UNIVERSITY OF CALIFORNIA
UCO/LICK OBSERVATORY TECHNICAL REPORT
NO. 63

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UCO/Lick Observatory Technical Report No. 63

ABSTRACT

The design, analysis and testing of a large mirror mount are described. The optic is a 44" dia, f/0.75 gas-fusion structured mirror manufactured by Hextek (Tucson, AZ). The mirror is the primary reflector for a split-corrector Schmidt camera system for the Keck Telescope High Resolution Echelle Spectrograph (HIRES). The spectrograph is mounted on the Nasmyth platform of the telescope, with the camera mirror optical axis downward-looking 10.3° below horizontal. This paper describes the finite element analysis of the mirror, conceptual and detail design of the mount, and interferometric testing of the mirror figure before and after installation in the support.

1. CONCEPTUAL DESIGN OF THE MIRROR SUPPORT

The Hextek mirror, at 44 inches in diameter, is the largest of its type ever fabricated. The construction of the mirror is a two step process. First, the front and rear face sheets, 0.47" thick Schott Tempax, are fusion bonded to a center section of Tempax tubes. The sandwich of face sheets and tubes is heated to molten temperature, the tubes are inflated at low pressure, and the face sheets and tubes fuse together. The second step involves reheating the blank as it sits on a convex mold. When the glass softens, it slumps to conform to the shape of the mold.

A variety of design considerations were evaluated for supporting the mirror. The support system was simplified by the fact the mirror would be stationary, and would always have the same orientation to gravity. The positioning requirements for the mirror were stringent, but once met, would not require repositioning or focusing. The mirror would actually be one of two mirrors, each with a coating optimized for red or blue wavelengths, so the support would need to be as light-weight as possible, and readily interchanged. The mirror is part of a camera system for a grating cross-dispersed echelle spectrograph, with a highly anamorphic beam profile[1]. The end result of the two diffraction grating dispersions is that the beam through the camera system, over a wide range of wavelengths, is roughly rectangular. Consequently, only about 60% of the clear aperture of the mirror, centered with the long axis about 8° from vertical with respect to the mirror, must meet the optical specifications. The thermal environment for the mirror would be cold, but stable on the order of +/–2° F per day, with a median temperature of about 32° F. The small daily temperature variation was especially favorable considering the 2 to 3 hour time constant for the 25% weight density mirror. On Hextek's recommendation, it was decided to exercise the internal mounting boss option (for $7000), which provided six 3–inch–square mounting bosses in the plane of the center of gravity, located symmetrically around the mirror at the 0.7 R locations. Hextek had previous experience providing both radial and axial support of smaller mirrors through these mounting bosses, using a relatively simple six-link kinematic connection to a sub-cell. The mirror was to be recoated with its mounting boss hardware intact, which required vacuum rated materials and components. Extensive mirror mounting research and development work conducted by others for the 36 Keck primary mirror segments was reviewed for possible adaptation to the Hextek mirror. The Keck segment design uses 36 individual axial supports bonded to the back of the segments, a torsional link for stiffness about the normal axis, and a stainless steel diaphragm radial support bonded into a pocket in the back of the segment and located at its center of gravity.

After much consideration and debate, it was decided to use a hybrid of the Keck and Hextek approaches, using the mid-plane mounting bosses for the axial support, a torsional link, and a diaphragm bonded to the back of the mirror for the radial support. The six axial supports would be reduced to three mounting points on three whiffle-tree balance beams. The diaphragm would be designed such that it was very stiff in the radial (in plane) direction and very compliant in the axial direction where it would be in conflict with the axial supports.

Several concepts dictated this choice. First, for collimation and initial focus, the mirror support would have to be readily adjustable. The proposed Hextek design would have required a sub-cell for kinematic support of the mirror, and a second cell for carrying and adjusting the mirror by way of the sub-cell. This duplication would be more complicated (and expensive) than a single support cell. The six-link kinematic support uses three pairs of crossed links to constrain the mirror, and these links would be long and relatively more complicated in order to reach into the submerged mounting bosses. In order to reach the sub-cell in the required locations and at the proper angles, the forces in the links would be much larger than required to simply support the mirror at the six locations. The first benefit of the hybrid support was that the kinematic support and the axial tilt adjustability would be combined in a single cell. The radial support minimized the forces input through the mounting bosses, allowed for differential thermal expansion between the radial and axial supports, and simplified the assembly and adjustment of the cell. Separating and isolating the radial and axial supports reduced the danger that the imperfectly realized kinematic supports would excessively strain the optic.

2. FINITE ELEMENT ANALYSIS OF THE MIRROR

The objective of the analysis was to determine whether or not the proposed support system would acceptably carry the mirror while maintaining its figure to a $\lambda/2$ specification. It was clear from the outset that the radial support, attached several inches away form the CG plane, would add a bending moment into the mirror, which would be counter-acted by the axial supports. The FEA would allow the testing of a variety of connection schemes, and would provide insight into the deflections and stresses as a function of the number and location of the radial support points.

Hextek provided a 2–D AutoCAD file containing the mirror's exterior geometry and interior tube structure. A 1/12th symmetric section of this file was translated into ANSYS, using the ANSYS/AutoCAD DXF file translator. Inside the solid modeling preprocessor of ANSYS, the "pie-slice" of tube and facesheet detail was projected on to a spherical surface of areas at the correct radius of curvature, and then spherically offset to create the rear surface of the mirror. Given the front and rear areas of the mirror, and the correct tube mesh from the translator, the tube wall areas were created by connecting the corresponding front and rear surface edges. Once the 1/12th section was complete, it was reflected three times to create an accurate half-geometry model. The mounting boss areas were added to the model after the main structure was finished. With solid model plane areas now in place for all the plate geometry of the mirror, 4 node, 3–D plate bending (no shear deformation) elements with the correct material constants and thicknesses were assigned to each area. In order to model the effects of the axial support whiffletrees, 3–D beam elements were defined to connect one pair of support points, while the third remained a simple constraint (see fig. 1). The beam elements were defined by the material constants to be very stiff, so that deformation of the whiffletree would be negligible compared to the displacements of the mirror. The finished model contained 1345 nodes, 2106 elements, and 7959 degrees of freedom (see fig. 2). The weight of the various support components was neglected in the analyses.

A total of about twenty configurations were run through ANSYS, several of which were used to determine the sensitivity of the model to parameters such as the modulus of elasticity and plate element thicknesses. The final version of the model (see Appendix A) showed 0.8λ deformation across the whole front surface, and about 0.5λ across the required aperture (see fig. 3). This residual deformation was primarily astigmatic, and judged to be acceptable for the requirements of the camera system. The analyses also indicated that the mirror was relatively insensitive to small variations in material constants, face sheet and cell wall thicknesses, and small weight loads such as the torque link. The satisfactory results from the FEA gave us the confidence to continue on the detail design of the mirror support.

3. DETAIL DESIGN OF THE MOUNTINGS

The conceptual design of the mirror support specified a kinematic arrangement of three mutually exclusive constraints for the radial, axial, and torsional degrees of freedom. The detail design process was then simply a matter of approximating the idealized supports with reliable hardware that could be reasonably manufactured and assembled. Stainless steel blade flexures were used in situations where small translations, high stiffness, and zero backlash were desired. Simple pin joints with stainless steel pins in aluminum bores were used where stiff, small angle pivots were required. Commercial (THK) spherical ball-joints were used for one-degree-of-freedom constraints. The design features of the radial, axial, and torsional supports will be discussed in that order.

3.1 Radial Support:

Keck Observatory Technical Note #142[2] derives several useful formulae for designing diaphragms for radial supports. The design of the Keck segment radial support has several well considered features which were adapted for the support of the Hextek mirror. The primary requirement of the diaphragm is that it safely carry the radial loads of the mirror under static (installed), as well as dynamic (transport and installation) loadings. It was anticipated that the mirror might easily see 3–G loads during handling, and perhaps as much as 5–6 G's. It was also required that the diaphragm be sufficiently compliant in its axial direction that it not adversely affect the figure of the mirror, by overconstraining the six axial supports. Keck Observatory Technical Note #189[3] documents the testing of a 8" diameter, 0.010" thick stainless steel diaphragm and found the small displacement radial and axial spring rates to be 200,000 lbs/in and 894 lbs/in respectively, for a stiffness ratio of 224:1. The results of the finite element analyses had indicated that a diaphragm of the same diameter and thickness as the Keck diaphragm would provide plenty of radial stiffness and axial compliance, even though the Hextek mirror is only 1/6 the weight of a Keck segment (180 vs. 1200 lbs.). The in-plane bending stiffness of the diaphragm was found to be the most important consideration because excessive stiffness would overconstrain the axial supports. Testing verified that the diaphragm was compliant enough to avoid deforming the mirror under a variety of axial adjustments.

There is a significant difference in the coefficient of thermal expansion for Tempax (borosilicate, 1.8 ppm/°F) and 304 stainless steel (9.6 ppm/°F). For a given temperature change, the diaphragm and its supporting ring would expand or contract 5–6 times as much as the mirror. This difference would lead to an axial strain in the mirror if it were not compensated. The Keck approach was to mount the diaphragm in a pocket at the center of gravity of the segment, with a ring of axial flex springs which would deflect to allow for the temperature induced size variations. The flex springs for the Hextek mirror were designed such that a 40°F change in temperature will create a force of 2–3 ounces at each of the six mounting points. The Keck design was modified for the camera mirror by attaching the flex springs to Pyrex blocks, which were in turn epoxied to the back of the Hextek mirror (see dwg H5530). A fixture was built to test the radial support system, using a Pyrex plate to substitute for the mirror (see dwg H5514). This set-up was used to test the mounting blocks and diaphragm assembly under varying temperatures and loads. The assembly was tested to failure in the case of the mounting blocks, two of which showed small fractures at the bond-line at about 1200 lbs, more that six times the weight of mirror. This failure was disappointing, but reassuring in several ways. First, the fractures were in the mounting blocks, which could conceivably be removed and replaced. Second, there was no apparent damage to the mirror. Finally, the failures were in no way catastrophic, and the support continued to carry the load after the fractures appeared.

3.2 Axial support:

Hextek provided six bosses evenly spaced around the mirror approximately two inches inside the back surface, which were to be used for the axial support connecting points. The bosses were 0.47" thick and roughly 3" square, with a 3/4" diameter hole bored through the center of the boss. These holes, and the clearance holes in the back sheet, were bored out in the Lick Optical Lab to 1–1/4" and 2" respectively. Several pieces of 0.47" thick Tempax were provided by Hextek for axial support testing. The first, and rather ill-advised, connection design used 2 stainless steel flanges to clamp to the mounting boss. The flanges indexed loosely on the hole, to axially locate the supporting link. Unfortunately, when the two flanges were clamped together, the indexing ridge managed to jam in the hole, and neatly cleaved the test mounting boss in half during tightening. An identical clamp made of Delrin was also able to fracture the mounting boss. With these enlightening experiences fresh in mind, all components expected to contact the glass were redesigned using plastic; Delrin in the case of the axial supports, and CPVC in the case of the radial support block clamps. Additionally, the clamps were redesigned to assure that only compressive stress could be generated in the mounting boss. Drawing H5537 shows the final design of the Delrin 3–point contacting mounts. The Delrin mounting flanges accommodate variations in the thickness of the mounting bosses, and the Delrin contact points are compliant enough to provide low contact stresses, and avoid introducing moment loads into the mounting boss. Drawing H5536 shows the remainder of the axial support, showing the THK spherical ball-joints, links, and whiffle-tree balance beams. The threaded connection between the spider and the balance beam allows for pointing the mirror during collimation, and remains fixed after alignment.

3.3 Torsional support:

The torsional support is largely redundant, but insures that under all conditions, the radial support is not subjected to large torque loads. The weight of the torsion link was a concern initially, but was not found to cause a problem. The weight of the torque link could be counterweighted or supported independently if necessary. Drawing H5539 shows the torque link and its connections to the supporting cell and the mirror. The Pyrex mounting block is identical to the radial support blocks.

4. MIRROR TESTING

The mirror was tested in two different positions in order to confirm the finite element modeling and to insure that the figure as polished was still acceptable once installed on the mount. Zenith and 10° below horizontal tests were performed on a large, vibration isolation stand which was designed for testing the Keck secondary mirror (see dwgs H5824,25). After several confusing tests it was determined that the only good time to test the mirror was early in the morning, before small temperature variations (1°F/hr) in the test tunnel began to change the mirror's figure. The Hextek blank is believed to thermalize in 2 to 3 hours, and is unstable under even small temperature changes.

4.1 Mirror figure tests:

The initial tests were performed on the mirror without its supporting cell, mounted instead on a layer of foam which closely matched the back radius of curvature. All mirror figure tests were conducted in the zenith-looking position. Interferograms were taken after a 12 to 18 hour soak in the test tunnel at 67° F. The mirror was then rotated 90°, allowed to soak again, and more interferograms taken. The figures found in the samples are very consistent, with amplitudes ranging from 1 to 1.5λ, mostly astigmatic (see figures 4,5,6). The amplitude of the astigmatism varied slightly with rotation of the part, suggesting that the foam support might not be as neutral as we thought. But the topography of the figure was very consistent, which gave us confidence in our ability to rotate the best part of the figure into the required aperture. Again, note that only a rectangular area of about 60% of the full aperture was required for the cross-dispersed beam.

