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A Comparison of Performance of Lightweight Mirrors

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ABSTRACT

Four lightweight solid contoured back mirror shapes (a double arch, a single arch, a modified single arch, and a double concave mirror) and a cellular sandwich lightweight meniscus mirror, have been considered for the primary mirror of the Space Infrared Telescope Facility (SIRTF) A parametric design study using these shapes for the SIRTF 40 inch primary mirror with a focal ratio f/2 is presented Evaluations of the optical performance and fundamental frequency analyses are performed to compare relative merits of each mirror configuration Included in these are structural, optical, and frequency analyses for (1) different back contour shapes, (2) different number and location of the support points, and (3) two gravity orientations (ZENITH and HORIZON positions) The finite element program NASTRAN is used to obtain the structural deflections of the optical surface For wavefront error analysis, FRINGE and PCFRINGE programs are used to evaluate the optical performance A scaling law relating the optical and structural performance for various mirror contoured back shapes is developed

1 INTRODUCTION

Structural and optical performance studies for the 40 inch primary lightweight mirror of the SIRTF are presented Shuttle launch load data were provided by the NASA Ames SIRTF technical staff The 40 inch primary mirror is designed to survive the shuttle launch load environment Optical quality must be assured for both the launch and cryogenic cooldown The baseline SIRTF telescope design requirements (mechanical, thermal, and optical) are given in reference 1 The optics of SIRTF are designed to remain uneffected by the temperature excursions that the facility will experience from fabrication to a cryogenically cooled state using liquid helium A flexure mount was designed for the primary mirror comprised of a "folded back" titanium flexure assembly needed to accommodate material stability effects, fabrication tolerences, and the differential thermal contraction between the aluminum telescope baseplate support and the mirror substrate[2,3]

Dynamic analyses of the SIRTF mirror and support system were conducted using several methods of combining modal responses from a Displacement Response Spectrum analysis (DRS) including Modified Root of Sum of the Squares (MRSS), Square Root Sum of the Squares (SRSS), and Absolute Sums (ABS) The results from DRS were compared those of a Modal Frequency Response analysis[4,5]

Programs to evaluate the performance of optical mirrors due to the effects of mechanical, gravity, and/or a thermal loads have been developed at the Optical Sciences Center of the University of Arizona The FRINGE program[6] is used to quantitatively evaluate the characteristics of optical surfaces from either test data or finite element analyses PCFRINGE[7] is a revised FRINGE program for personal computers, and uses the output data from structural analysis programs such as NASTRAN, PAL, ANSYS, SAPIV, GIFTS, and COSMOS

Surface distortions over the mirror control the qualitative performance of the optical system For optical design purposes, the wavefront variations are described in terms of tilt, defocus, astigmatism, coma, spherical, trefoil, and the higher order aberrations using the Zernike polynomials Tilt and focus terms are removed for all optical analyses in this parametric design study of mirror shapes

Four typical solid contoured back mirror shapes (*Double concave, Single arch, modified Single arch, and Double arch*) and a cellular sandwich lightweight meniscus mirror were selected for the study of structural and optical properties The mirror materials used in this design analyses are SXA, an aluminum and silicon carbide metal matrix composite, and Fused Silica, Corning code 7940 The material properties are

SXA	Fused Silica
Elastic modulus = 16 0 x 10^6 psi	Elastic modulus = 10 7 x 10^6 psi
Poisson's ratio = 0 30	Poisson's ratio = 0 17
Weight density = 0 10 lb/in^3	Weight density = 0 092 lb/in^3

2 SOLID CONTOUR MIRROR DESIGN ANALYSES

Spaceborne mirror designs require dynamic analyses of both the primary mirror and its structural support system The support system of a proposed 40 inch primary SIRTF mirror and the mirror itself must be strong enough to sustain a severe launch environment Fundamental frequency estimates of various mirror shapes were made for equivalent height and equivalent weight contoured back mirrors at the University of Arizona[8]

Fundamental frequencies depend upon the support conditions, therefore, the following conditions were used in this parametric design study: (1) a RING, a six at 60 degrees (6-60), or a three at 120 degrees (3-120) support system for every mirror configuration with (2) support point ratios ranging from 0 50 through 0 70 for the double arch mirror shapes. For this parametric design study, each mirror has a 40 inch diameter supported for both the ZENITH position (optical axis vertical) and the HORIZON position (optical axis horizon)

2 1. Double concave mirror

An attribute of double concave mirror shapes is the symmetry of the optical and the back surfaces This geometric feature ensures that the structural plane of symmetry normal to the optical axis and the gravity plane are coincident Therefore, it generally is used in a HORIZON application[9] A 40 inch diameter f/2 SXA mirror with both the optical and back surfaces concave and supported at the outer edge (r/Ro=1 0) was analyzed This mirror has a radius of curvature of 160 inches for the front and back surfaces with an outer edge thickness of 5 0 inches and an inner edge thickness of 2 6 inches This mirror was labeled as configuration 1 and is shown in Figure 1 Evaluation of the optical performance for this configuration was made for various boundary conditions In order to examine the effect of the thickness of the mirror, another configuration with an outer edge thickness of 4 0 inches and an inner edge thickness of 1 6 inches, labeled as configuration 2 as shown in Figure 2, was analyzed as well

