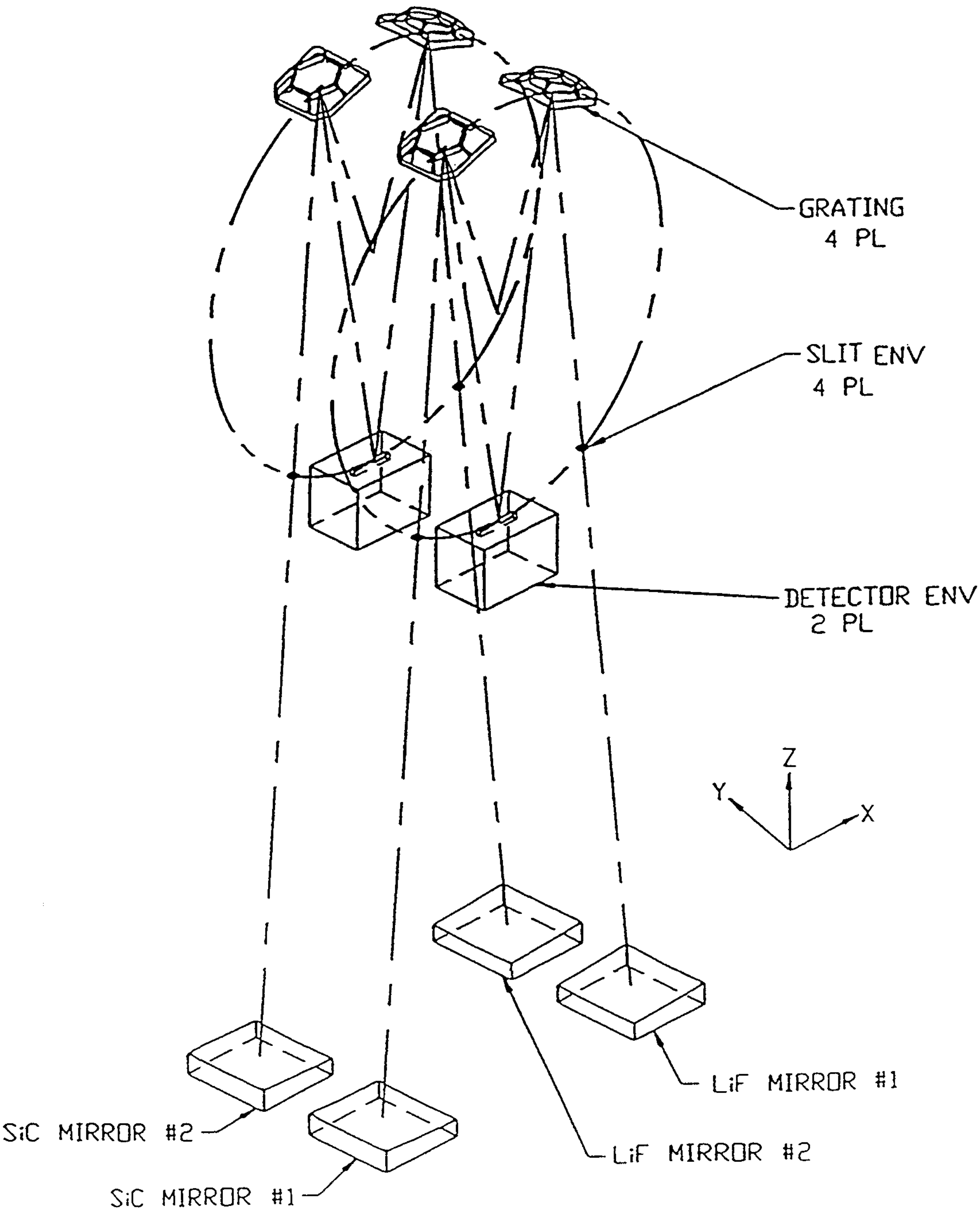

Figure 1. FUSE Optical Layout

One of FUSE's primary limits on effective area is grating size. Therefore, the grating's dimensions are maximized within current holographic recording capabilities at the required high line densities. Each grating blank is rectangular with a spherical optic surface and a machined rib pattern in its back as shown in Figure 2. Given these limitations, the maximum blank dimensions are 266mm x 275mm x 68.1mm. The outer 4mm perimeter of the grating optical surface is not considered active area. Each optical edge reserves 3mm for holographic recording tolerance (which degrades near the optical surface edge), plus 1mm for manufacturing and alignment tolerances. Two corners of the blank are missing because one corner of the mounted grating invaded the original launch vehicle static envelope. The opposing corner was removed to make all grating blanks identical, which simplifies fabrication and provides interchangeability.