4.2 Mirror/Cell figure tests:

After the horizontal testing was completed, the mirror was installed in its supporting cell, mounted on the kinematic camera structure, and tested again. The finite element analyses had indicated that the predominant aberrations induced by the cell would be astigmatism and coma, with a vertical axis of symmetry. The interferogram and fringe analysis data (WYCO WISP®) shows the predicted astigmatism and coma, with amplitudes roughly three times the expected values (see figures 7,8,9). The next data summary and contour plot show the part figure subtracted from the figure seen in the cell (see figures 10,11). This figure most closely matches the FEA predicted topography, but still shows twice the expected amplitude. It is not entirely clear how much of the amplitude discrepancy is due to testing and data analysis uncertainty or the FEA model predictions. Part of the difference may be attributed to the fact that the finite element model considers only plate bending, without regard for shear deformation, but this concern has not been investigated. Nevertheless, by rotating the raised wings of the mirror figure to a horizontal axis of symmetry, we were able to minimize the mirror and cell figure errors against each other. The last interferogram data set shows the required clear aperture and the figure over that area (see figures 12,13,14). The 1.28λ P-V and 0.25λ RMS values exceed the initial $\lambda/2$ P-V specification, but were judged to be acceptable based on analysis of the worst slope errors. The worst-case slope error of 4.4 micro-radians was found to cause a 6.7μm deviation at the focal plane. The optical design of the camera system (i.e. perfect optics) predicted a 12.6μm RMS image diameter. The actual degraded image diameter can be estimated by adding the predicted image size and worst case ray deviation in quadrature, which yields a 13.9μm RMS image size. This was considered to be a negligible degradation of the ideal image, and consequently an acceptable figure for the camera mirror.

5. CONCLUSIONS

A stationary support was designed to carry a very large and fragile gas-fusion structured mirror. Finite element analysis was successfully used to analyze deformation of the mirror under a variety of conditions and orientations. Extensive testing of the mirror confirmed the results of the analyses, and although the amplitudes of the deflections were greater than expected, it was not entirely clear how much of the difference was due to the models, the final figure on the mirror, testing conditions, or unexpected effects from the cell. In terms of topography, the finite element model did an exceptional job of predicting the flexural behavior of a large and complicated structured mirror. Finally, optical testing and slope error analysis confirmed the acceptability of the mirror, its figure, and the hybrid kinematic mounting.

6. ACKNOWLEDGMENTS

This work was performed as a part of development and design of the Keck Telescope High Resolution Echelle Spectrograph, and was funded by the California Association for Research in Astronomy (CARA). Dr. Steven S. Vogt was Principle Investigator, responsible for the overall conceptual design of the spectrograph. Dr. Harland W. Epps was responsible for the unique optical design of the camera. David Hilyard ground and figured the mirror, and performed all of the (extensive) optical testing and fringe analysis. Many people from the Lick Observatory Instrument Lab participated in the fabrication and assembly of the mirror cell, with special thanks to Richard W. Kanto, Jeffrey P. Lewis, and James A. Ward. Jack Osborne provided technical support and encouragement throughout the design and fabrication of the mirror cell. Carol Osborne did the hard part, drafting and detailing 300 E-size sheets of drawings for the camera cell, structure, and test fixtures.

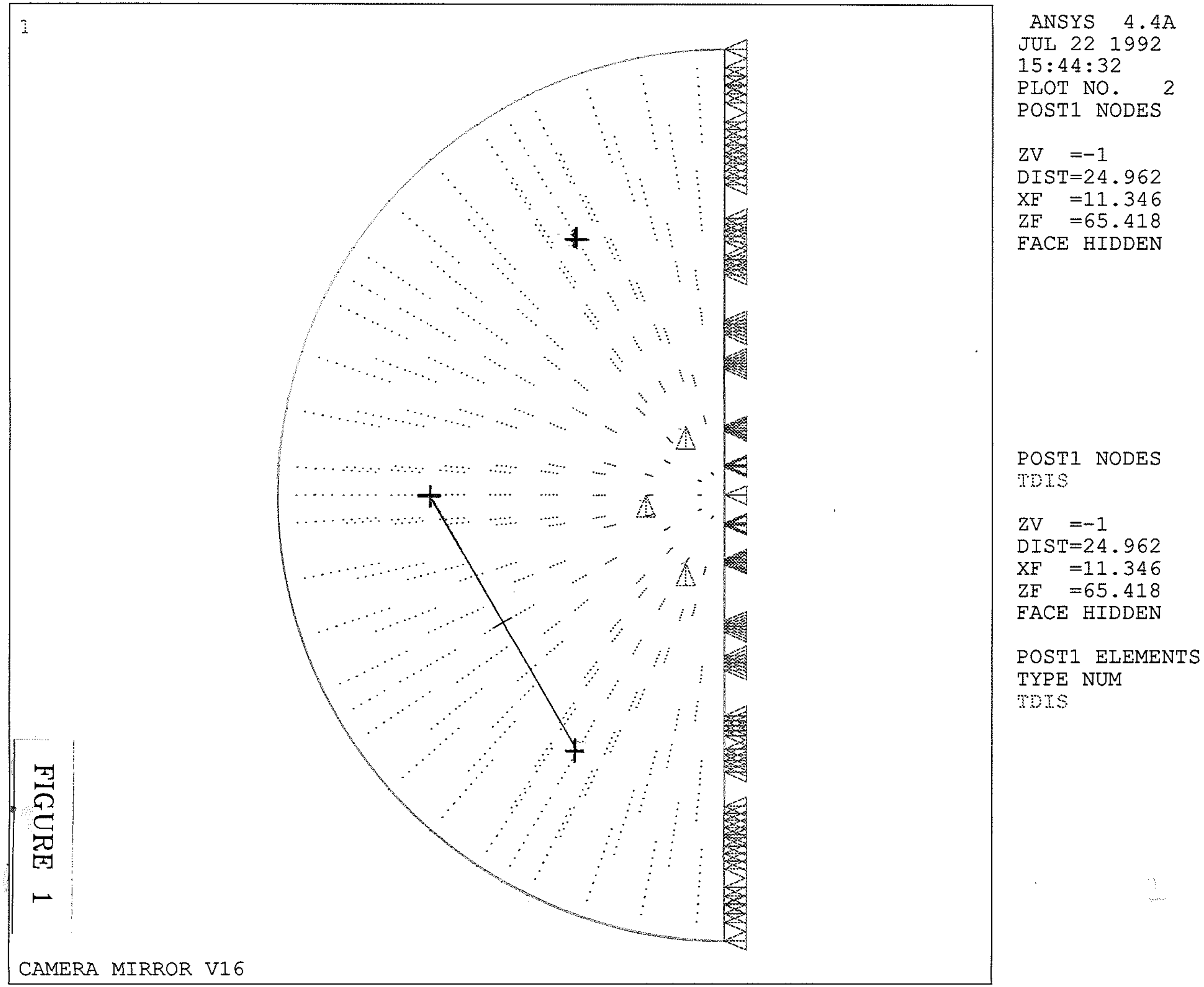
Finally, thanks to Mark Rodamaker of MCR Associates, Sunnyvale, California, for help with the creation of the ANSYS® FEA model, and to Robert Parks and Richard Whortley, of Hextek Corporation, Tucson, Arizona, for endless assistance concerning the handling, figuring, and support of the mirror.

7. REFERENCES

1. H.W. Epps and S.S. Vogt, Applied Optics, in press.

2. R. H. Weitzmann, "Keck Observatory Technical Note #142, Stress/Strain Relationship for a Diaphragm Clamped at the Inner and Outer Edges, and Subjected to Axial Displacements," May, 1985

3. R. H. Weitzmann, Keck Observatory Technical Note #189, Keck Telescope Radial Support Assembly Test Results," May, 1986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ZF =65.418
FACE HIDDEN
POST1 NODES
TDIS
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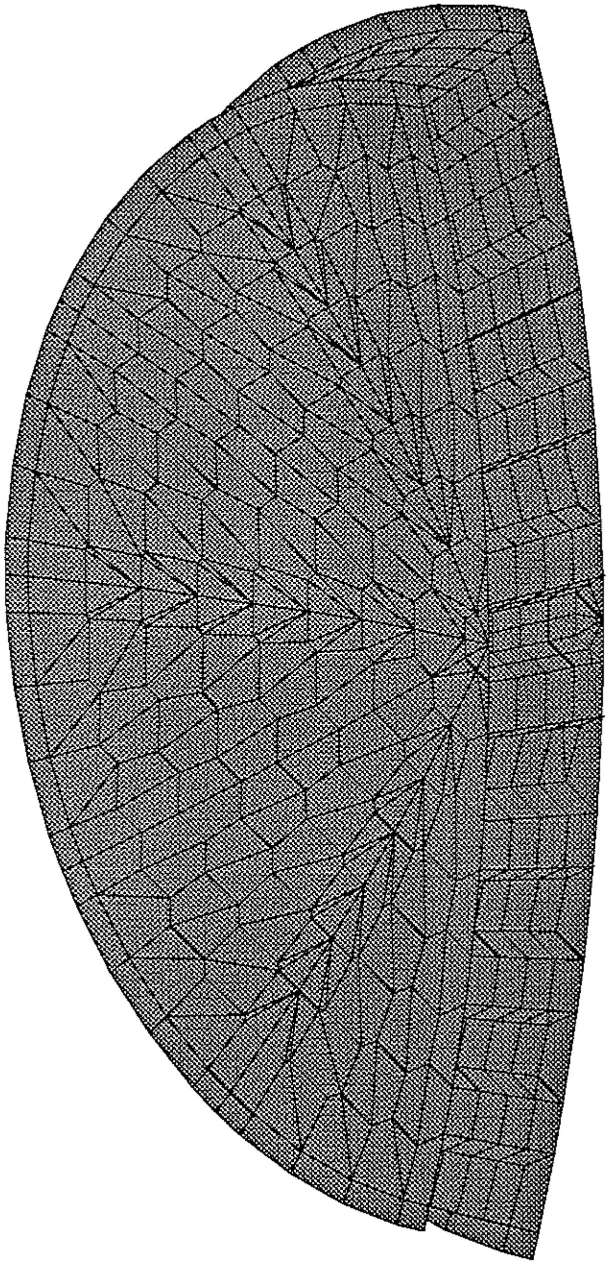
XF =11.346
ZF =65.418
FACE HIDDEN
POST1 ELEMENTS
TYPE NUM
TDIS
CAMERA MIRROR V16

FIGURE 1



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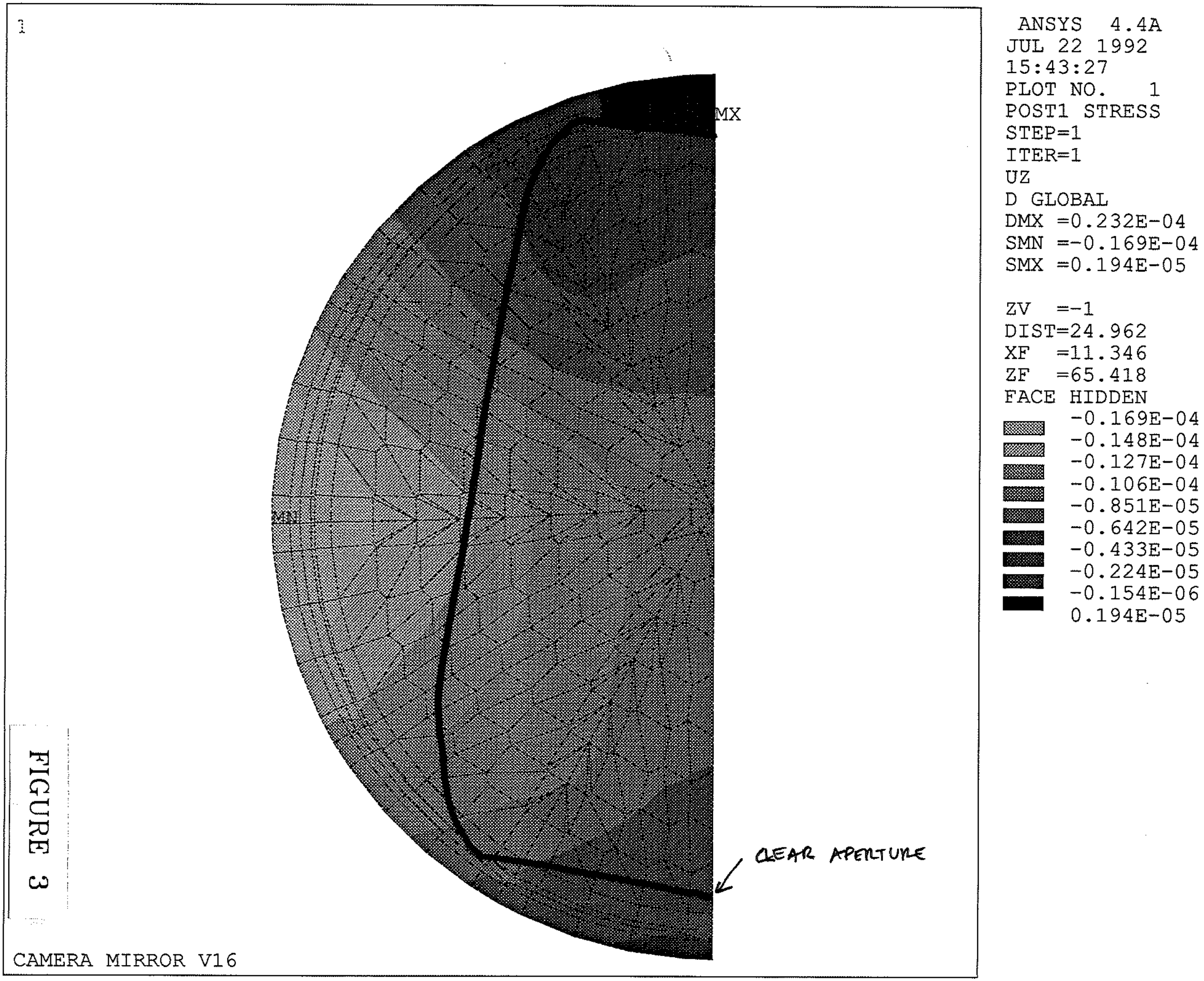
ZF =65.418
FACE HIDDEN
CAMERA MIRROR V16

