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# Pilot Plant Mirror Module Testing and Evaluation

W. R. Delameter and V. P. Burolla

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# PILOT PLANT MIRROR MODULE TESTING AND EVALUATION

W. R. Delameter
Applied Mechanics Division 8122

V. P. Burolla
Model Labs Division 8424

## ABSTRACT

Ten Styrofoam®-core mirror modules designed by McDonnell Douglas Astronautics Company for the solar central receiver pilot plant to be built at Barstow, California, were fabricated and tested at Sandia Laboratories, Livermore. The purpose of the testing was to determine whether the mirror modules could survive the expected environment. The mirror modules passed the survival tests with no glass breakage and suffered only minimal damage from a thaw-freeze cycling. An apparent change in curvature of the modules was observed after thermal cycling and further testing is recommended.

ACKNOWLEDGMENTS

The authors wish to thank Dale Boehme (8313) for fabricating the mirror modules, running the tests, and recording most of the data. His innovation, skillful craftsmanship, and willingness to get into an environmental chamber at 20°F and 120°F to measure mirror contours are most appreciated.

We are also grateful to Wil Jorgenson and Wil Vandermolen (8123) for measuring residual stresses in the mirrors.

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# PILOT PLANT MIRROR MODULE TESTING AND EVALUATION

## Introduction

Ten Styrofoam®-core mirror modules designed by McDonnell Douglas Astronautics Company (MDAC) for the solar central receiver pilot plant to be built at Barstow, California, were fabricated and tested at Sandia Laboratories, Livermore. The mirror modules were sandwiches of 1/8-in. mirrored low iron float glass, a 2- or 4-in. core of polystyrene foam, and a 26-gage galvanized steel sheet. These mirrors were subjected to nine different tests to determine whether the design would perform as expected and survive the environmental elements for the required 30-year life span. Specific questions to be resolved included the stress levels in the glass, the contour change of the mirror modules with temperature, hailstone survival, the effects of thaw-freeze cycling, the presence of long-term creep, and the effects of cold-water shock on the glass. In addition to the testing of these ten modules, four mirror modules of the same design fabricated by MDAC were subjected to a partial test program, and a foam-core mirror module using 0.060-inch fusion glass was tested for hailstone survival.

### Summary of Test Results

The significant test results are:

1. Residual stresses measured in the glass at the edges were found all to be compressive and ranged from 0 to 500 psi.

2. Deflections due to gravity were found to have typical maximum values of 0.2 mm or less for the 2-in. thick modules and less than 0.1 mm for the 4-in. thick modules.

3. Most of the mirror modules assumed a convex set when the adhesive cured. In general, the 4-in. thick modules were flatter than the 2-in.

4. Simulated maximum operational wind loading (30 mph) on a 2-in. mirror module resulted in deflections roughly equivalent to those of gravity loading.

5. Contour changes due to temperature closely followed those predicted by theory. A 50°F temperature increase would result in focal lengths of 767 and 1507 feet, respectively, for initially flat 2-in. and 4-in. thick mirror modules.

6. The highest thermal stresses measured at the edges of the glass of a 2-in. and a 4-in. mirror module were less than 300 and 560 psi, respectively, for a temperature increase of 50°F.

7. More than 200 thaw-freeze cycles between -20°F and 120°F resulted in no damage to a MDAC-built mirror module and minimal damage to two of three Sandia-built modules. Some significant contour changes as a result of the thermal cycling were observed in all of the mirror modules.

8. Eighth-in. float glass mounted on styrofoam was shown to survive 3/4-in. hailstones at 65 ft/sec but broke when struck near the edge with 1-in. hailstones at 75 ft/sec. 0.060-in. fusion glass mounted on Styrofoam did not survive the 3/4-in. hail test.

9. The contour changes due to creep at room temperature in two mirror modules during a period of several months were found to be insignificantly small.

10. Cold water shock caused no damage to the mirror modules.

## Mirror Module Fabrication

### Description

An exploded view of the Styrofoam-core mirror modules as built at Sandia is shown in Figure 1. The design is a sandwich of 1/8-in. mirrored low-iron float glass, a 2 or 4-inch core of polystyrene foam (Dow Chemical Co. IB Styrofoam, nominal 1.8 lb/ft$^3$ density), and a 26-gage galvanized steel sheet. The sandwich is bonded together with polyurethane adhesive (3M brand adhesive EC-3549 with 0.5% Union Carbide A-187 added to improve moisture resistance). The edges are sealed and the galvanized steel edge caps held in place with Dow Corning 790 Building Sealant. Four mounting cups which contain nuts for bolting the mirror module to its supporting frame are bonded to the back side galvanized sheet with the same polyurethane adhesive.

The Styrofoam is larger than the glass by 1/4-inch around all of the edges to help protect the glass from damage. The Styrofoam-core panel is pieced together from four sections due to size limitations of the procured foam. Similarly, the long edge caps are also pieced together due to the limited size of galvanized sheet on hand.

The mirror modules fabricated at Sandia differed from those built by MDAC in three significant respects. First, MDAC used SM Styrofoam which differs from IB Styrofoam in that it is slightly denser and has skinned surfaces. (The skinned surfaces are planed off before use.) SM Styrofoam is manufactured in 48-inch widths and MDAC was able to make one-piece foam cores rather than piecing together four sections. The second difference was that the MDAC edge caps did not overlap the glass as did the Sandia-made edge caps, as shown in Figure 2. MDAC felt that this design would help keep the mirror clean. Finally, the MDAC mirror modules have the mounting cups located four inches closer to one end of the module than the other. The mounting cups on the Sandia-made modules were inadvertently placed symmetrically about the line bisecting the long direction of the mirror.

### Fabrication Procedure

The following is a step-by-step description of the mirror module fabrication procedure used at Sandia. A flat table made of two 48 x 60 x 1/2-in. steel plates ground and leveled to within .0015 inches over the entire surface was used during the bonding process.

The mirror module fabrication steps were:

1. The four-piece Styrofoam panel was bonded together with polyurethane adhesive. The pieces were held together with a clamping fixture for

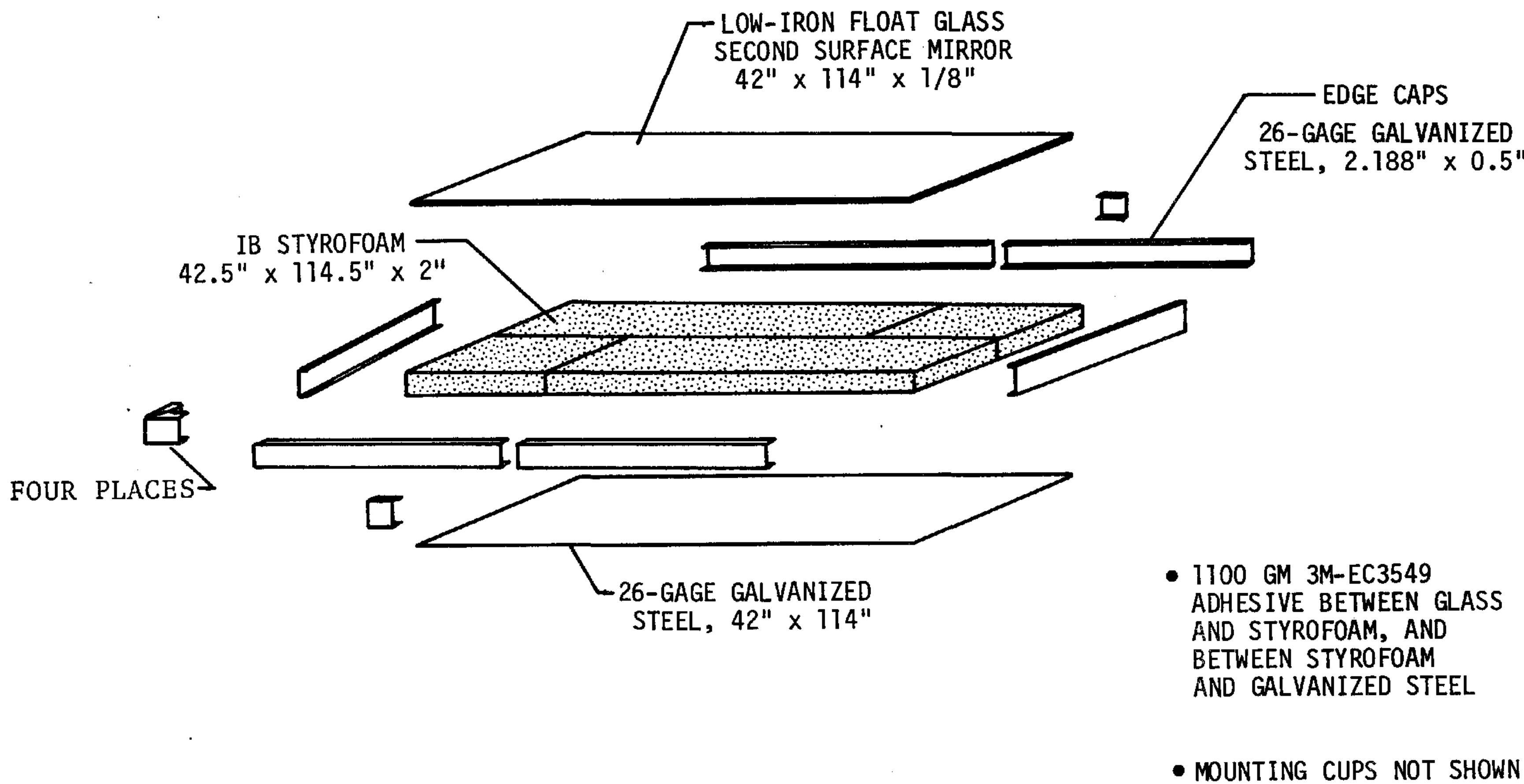



Figure 1. Styrofoam Core Mirror Module

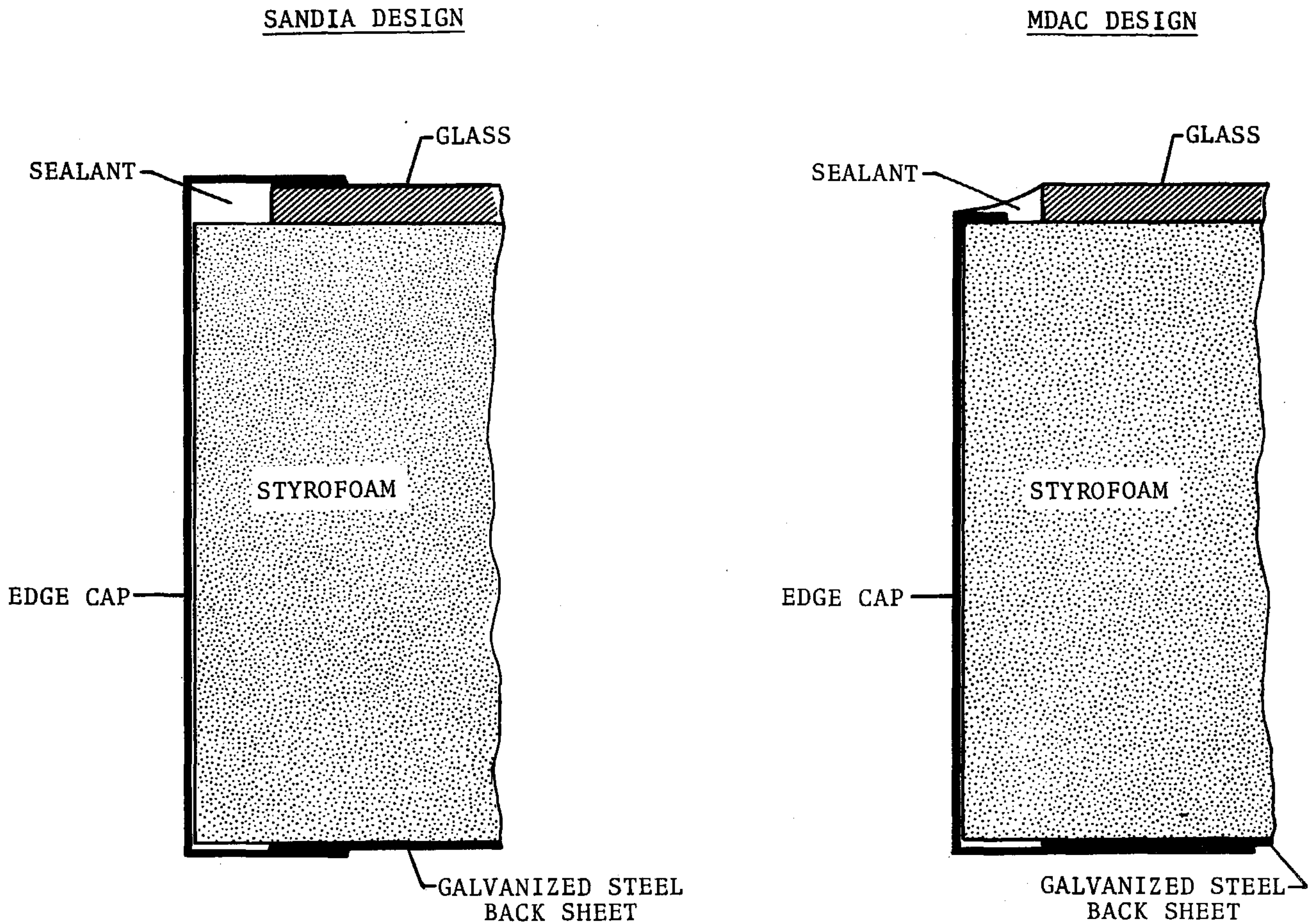



Figure 2. Mirror Module Edge Cap Configurations

at least ten hours. When the adhesive cured, the two surfaces of the Styrofoam panel were hand sanded to remove any irregularities.