The fundamental mode shape for configuration 1 supported by 6-60 are shown in Figure 3 In this figure, only the top layer of elements of the mirror model was used for illustration The first mode shape which is a pure vertical motion is at 470 Hz The second mode, which is a mixed torsional plus vertical translation, occurred at 1850 Hz[10] A summary of the structural and optical results for both configurations is listed in Table 1 The optical surface RMS (the square Root of the Mean Squares) wavefront variations for configuration 2 were estimated twice larger than those for configuration 1 For this particular shape of mirror, the lowest RMS wavefront error is 0 282 waves (λ = 6,330 angstroms, 0 6328 microns, or 25 micro inches) and results when configuration 1 is supported by a RING

The fundamental frequencies, obtained from NASTRAN models for a ring support, were 492 Hz for mirror configuration 1 and 360 Hz for configuration 2 For a 6-60 support system, the fundamental frequency as well as the maximum surface deflection were very close to that for a RING support The natural frequencies for these configurations, supported by a 3-120 system, were calculated as 362 Hz and 281 Hz, respectively

2 2. Single arch mirror design analyses

A 40 inch single arch SXA mirror with a maximum depth of 5 0 inches was optimally designed for minimum weight based upon self weight loading along the optical axis As shown in Figure 4, the mirror has a 4 0 inch diameter central hole, an outer edge thickness of 0 5 inches, and a 2 0 inch land The self-weight was 135 pounds and it was supported at r/Ro=0 15 (Configuration 1) Another single arch shape of the same configuration with the exception of the size of the land with r/Ro=0 20 was also optimally designed and analyzed (Configuration 2 as shown in Figure 5)

A comparison between the two configurations was made and listed in Table 2 For a RING support, the fundamental frequency was estimated to be 435 Hz for configuration 1, and 556 Hz for configuration 2 The optical RMS wavefront error was 0 175 λ for configuration 1, and for configuration 2 the RMS was approximately 30 percent greater A comparison of the results for these specific mirrors supported by a RING, a 6-60, and a 3-120 support system, shows that for all practical purposes the mirror performances are identical to one another statically, optically and dynamically The conclusion can be drawn that for this 40 inch f/2 single arch mirror the structural and the optical performances are practically identical regardless of the support conditions

2 3. Modified single arch mirror design analyses

The mechanical and optical performance of two alternative single arch mirror designs was investigated as part of this study Both proposed mirrors are of similar configuration, but differ in edge thickness and use different back curves as shown in Figure 6 Both mirrors are supported and located by a central preloaded hub clamp as shown in Figure 7 The supporting hub and clamp assembly provides both radial location and restraint along the optical axis. Preloading of the clamp is required to ensure that the mirror remains correctly positioned during conditions where acceleration loading would otherwise cause separation between the support land and the mirror base At the mirror/support interface, three raised dimples machined or mechanically attached to the support land will furnish a positive means of preventing wobble and tilt of the mirror Mechanical deformation of the mirror caused by the preloading forces has been included in this investigation

In order to study deformation of the single arch mirror under various loadings, a finite element model was generated configured as shown in Figure 8 The following fundamental loading cases are considered: 1) 1g ZENITH 2) 1g HORIZON 3) 1g preload on hub clamp assembly Preload forces are modeled by a uniform pressure exerted over the conical hub area as shown by Figure 9 For gravity loading along the optical axis (case 1) and hub preload (case 3), the three point support provides restraint and produces six fold symmetry in the model Consequently, a 60 degree pie model was used for this portion of the analysis The model is restrained along the optical axis by rollers extending radially along the mirror base as shown in Figure 9 In order to investigate how the mirror deflection behavior will change as these linear supports become point supports (the actual case may be somewhere between these two extremes), the same model was run again using a shorter linear support denoted as restraint B For horizon pointing (case 2), two fold symmetry occurs and a 180 degree pie model is used Radial restraint by the hub ring is assumed to occur at the locations shown by Figure 10 Actual location of the radial restraint is dependent on the relative stiffness of the hub assembly as compared with stiffness of the mirror hub region The assumed support locations represent a compromise between a very stiff hub and a very flexible one

Mechanical deflections at all surface nodes were compiled for each of the fundamental load cases 1, 2, and 3 These mechanical deflections were combined for the two following cases: 4) 5g preload + 1g ZENITH 5) 5g preload + 1g HORIZON A 5g preloading of the clamp assembly was chosen as a realistic minimum needed to safely withstand typical handling environments without metal to glass separation Mechanical deflections of the optical surface resulting from the fundamental loads and the combined loading cases were used to predict optical wavefront errors which are summarized in table 3 A contour plot of a typical deformed surface is displayed by Figure 11 Tilt and focus errors of the deformed wavefront are not included in any of the results because these errors are removed by positioning of the secondary mirror

RMS wavefront errors of the modified single arch alternatives are found to be comparable with those of the single arch mirrors for ZENITH and HORIZON pointing The heavier Type B mirror shows improved optical performance compared with the Type A mirror, indicating sensitivity to the contoured back surface shape Both mirror configurations exhibit significant deterioration of the optical performance when 5g preload forces are included For 1g zenith loading, a substantial improvement in optical performance is noted as the support restraint at the mirror base is changed from full width to 3/5 width