FIGURE 2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ZF =65.418
FACE HIDDEN
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-0.106E-04
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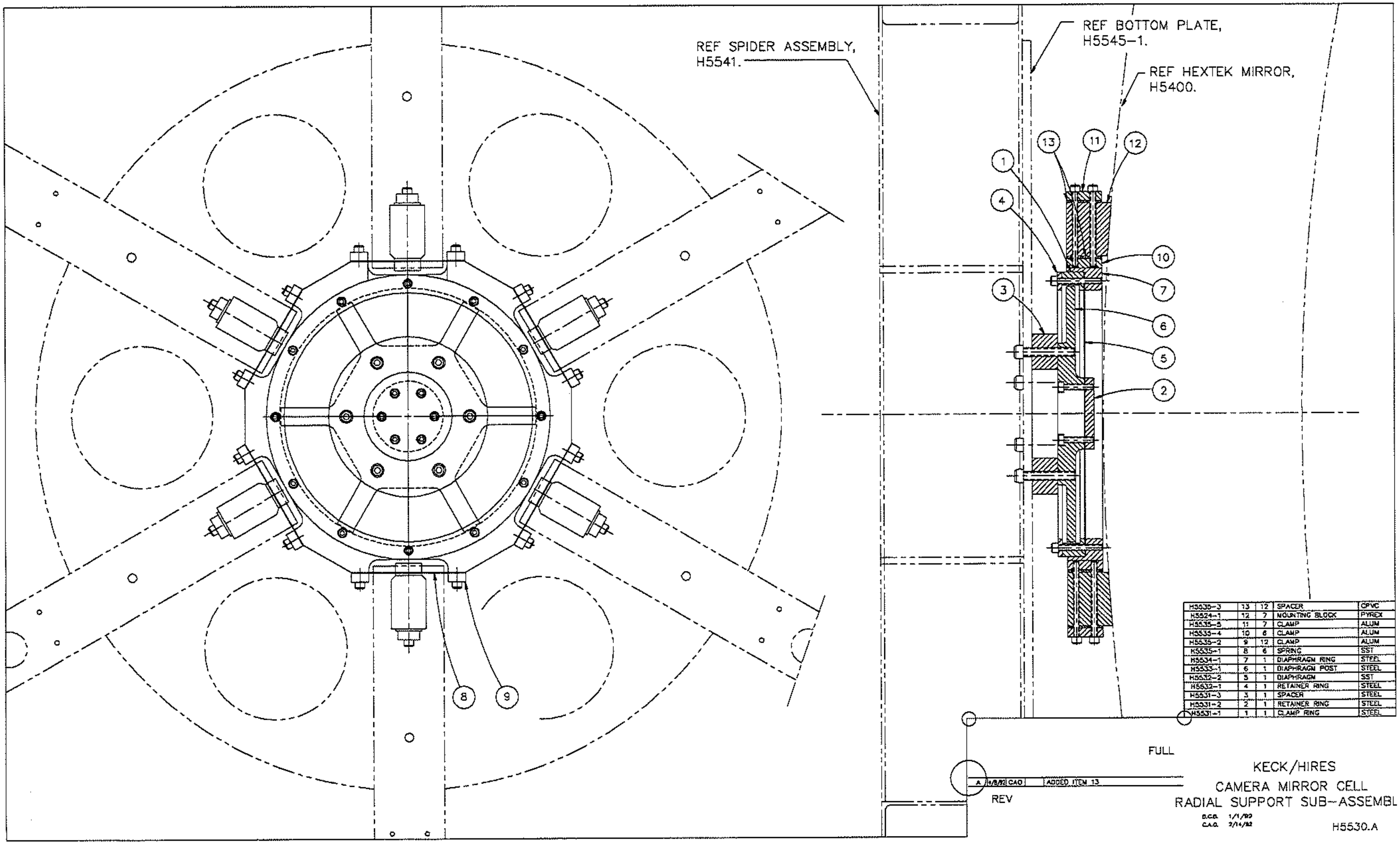
MX
MN
CLEAR APERTURE
CAMERA MIRROR V16

FIGURE 3



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H5524-1	12	7	MOUNTING BLOCK	PYREX
H5535-5	11	7	CLAMP	ALUM
H5533-4	10	6	CLAMP	ALUM
H5535-2	9	12	CLAMP	ALUM
H5535-1	8	6	SPRING	SST
H5534-1	7	1	DIAPHRAGM RING	STEEL
H5533-1	6	1	DIAPHRAGM POST	STEEL
H5532-2	5	1	DIAPHRAGM	SST
H5532-1	4	1	RETAINER RING	STEEL
H5531-3	3	1	SPACER	STEEL
H5531-2	2	1	RETAINER RING	STEEL
H5531-1	1	1	CLAMP RING	STEEL

A	4/8/92	CAO		ADDED ITEM 13

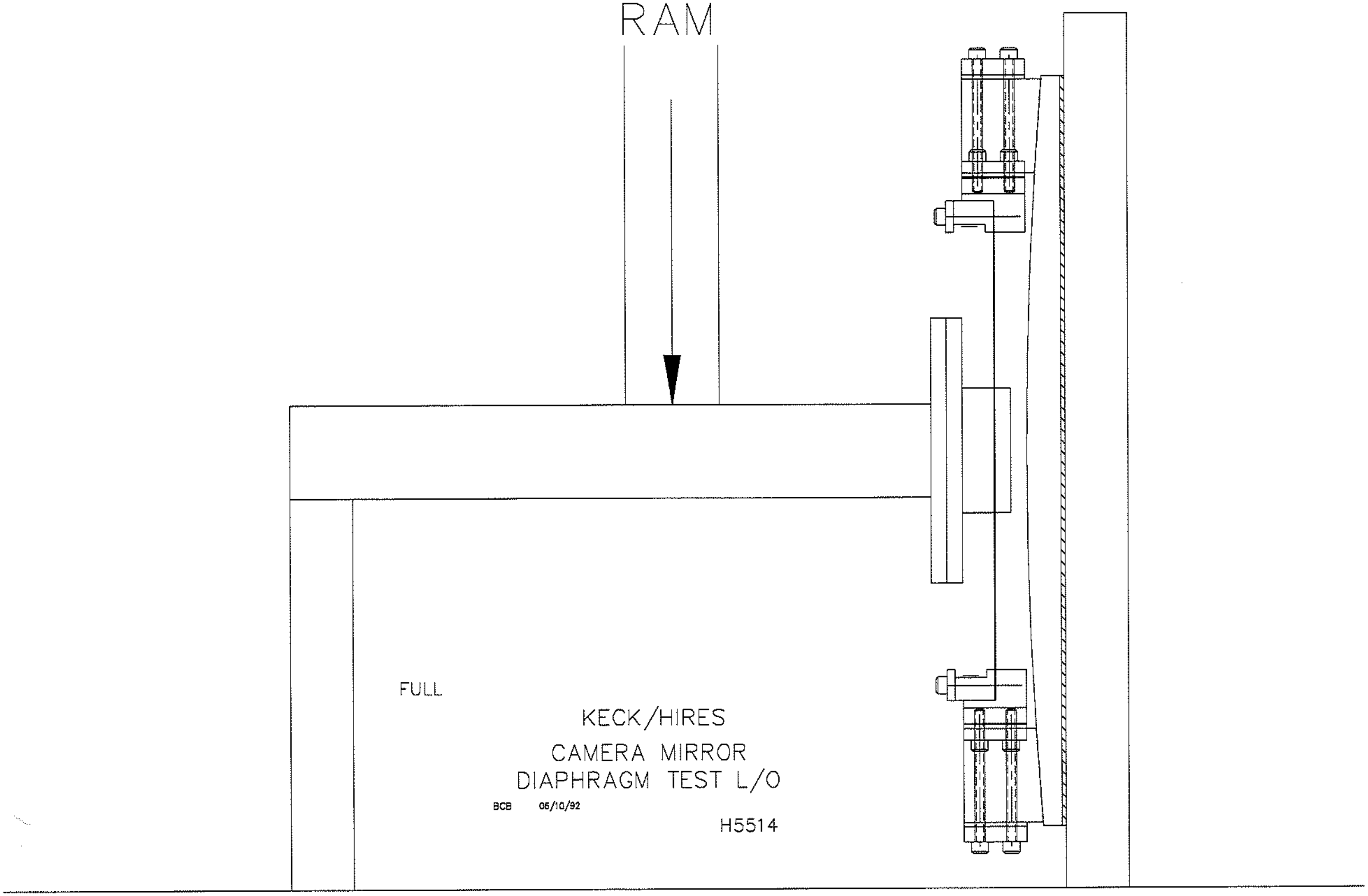
REV

FULL

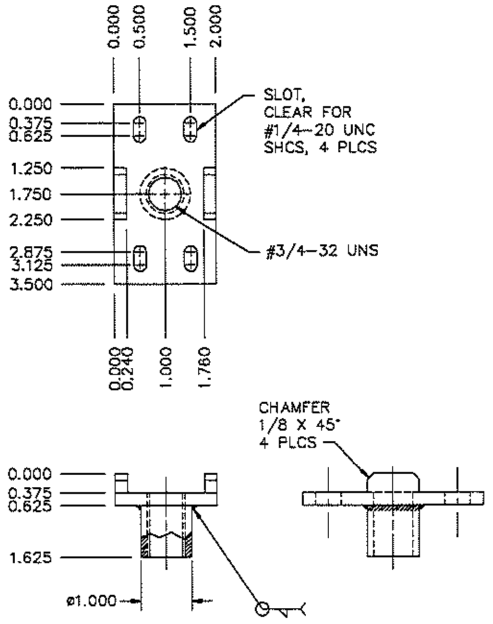
KECK/HIRES
CAMERA MIRROR CELL
RADIAL SUPPORT SUB-ASSEMBL

B.C.B. 1/1/92
C.A.O. 2/14/92

H5530.A



KECK/HIRES
CAMERA MIRROR
DIAPHRAGM TEST L/O
BCB 05/10/92
H5514



-1 BEAM SUPPORT

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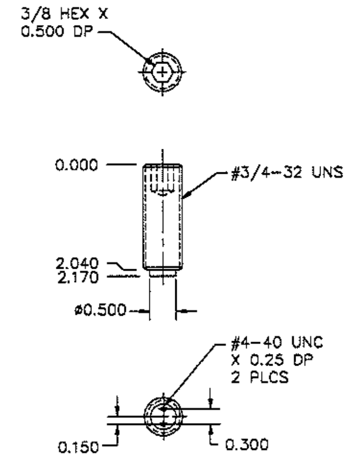
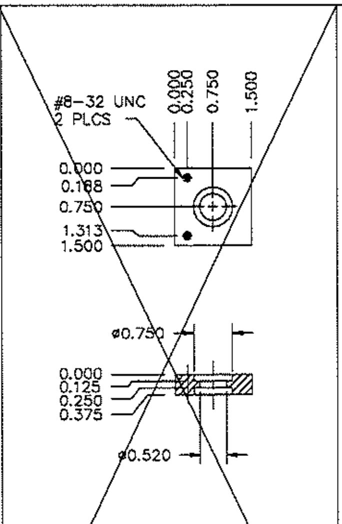


-2 AXIAL ADJUSTER

3 REQ'D PER CELL
BRASS



-4 PIVOT BASE

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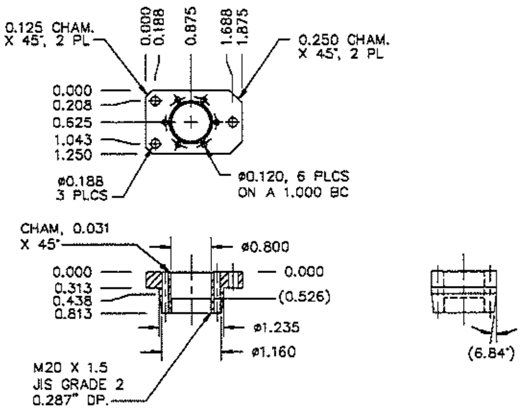
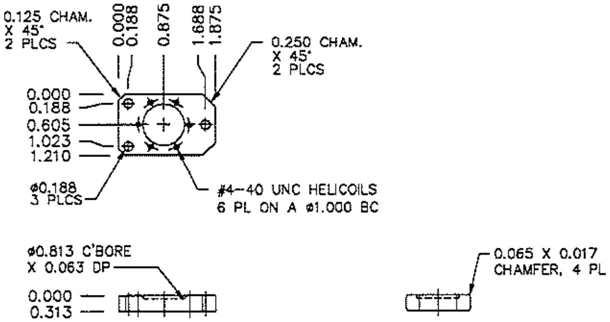
ALUMINUM, 6061-T6
BLACK ANODIZE

OBS.