2. The Styrofoam panel was bonded to the 42 by 114-in., 26-gage galvanized steel sheet, which was first cleaned with acetone and then prepared with a metal primer (Corogard #9) for bonding. Eleven hundred grams of polyurethane adhesive (550 gm Part A, 550 gm Part B, and 0.5% A-187) were mixed and spread uniformly over the galvanized sheet with a common tile adhesive trowel that had 1/16-inch grooves. The Styrofoam panel was placed on the galvanized sheet and secured with hand pressure, allowing 1/4-inch overlap around the edges.

3. The Styrofoam and galvanized sheet panel were then bonded to the mirrored glass. The bonding table surface was first cleaned with acetone and then the mirror was placed face-down on the table. The back surface of the mirror was cleaned with acetone. Eleven hundred grams of polyurethane adhesive were mixed and spread uniformly on the mirror, as was done with the galvanized sheet in Step 2. Tape was used to mask the table around the mirror from any adhesive which might have squeezed from the joint. The Styrofoam and steel panel was carefully placed onto the glass, allowing 1/4-inch of Styrofoam to overhang around the edges of the mirror. The sandwich was secured together with hand pressure, and the tape masking the table was removed.

4. A bonding pressure of 1.5 psi was applied to the mirror module panel with a vacuum bag for approximately 20 hours. The vacuum bag, designed to put a uniform pressure over the sandwich, consisted of a wooden frame around the edges of the panel, a fiberglass bleeder cloth, and a .010-inch thick sheet of urethane plastic, as shown in Figure 3. The plastic sheet was sealed air-tight to the bonding table with zinc-chromate plastic tape, and the bag was evacuated with a vacuum pump controlled with a needle valve. When the bag was evacuated, the sealed edges were checked for leakage and the needle valve readjusted until an equilibrium pressure was reached. This bonding pressure had to be attained within 30 minutes after the adhesive for both layers was first mixed due to the adhesive's limited pot life.

5. Mounting cups (see Figure 4) were bonded to the back side of the mirror panel with polyurethane adhesive after the panel was removed from the vacuum bag. Both metal surfaces were first cleaned with acetone and then primed with Corogard #9. The cups were attached to a frame to insure the correct spacing between them and were bonded simultaneously to the mirror module. These bonds were allowed to cure for approximately 20 hours.

6. The edges of the mirror module were sealed and the galvanized steel edge caps mounted with Dow Corning 790 Building Sealant, as shown in Figures 1 and 2.

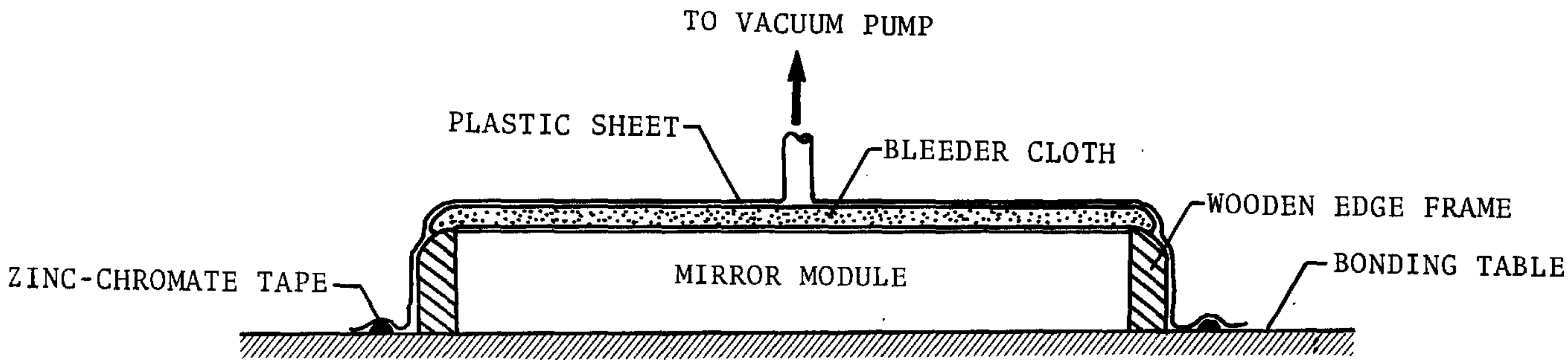



Figure 3. Vacuum Bag for Applying Uniform Pressure to Mirror Module during Bonding

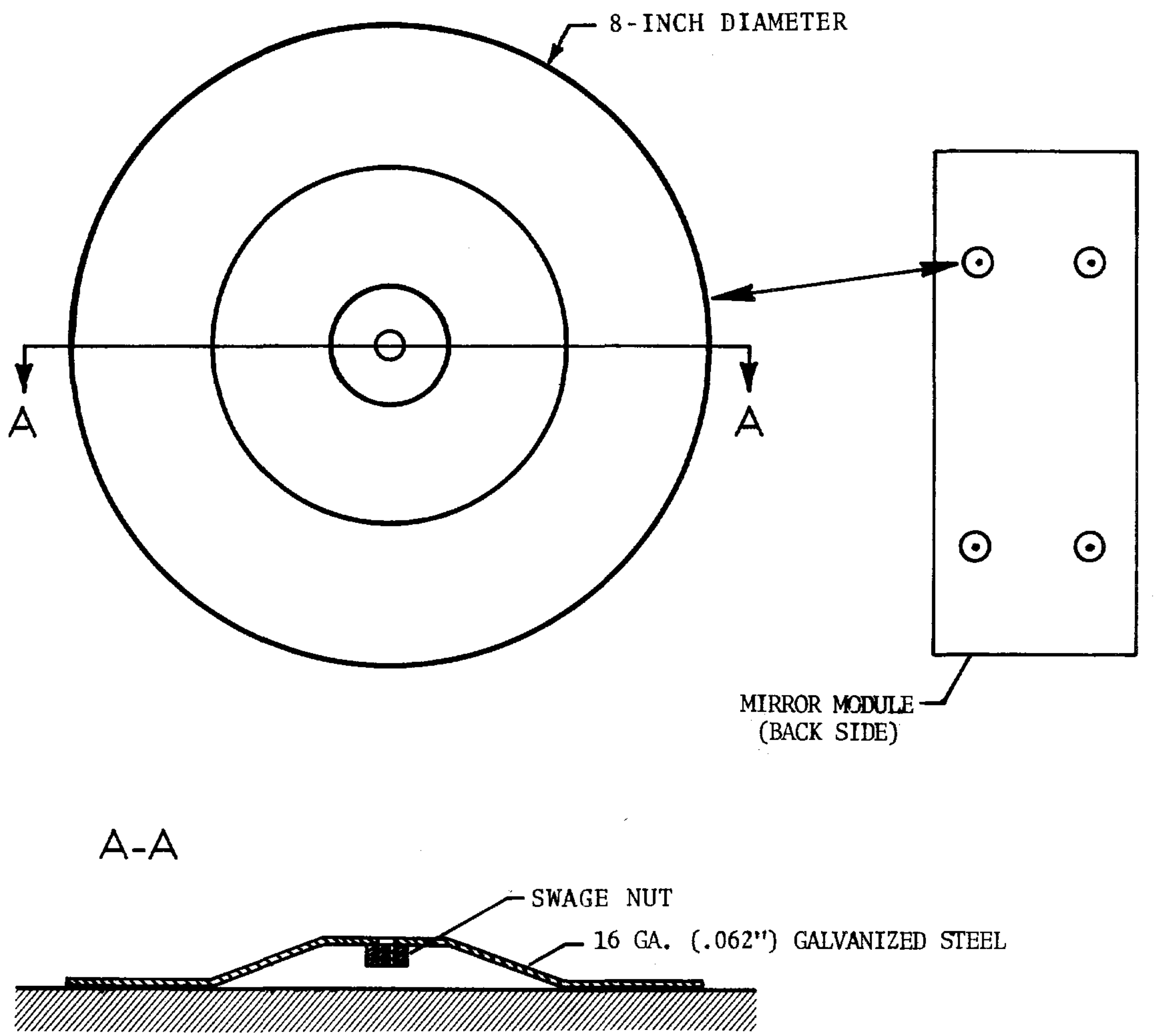



Figure 4. Mirror Module Mounting Cup

## Testing Procedures and Results

A matrix showing which mirror modules were subjected to each test is shown in Table I. The tests, all of which have been completed, were designed to determine the stresses in the glass under operating conditions, measure the initial and subsequent changes in the mirror surface contour so that the performance of the mirror can be evaluated, and determine whether the mirror modules will survive the specified environmental conditions.

### Residual Glass Stress

Residual stresses in the mirrors were measured with a reflection polariscope along the edges of each mirror before bonding. This device measures the average in-plane stresses in the glass. Measurements were taken at 6-in. intervals one inch from the edge of the mirror. The resolution of this technique is about ± 50 psi. The stresses were measured only along the edges of the glass for several reasons. First, the information obtained with each reading of the reflection polariscope is the difference of the two in-plane principal stresses plus the orientation (principal direction) of the stresses. A reading at the edge of the glass yields the level of stress parallel to the edge since the stress normal to the stress-free edge is known to vanish. Second, the stress at the edge of the glass controls the growth of cracks and flaws at the glass edge where almost all fractures in glass initiate. Finally, the measuring technique is somewhat tedious and in order to conserve time the choice was made to limit the stress measurements to the edges of the mirrors.

Stresses, all compressive, ranging from zero to 500 psi were found along the edges of the mirrors. Mirrors with residual stresses less than 100 psi were used in the fabrication of all of the mirror modules except the first two (1 and 2), which were fabricated before the decision was made to use only the low-stress mirrors. Residual stresses of 400 and 300 psi were measured in mirror modules 1 and 2, respectively. Stresses were also measured in six of the ten mirrors after they were bonded with the Styrofoam and steel. Within the accuracy of the measuring technique the stresses in the glass remained unchanged after bonding.

It is concluded from these measurements that residual stresses found in 1/8-in. float glass mirrors will probably be compressive at the edges. However, this phenomenon cannot be used to advantage because of the large fraction of mirrors in which the compressive stress was found to be very small. Therefore, the residual stress must be assumed to be zero as a worst case in the stress analysis of the mirror modules.

### Mirror Contour, Gravity Load

The initial mirror module contour and the sag due to gravity were measured on eight Sandia-made mirror modules and four MDAC-made modules. The beam-dial indicator instrument shown in Figure 5 was fabricated at Sandia to simultaneously measure the mirror surface deflections with displacement gages at nine points along a straight line. Displacement readings were taken at

Table I. Mirror Module Test Summary

| Mirror Module Number (Module Thickness-in.) | 1 (2) | 2 (2) | 3 (2) | 4 (4) | 5 (4) | 6 (4) | 7 (4) | 8 (2) | 9 (2) | 10 (2) |
|---|---|---|---|---|---|---|---|---|---|---|
| Tests | | | | | | | | | | |
| 1. Residual Glass Stress | X | X | X | X | X | X | X | X | X | X |
| 2. Contour - Gravity | X | X | X | | X | X | X | X | X | |
| 3. Contour - Wind | | X | | | | | | | | |
| 4. Contour - Temperature | | | X | | X | | X | X | | |
| 5. Thermal Glass Stress | | | X | | X | | | | | |
| 6. Thaw-Freeze Cycle | | | X | | X | | X | | | |
| 7. Adhesive Creep and Cure | | | | | | | | | X | X |
| 8. Hailstone Survival | | | | X | | | | | | |
| 9. Cold Water Shock | X | | | | | X | | | | |