2.4. Double arch mirror designs

Four typical 40 inch f/2 SXA double arch mirrors with various support conditions were considered Each has a distinctive back contour, but all have the same inner edge thickness of 0 5 inches and outer edge of 0 5 inches The 0 5 inch minimum thickness of the edge was a fabrication constraint Making mirrors of these sizes with thinner edges is not practical The radius of curvature is 160 inches for all mirrors Typical cross sections of the basic shapes and the parameters of each back contour, defined by the generic contoured back equation[11], are shown in Figure 12 A typical finite element model for a 40 inch double arch mirror is comprised of 1548 solid elements and 1862 grid points for a total of 5586 total degrees of freedom

The evaluation of the optical surface performance in terms of RMS wavefront errors were listed in reference 9, which showed that the RMS wavefront error value is strongly dependent upon both the contour back shape and support system Fundamental frequency analyses were performed for the same contoured back shapes In order to examine the effect of the support location, mirrors of various contoured back shape equations with support ratio ranging from 0 5 to 0 7 were used Each mirror configuration was supported by a different number of support points

Listed in the Table 4 is a summary of the results for double arch mirror shapes with the contoured back equation of (EQN 2-3) for various support conditions The fundamental frequencies obtained from NASTRAN were bounded to within ten percent of a maximum difference for the various support conditions When the mirror with (EQN 2-3) contoured back shape, for example, is supported by a RING at r/Ro=0 50, the fundamental natural frequency is 1080 Hz For a 3-120 at the same support location for the same shape, a lower frequency at 930 Hz is found The stiffest model in a dynamic sense was a mirror supported by a RING at r/Ro=0 60, here the smallest surface deflection can be found as well. For a further verification of the effect of the mirror back shape, the contoured back equations of (EQN 4-5) and (EQN 6-7) were also chosen The results obtained from these three contoured back shapes supported by a RING at r/Ro=0 5 are summarized in Table 5

In order to integrate the effects of support conditions in the estimation of fundamental frequencies, a frequency ratio was used, as shown in Table 6, where the frequency ratios for a 6-60 and a 3-120 to a RING support system are listed For example, fundamental natural frequencies of 6-60 supported mirrors are about 97 percent of those for RING supported mirrors of identical shape For a double concave mirror supported by a 3-120, the fundamental frequency may be estimated as about 75 percent of that for a RING Similarly, the fundamental frequency of a three point supported single arch is 95 percent of that for a RING For double arch mirror shapes, the ratio is about 85 percent This implies that a great saving in effort is possible during input data preparation and the computer access time A mirror with a RING support can be modeled as an axisymmetric model, therefore, at least one order of magnitude of the computer access time can be saved when compared to the analysis for a 3-120

3 CELLULAR SANDWICH LIGHTWEIGHT MIRROR

An alternative design of a lightweight primary mirror and mirror cell for SIRTF uses a cellular sandwich mirror design made out of Fused Silica, Corning code 7940 The severe load effects on the mirror are circumvented by clamping the mirror in the cell during launch This preliminary design consists of a 135 pounds sandwich mirror having triangular cellular structure The mirror design has three socket inserts machined into blocks near the edge for the tangent bar mount Tangent bar flexures connected to the socket blocks and the inside of the mirror cell support and position the mirror during space operations

This cellular sandwich mirror, shown in Figure 13, has the following physical dimensions

faceplate thickness = 0 3 inches	overall depth = 4 0 inches
backplate thickness = 0 2 inches	cell shape = triangular
cell rib thickness = 0 2 inches	outer edge thickness = 0 25 inches
weight without socket blocks = 100 pounds	overall mirror weight = 135 pounds

Strength of material solutions[12] (SOM) were utilized to obtain a first order approximation of dimensions which maximize mirror stiffness to weight The MAP[13] (Mirror Analysis Program) program was employed to optimize the mirror configuration determined by SOM approach Additionally, a finite element model using the GIFTS program was generated to provide a means of evaluating both static stresses and the fundamental frequencies In Table 7 the fundamental frequencies along the optical axes and the maximum global stresses at the optical surface were listed for a three point edge support

4 SUMMARY AND CONCLUSIONS

A comparison of the proposed SIRTF 40 inch mirrors is summarized in Table 8 Single arch shapes produced the lowest wavefront errors, whereas double concave have the highest Double arch mirrors have the highest fundamental frequency Through these studies of various contoured back shapes and support conditions, the following conclusions are drawn

(1) The structural and optical performances are sensitive to the material parameters, contoured back shape, and support location

(2) The optical performances for the 40 inch single arch mirror shapes were similar regardless of the support systems

(3) RMS wavefront variations and fundamental frequencies of all 40 inch f/2 mirror configurations supported by a 6-60 were practically identical to those supported by a RING

The following observations were made by comparing the results from various mirror configurations analyzed in this study:

(1) Double concave mirrors have the lowest stiffness to weight ratio which implies that they are rather heavy compared to their stiffness

(2) Single arch mirrors perform the best optically, however, the fundamental frequency is somewhat low

(3) Double arch mirrors have reasonably good optical performance and have high stiffness

(4) The modified single arch mirrors provide optical performance similar to the other single arch mirrors studied However, preload clamping forces degrade the optical performance significantly