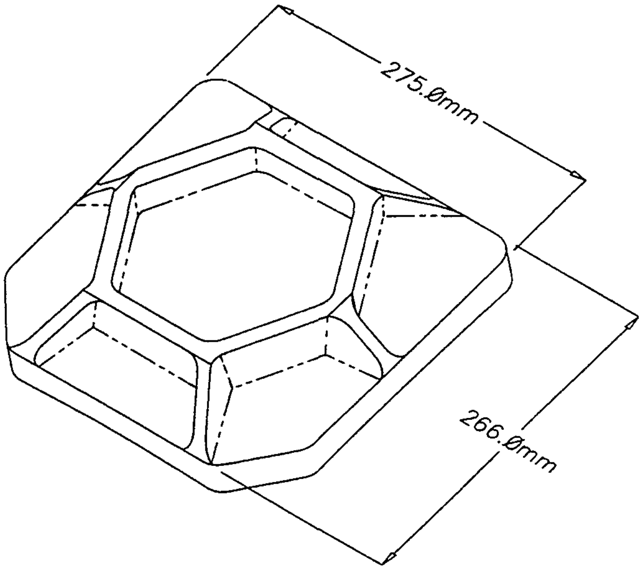

Figure 2. FUSE Grating Blank

The grating blank material is Corning 7940 fused silica, class 0, grade F. This material was chosen to accommodate the holographic recording process, for its coefficient of thermal expansion (CTE), and availability under aggressive development schedule constraints. Holographic recording requires zero inclusion class material, but homogeneity requirements are not quantified allowing a grade F designation.

The grating blank as a solid is quite heavy and creates large inertial loads. Larger loads make optical surface deflections difficult to control, in addition to complicating mount design and remote alignment. Traditional honeycomb lightweighting methods are prohibited for FUSE gratings because the holographic recording process requires a minimum 20mm of unobstructed glass behind the optical surface. Consequently, an alternate approach was taken to lighten the grating and ease mounting.

The machined rib pattern in the back of the grating blank is a function of its mounting points. The mount pattern employs a three point system to minimize distortions in the grating optical surface. Locations were chosen in an effort to apply established optimal mounting points for double-arch mirrors.[2] Since the FUSE gratings are not round and not double-arch configuration, some diversion was taken from general methods. Vukobratovich et al.[3] found double-arch mirror optimized mount points at 0.65R, which is somewhat close to equal sector centroids. Thus, initial FUSE grating mount points were located at the centroids of equal areas. Figure 3 shows how the FUSE grating shape has been divided into equal areas. The two missing corners contribute ease in dividing the rectangular shape into three equal areas and are within acceptable effective area cost. As a result, the two corners were left off even though the NASA Med-Lite vehicle envelope may accommodate them. The center hexagonal rib pattern was chosen over a circular pattern to facilitate design, fabrication and assembly of the mount brackets described later in this paper. The hexagonal rib height was chosen to allow enough mount bracket overlap for good bond strength, and the hexagon center was removed for weight reduction. Outer ribs extend from each corner of the hexagon to support the grating outer edges and are located such that their center lines intersect at the hexagon center.

The holographic ruling process requires that the entire exterior, except the grating spherical recording surface, be opaque and non-scattering. Strength and fracture control requirements also impose restrictions on the grating blank's surfaces. Therefore, following the blank's initial machining, it is acid etched, followed by a process to remove etch residue, and finally polished to a spherical radius with a λ/10 figure.