-6 CLAMP TOP

7 REQ'D PER CELL
BLACK DELRIN



-7 CLAMP BASE

7 REQ'D PER CELL
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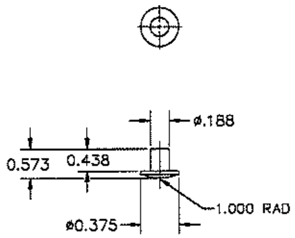
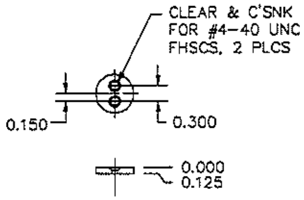


-8 BUTTON

42 REQ'D
DELRIN
SCALE: 2/1



-3 CAP

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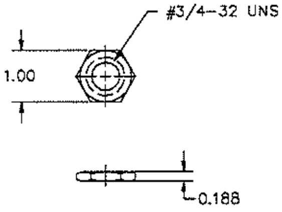


-5 NUT

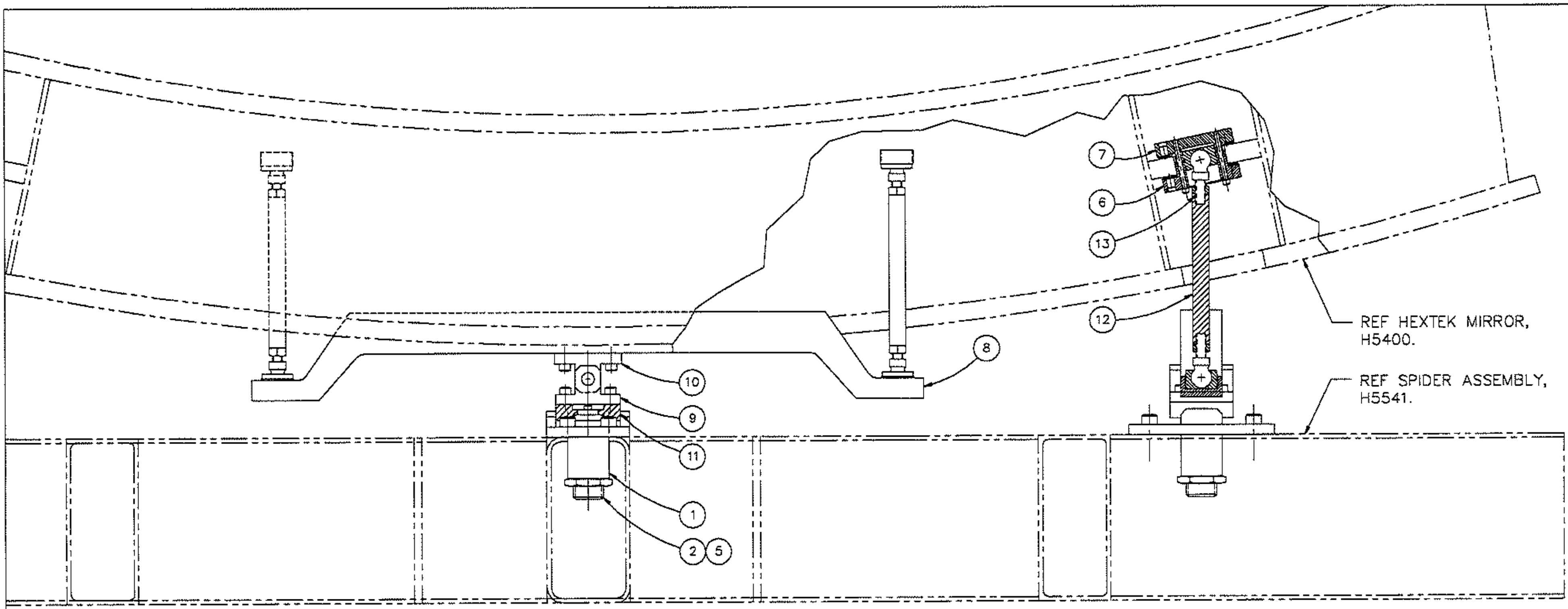
3 REQ'D PER ASSY
304 STAINLESS STEEL

REV				
A	3/20/92	CAO		REVISED ITEMS 6 & 7
B	4/7/92	CAO		REVISED ITEMS 6 & 7

KECK/HIRES
CAMERA MIRROR CELL
AXIAL SUPPORT DETAILS

B.C.B. 1/1/92
C.A.O. 1/24/92

H5537.B



(-1) AXIAL SUPPORT SUB-ASSEMBLY

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H5538-3	10	3	PIVOT BLOCK	ALUM
H5538-2	9	3	PIVOT BASE	ALUM
H5538-1	8	3	ARM	ALUM
H5537-7	7	6	CLAMP BASE	DELRIN
H5537-6	6	6	CLAMP	DELRIN
H5537-5	5	3	NUT	SST
H5537-4	4	3	SPRING BASE	ALUM
H5537-3	3	3	CAP	ALUM
H5537-2	2	3	AXIAL ADJUSTER	BRASS
H5537-1	1	3	BEAM SUPPORT	SST

FULL

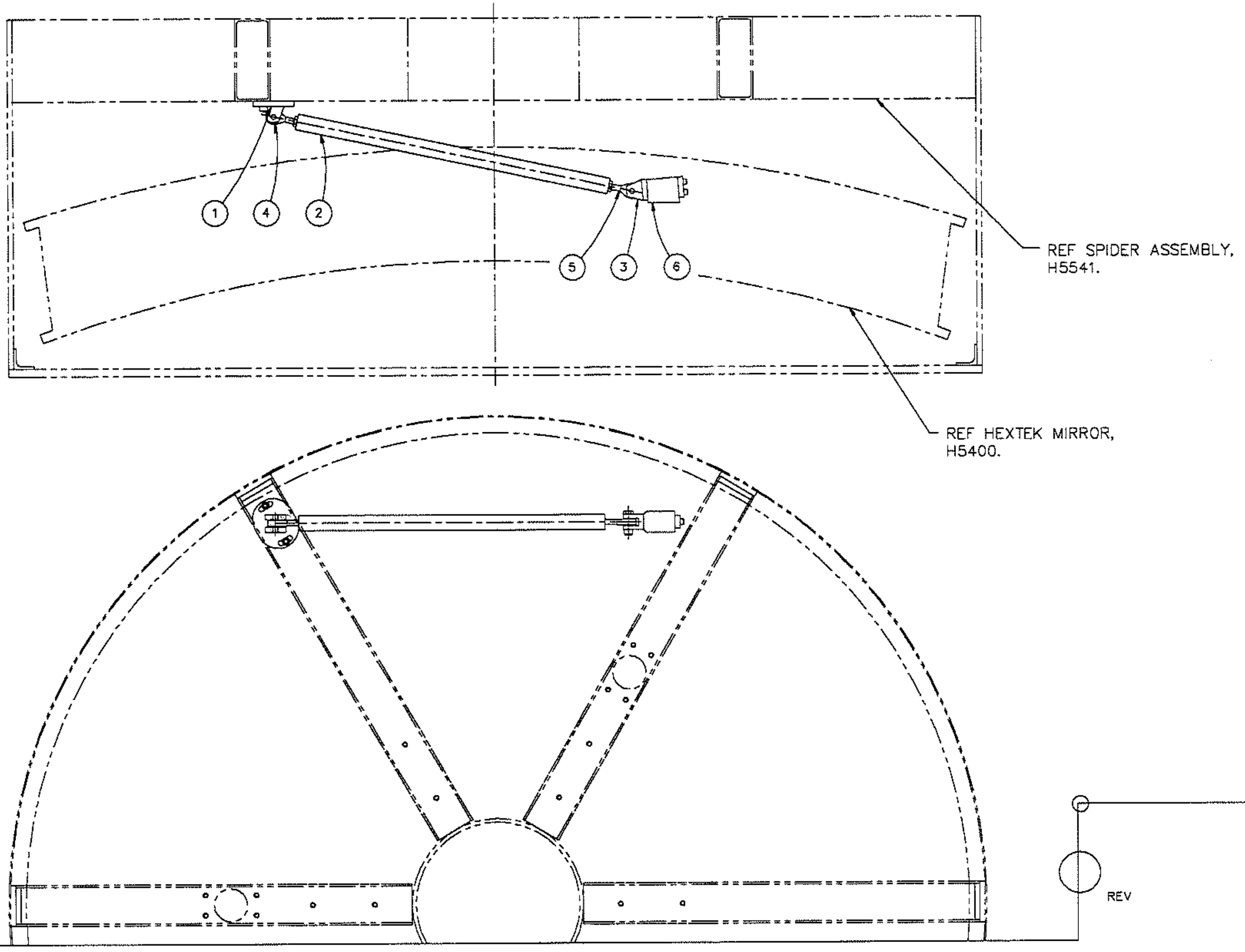
A	1/28/92	CAO		REVISED & REDRAWN
B	3/12/92	CAO		REVISED & REDRAWN

REV

KECK/HIRES
CAMERA MIRROR CELL
AXIAL SUPPORT ASSY

S.C.B. 1/1/92
C.A.O. 1/24/92

H5536.B



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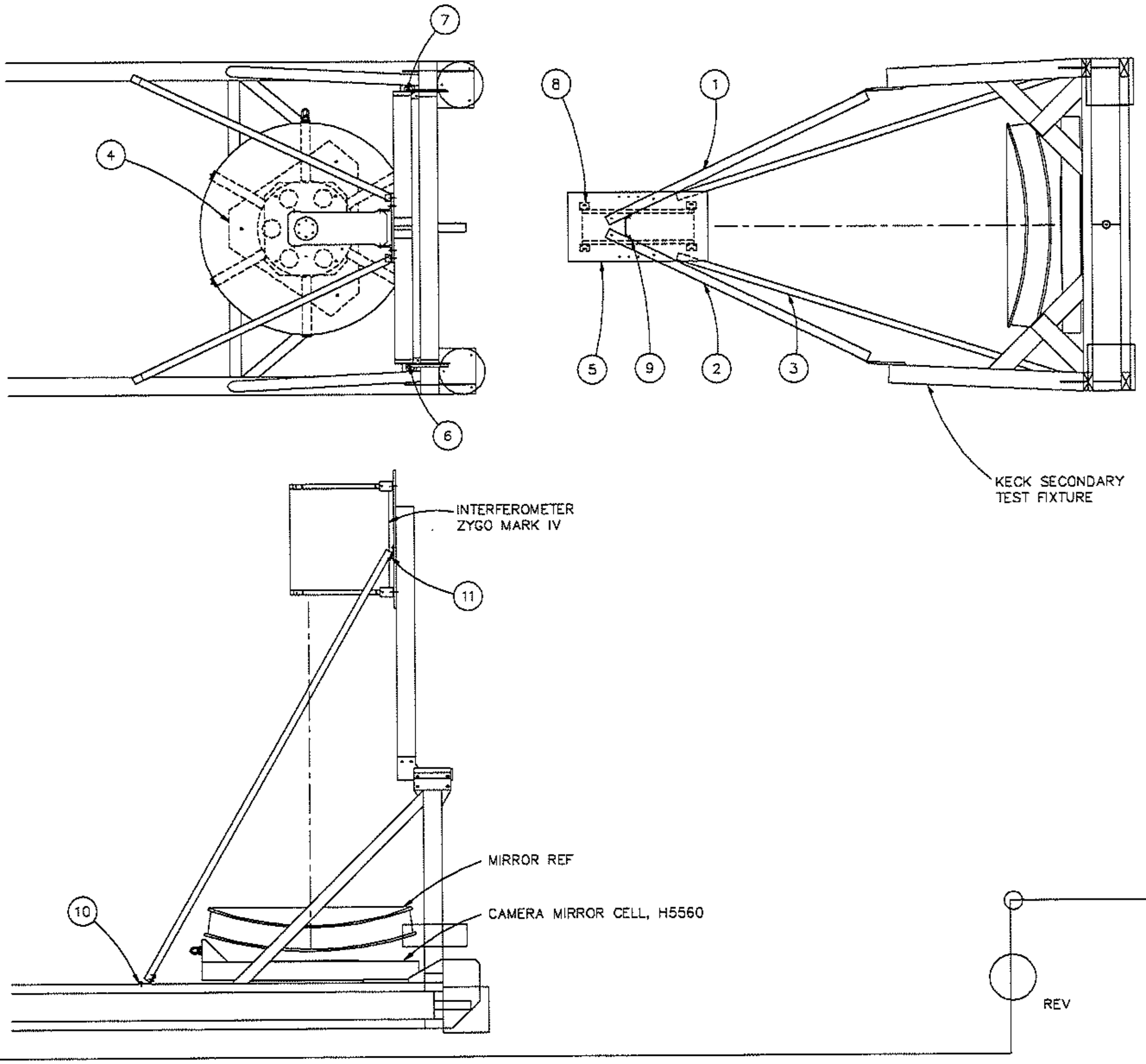
H5540-3	3	1	PIVOT	ALUM
H5540-2	2	1	TANGENT SHAFT	SST
H5540-1	1	1	PIVOT	ALUM