(5) The cellular sandwich mirror has approximately the same stiffness weight ratio as single arch, but the optical performance is not as good as single arch

Generic scaling laws[10] can be utilized to evaluate optical performance and fundamental frequencies of different mirrors having geometric similarity and/or different material properties These laws are

$$\mathrm{RMS} = \left[\frac{\rho}{\rho_{ref}}\right] \left[\frac{E_{ref}}{E}\right] \left[\frac{A}{A_{ref}}\right] \mathrm{RMS}_{ref}$$

where RMS is the root mean square surface wavefront error, A stands for the cross sectional area of a mirror, E is Young's modulus, ρ is the density, and the subscript of "ref" in this equation represents the values or parameters associated with the reference mirror configuration

Also:

$$f = \left[\frac{\rho_{ref}}{\rho}\right]^{\frac{1}{2}} \left[\frac{E}{E_{ref}}\right]^{\frac{1}{2}} \left[\frac{D_{ref}}{D}\right] f_{ref}$$

where f is the fundamental frequency, D is the diameter of a mirror

5. ACKNOWLEDGEMENT

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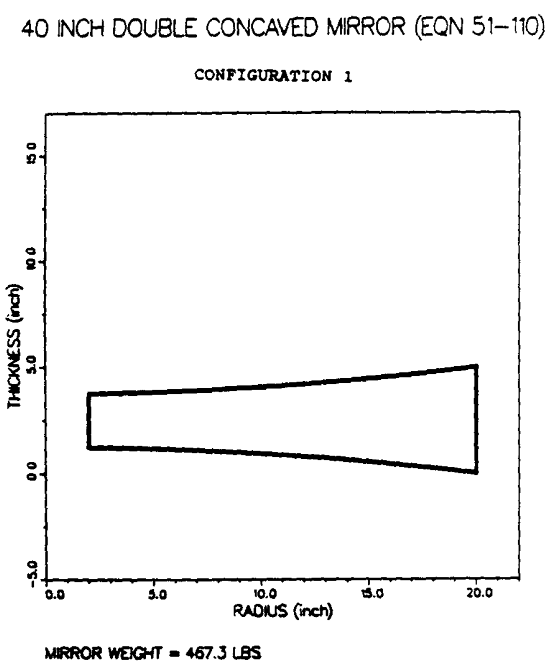

Fig. 1. A 40 inch double concave mirror (Configuration 1).

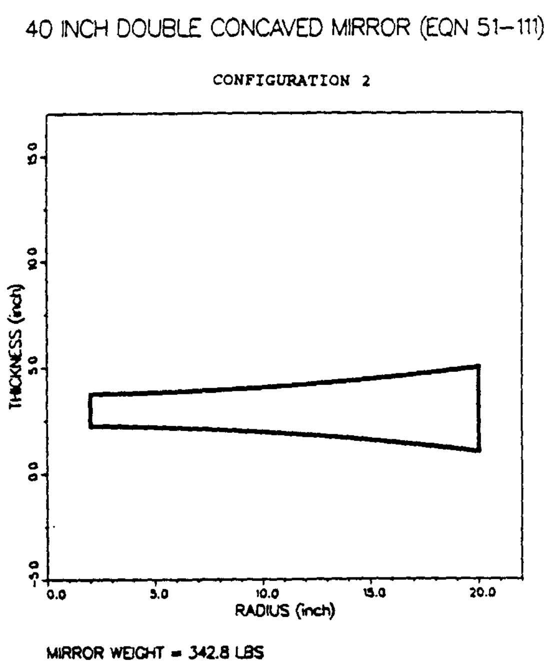

Fig. 2. A 40 inch double concave mirror (Configuration 2).