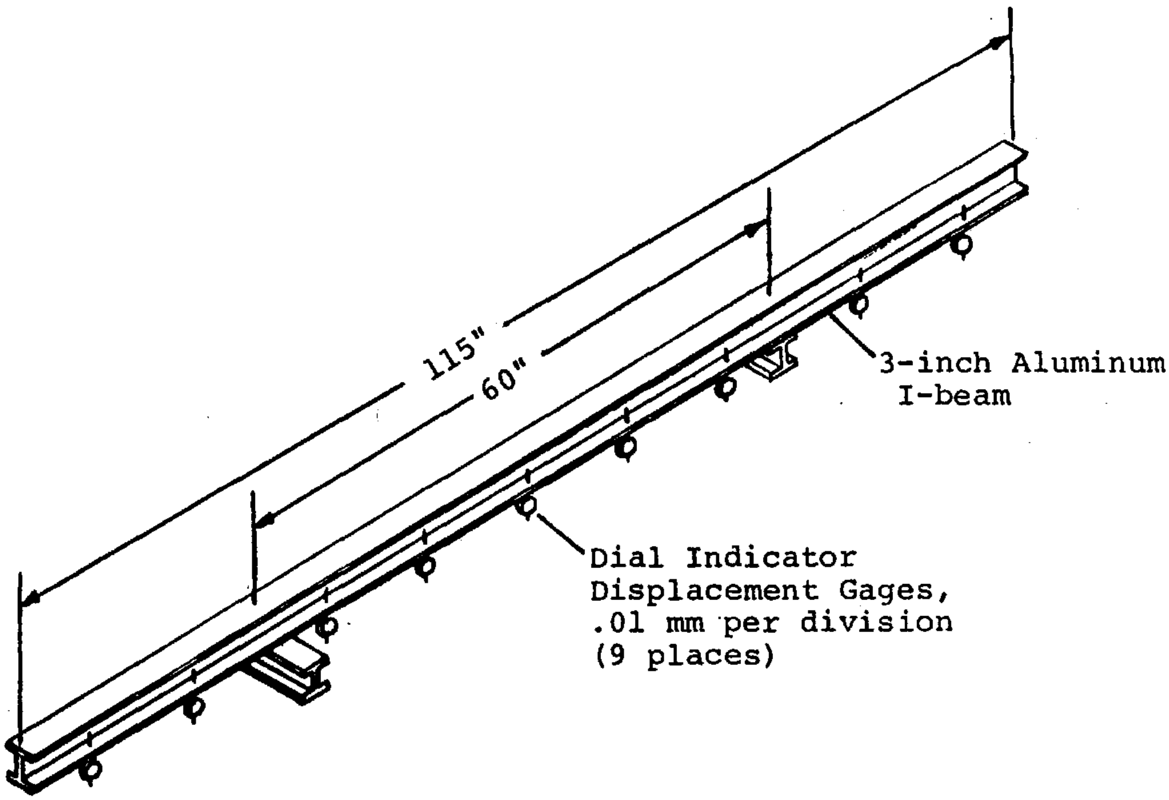



Figure 5. Beam-Dial Indicator Instrument for Measuring Contours

three width-wise positions along the mirror for a total of 27 readings per mirror module, as shown in Figure 6. The displacement gages were initially set to zero with the instrument set on a granite microflat table.

Deflections due to gravity and the initial contour of the mirror module were determined as follows. Assuming that the out-of-plane deflections $w_1$ measured on a horizontal mirror module are comprised of gravity deflections $w_g$ and the initial contour $w_o$, then

$$w_1 = w_o + w_g$$

After the set of deflections called $w_1$ has been read on a mirror module, the surface of the mirror module is loaded with 2-1/2 lb sandbags spread uniformly over the glass which equal in total weight that of the mirror module (a total of forty sandbags). The deflections of the loaded mirror module differ from those of the unloaded module by $w_g$, and if the new deflections read at the same 27 points are called $w_2$, then

$$w_2 = w_1 + w_g = w_o + 2w_g.$$

The gravity sag and the initial contour of the mirror module are determined by the following simple equations:

$$w_g = w_2 - w_1$$

$$w_o = w_1 - w_g$$

The results of these contour measurements are plotted in Figures 7 through 18. The following observations are made from these plots:

- The deviations from a flat surface of the initial contour are significantly greater than the deflections due to gravity.
- The initial mirror contours are almost all convex.
- The initial contour curvatures are in general greater for the 2-in. thick mirror modules than for the 4-in. thick modules.
- The gravity sag is greater for the 2-in. mirror modules than for the 4-in.

Initial convex contours of the magnitude measured in these mirror modules are unacceptable from a heliostat performance standpoint. To compensate for this curvature, the mirror modules must be bonded in a concave curvature to assure that the mirrors are either flat or focused (concave) when the adhesive cures.