1/2

KECK/HIRES
CAMERA MIRROR CELL
TANGENT LINK SUB-ASSEMBLY

B.C.B. 01-10-92
C.A.D. 2/13/92

H5539

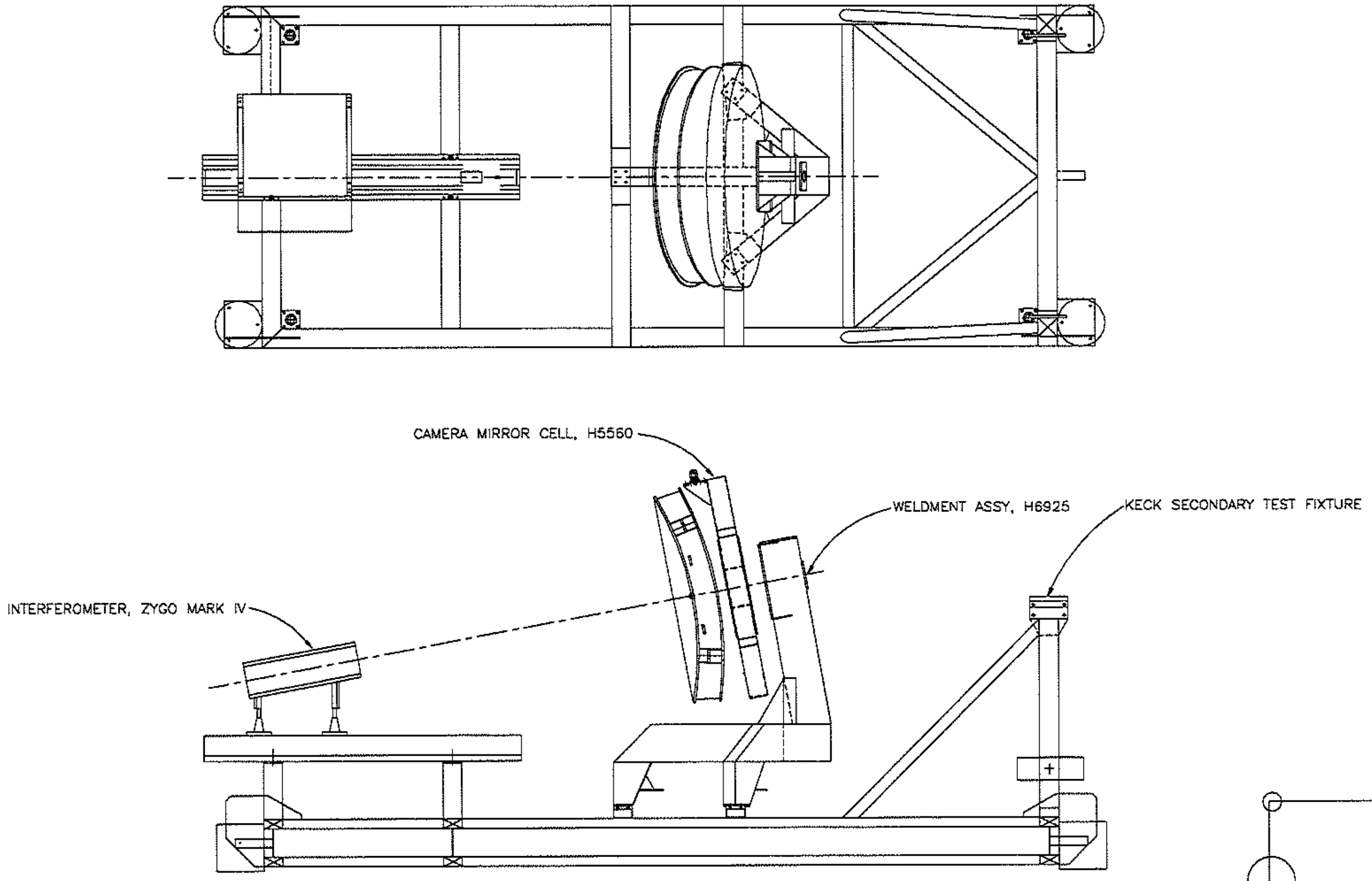


H5823-4	11	2	BRACKET	ALUM
H5823-3	10	2	BRACKET	ALUM
H5823-2	9	1	BRACKET	ALUM
H5823-1	8	4	BRACKET	ALUM
H5822-3	7	1	BRACKET	ALUM
H5822-2	6	1	BRACKET	ALUM
H5822-1	5	1	MOUNTING PLATE	ALUM
H5821-2	4	1	MOUNTING PLATE	ALUM
H5821-1	3	2	STRUT	STEEL
H5820-2	2	1	POST	STEEL
H5820-1	1	1	POST	STEEL

.1

REV

KECK/HIRES
CAMERA MIRROR
HORIZONTAL TEST ASSY
B.C.B. 4/14/92
C.A.O. 4/17/92
H5824



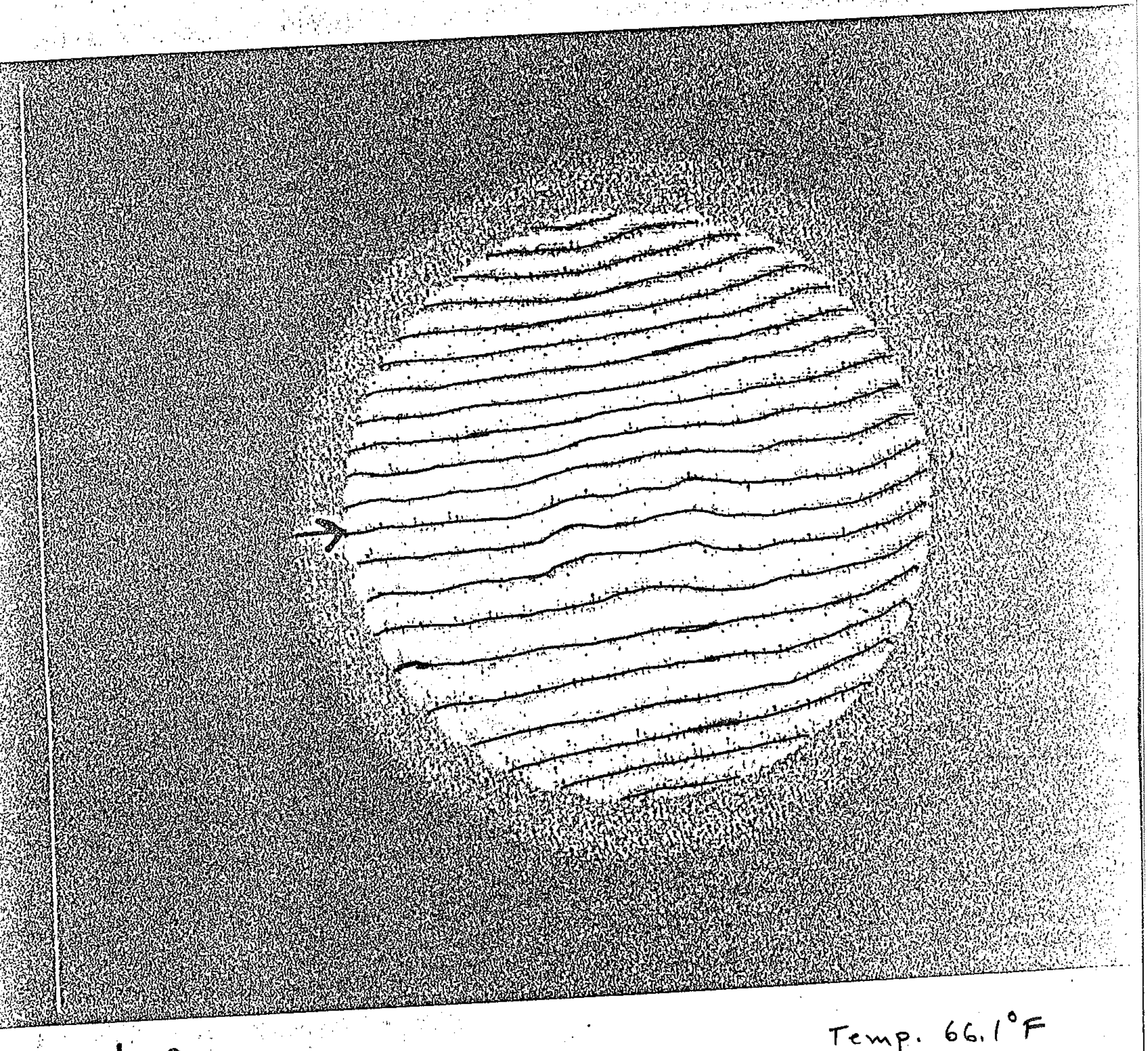
.1

REV

KECK/HIRES
CAMERA MIRROR
10" TEST ASSY

B.C.B. 7/1/92
C.A.G. 8/5/92

H5825



#2

File: HXODg#2

Temp. 66.1°F
Horizontal

FIGURE 4

```
WISP [Ver. 3.13]     SN-  189     07-09-92
Hextek Horz#2 0Deg   11:36:59 07-09-92
OPD data

TERM         RMS FIT        COEFFICIENTS
TILT          0.210        -4.7555     -0.5753
FOCUS         0.193        -4.7488     -0.5755        0.1527
SEIDEL        0.072        -4.7659     -0.5853        0.1326       0.4064
                            0.1118     -0.0934       -0.0724      -0.1545

               AMT          ANGLE
TILT           4.600        185.5
FOCUS          0.771
ASTIG          0.843          7.7
COMA           0.355        217.8
SA3           -0.927
TERMS REMOVED:  TILT  FOCUS

x center    y center    radius
  50.00      51.00      47.68


DATA PTS   WEDGE      PEAK    VALLEY     P-V      RMS      STREHL RATIO
  6604      0.50     0.618    -0.461    1.079    0.193        0.230
```