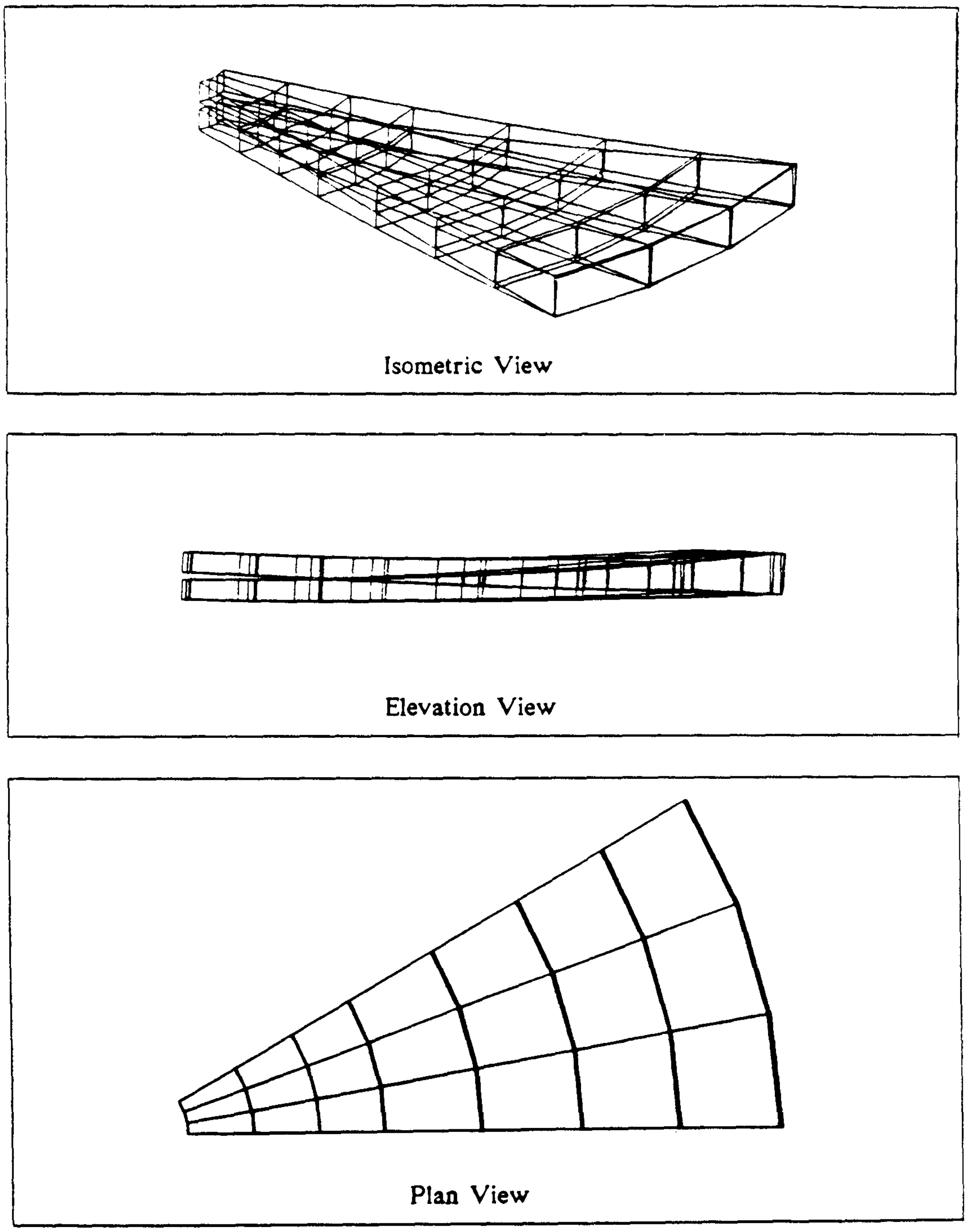

Fig 3. Frequency mode 1 at 470 Hz for Configuration 1 (6-60 support)

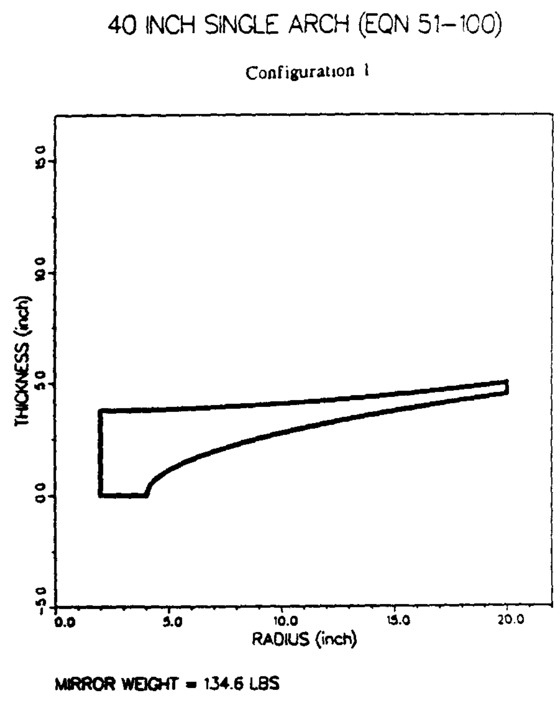

Fig. 4. A 40 inch single arch mirror (Configuration 1).

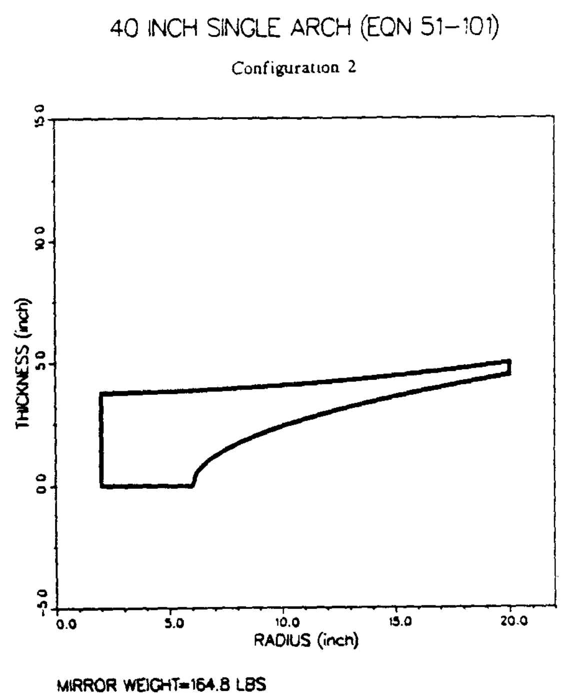

Fig. 5. A 40 inch single arch mirror (Configuration 2).