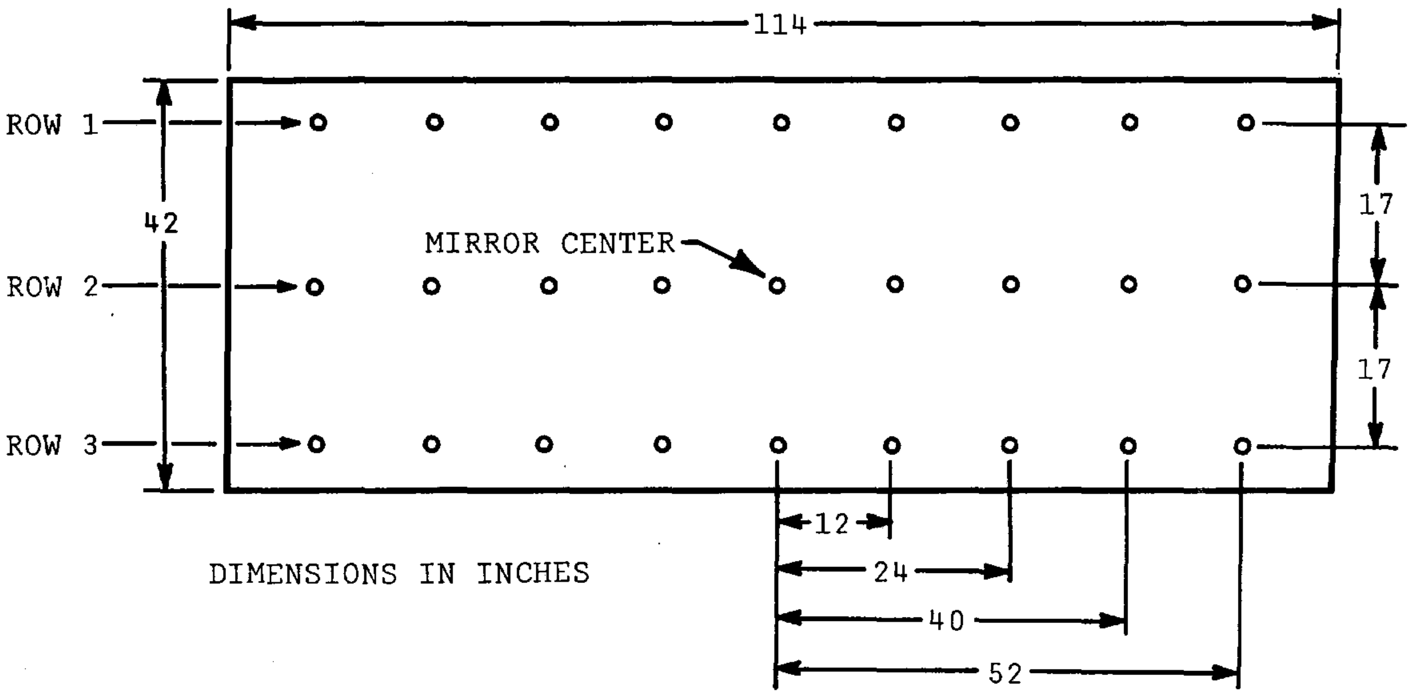



Figure 6. Locations of Mirror Contour Measurements

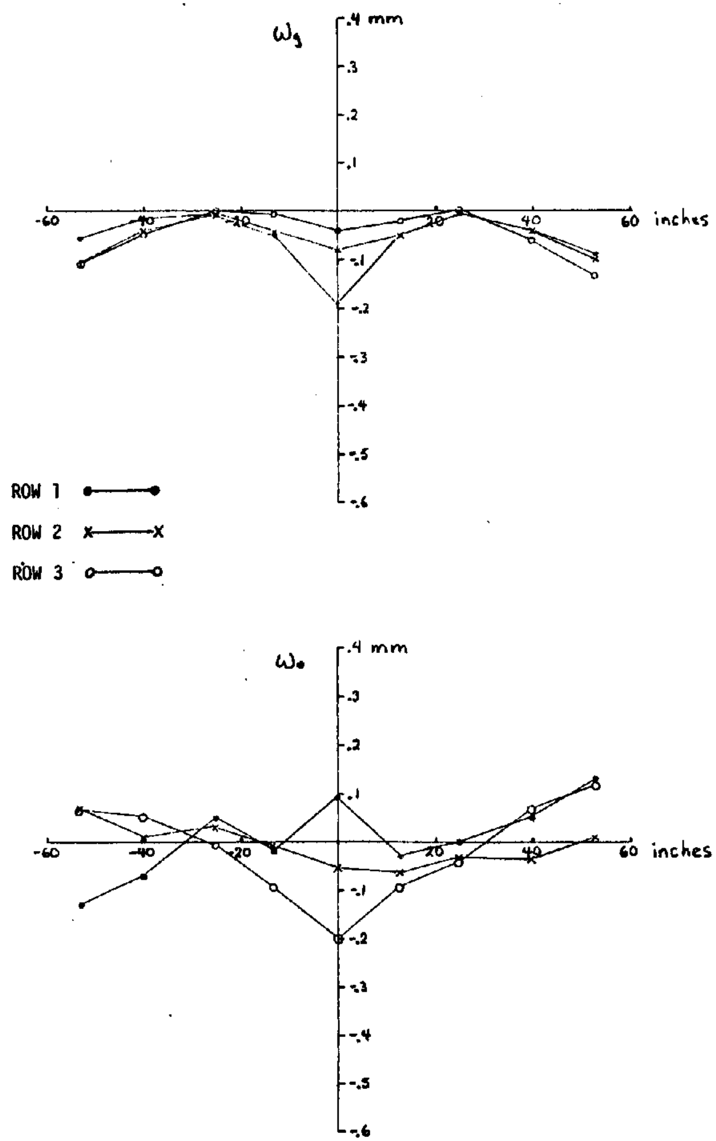



Figure 7. Contour ($w_o$) and Gravity Deflection ($w_g$) of Mirror Module 1

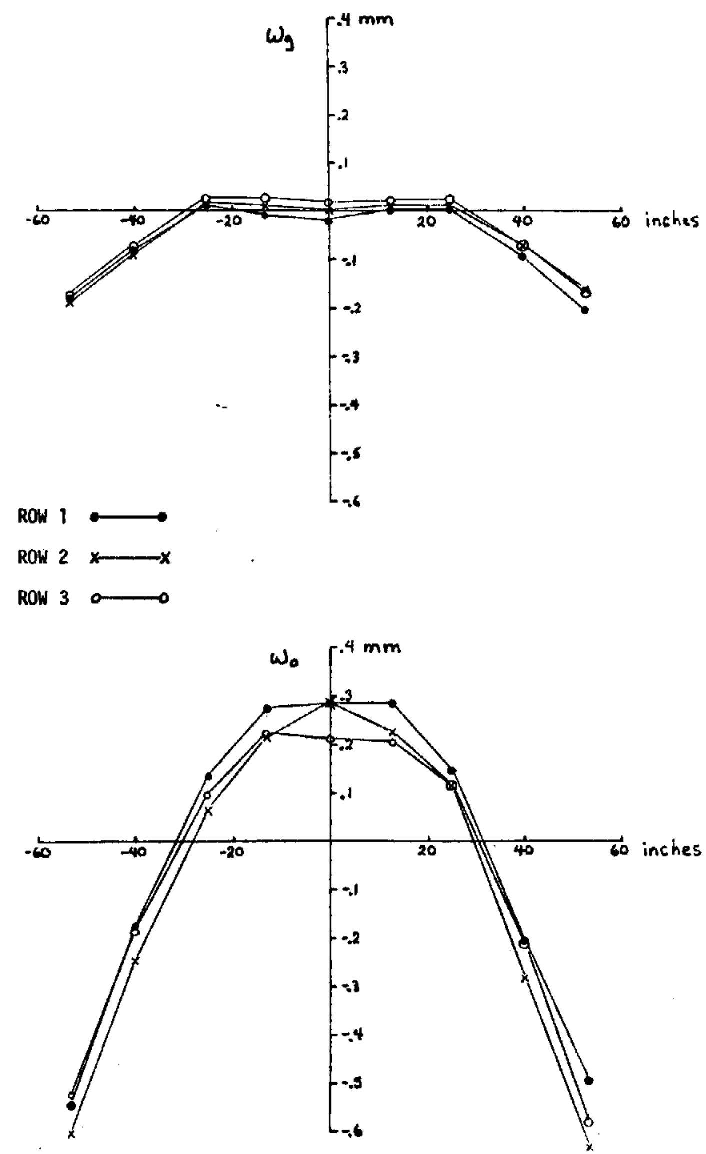



Figure 8. Contour ($w_o$) and Gravity Deflection ($w_g$) of Mirror Module 2

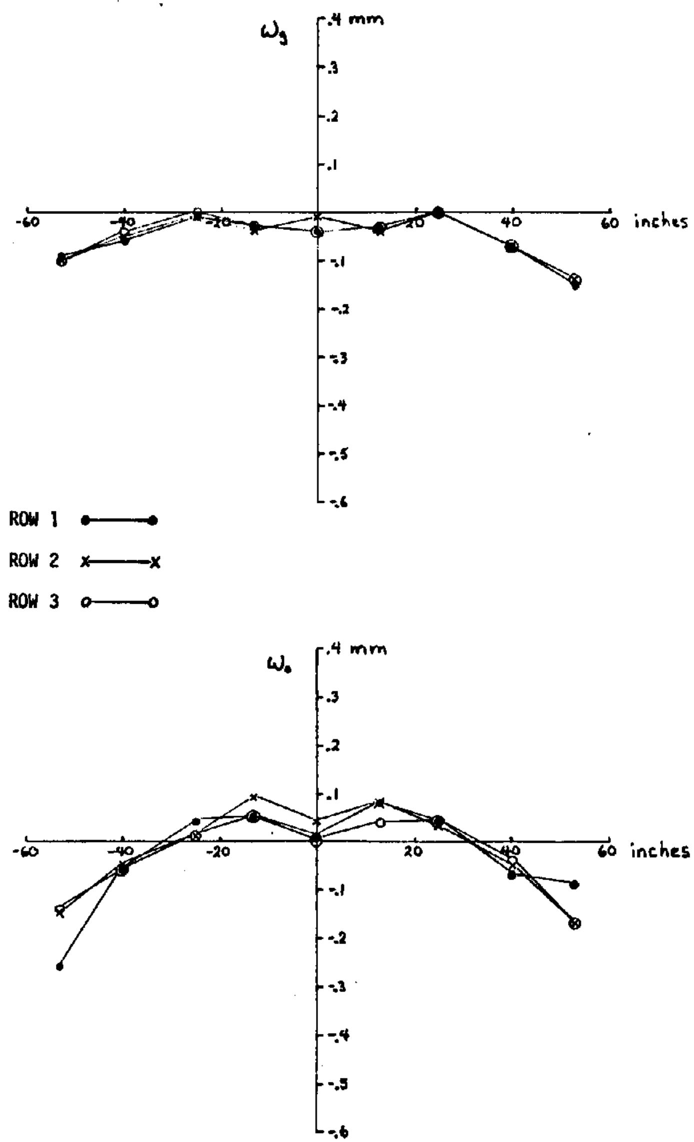



Figure 9. Contour ($w_o$) and Gravity Deflection ($w_g$) of Mirror Module 3

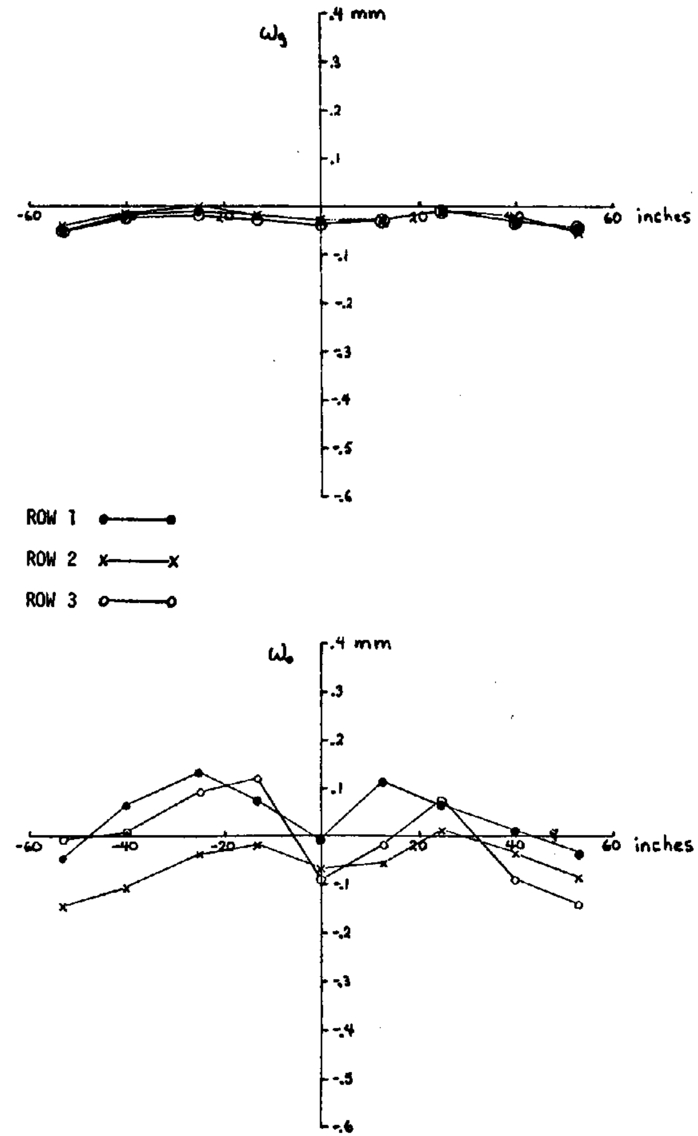



Figure 10. Contour ($w_o$) and Gravity Deflection ($w_g$) of Mirror Module 5

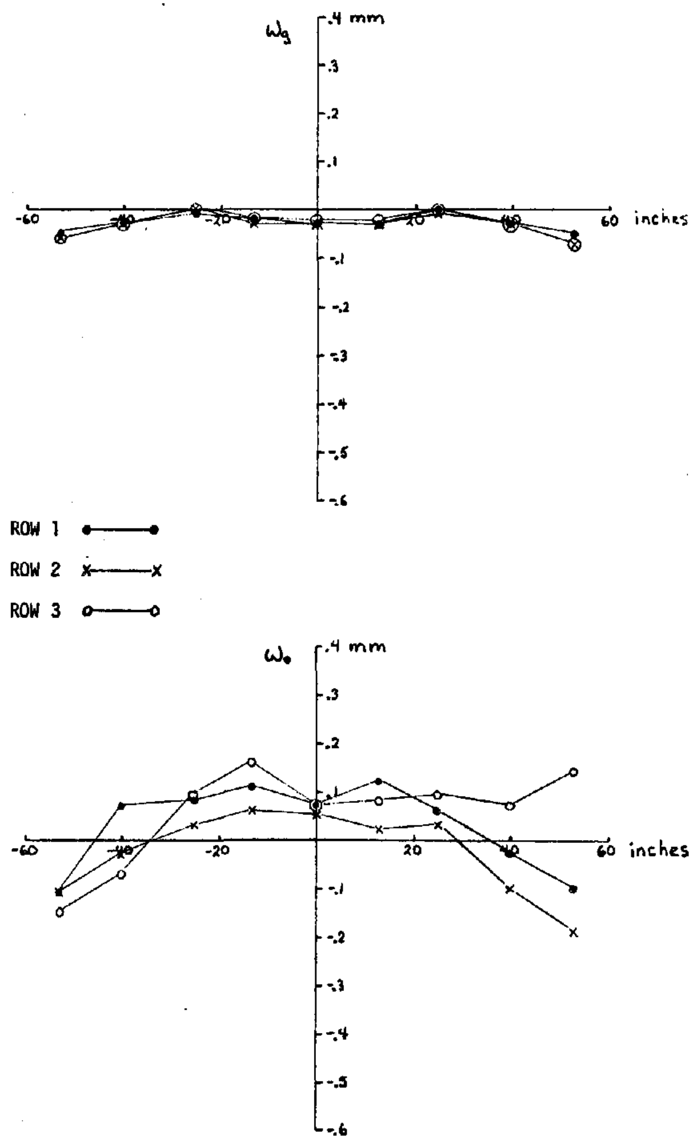



Figure 11. Contour ($w_o$) and Gravity Deflection ($w_g$) of Mirror Module 6

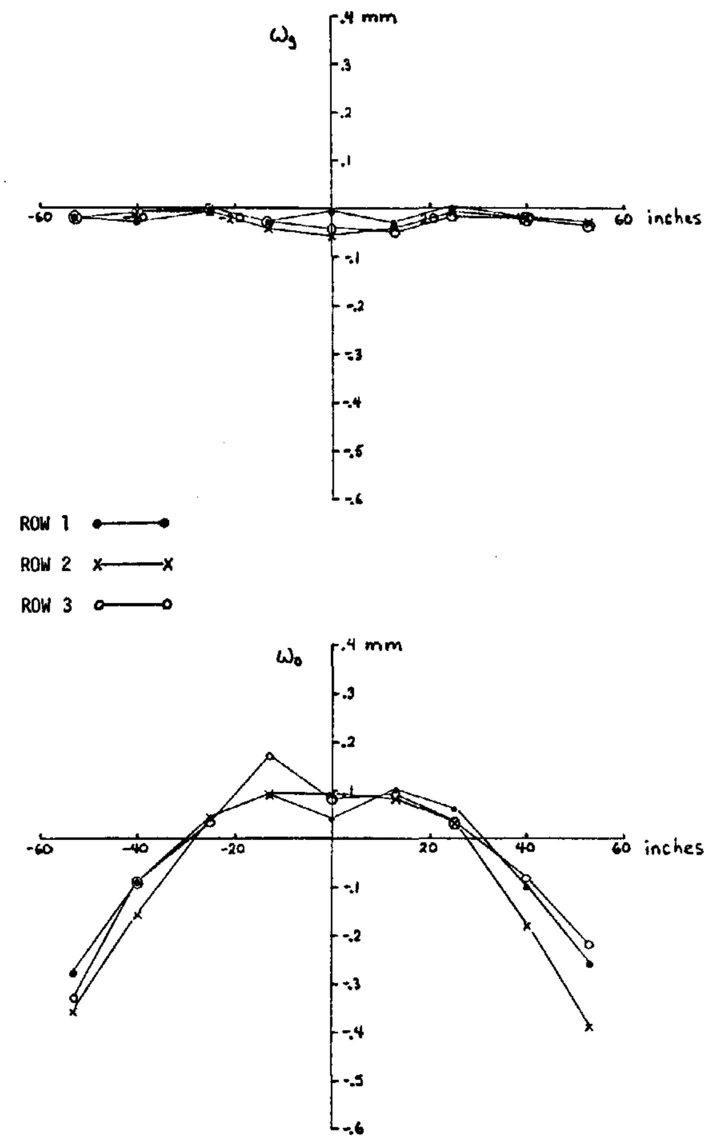



Figure 12. Contour ($w_o$) and Gravity Deflection ($w_g$) of Mirror Module 7

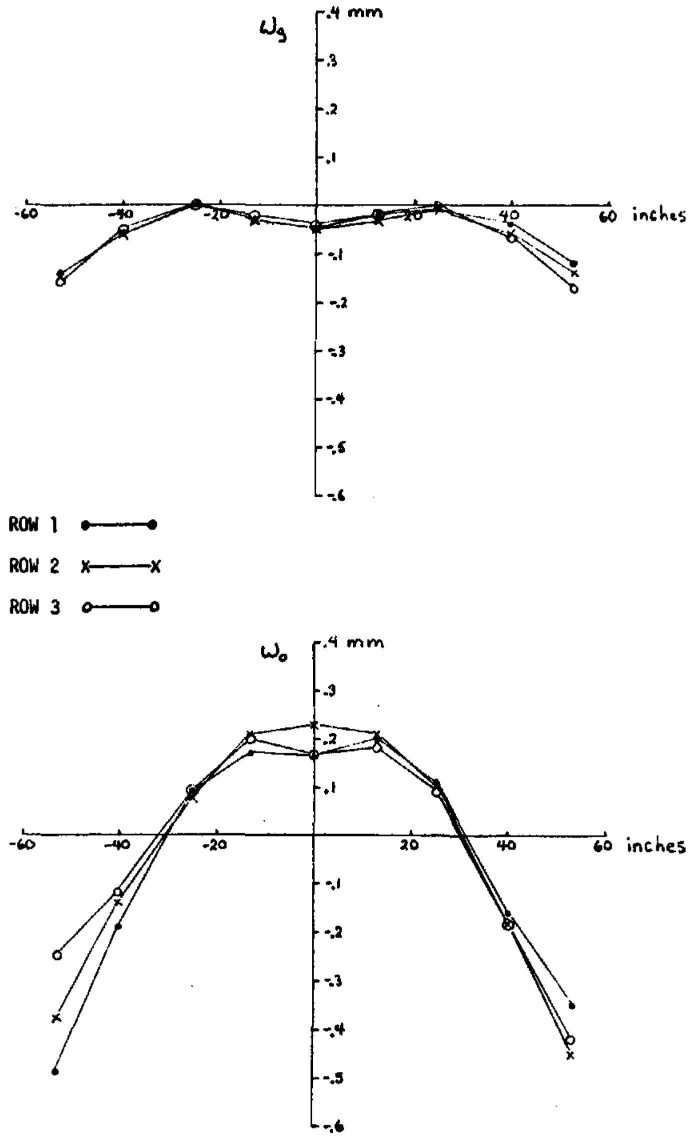



Figure 13. Contour ($w_o$) and Gravity Deflection ($w_g$) of Mirror Module 8

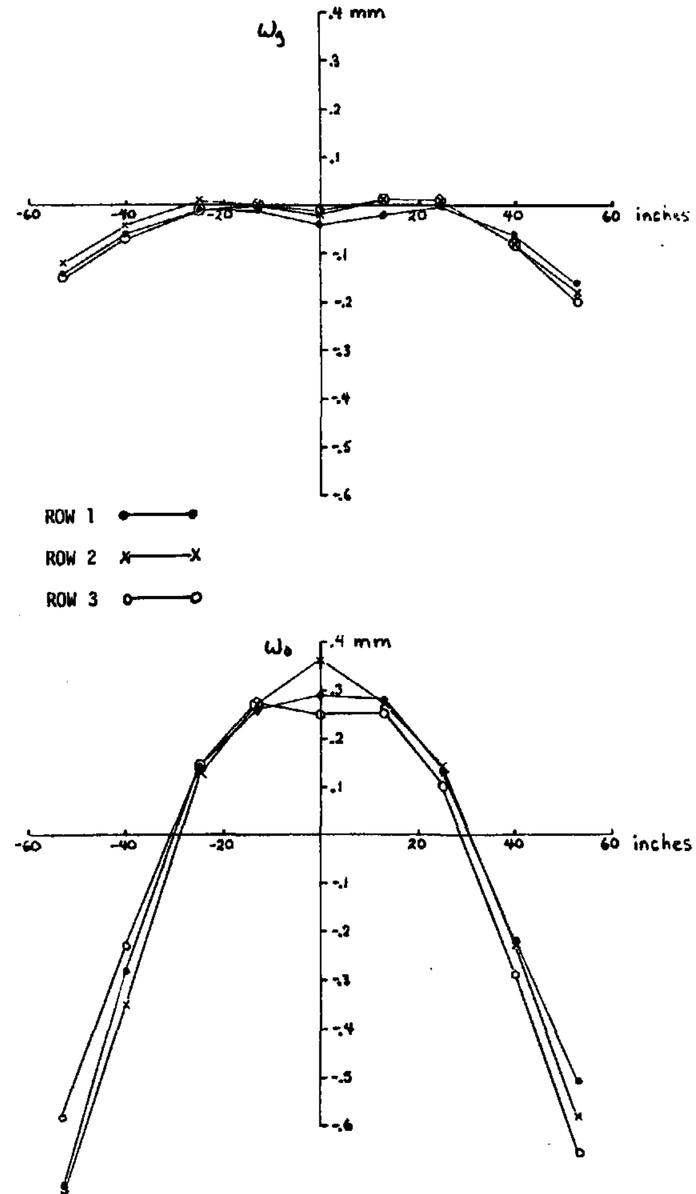



Figure 14. Contour ($w_o$) and Gravity Deflection ($w_g$) of Mirror Module 9

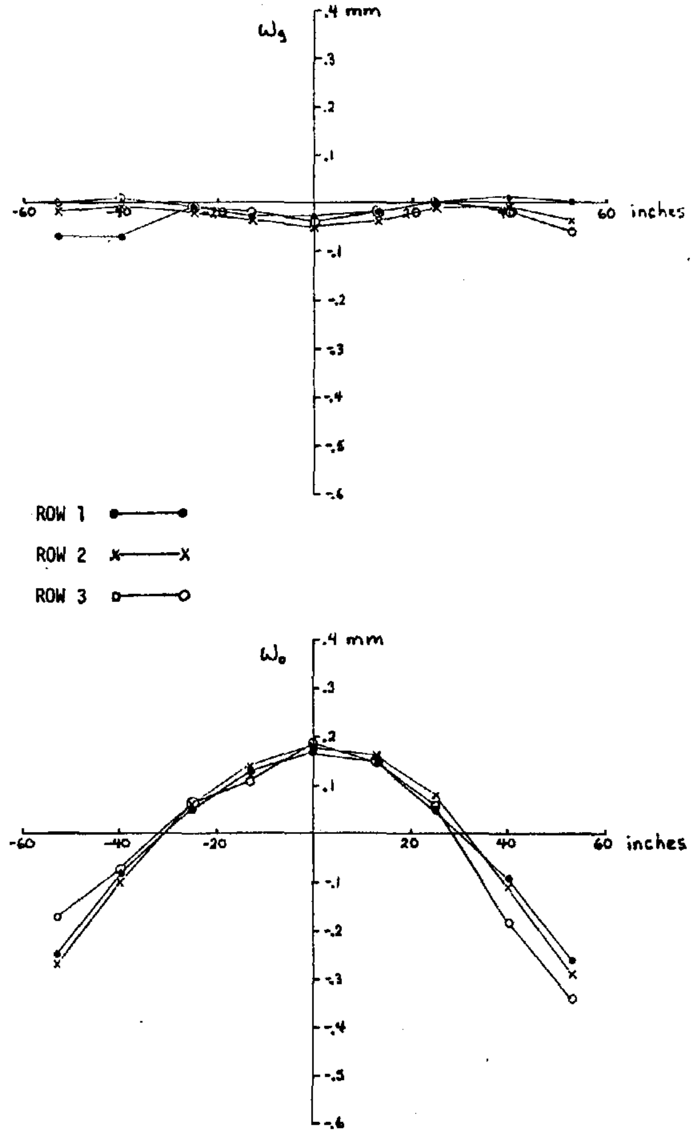



Figure 15. Contour ($w_o$) and Gravity Deflection ($w_g$) of MDAC Mirror Module S/N 021

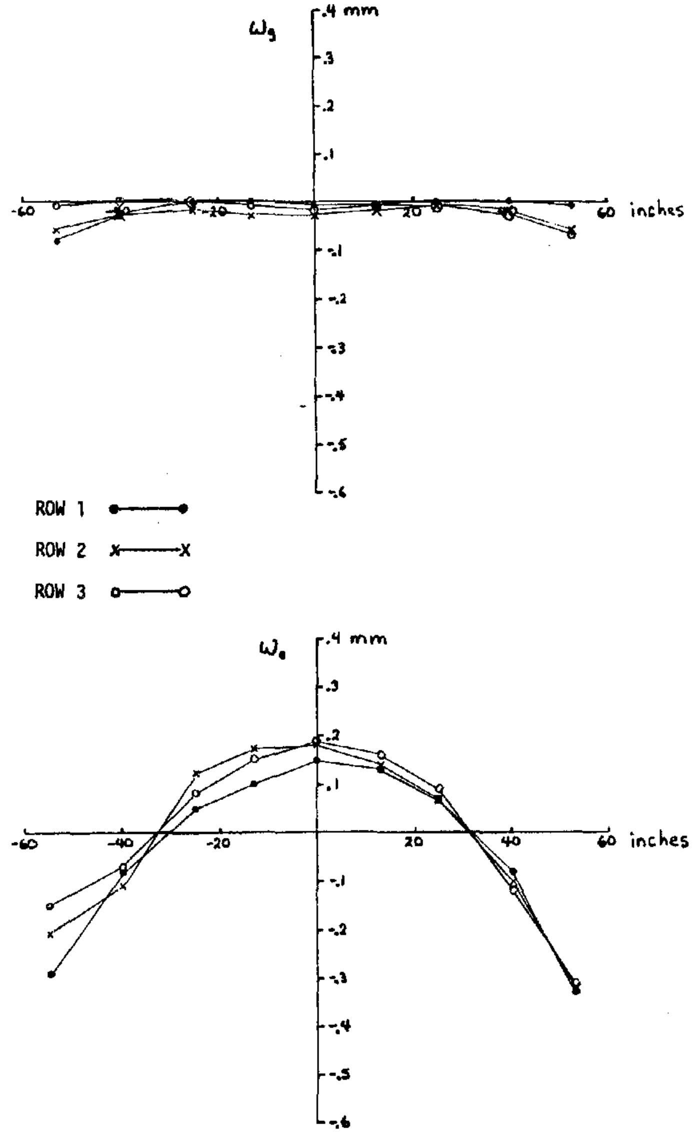



Figure 16. Contour ($w_o$) and Gravity Deflection ($w_g$) of MDAC Mirror Module S/N 018

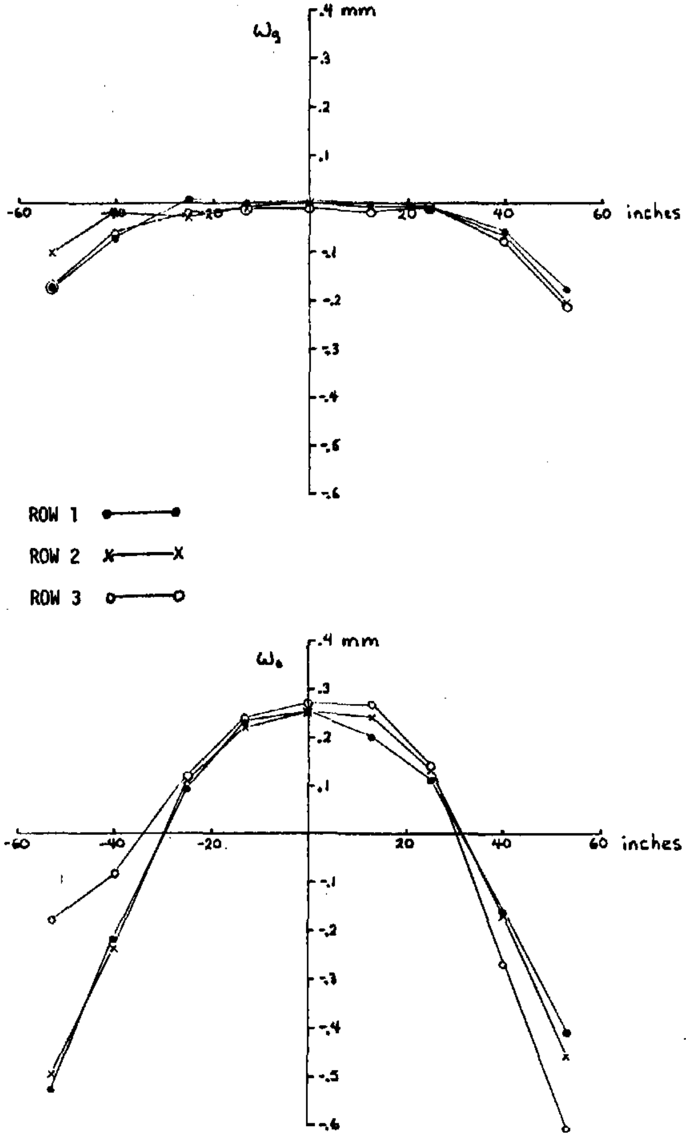