FIGURE 5

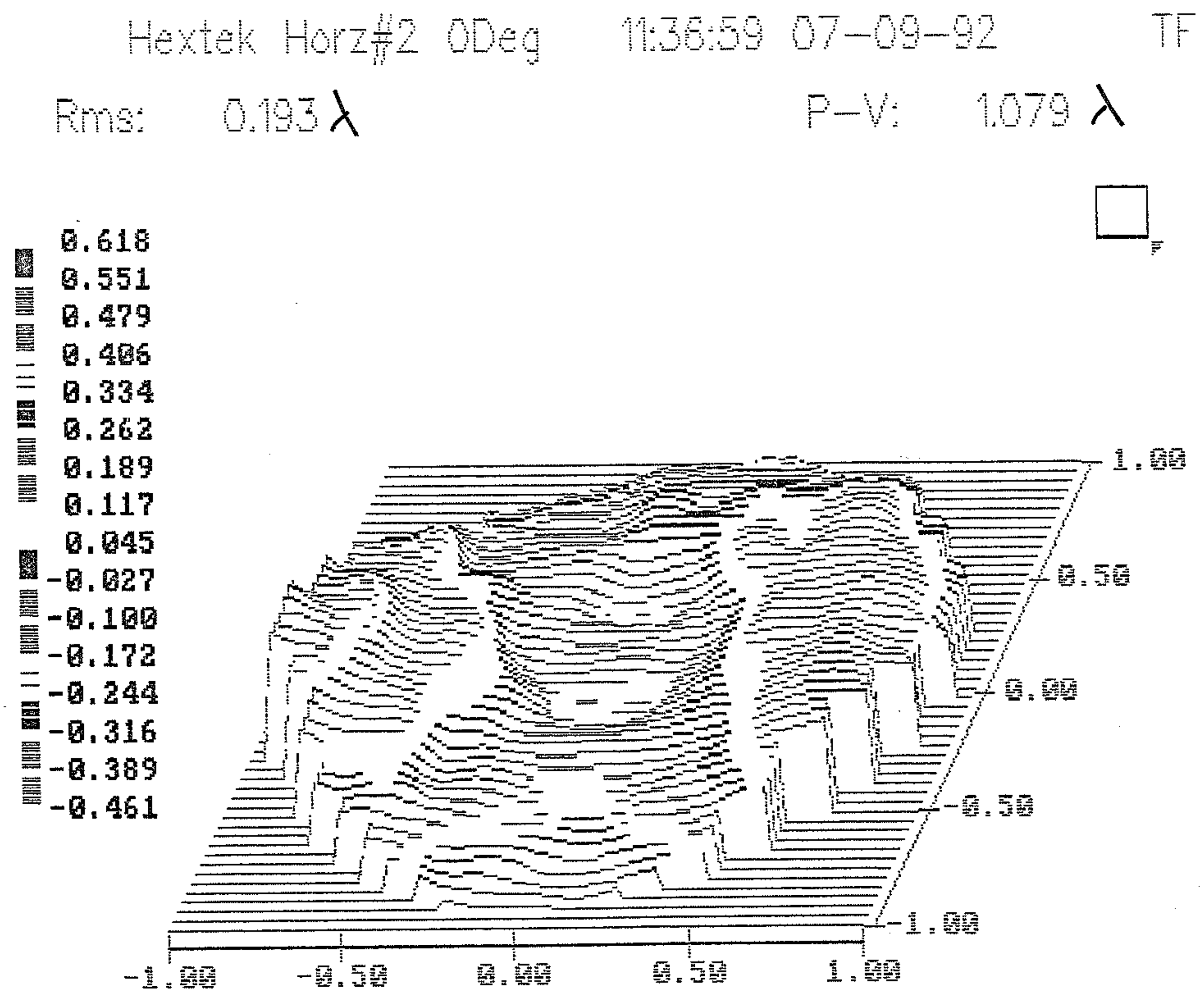
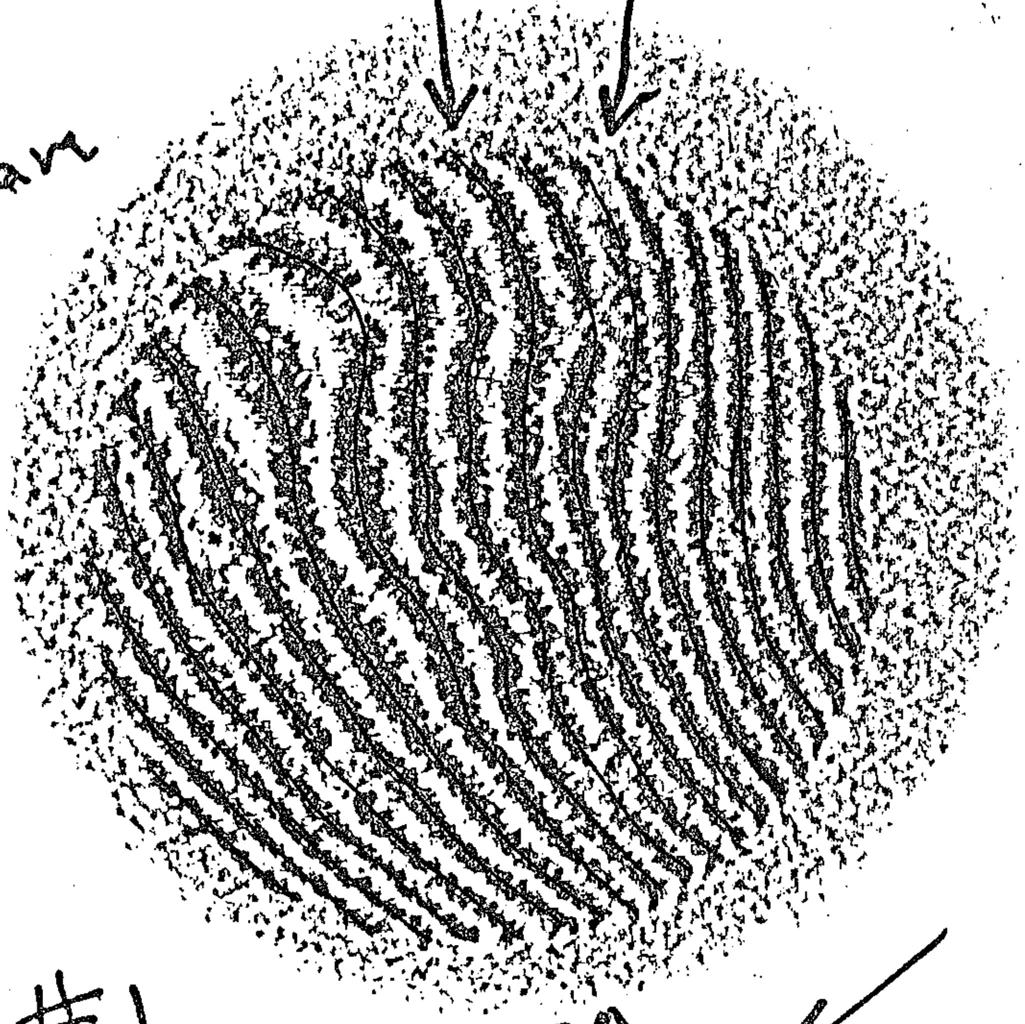

Hextek Horz#2 0Deg 11:36:59 07-09-92 TF
Rms: 0.193 λ
P-V: 1.079 λ
0.618
0.551
0.479
0.406
0.334
0.262
0.189
0.117
0.045
-0.027
-0.100
-0.172
-0.244
-0.316
-0.389
-0.461
1.00
0.50
0.00
-0.50
-1.00
-1.00
-0.50
0.00
0.50
1.00

FIGURE 6

Top Fiducial

10° Lean



#1

7-16-92

File: HXCL#1
(cell)

69.°F
7-16-92

FIGURE 7

```
~~WISP [Ver. 3.13]      SN-    189    08-02-92

Hextek Cell #1          12:51:28 08-02-92
OPD data

TERM             RMS FIT          COEFFICIENTS
TILT              0.439         -3.9270         -1.4229
FOCUS             0.433         -3.9288         -1.4092          0.1429
SEIDEL            0.094         -3.8779         -1.4505          0.0732         -1.1144
                                 0.2077         -0.0721         -0.2811          0.0025

                   AMT           ANGLE
TILT              3.838          193.4
FOCUS            -1.002
ASTIG             2.267           84.7
COMA              0.870          255.6
SA3               0.015

TERMS REMOVED:   TILT   FOCUS

x center      y center       radius
  51.00         51.00         48.08


DATA PTS      WEDGE       PEAK      VALLEY      P-V       RMS       STREHL RATIO
  6433         0.50       1.188     -1.159     2.347     0.439         0.000
```

FIGURE 8

Hextek Cell #1 12:51:28 08-02-92 TF

Rms: 0.439 λ P-V: 2.347 λ

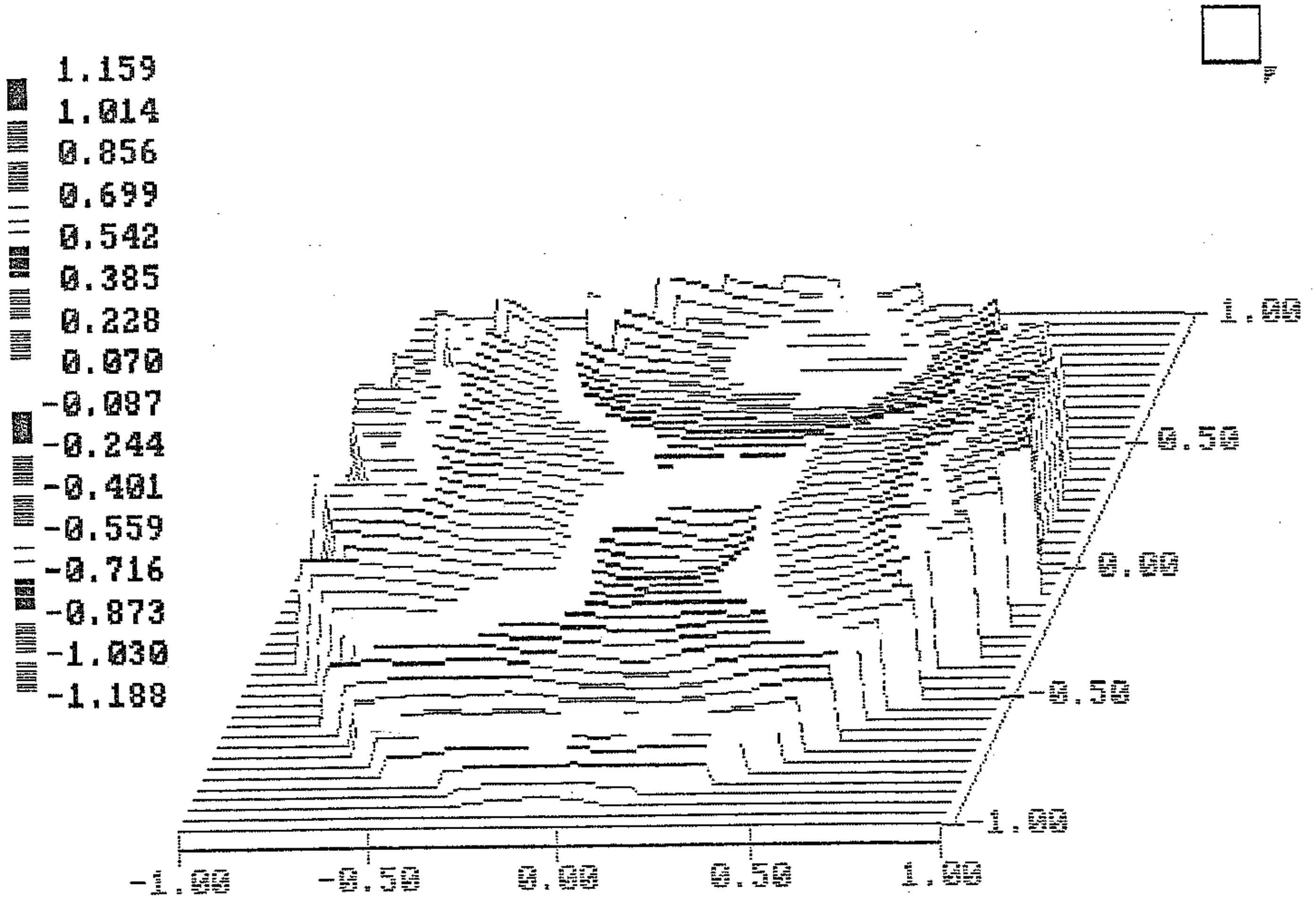


FIGURE 9

```
WISP [Ver. 3.13]     SN-   189    08-02-92
Hextek Cell #1       12:51:28 08-02-92
OPD data

TERM         RMS FIT        COEFFICIENTS
TILT          0.368          8.5098      1.9563
FOCUS         0.326          8.5274      1.9338      -0.3352
SEIDEL        0.114          8.5029      1.9826      -0.1994      0.6827
                            -0.3183      0.1703       0.3204      0.1654

               AMT          ANGLE
TILT           8.272          9.3
FOCUS         -0.638
ASTIG         -1.506         77.5
COMA           1.089         62.0
SA3            0.992

TERMS REMOVED:  TILT  FOCUS
REF SUBTRACTED: c:\wispdata\hx0dg#2.opd
x center    y center     radius
  50.00       51.00       47.30


DATA PTS    WEDGE      PEAK      VALLEY     P-V      RMS      STREHL RATIO
  6239      -0.50     1.252      -0.765    2.017    0.325        0.015
```