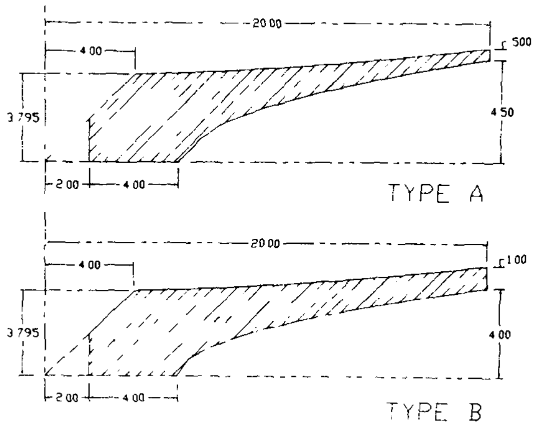

Fig 6 Alternative sections of the single arch mirror option

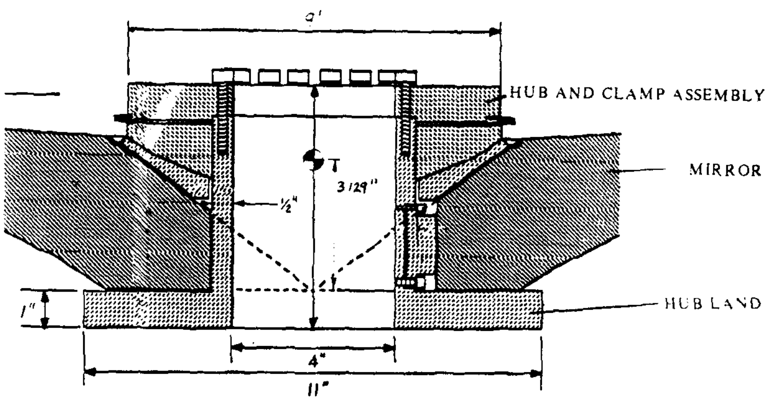

Fig 7 Hub and clamp assemby securing the modified single arch mirror

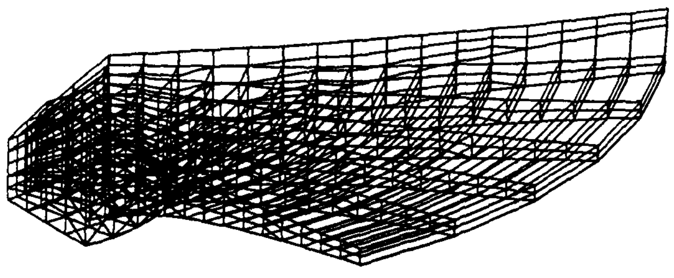

Fig 8 Sixty degree finite element model of the modified single arch mirror

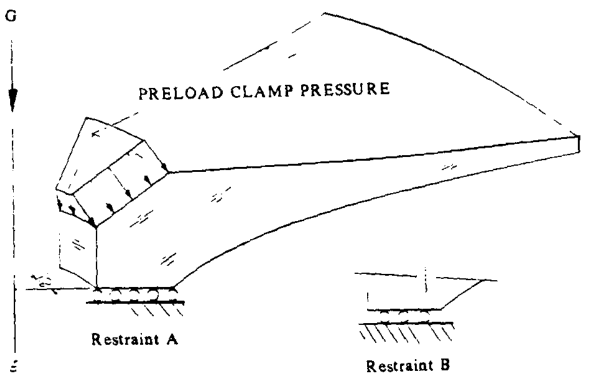

Fig 9 Hub preload and physical restraint of the sixty degree model

Restraint A Support across full land