Figure 17. Contour ($w_o$) and Gravity Deflection ($w_g$) of MDAC Mirror Module S/N 03

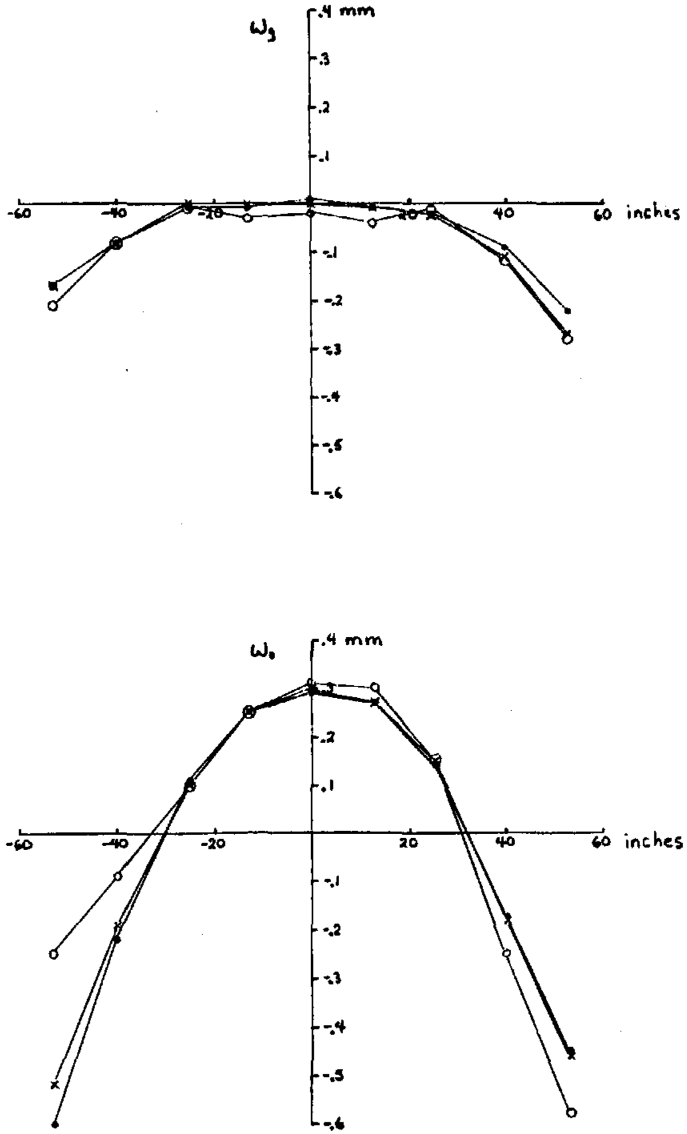



Figure 18. Contour ($w_o$) and Gravity Deflection ($w_g$) of MDAC Mirror Module S/N 07

## Mirror Contour, Wind Load

The change in the mirror contour in a 30 mph wind was measured to evaluate the effect of wind on mirror module performance. Sandbags were distributed over the surface of a 2-in. thick mirror module as prescribed in Figure 19 to simulate a 30 mph wind at a 45° angle of attack. Out-of-plane deflections were measured with the beam-dial indicator instrument shown in Figure 5, and measurements taken on the unloaded mirror module were subtracted from these to determine the change in the contour due to simulated wind loading. The results, plotted in Figure 20, show that the deflections are slightly greater than the gravity deflections. Considering both bending and shear deflections of the sandwich, it can be seen that wind-induced contour changes for a 4-in. thick module should be less than half of those for the 2-in. module. Contour changes due to lower wind speeds scale as the square of the wind speed, and it may be concluded that winds lower than 30 mph will have little effect on mirror module performance. (This does not consider deflections of the supporting structural members of the heliostat which could degrade total heliostat performance.)