FIGURE 10

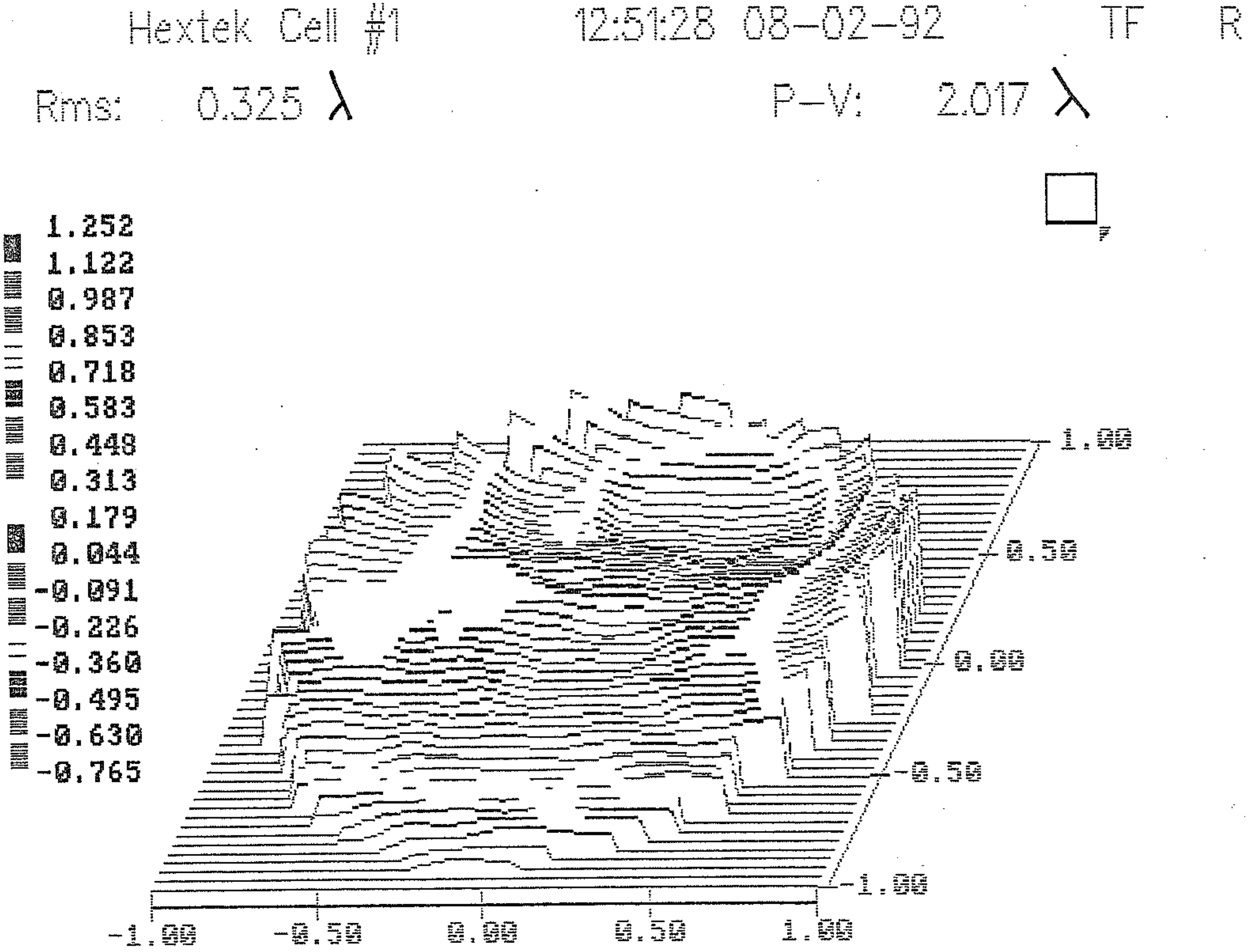
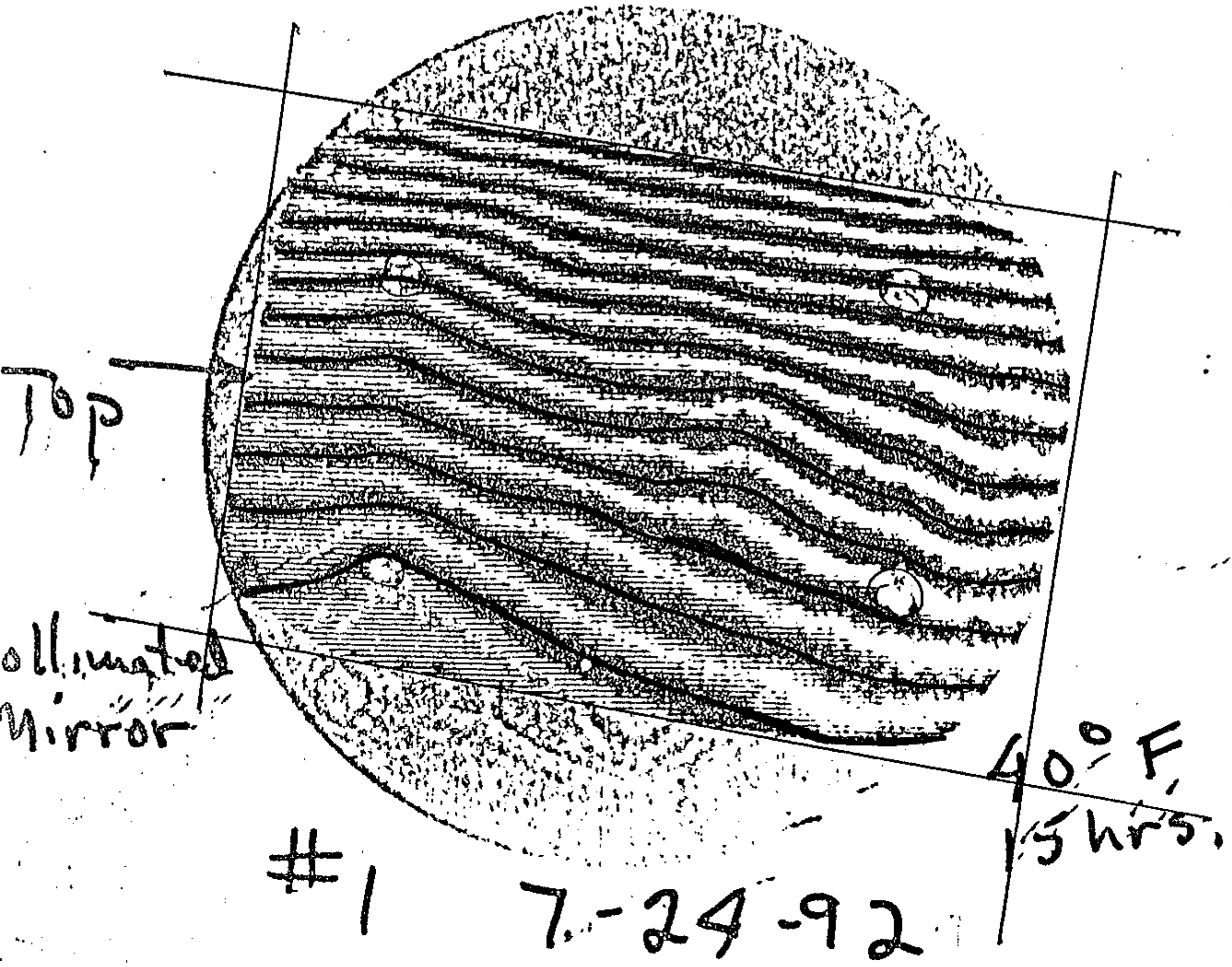

Hextek Cell #1
12:51:28 08-02-92
TF
R
Rms: 0.325 λ
P-V: 2.017 λ
1.252
1.122
0.987
0.853
0.718
0.583
0.448
0.313
0.179
0.044
-0.091
-0.226
-0.360
-0.495
-0.630
-0.765
1.00
0.50
0.00
-0.50
-1.00
-1.00
-0.50
0.00
0.50
1.00

FIGURE 11

AFTER Initial Collimation of Mirror.



Hextek

Cold 15 hrs. after
Collimation of mirror.
Best Figure = 1.28λ P-V.

File: HXcld15h

FIGURE 12

```
~~WISP [Ver. 3.13]     SN-   189    07-24-92

Hextek Cold 15h 7-24 08:42:43 07-24-92
OPD data

TERM         RMS FIT        COEFFICIENTS
TILT          0.262         4.8499      -0.1253
FOCUS         0.243         4.8569      -0.1309       0.1975
SEIDEL        0.089         4.8569      -0.0651       0.5750       1.0083
                            0.3275      -0.0569       0.0803       0.0193

               AMT          ANGLE
TILT           4.976          -2.6
FOCUS         -0.026
ASTIG          2.120           9.0
COMA           0.295       -234.7
SA3            0.116

TERMS REMOVED:  TILT  FOCUS

x center    y center     radius
  50.00       50.00      40.85


DATA PTS    WEDGE      PEAK     VALLEY     P-V      RMS      STREHL RATIO
  3404       0.50     0.777     -0.510    1.287    0.254        0.079
```

FIGURE 13

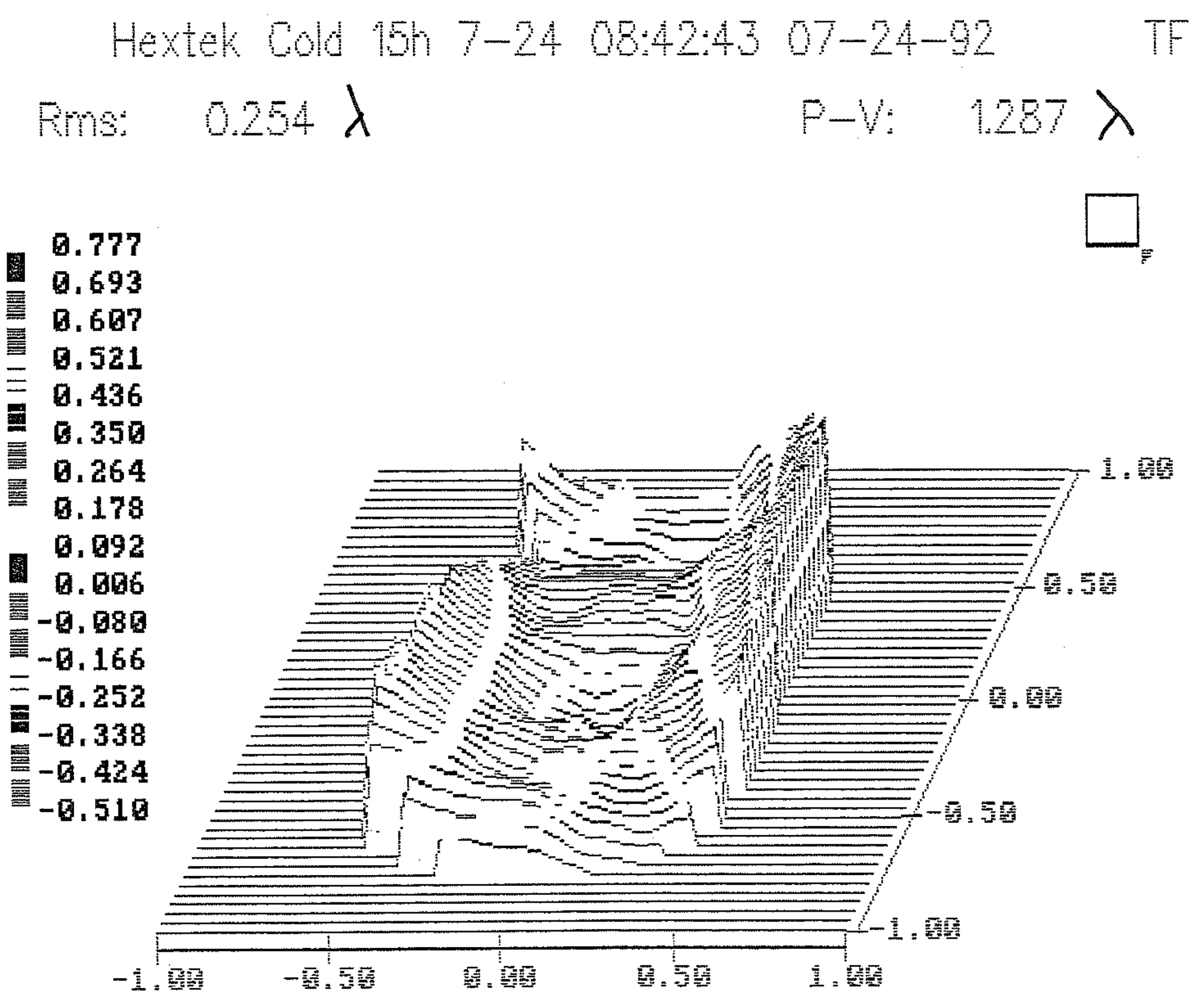

Hextek Cold 15h 7-24 08:42:43 07-24-92 TF
Rms: 0.254 λ
P-V: 1.287 λ
0.777
0.693
0.607
0.521
0.436
0.350
0.264
0.178
0.092
0.006
-0.080
-0.166
-0.252
-0.338
-0.424
-0.510
1.00
0.50
0.00
-0.50
-1.00
-1.00
-0.50
0.00
0.50
1.00