Restraint B Support across 3/5 of land

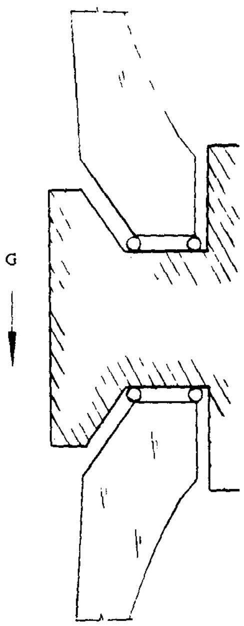

Fig 10 Loading and physical restraint for horizon pointing case

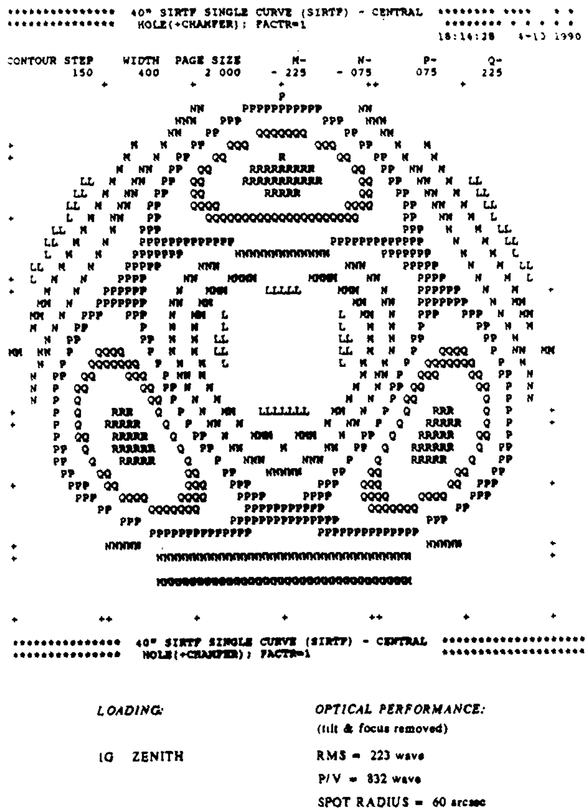

Fig 11 Contour plot of the deformed optical surface for 1g zenith loading

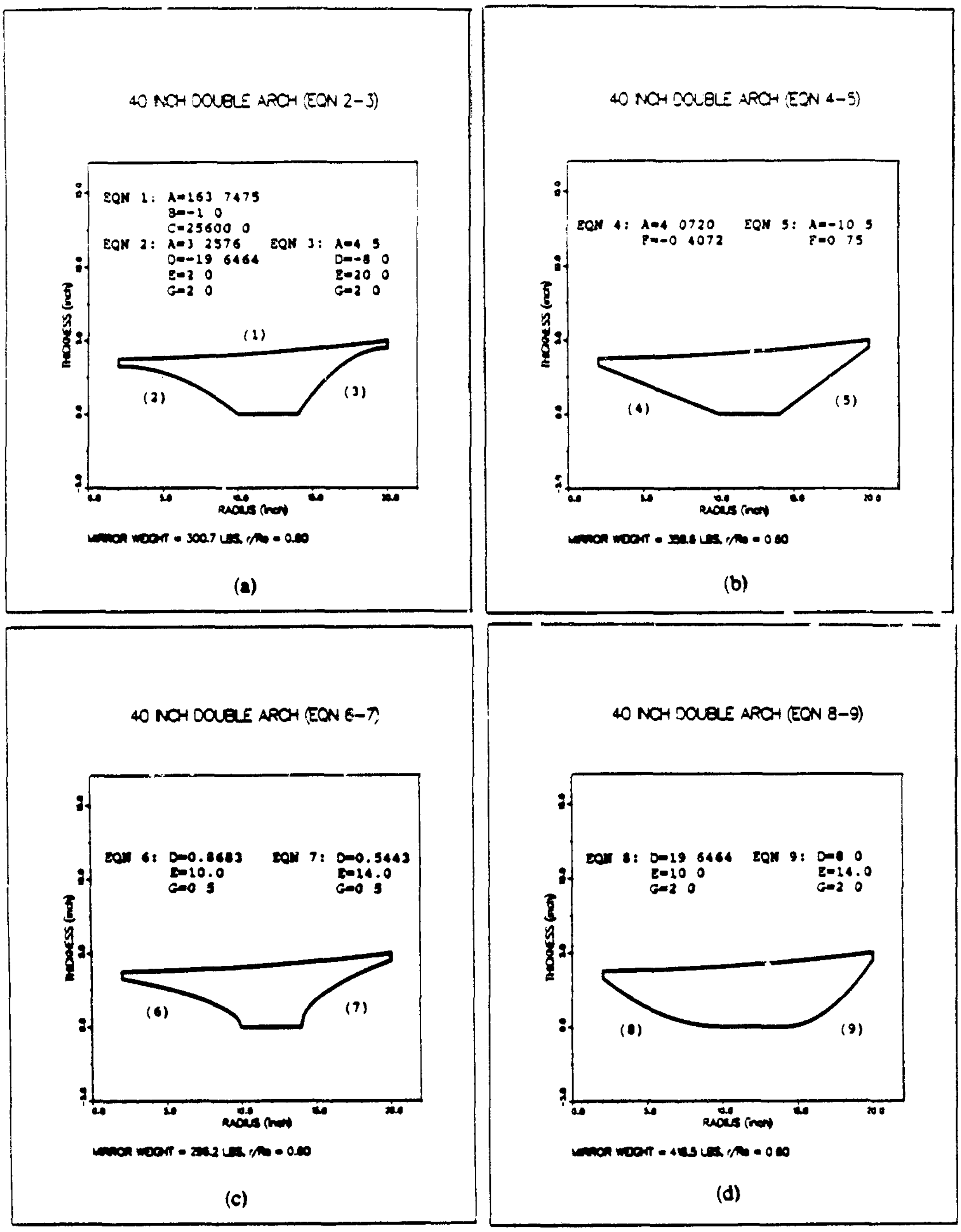

Fig 12 40 inch double arch mirrors

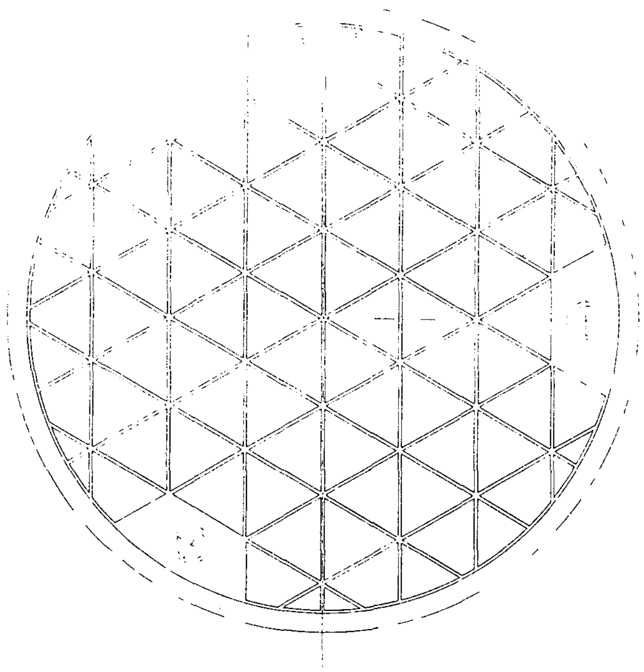

Fig 13. Typical cellular sandwich mirror

Table I A Comparison Summary of Double Concave Mirrors (Configuration I and 2)