## Mirror Contour, Temperature Change

Contour changes in the mirror modules due to temperature change ($\Delta T$) were determined by measuring the out-of-plane deflections at several different temperatures and taking the differences of the recorded readings. To accomplish the temperature change, four mirror modules were placed one at a time in a large environmental chamber. Contours were measured at room temperature, 120°F, and 20°F. Temperatures on and within two of the mirror modules were monitored with thermocouples to determine the time necessary to reach a uniform temperature.

The measured contour changes are plotted in Figures 21 through 24. It is seen that a rise in temperature causes a concave change in curvature resulting in a focused mirror. This is because steel expands more than glass for a given temperature increase. Negative temperature changes result in a convex, defocused mirror. Notice that the contour change of a 2-in. mirror module is about twice that of a 4-in. module for the same $\Delta T$, as is expected.

The temperature-induced radius of curvature R of a sandwich panel with dissimilar skins and a compliant core (i.e., no bending stiffness) may be approximated by the equation

$$R = \frac{t}{(\varepsilon_2 - \varepsilon_1)\ \Delta T}$$

where t is the distance between the midplanes of the skins, $\varepsilon_1$ and $\varepsilon_2$ are the coefficients of linear thermal expansion of the first (glass) and second (steel) skins of the sandwich, and $\Delta T$ is the change from the temperature at which the panel is flat. For small curvatures, the focal length f is half the radius of curvature, and therefore

$$f = \frac{t}{2(\varepsilon_1 - \varepsilon_1)\ \Delta T}$$

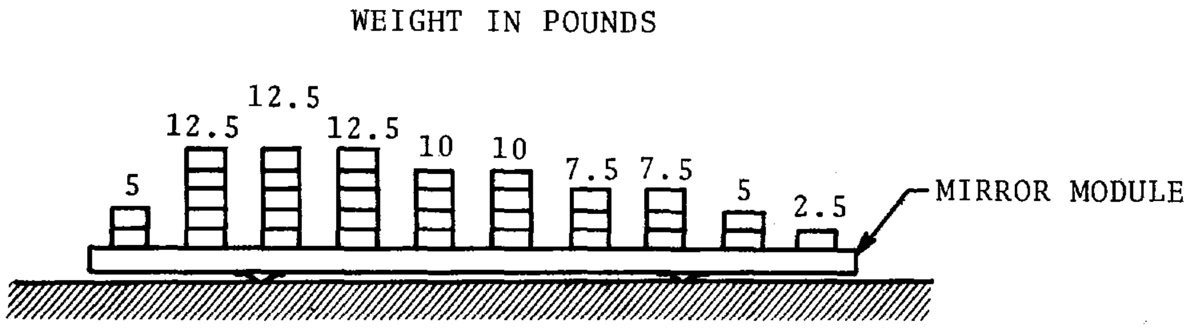



Figure 19. Simulated Loading of 30 mph Wind at 45° Angle of Attack

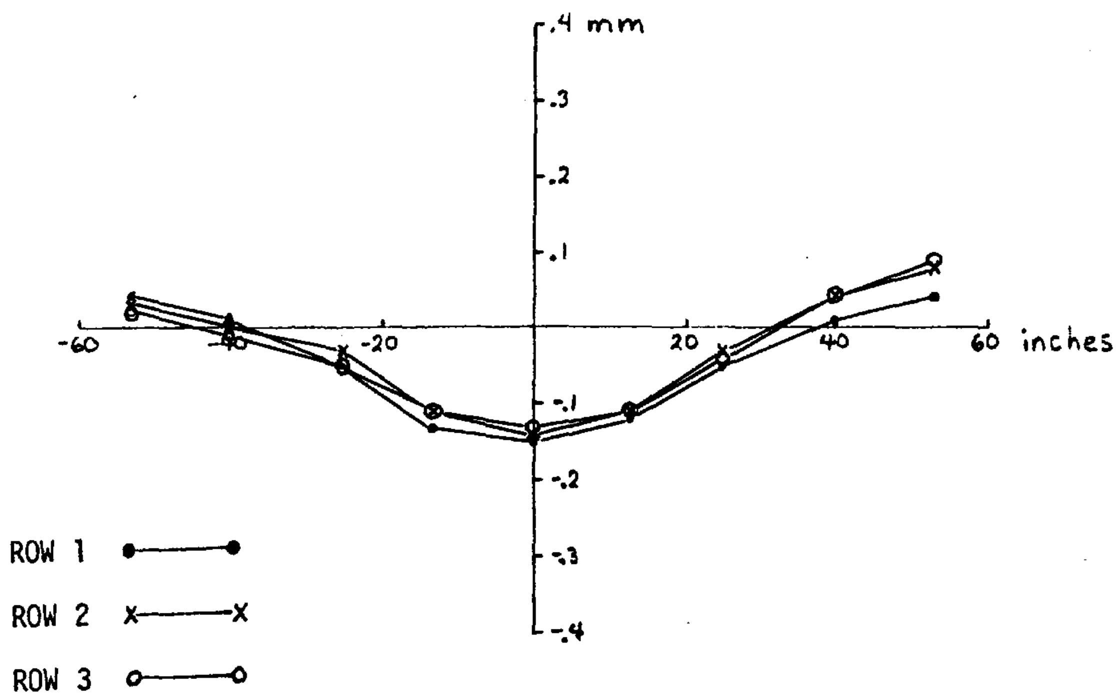



Figure 20. Contour Change of Mirror Module 2 Due to Simulated Loading of 30 mph Wind at 45° Angle of Attack