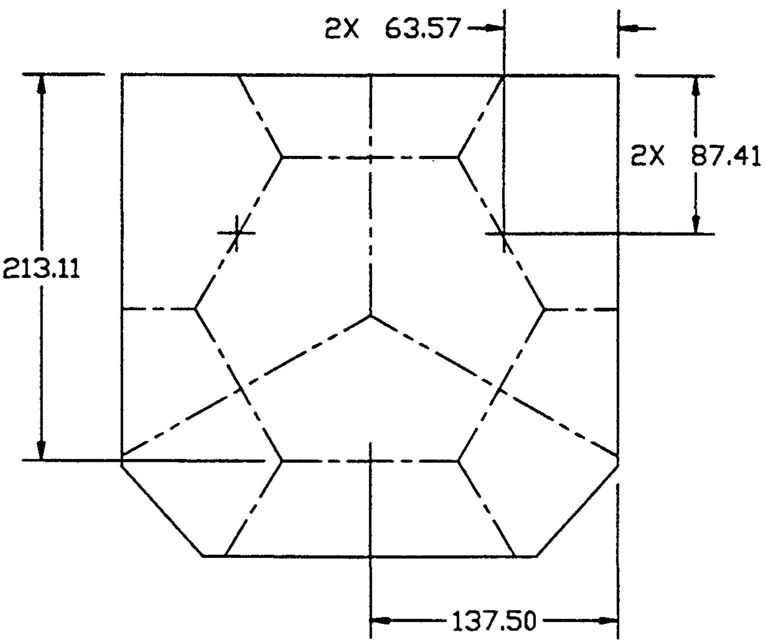

Figure 3. FUSE Grating Mount Pattern

2.2 Grating Blank Analysis

The grating blank is only somewhat lightweighted, and print-thru of the web pattern was not of major concern. This conclusion can be justified by calculating the peak to peak quilting deflection (Valente and Vukobratovich)[4].

$$\delta_c = \psi\left[\frac{Et_f^{\,3}}{12\left(1-\upsilon^2\right)}\right]^{-1} PB^4 = 1.216\text{e-}6 \text{ in} \cong 0.03\mu \qquad (1)$$

where: material = 7940 Corning fused silica
δ_c = quilting amplitude (peak to peak)
ψ = geometric quilting constant (hexagonal) = .00111
E = 10.1e6 psi ≅ 6.98e4 N/mm^2
t_f = front face sheet thickness = 0.7874 in ≅ 20mm
$\nu = 0.17$
P = 0.3 psi
B = diameter of cell inscribed circle = 6.225 in ≅ 158mm

A finite element model of the grating blank was generated on a millimeter scale. Radii between the ribs and grating back are not represented in the model, and the spherical optic surface is represented as a 30mm thick flat. The nodes on both sides of each of three ribs are constrained where mount brackets will be bonded in place. 15g body forces were applied to the model in three degrees of freedom (DOF) simultaneously. Von-mises stress results are shown in Figure 4. The simultaneous body force loads in conjunction with restraints directly on the glass are considered conservative since the load carrying contributions of the mount brackets, adhesive, and flexures are neglected in this model.