		Configuration I (weight=467lbs)	Configuration 2 (weight=343lbs)
Maximum Structural Deflection (ZENITH)	RING	7.03×10^{-5}	13.92×10^{-5}
	6-60	7.74	14.71
	3-120	11.44	20.25
Optical Performance (RMS wave) (ZENITH)	RING	0.282	0.646
	6-60	0.292	0.653
	3-120	0.883	1.473
Optical Performance (RMS wave) (HORIZON)	RING	0.002	0.002
	6-60	0.008	0.007
	3-120	0.020	0.020
Frequency (NASTRAN)	RING	492 Hz	360 Hz
	6-60	470	350
	3-120	362	281

Table 2. A Comparison Summary of Single Arch Mirrors. (Configuration 1 and 2)

		Configuration 1 (weight=135lbs)	Configuration 2 (weight=165lbs)
Maximum Structural Deflection (ZENITH)	RING	8.32×10^{-5}	5.38×10^{-5}
	6-60	8.54	5.67
	3-120	8.89	6.16
Optical Performance (RMS wave) (ZENITH)	RING	0.175	0.132
	6-60	0.170	0.130
	3-120	0.162	0.130
Optical Performance (RMS wave) (HORIZON)	RING	0.226	0.153
	6-60	0.226	0.153
	3-120	0.271	0.197
Frequency (NASTRAN)	RING	435 Hz	556 Hz
	6-60	430	550
	3-120	424	541

Table 3. Optical performance of Modified Single Arch Mirrors.

	187 lbs (3.5" pad) (TYPE B)	187 lbs (2.5" pad) (TYPE B)	150 lbs (3.5" pad) (TYPE A)
1g ZENITH	0.130 waves	0.089 waves	0.220 waves
1g HORIZON	—	—	0.340
1g Clamp	0.069	0.058	0.070
5g Clamp + 1g Horizon	—	—	0.510
5g Clamp + 1g ZENITH	0.470	0.370	0.490

Table 5. A Comparison Summary of Double Arch Mirrors for a Ring Support at r/Ro=0.50.

	Contoured Back Shape Equation		
	EQN 2-3	EQN 4-5	EQN 6-7
Maximum Structural Deflection	10.66×10^{-6}	12.02×10^{-6}	11.52×10^{-6}
Frequency (NASTRAN)	1080 Hz	950 Hz	1030 Hz

Table 4. A Comparison Summary of Double Arch Mirrors for a Contoured Back Shape Equation of EQN 2-3.

		Support point Ratio (r/Ro)		
		0.50	0.60	0.70
Maximum Structural Deflection	RING	10.66×10^{-6}	3.26×10^{-6}	8.03×10^{-6}
	6-60	14.04	6.61	11.25
	3-120	27.04	21.06	25.33
Frequency (NASTRAN)	RING	1080 Hz	1110 Hz	1000 Hz
	6-60	1050	1080	980
	3-120	930	920	900

Table 6. A Comparison in Frequencies for Various Mirror Shapes.

	$\frac{r}{Ro}$	RING	6-60	3-120
Double Concave (Configuration 1)	1.00	1.00	0.96	0.74
Double Concave (Configuration 2)	1.00	1.00	0.97	0.78
Single Arch (Configuration 1)	0.15	1.00	0.98	0.96
Single Arch (Configuration 2)	0.20	1.00	0.97	0.95
Double Arch (EQN 2-3)	0.50	1.00	0.97	0.86
	0.60	1.00	0.97	0.83
	0.70	1.00	0.98	0.90

Table 7. A Comparison Summary of Cellular Sandwich mirror for a 3-120 Support at r/Ro=1.0.

	MAP	SOM	GIFTS
Maximum Structural Deflection	76.1×10^{-6}	86.3×10^{-6}	80.0×10^{-6}
Optical axes Frequency	406 Hz	—	—
Maximum Stress	12.6 psi	—	14.0 psi
Wavefront Error	0.82 waves	—	—

Table 8. A Comparison of performance for Various Mirror Shapes.

	weight (lbs)	RMS (ZENITH)	RMS (HORIZON)	frequency (Hz)
Double Concave				
(Configuration 1)	467	0.883	0.020	362
(Configuration 2)	343	1.473	0.020	281
Single Arch				
(Configuration 1)	135	0.162	0.271	424
(Configuration 2)	165	0.130	0.191	541
Mod. Single Arch				
(Configuration 1)	187	0.130	—	—
(Configuration 2)	150	0.220	0.340	—
Double Arch				
(EQN 2-3)	254	0.234	0.098	1080
(EQN 4-5)	324	0.229	0.136	950
(EQN 6-7)	256	0.253	0.119	1030
Sandwich	135	0.820	—	406