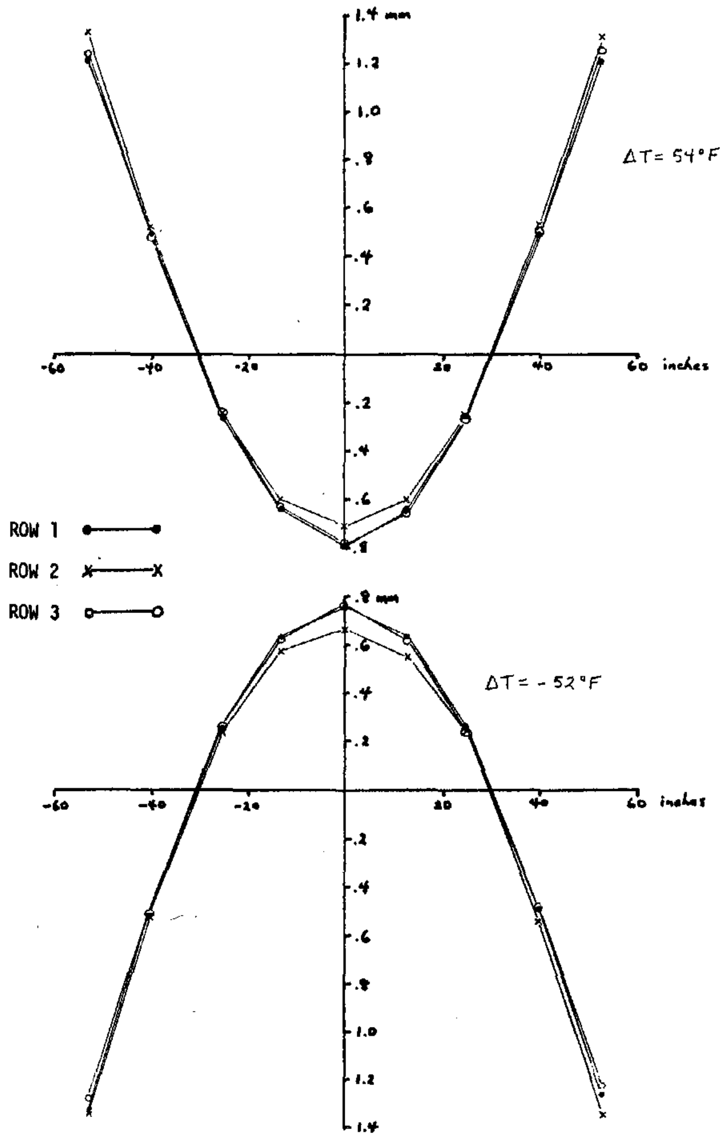



Figure 21. Change in Contour of Mirror Module 3 due to Temperature Change ΔT

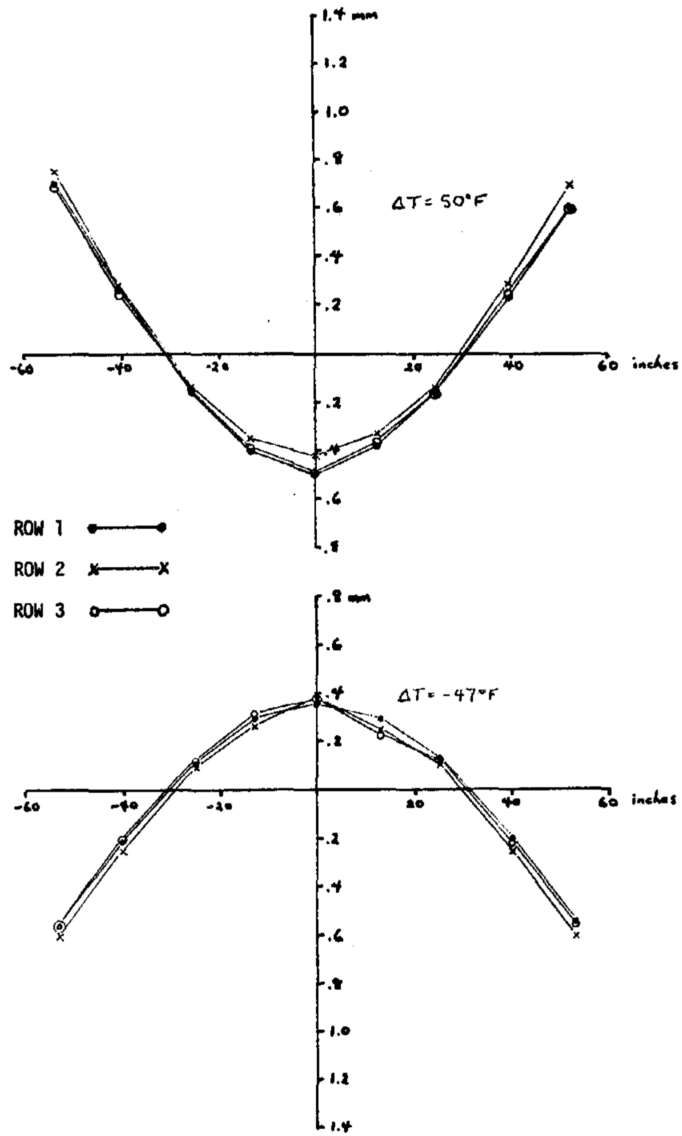



Figure 22. Change in Contour of Mirror Module 5 due to Temperature Change ΔT

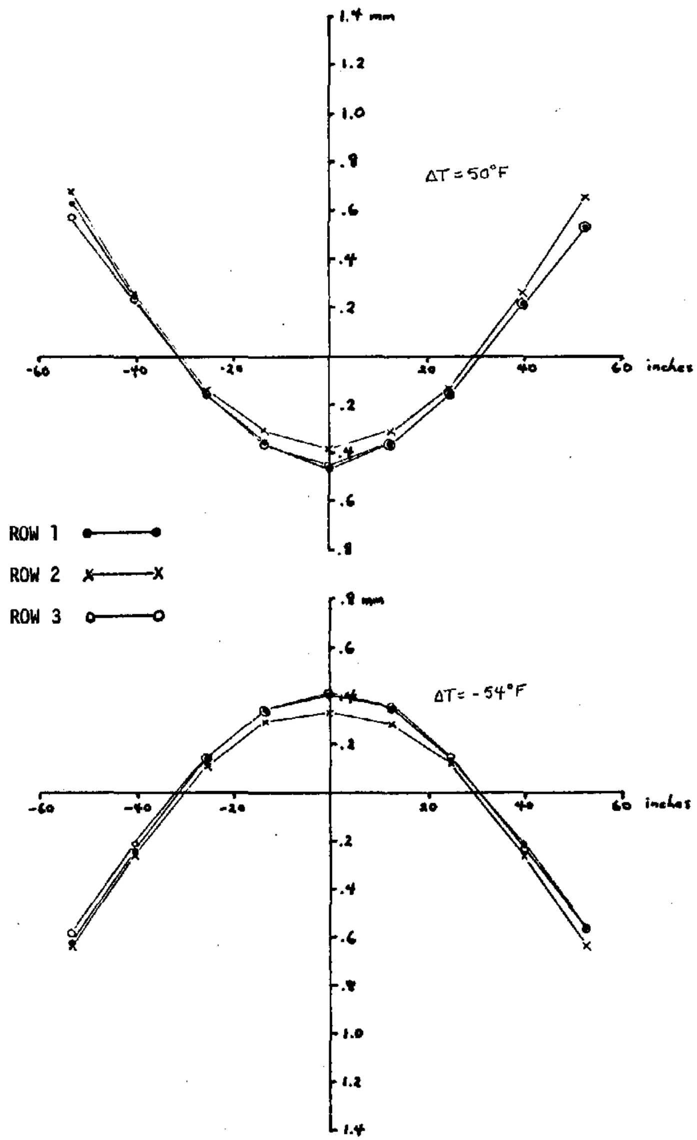



Figure 23. Change in Contour of Mirror Module 7 due to Temperature Change ΔT

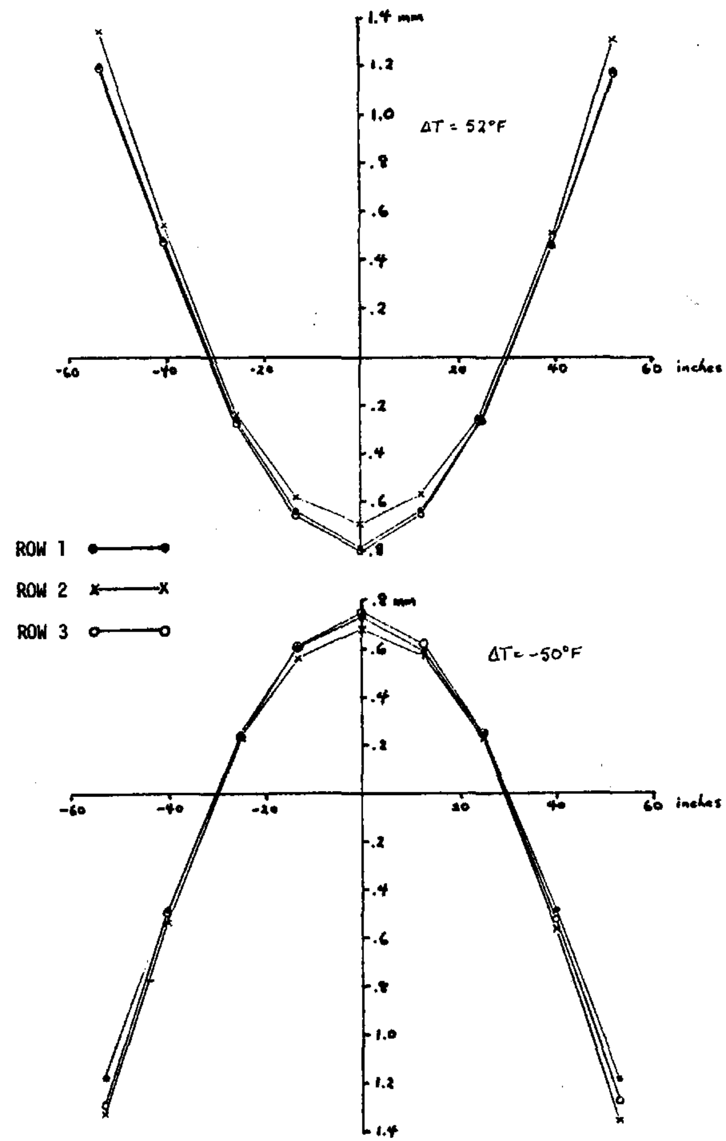



Figure 24. Change in Contour of Mirror Module 8 due to Temperature Change ΔT

For the 2-in. thick mirror modules, t = 2.07 in., and for the 4-in. modules, t = 4.07 in. If it is assumed that

$$\varepsilon(\text{steel}) - \varepsilon(\text{glass}) = 2.25 \times 10^{-6}/°\text{F},$$

then the theoretical focal lengths of the 2-in. and 4-in. thick modules may be shown to be 767 and 1507 ft, respectively, for a $\Delta T$ of 50°F.

Focal lengths and contour shapes have been calculated for one of the 2-in. modules and one of the 4-in. modules and compared with the measured data. These comparisons, plotted in Figures 25 and 26, show that the measured contours agree very well with the calculated shapes.

Thermal Glass Stress

Thermal stresses in the glass were determined by measuring strains with SR-4 resistance strain gages while the mirror modules were subjected to temperature changes in an environmental chamber. The strain gages were nulled at room temperature, and strains were then read when the mirror modules had been heated or cooled uniformly to temperatures of either 120°F or -20°F. Thermocouples mounted on the mirror modules were used to assure that a uniform temperature throughout each mirror module had been reached. The glass-mounted strain gages were temperature compensated with a dummy gage mounted on a small piece of glass, and steel-mounted strain gages were similarly temperature compensated with a gage mounted on a stress-free piece of steel. To minimize errors, strain gages from the same production lot and lead wires of the same length were used. The locations of the eight strain gages and five thermocouples per module are shown in Figure 27. One 2-inch mirror module and one 4-inch module were instrumented and tested.

The strain data which was recorded indicated a considerable amount of hysteresis in the mirror module, most likely due to viscoelastic behavior of the Styrofoam and/or the adhesive layers. This hysteresis became evident when the strain readings did not return to zero for a mirror module which had been temperature cycled and returned to the temperature at which the strain gages had been initially nulled.

Changes in strain readings with temperature change ($T_1$ to $T_2$) are given in Table II for a 2-in. thick mirror module. From these values, equivalent mechanical stresses which would be associated with a uniform temperature rise of 50°F have been calculated and are listed in Table III. It is seen that the highest edge stresses are in the middle of the short edge and are all less than 300 psi, with an average value of 254 psi.

Similar measurements were made for a 4-in. mirror module, and the measured strains and stresses calculated for a $\Delta T$ of 50°F are shown in Tables IV and V. It is seen that the stresses in the glass of a 4-in. module are higher than for the 2-in. module. The highest edge stresses in the mirror are again found to be on the short edge, with an average value of 506 psi.

These calculated stresses indicate that the thermal stress levels in the 2-in. mirror modules are sufficiently low, but that the thermal stresses

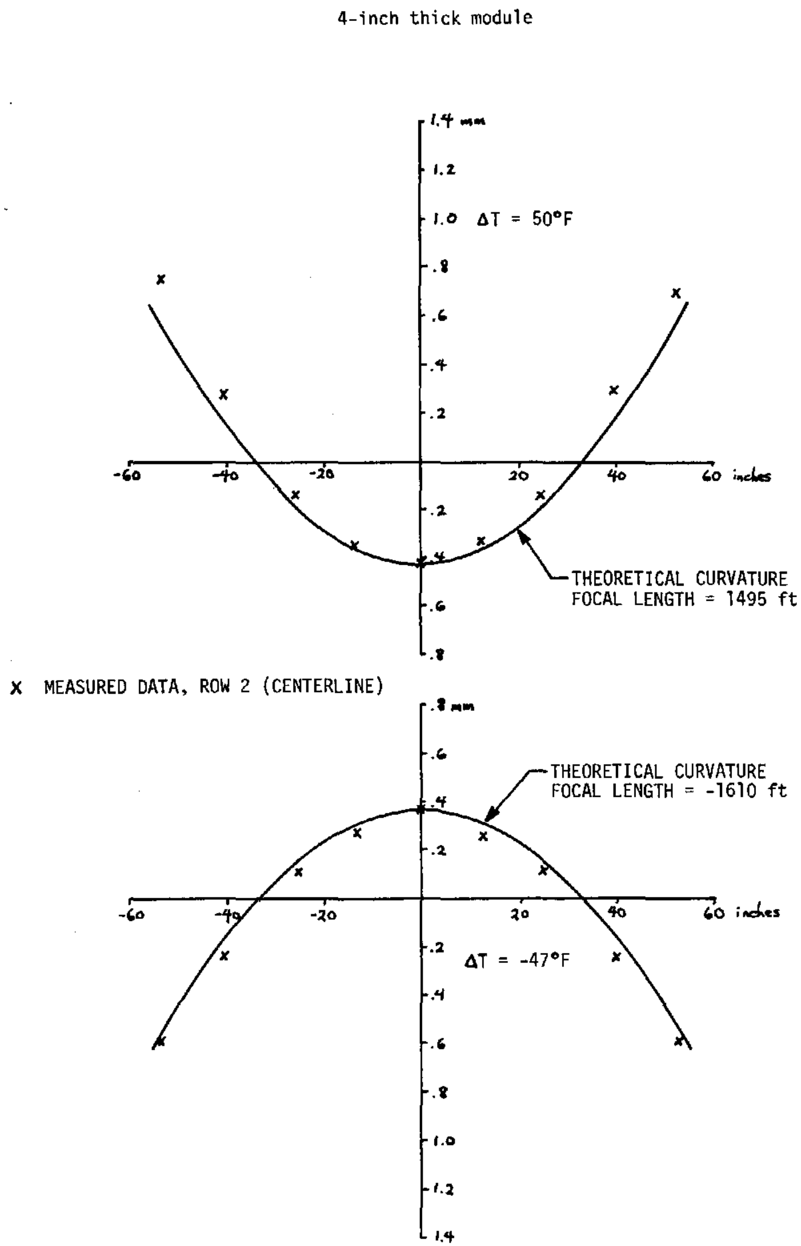



Figure 25. Change in Contour of Mirror Module 5 due to Temperature Change ΔT Compared with Theoretical Contour