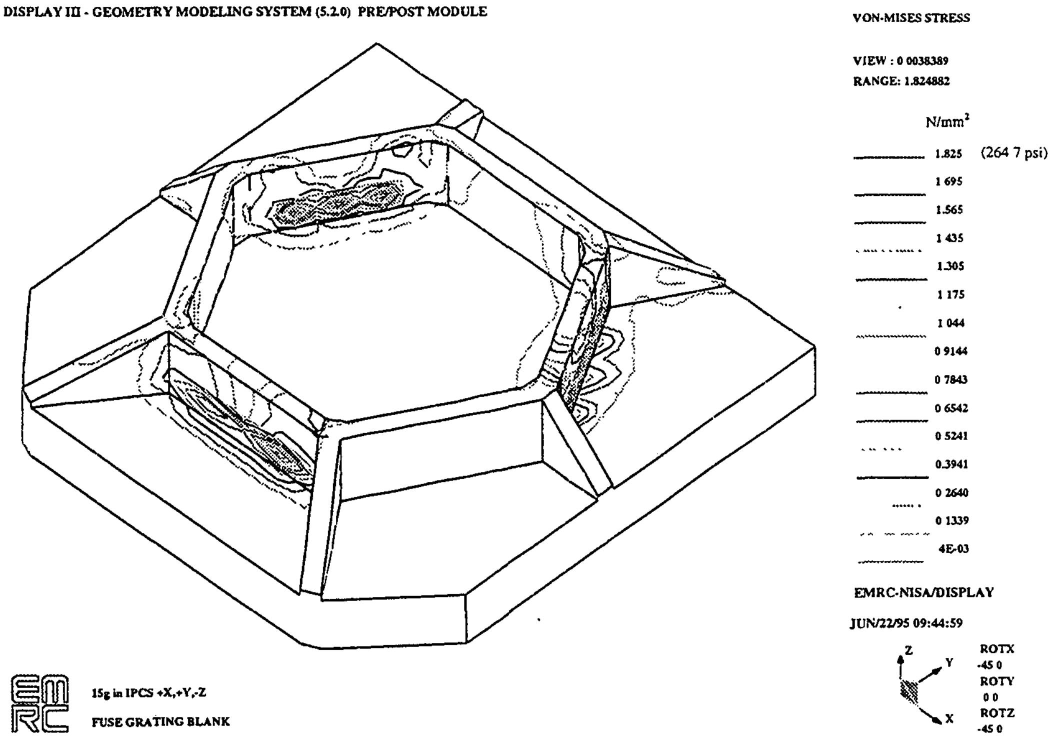

Figure 4. FUSE Grating Blank Von-mises Results

An eigenvalue analysis of the finite element model was run with the grating mount areas constrained. The frequencies of the first four modes are shown in Table 1.

Table 1: Grating Blank Modes

Mode #	Frequency (Hz)
1	2181
2	2315
3	2930
4	3227

Grating optical surface deflections have been estimated by applying body forces and temperature changes to a similar finite element model of the grating, which includes mount brackets and flexures (see Figure 5). The resultant optical surface node deflections are used as input for a separate program which removes tilt and focus via Zernike polynomial fits. Figure 6 shows the optical surface wavefront error when the grating is mounted in the spectrograph and subjected to 1g during alignment. Figure 7 shows a similar wavefront error resulting from a 5°C temperature increase of the entire model. Wavefront errors are based on 6328Å. These sub-micron deflections are within allowable 1g release requirements to maintain alignment on orbit. Since all of the deflection models indicated optical surface distortions are within an acceptable range, the rib pattern mount points were not altered from the original equal area centroid locations.