FIGURE 14

APPEDIX A

```
/prep7
/show,x11,,1
!
/TITLE,CAMERA MIRROR V16
!   /u/bruce/anfiles/cam/v16  5-18-92
!
!   plate element thicknesses
!
! t1 = front sheet thickness
! t2 = back sheet thickness
! t3 = inner cell walls
! t4 = outer cell walls
! t5 = mounting boss thickness
!
t1=.34
t2=.43
t3=.188
t4=.1
t5=2
!
r1=64.25
r2=r1 + 5.8
!
et,1,63
type,1
!
r,1,t1
r,2,t2
r,3,t3
r,4,t4
r,5,t5
!
!   material constants (pyrex)
!
ex,1,9.5e6
dens,1,0.081
nuxy,1,0.2
alpx,1,33e-7
!
/NOPR
local,11,0,- 28.6216500000    , -28.0000860000    , 0.000000000000E+00
!
!
!    DXF TO ANSYS TRANSLATOR - REV. 3A
!    READING KEYPOINTS
!
K,     1,  39.6216500000    ,  8.94752700000    , 0.000000000000E+00
K,     2,  28.6216500000    ,  6.00008600000    , 0.000000000000E+00
K,     3,  28.6216500000    ,  28.0000860000    , 0.000000000000E+00
K,     4,  28.6216602640    ,  7.00008600000    , 0.000000000000E+00
K,     5,  39.1216598765    ,  9.81355822275    , 0.000000000000E+00
K,     6,  28.6216500000    ,  11.6603620000    , 0.000000000000E+00
K,     7,  28.6216500000    ,  21.5443550000    , 0.000000000000E+00
K,     8,  28.6216500000    ,  24.7399600000    , 0.000000000000E+00
K,     9,  28.6216500000    ,  19.7499980000    , 0.000000000000E+00
K,    10,  28.6216500000    ,  26.5771490000    , 0.000000000000E+00
K,    11,  29.2378000000    ,  26.9328830000    , 0.000000000000E+00
K,    12,  30.1307490000    ,  22.3680530000    , 0.000000000000E+00
K,    13,  29.7840410000    ,  19.1708530000    , 0.000000000000E+00
K,    14,  28.6216500000    ,  16.5970510000    , 0.000000000000E+00
K,    15,  29.8297350000    ,  14.1916110000    , 0.000000000000E+00
K,    16,  28.6216500000    ,  14.8061740000    , 0.000000000000E+00
K,    17,  29.8512800000    ,  9.23956100000    , 0.000000000000E+00
K,    18,  28.6216500000    ,  9.87044500000    , 0.000000000000E+00
K,    19,  30.7615170000    ,  22.1208510000    , 0.000000000000E+00
K,    20,  31.7024000000    ,  22.6640710000    , 0.000000000000E+00
```

```
K,     21,  32.9347000000     ,  20.5296640000     , 0.000000000000E+00
K,     22,  34.1670000000     ,  18.3952580000     , 0.000000000000E+00
K,     23,  35.3993000000     ,  16.2608520000     , 0.000000000000E+00
K,     24,  35.5919150000     ,  13.5261830000     , 0.000000000000E+00
K,     25,  36.6316000000     ,  14.1264460000     , 0.000000000000E+00
K,     26,  37.8639000000     ,  11.9920400000     , 0.000000000000E+00
K,     27,  38.3520020000     ,  8.26888600000     , 0.000000000000E+00
K,     28,  35.6933190000     ,  7.16762300000     , 0.000000000000E+00
K,     29,  32.9136380000     ,  6.42281000000     , 0.000000000000E+00
K,     30,  30.0605190000     ,  6.04719000000     , 0.000000000000E+00
K,     31,  31.3274450000     ,  10.0483110000     , 0.000000000000E+00
K,     32,  32.2803920000     ,  9.60635100000     , 0.000000000000E+00
K,     33,  29.9874360000     ,  12.3890830000     , 0.000000000000E+00
K,     34,  31.0523360000     ,  11.8735380000     , 0.000000000000E+00
K,     35,  33.4015070000     ,  12.5041730000     , 0.000000000000E+00
K,     36,  34.0655430000     ,  15.7729040000     , 0.000000000000E+00
K,     37,  36.8146780000     ,  11.3862710000     , 0.000000000000E+00
K,     38,  36.5861190000     ,  11.4616960000     , 0.000000000000E+00
K,     39,  34.3722510000     ,  15.6678850000     , 0.000000000000E+00
K,     40,  35.3299860000     ,  13.6140130000     , 0.000000000000E+00
K,     41,  32.7875290000     ,  17.9427660000     , 0.000000000000E+00
K,     42,  33.1574920000     ,  17.8124180000     , 0.000000000000E+00
K,     43,  34.6201680000     ,  10.3290240000     , 0.000000000000E+00
K,     44,  33.9949390000     ,  10.5803130000     , 0.000000000000E+00
K,     45,  32.1869930000     ,  14.6940480000     , 0.000000000000E+00
K,     46,  32.6948460000     ,  12.7987140000     , 0.000000000000E+00
K,     47,  31.3746130000     ,  15.0484160000     , 0.000000000000E+00
K,     48,  30.9791870000     ,  16.9087480000     , 0.000000000000E+00
K,     49,  30.0237010000     ,  17.3504580000     , 0.000000000000E+00
K,     50,  31.9512010000     ,  19.9618410000     , 0.000000000000E+00
K,     51,  31.4850310000     ,  20.1330130000     , 0.000000000000E+00
K,     52,  29.6122320000     ,  24.3031860000     , 0.000000000000E+00
K,     53,  30.4701000000     ,  24.7984770000     , 0.000000000000E+00
!
!     READING MESH MODULE COMMANDS
!
L,      3,      1
L,      2,      3
LARC,      4,       5,      3,  21.0000000000
L,     18,      6
L,     16,     14
L,      9,      7
L,      8,     10
L,      8,     10
L,      9,      7
L,     16,     14
L,     18,      6
L,     10,     11
L,     52,      8
L,     12,      7
L,     13,      9
L,     49,     14
L,     15,     16
L,     33,      6
L,     17,     18
L,     19,     20
L,     50,     21
L,     41,     50
L,     42,     22
L,     39,     23
L,     24,     25
L,     37,     26
L,     37,     27
L,     43,     28
L,     32,     29
L,     17,     30
```

```
L,     31,     17
L,     32,     44
L,     31,     32
L,     34,     31
L,     15,     47
L,     33,     15
L,     34,     33
L,     46,     34
L,     43,     38
L,     40,     35
L,     36,     45
L,     38,     37
L,     24,     38
L,     40,     24
L,     39,     40
L,     36,     39
L,     42,     36
L,     41,     42
L,     48,     41
L,     44,     43
L,     35,     44
L,     46,     35
L,     45,     46
L,     47,     45
L,     48,     47
L,     49,     48
L,     13,     49
L,     51,     13
L,     51,     50
L,     19,     51
L,     12,     19
L,     52,     12
L,     52,     53
LARC,      4,      5,      3,  21.0000000000
LARC,      2,      1,      3,  22.0000000000
!
!   end of dxf input
!
!   clean-up geometry
!
KPUSEL, POIN,     3
/GOPR
kpal
lsal
lint,26,3
,25,62
,24,64
,23,66
ldel,1
ldel,60
csys,1
L,      2,     30
L,     30,     29
L,     29,     28
L,     28,     27
L,     27,      1
L,     11,     53
L,     53,     20
L,     20,     21
L,     21,     22
L,     22,     23
L,     23,     25
L,     25,     26
L,     26,      5
L,      5,      1
l,3,11
```

```
!
!   complete geometry
!
lgen,2,all,,,0,0,r1
kpse,z,r1
lskp,1
csys,2
kmod,all,r1
kpal
lsal
ldel,2
ldel,83
kpse,x,r1
lskp,1
ldel,162
csys
l,60,71
,60,70
A,     58,     59,     62,     61
A,     59,    110,     96,     62
A,    110,    111,     94,     96
A,    111,    112,     92,     94
A,    112,    114,    113,     92
A,     61,     62,     78,     63
A,     92,    113,     91,     90
A,     64,     77,     76,     65
A,     66,     75,     74,     67
A,     68,     73,     72,     69
A,     70,     71,     60,     60
csys,2
A,     62,     96,     95,     97
A,     62,     97,     78,     78
A,     96,     94,     93,     98
A,     96,     98,     95,     95
A,     94,     92,     90,    102
A,     94,    102,     93,     93
A,     63,     78,     77,     64
A,     78,     97,     99,     77
A,     97,     95,    101,     99
A,     95,     98,    104,    101
A,     98,     93,    102,     88
A,     98,     88,    103,    104
A,    102,     90,     91,     89
A,    102,     89,     88,     88
A,     77,     99,    100,     76
A,     99,    101,    106,    100
A,    101,    104,    105,    106
A,    104,    103,     86,    105
A,    103,     88,     89,     87
A,    103,     87,     86,     86
A,    105,     86,     87,     85
A,    105,     85,     84,     84
A,    106,    105,     84,     83
A,    106,     83,    107,    100
A,     76,    100,    107,     75
A,     76,     75,     66,     65
A,     75,    107,    108,     74
A,    107,     83,     81,    108
A,     83,     84,     85,     82
A,     83,     82,     81,     81
A,    108,     81,     82,     80
A,    108,     80,     79,     79
A,     74,    108,     79,     73
A,     74,     73,     68,     67
A,     73,     79,     80,    109
A,     73,    109,     72,     72
```

```
A,    69,    72,   109,    71
A,    69,    71,    70,    70
!
!
ldvs,all,,1
!
csys,2
!  generate second layer of areas
!
agen,2,all,,,r2-r1
kpse,x,r1
lskp,1
arls,1
real,1
ames,all
kpse,x,r2
lskp,1
arls,1
real,2
ames,all
csys,0
kpal
lsal
aral
!
!   side wall areas
!
A,    62,    61,   118,   117
A,    96,    62,   117,   120
A,    94,    96,   120,   122
A,    92,    94,   122,   124
A,   113,    92,   124,   126
!
!   0.125 thk.
!
real,4
ldvs,all,1.5
ames,all
!
!   vertical (cell) areas
!
A,    62,    78,   127,   117
A,    97,    78,   127,   147
A,    95,    97,   147,   146
A,    96,    95,   146,   120
A,    78,    63,   128,   127
A,    63,    64,   132,   128
A,    77,    64,   132,   131
A,    99,    77,   131,   151
A,    97,    99,   151,   147
A,    98,    95,   146,   149
A,    93,    98,   149,   148
A,    94,    93,   148,   122
A,   102,    93,   148,   150
A,    90,   102,   150,   130
A,    92,    90,   130,   124
A,    77,    76,   133,   131
A,    76,    65,   134,   133
A,   100,    76,   133,   157
A,   106,   100,   157,   158
A,   101,    99,   151,   152
A,   101,   106,   158,   152
A,   104,   101,   152,   153
A,    98,   104,   153,   149
A,   103,   104,   153,   155
A,    88,   103,   155,   154
```

```
A,   102,    88,   154,   150
A,    91,    90,   130,   129
A,    89,    88,   154,   156
A,   105,   106,   158,   159
A,    86,   105,   159,   160
A,   103,    86,   160,   155
A,    87,    86,   160,   161
A,    65,    66,   136,   134
A,    75,    66,   136,   135
A,   107,    75,   135,   165
A,   100,   107,   165,   157
A,    83,   107,   165,   164
A,    84,    83,   164,   163
A,   105,    84,   163,   159
A,    85,    84,   163,   162
A,    75,    74,   137,   135
A,    74,    67,   138,   137
A,   108,    74,   137,   166
A,    81,   108,   166,   167
A,    83,    81,   167,   164
A,    82,    81,   167,   168
A,    67,    68,   140,   138
A,    73,    68,   140,   139
A,    79,    73,   139,   170
A,   108,    79,   170,   166
A,    80,    79,   170,   169
A,    73,    72,   141,   139
A,    72,    69,   142,   141
A,   109,    72,   141,   171
A,    69,    70,   143,   142
A,    71,    70,   143,   144
real,3
!
!  set number of cell elements
ldvs,all,1.5
ames,all
arall
!
!-------------- stop to add bosses-----
!
c*** start for midplane nodes
!
!  select local areas
!
ARSE,AREA,         80
ARAS,AREA,         79
ARAS,AREA,        135
ARAS,AREA,         31
ARAS,AREA,         30
ARAS,AREA,        134
ARAS,AREA,        131
!
C*** now have the areas
!
earea
nelem
lsar
!
!  add center node
!
fill,194,203,1,300
!
!  create midplane elements (real 5)
!
Real,5
!
```

```
E,   185,   200,   203,   300,
E,   300,   194,   188,   185,
!
eall
nall
arall
lsall
!
numm,nodes
!
!   mirror geometry to create 1/2 model
!
csys,1
local,12,1,0,0,0,-60
symm,2,1000,all
esym,,1000,all
!
local,12,1,0,0,0,-30
symm,2,2000,all
esym,,2000,all
!
csys,1
enod,1
nsel,,1,2000
enod,1
symm,2,4000,all
esym,,4000,all
!
eall
nall
numm,nodes
!
!   remove dup elems
!
csys,1
!
nsel,y,-30
enod,1
EDEL,   510
EDEL,   509
EDEL,   508
EDEL,   507
EDEL,   618
EDEL,  1329
EDEL,   616
EDEL,   615
EDEL,   671
EDEL,   672
EDEL,   673
EDEL,   674
EDEL,   703
EDEL,   704
EDEL,   705
EDEL,   706
!
nsel,y,30
enode,1
EDEL,  2127
EDEL,  1060
EDEL,  2129
EDEL,  1062
EDEL,  1027
EDEL,  1028
EDEL,  1029
EDEL,  1030
EDEL,   971
```

```
EDEL,   972
EDEL,  2041
EDEL,   974
EDEL,   866
EDEL,   865
EDEL,   864
EDEL,   863
!
!
nall
eall
csys,0
!
!----- ADD BEAM ELEMENTS FOR WHIFFLETREES ----
!
! very stiff material! (minimize beam deflection)
!
mp,ex,2,1e15
mp,nuxy,2,0.27
mp,dens,2,0.01
!
! 2" dia. rod
!
r,10,3.14,0.785,0.785,2,2
!
et,2,4
mat,2
real,10
type,2
!
! create beam nodes
!
fill,300,2300,1,6000
numstr,elem,3000
n,6001,7.5,-13,65.4
n,6002,15,0,65.4
!
! rotate nodes into beam coordinate sys
!
nall
nsel,node,6000,7000
ngen,2,5,6000,,,-5
cs,15,0,6001,6002,6005
nase,node,300
nase,node,2300
ndel,6005
nrot,all
nall
csys
!
! create beam elements
!
e,6001,6000
e,6000,6002
!
! couple DOF's
!
cp,1,ux,300,6001
cp,2,uy,300,6001
cp,3,uz,300,6001
cp,4,rotx,300,6001
cp,5,rotz,300,6001
!
cp,6,ux,2300,6002
cp,7,uy,2300,6002
cp,8,uz,2300,6002
```

```
cp,9,rotx,2300,6002
cp,10,rotz,2300,6002
!
! -----------------------------------------------
!   apply constraints
!
!   axial contraints
!
!d,300,uz,
!d,2300,uz,0
d,6000,uz,-12e-6
d,4300,uz,0
!
!   radial constraints
!
d,114,uy,0
d,2114,uy,0
d,4114,uy,0
!
!   x=0  symmetry constraint
!
!symb,0,1,0
csys,0
nsel,x,-.5,0.1
d,all,ux,0
nall
eall
!
!   apply gravity at 10.3 degree angle
!
!   z-component
acel,,,0.178
!   y-component
acel,,0.984
!
wsort,y
!
afwr
fini
/inp,27
```