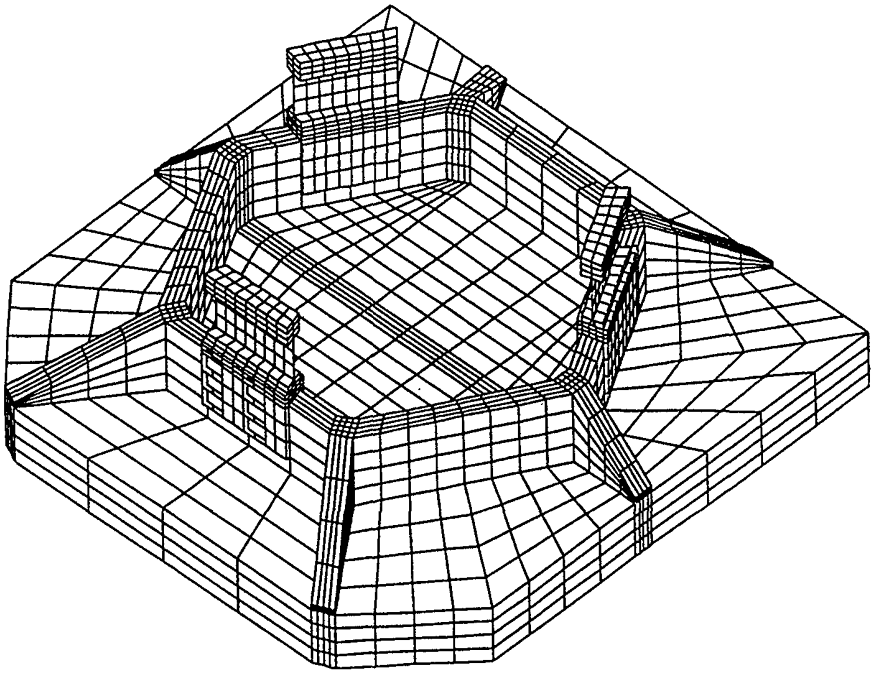

Figure 5. FUSE Grating/bracket/flexure FEM

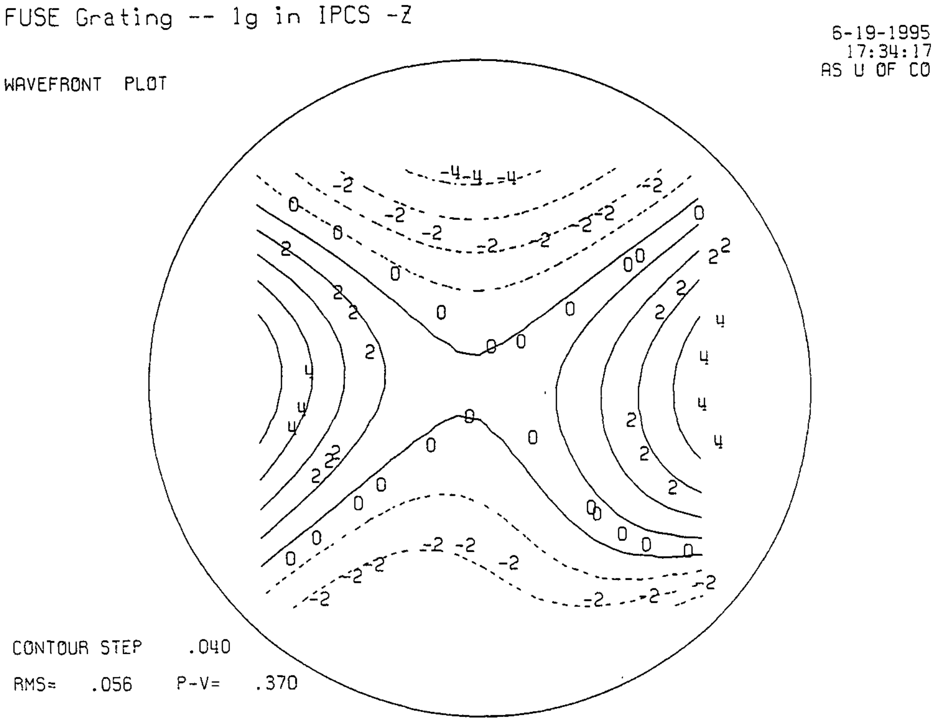

Figure 6. FUSE Grating Wavefront Error (1g in alignment orientation)

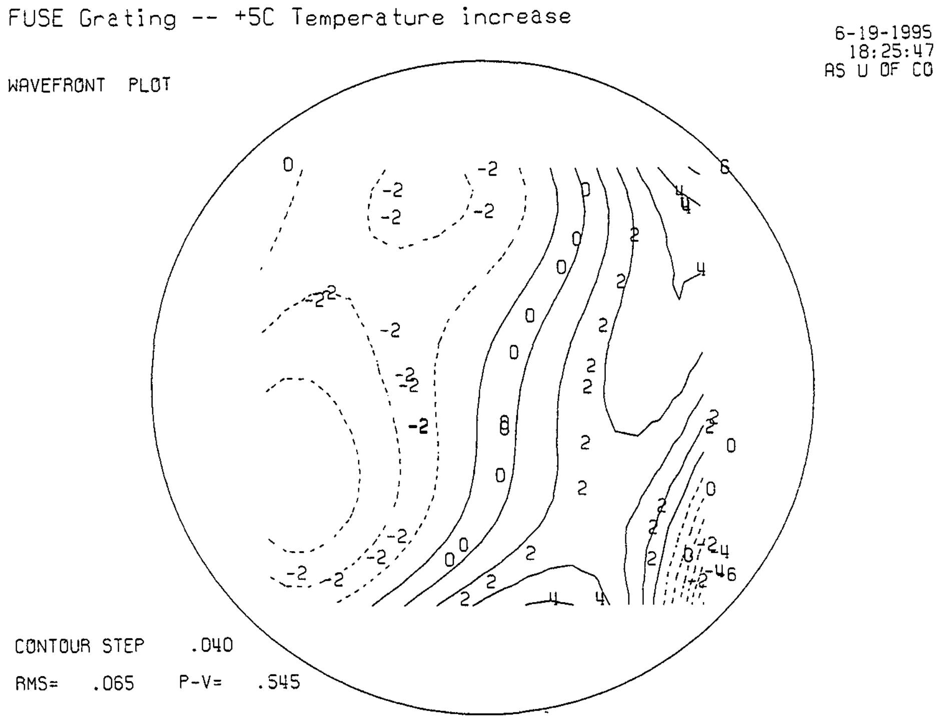

Figure 7. FUSE Grating Wavefront Error (+5C bulk temperature increase)

The probability of grating blank fracture is given by the following Weibull distribution function:[5]

$$P_{FW} = 1 - \exp\left[-\left(\frac{\sigma_a}{\sigma_0} \right)^m \right] = 1.67 \text{ x } 10^{-5} \tag{2}$$

where: P_{FW} = probability of failure
σ_a = applied stress = .384 N/mm^2 {from section 3.2, equation (5)}
m = Weibull modulus = 4-5
σ_0 = scale factor = 6-7 N/mm^2

This implies there is 1 chance in 59,880 the grating blank will fracture at one mount area. The entire FUSE instrument has four gratings with 3 mount areas each. The probability that a grating fracture will occur at any mount area on the instrument is 1 chance in 2495. The most conservative combination of Weibull modulus, and the scale factor are used in this calculation, in addition to the conservative contact stress calculation based on Miles' approximation.

3.0 GRATING MOUNT ASSEMBLY

The grating mount assembly (GMA) must support the grating from behind and attach it to the structure optical bench. The mount must protect the grating from stresses which would induce fracture or optical active area distortion at a sub-micron level. The GMA must also prevent micron level grating position changes during 1g release, in addition to providing remote alignment capability in 3 axes of motion.

3.1 Grating Mount Assembly Design

Three "u"-shaped mount brackets are bonded over three ribs at the chosen mount areas described in section 2.1. A radially compliant flexure is attached to the top of each mount bracket as shown in Figure 8. An isometric view of the GMA (Figure 9) depicts a view of the outer components from above. Three 3/8-16 bolts hold the outer tube mount flange to the FUSE structure grating bench.

Several adhesives were considered for bonding the mount brackets to the grating ribs. The structural adhesive must be fully curable at room temperature, conform to FUSE outgassing contamination requirements, and have a service temperature within FUSE survival and test temperatures. Other factors affecting the adhesive selection are viscosity, pot life, adhesion quality to invar 36 and fused silica substrates, and resistance to certain solvents used in the grating development. Lap shear tests with invar and fused silica coupons were performed using several candidate adhesives. Test results proved lap shear strength to the dissimilar substrates was very close to the ASTM D1002 aluminum lap shear test results quoted in each adhesive's specification sheet. Since all of the tested adhesives fit the FUSE curing, service temperature, and contamination criteria, the final adhesive selection was driven by manufacturing requirements. The mount brackets will be injection bonded onto the grating ribs in order to tightly control the bracket position and bondline, while ensuring a lack of voids in the bond joint. Therefore, Hysol EA9396 was chosen for its lower viscosity and longer pot life characteristics.

Material selection for the GMA components is driven not only by strength and weight, but is also greatly affected by coefficient of thermal expansion (CTE). Variations in ambient temperature during test and alignment with respect to on orbit temperatures could push the gratings out of alignment with the rest of the spectrograph. Titanium is the material of choice for the inner and out mount tubes, flexures and flexure mount because of its low CTE and high strength to weight ratio. Small GMA axial movements may be compensated for by on-orbit slit plane control (see Figure 1).

The GMA flexures must prevent temperature fluctuations from inducing stresses into the grating blank, hence resulting in optical surface distortions. The flexures must also carry launch loads, resist buckling, and maintain the same micron level grating position during alignment in 1g as well as on orbit. Unit loads were applied to the grating finite element model in both radial and tangential directions. Tilt and focus distortions were removed from the resulting optical surface deflections. Some simple math based on the greatest allowable optical surface deflection provided an allowable unit load, which in turn was used to predict flexure physical parameters. Equations used in this method can be found in Vukobratovich and Richard[6], and Weinstein[7].

The grating mount assembly estimated mass is 8.5 Kg, which includes the actual grating blank mass of 4.5 Kg.

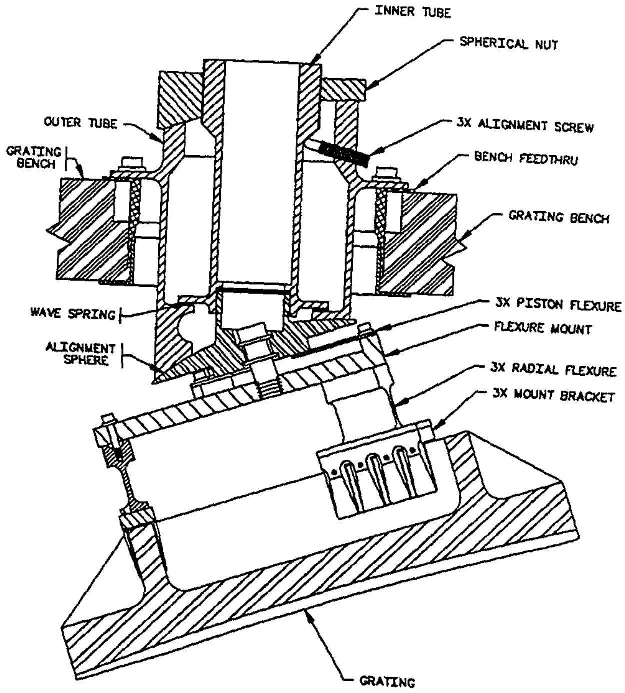

Figure 8. FUSE Grating Mount Assembly Cross Section

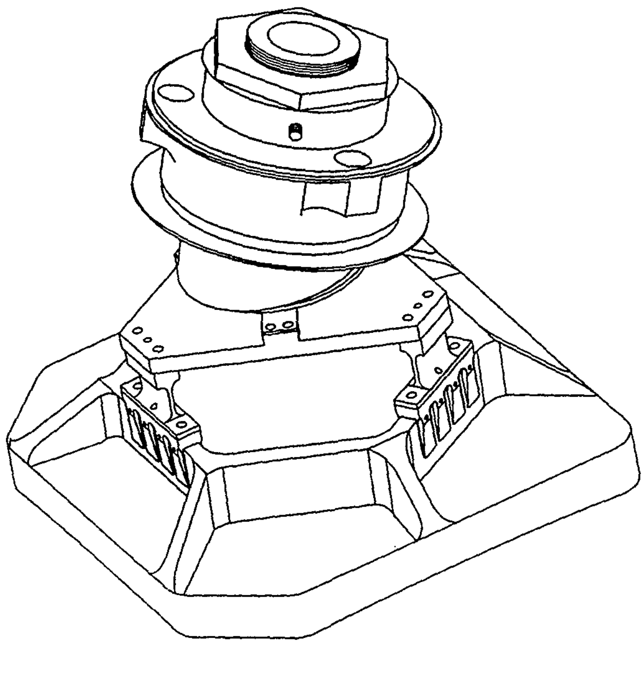

Figure 9. FUSE Grating Mount Assembly

3.2 Grating Mount Assembly Analysis

One GMA analysis requirement which became obvious early in the design was the importance of addressing a structural bonded joint of dissimilar materials. The mount brackets had to provide a good mounting medium while protecting the brittle glass from possible stress concentrations followed by inevitable fracture. A controlled bondline will distribute the loads over a defined area, but thermally induced stress between the adhesive, bracket material, and glass ribs must be controlled. Matching the material CTE's of the grating blank and mount bracket lowers thermally induced stresses in the grating blank ribs, in addition to reducing potential optical surface deflection. The bracket bond areas are broken into long narrow rectangular sections which put the adhesive in a uniaxial state, making stresses easier to predict. Thermally induced stress between Invar 36 and fused silica yields a 6.8 factor of safety if EA9396 epoxy is used in the bond joint. The equation used to calculate thermally induced stress in a uniaxial state is shown below.[8]

$$\alpha_t = \frac{E_1 E_2 \Delta T \Delta X}{E_1 + E_2} \tag{3}$$

where: α_t=thermally induced stress
E_1, E_2=Young's modulus of adherands
ΔT=difference in temperature (T_2 to T_1)
ΔX=difference in substrate CTE's

Inertial loads for GMA stress calculations are estimated using Miles' approximation. The contact area applied stress at the mount bracket/grating bond joint is shown below.

$$3rms = [\frac{\pi}{2}(f_n)(Q)(PSD)_{f_n}]^{\frac{1}{2}} = 67g \tag{4}$$

where: f_n=GMA fundamental frequency
Q=30
PSD=0.08 g^2/Hz

$$\sigma_a = \frac{(67g)(4.5Kg)(9.81m/s^2)}{.0077m^2} = 384119\frac{N}{m^2} = 0.384\frac{N}{mm^2} \tag{5}$$

where: σ_a = grating contact area stress

A finite element model was built to simulate a grating mounted on flexures. An eigenvalue analysis was run with the flexure mount areas constrained and yielded a fundamental frequency of 747 Hz. The model was expanded to include the rest of the GMA components with constraints at the three mount locations on the structure optical bench. Table 2 shows the GMA model's eigenvalue analysis results.

Table 2: GMA Modes

Mode #	Frequency (Hz)
1	131
2	274
3	293
4	418
5	513
6	724

3.3 GMA Alignment Requirements

Two gratings must be simultaneously aligned with their respective entrance slits and a shared detector; all which lie on respective rowland circles as shown in Figure 1. This drives the GMA alignment requirements to be quite stringent as shown in Table 3. Coarse alignment is required in six degrees of freedom (DOF) in a cleanroom environment with a visible light source. Final alignment of three DOF requires an ultraviolet source and must be done in a vacuum tank with remote control.

Table 3: GMA Alignment Requirements

Parameter	Coarse Installation Tolerance Class 10,000 clean room, visible light, 22±5C	Fine Alignment Requirement Vacuum tank (10^{-5} Torr max.) ultraviolet light, 22±5C
U_x	±0.25mm	N/A
U_y	±1.00mm	N/A
U_z	±0.50mm	±2.0mm (±10μm step)
θ_X	Installation error	±200 arcsec + installation error (±1 arcsec step)
θ_Y	Installation error	±60 arcsec + installation error (±1 arcsec step)
θ_Z	±60 arcsec	N/A

Coarse positioning of the grating in the global axial direction (U_z) can be accomplished by shimming between the outer tube mount flange and the structure grating bench feedthru. Coarse rotation about Z is controlled by rotation of the inner tube with respect to the outer tube. Coarse positioning in lateral directions (U_x and U_y) and rotations about X and Y axes (θ_X and θ_Y) are controlled by moving the outer tube flange with respect to the grating bench mounting holes. The outer tube flange mount holes will be oversized to accommodate required travel. The three mount bolts will be tightened in place once coarse alignment is complete.

Final alignment is more complicated. A GSE alignment mechanism will be mounted to a GSE support plate suspended over the structure optical bench and attached at four sturdy points on the bench. U_z positioning will be achieved by driving the piston screw through the alignment sphere via a ball end driver controlled by a motor on the GSE support plate. The piston screw will move the flexure mount with respect to the alignment sphere and mount tubes by bending the piston flexures. θ_X and θ_Y will be controlled by three motors which drive each alignment screw and rotate the grating about its optical center via the inner tube. When the desired final position is found, another motor drives each lock nut down and completely compresses the spherical washer spring. The nuts will be staked to hold final alignment position after the spectrograph is removed from the vacuum tank.

4.0 VERIFICATION PLAN

The FUSE gratings are larger than previously recorded holographic gratings of such high line densities. Therefore, a prototype grating was produced at J-Y so optical tests could be performed by LAS and CU. Flight gratings will be optically characterized by efficiency and imaging tests at LAS after recording, and again at CU after assembly into a grating mount. A mechanical engineering test unit was also fabricated and will be subjected to random vibration in all axes and sine burst tests to qualify the grating blank design. Flight grating blank material will be procured to a class 0 inclusion specification and inspected prior to and following machining. The blank will also be periodically inspected throughout its development for critical flaws. Flight gratings will be structurally and thermally qualified at GMA level vibration and thermal testing.

A prototype grating mount assembly will be fabricated and undergo 3-axis random vibration and sine burst tests to structurally qualify the mount using a grating mass model. The GMA will also be subjected to thermal vacuum and thermal balance tests to search for possible hysteresis. Flight GMA's will be structurally and thermally qualified.

5.0 GMA CONTAMINATION ISSUES

The FUSE spectrograph performance is very dependent on the condition of each grating's bandpass coating. Therefore, each grating's environment is closely monitored throughout its development and storage. Witness samples are kept with each grating and subjected to all processes and environments throughout the grating's development. Both coatings (SiC and LiF) are sensitive to particulates and outgassed contaminants, so the gratings are kept in a maximum class 10,000 clean room environment, unless they are in a $1x10^{-5}$ torr vacuum, or stored with protective covers. The LiF coating degrades rapidly in the presence of moisture and is protected in storage by a continuous dry nitrogen purge. Once the spectrograph is completely assembled and aligned, contamination control is at the FUSE system level and implemented by the FUSE systems integrator, Johns Hopkins University.

6.0 ACKNOWLEDGMENTS

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8.0 ACRONYMS

CTE - coefficient of thermal expansion
CU - University of Colorado at Boulder
DOF - degrees of freedom
ELV - expendable launch vehicle
FEM - finite element model
FUSE - Far Ultraviolet Spectroscopic Explorer
FUVS - Far Ultraviolet Spectrograph
GMA - Grating Mount Assembly
GSE - ground support equipment
IPCS - instrument prime coordinate system
JHU - Johns Hopkins University
J-Y - Jobin-Yvon
LAS - Laboratoire D'Astronomie Spatiale
LiF - lithium flouride
NASA - National Aeronautics and Space Administration
SiC - silicon carbide