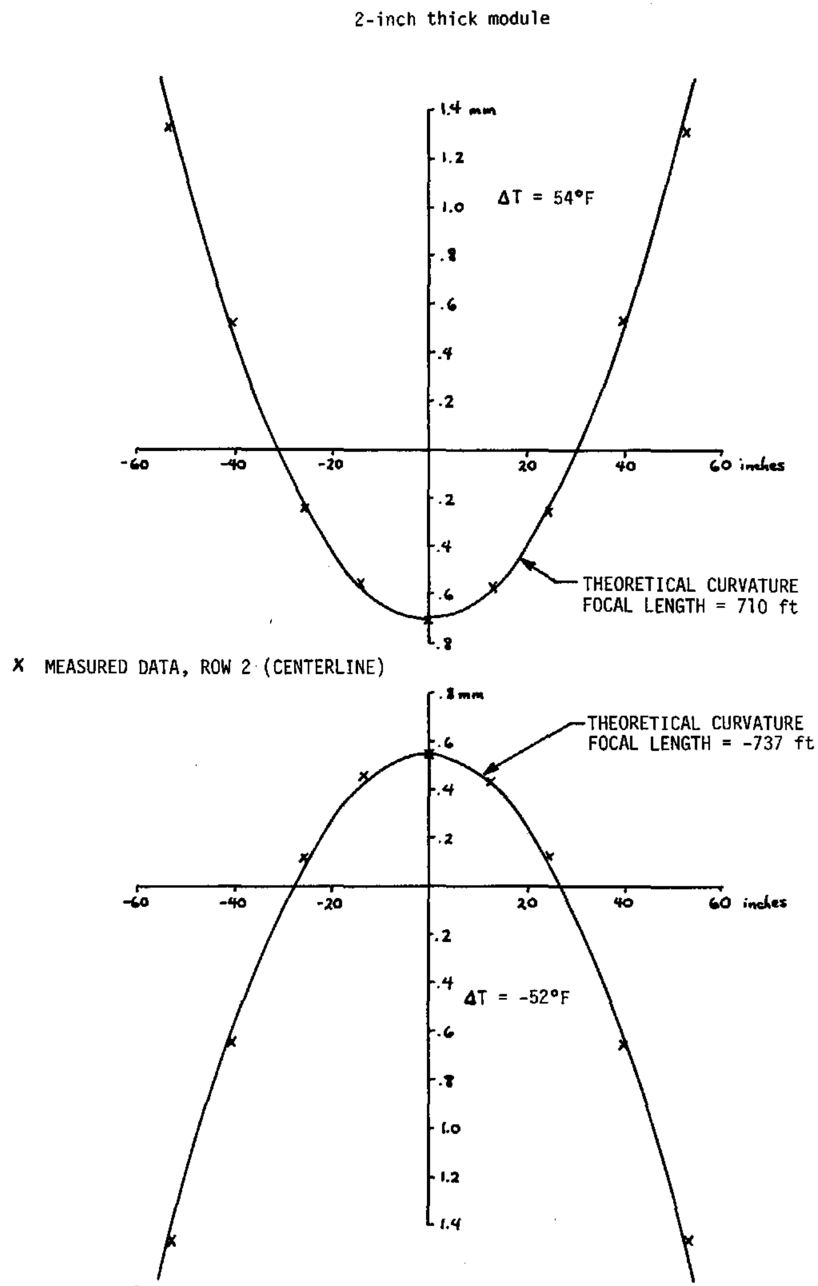
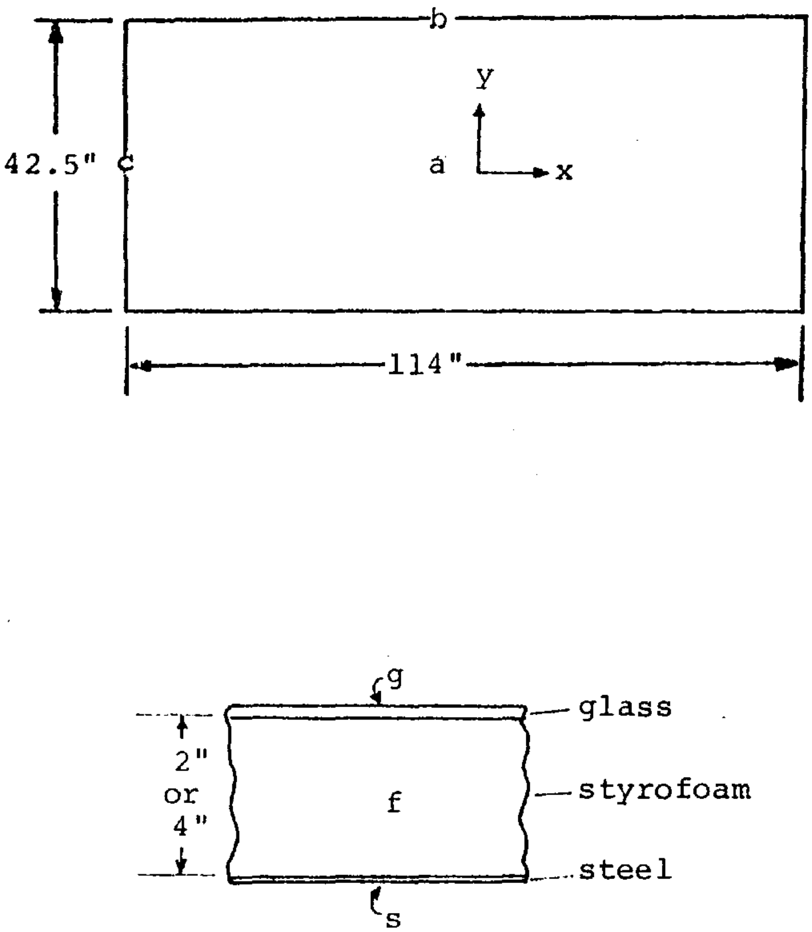



Figure 26. Change in Contour of Mirror Module 3 due to Temperature Change ΔT Compared with Theoretical Contour




Strain Gages (8)

| Location | Direction |
|---|---|
| a – g | x,y |
| a – s | x,y |
| b – g | x |
| b – s | x |
| c – g | y |
| c – s | y |

Thermocouples (5)

| Location | |
|---|---|
| a – g | |
| a – s | |
| b – g | |
| b – g | (1" from edge) |
| b – f | (6" from edge, w/heat sink) |

Strain gages are CEA-06-125 UW-350, GF. = 2.105 ± 0.5%, M-Bond 200 adhesive, with 12' leads.

Thermocouples are .005-inch chromel-alumel.

Figure 27. Locations of Thermocouples and Strain Gages

| Case | $T_1$ (°C) | $T_2$ (°C) | $\Delta T$ (°C) | Change in Strain ($10^{-6}$ in/in) Center of short edge $\Delta\varepsilon_y$ | Center of long edge $\Delta\varepsilon_x$ | Center of mirror $\Delta\varepsilon_y$ | Center of mirror $\Delta\varepsilon_x$ |
|---|---|---|---|---|---|---|---|
| 1 | 20 | 47 | 27 | 23 | 12 | -2 | 17 |
| 2 | 47 | 19 | -28 | -27 | -6 | -2 | -25 |
| 3 | 18 | 46 | 28 | 23 | 6 | -7 | 14 |
| 4 | 46 | -31 | -77 | -67 | -19 | 21 | -56 |
| 5 | -31 | 19 | 50 | 53 | 25 | -4 | 50 |

Table II. Changes in Strain $\Delta\varepsilon$ for Changes in Temperature $\Delta T$ Measured on Glass of Mirror Module 3.

| Case | Stress (psi) Center of short edge $\sigma_y$ | Center of long edge $\sigma_x$ | Center of mirror $\sigma_y$ | Center of mirror $\sigma_x$ |
|---|---|---|---|---|
| 1 | 237 | 123 | 186 | 35 |
| 2 | 268 | 59 | 279 | 103 |
| 3 | 228 | 59 | 130 | -31 |
| 4 | 242 | 69 | 197 | -17 |
| 5 | 294 | 139 | 298 | 67 |
| Average | 254 | 90 | 218 | 31 |

Table III. Equivalent Stress Changes for $\Delta T$ = 50°F Calculated from Strains in Table II for Mirror Module 3

Notes: x-direction parallel to long edge
y-direction parallel to short edge
Young's modulus = 10 x $10^6$ psi and Poisson's ratio = 0.3 assumed

| Case | $T_1$ (°C) | $T_2$ (°C) | $\Delta T$ (°C) | Change in Strain ($10^{-6}$ in/in) Center of short edge $\Delta\varepsilon_y$ | Center of long edge $\Delta\varepsilon_x$ | Center of mirror $\Delta\varepsilon_y$ | Center of mirror $\Delta\varepsilon_x$ |
|---|---|---|---|---|---|---|---|
| 1 | 18 | 46 | 28 | 50 | -2 | 16 | 42 |
| 2 | 47 | 19 | -27 | -54 | -1 | -20 | -47 |
| 3 | 20 | 50 | 30 | 49 | 33 | 51 | 63 |
| 4 | 50 | 20 | -30 | -56 | -38 | -58 | -58 |

Table IV. Changes in Strain $\Delta\varepsilon$ for Changes in Temperature $\Delta T$ Measured on Glass of Mirror Module 5.

| Case | Stress (psi) Center of short edge $\sigma_y$ | Center of long edge $\sigma_x$ | Center of mirror $\sigma_y$ | Center of mirror $\sigma_x$ |
|---|---|---|---|---|
| 1 | 496 | -20 | 510 | 312 |
| 2 | 556 | 10 | 599 | 386 |
| 3 | 454 | 306 | 797 | 711 |
| 4 | 519 | 352 | 869 | 798 |
| Average | 506 | 162 | 694 | 552 |

Table V. Equivalent Stress Changes for $\Delta T$ = 50°F Calculated from Strains in Table IV for Mirror Module 5

Notes: x-direction parallel to long edge
y-direction parallel to short edge
Young's modulus = $10 \times 10^6$ psi and Poisson's ratio = 0.3 assumed

in the 4-in. thick modules probably exceed the design goal of 500 psi for the thermal edge stress in the glass for $\Delta T = 50°F$.

## Thaw-Freeze Cycle

Three Sandia-built mirror modules and one MDAC module were temperature cycled for an excess of 200 cycles to determine whether thermal cycling resulted in damage to or contour changes in the mirror modules. The time-temperature profile of each cycle, shown in Figure 28, was chosen to provide sufficiently slow heating and cooling rates to avoid excessive thermal gradients within the modules and also to provide enough time for complete temperature saturation of the modules at the temperature extremes. The contour of each mirror was measured before and after cycling to detect any permanent contour changes. Also, visual inspections for physical damage were made following the test. The modules were stored vertically on the long edge during and after the test to eliminate any effects of gravity loading normal to the plane of the mirror. Humidity was not controlled or measured during the test.

Significant changes in the mirror module contours as a result of thermal cycling were observed. Figures 29 through 32 show the $w_0$ contours of the modules before and after cycling. The MDAC module (Figure 32) initially had the greatest curvature and underwent the greatest curvature change, flattening the module considerably. In addition, this module suffered some degree of twist, which can be inferred from the figure by noting the relative positions of the symbols denoting the three rows of measurements. The flattening effect was also observed in one Sandia 4-in. module (#7, Figure 31) and one 2-in. module (#3, Figure 29), but is not clearly discernable in the other 4-in. module (#5, Figure 30). However, mirror module 5 was fairly flat to begin with. It appears that Sandia module #7 was the only module not to have sustained a contour twist as did Sandia modules 3 and 5, and as previously mentioned, the MDAC module.

A second thermal cycling test was performed recently to determine whether adhesive cure time has an effect on mirror module creep. Sandia mirror modules 3 and 10, and MDAC modules S/N 07 and S/N 021 were temperature cycled 84 times. Modules 10 and S/N 021 showed no contour change. Module 3 started out essentially flat and ended with a slight convex curvature. Module S/N 07 started with a slight convex curvature which became more pronounced with thermal cycling. These changes in curvature are opposite of those observed in the original test. All of these mirrors were well aged--at least six months. Module 10, which had no curvature change, had been subjected to an elevated-temperature cure immediately after fabrication; this suggests the possible necessity of an elevated-temperature cure for the production mirror modules. Ambient temperatures were carefully noted at the time of each contour measurement to preclude curvature differences due to temperature. This problem of contour change with thermal cycling needs further study to understand the phenomenon and its significance under the expected temperature excursions of a desert environment.

There was no damage to the mirror facets of any of the four modules. In fact the only damage observed was that the edge sealant in two of the Sandia

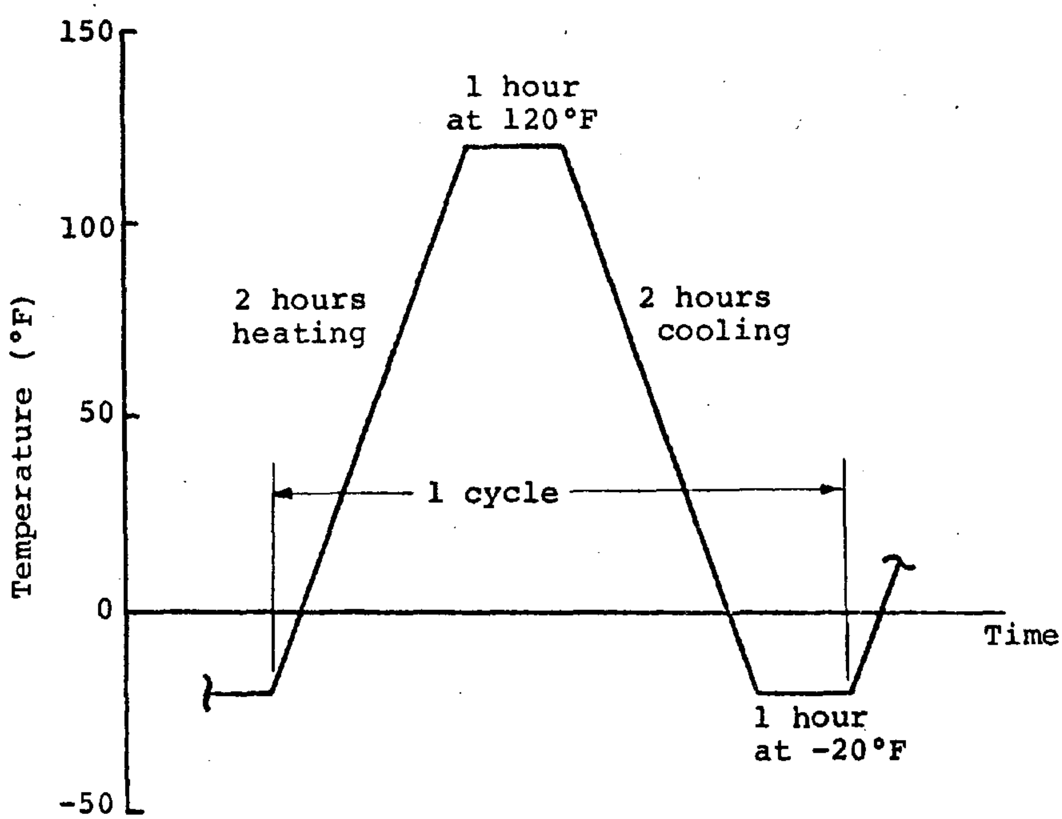



Figure 28. Thaw-Freeze Temperature Cycle

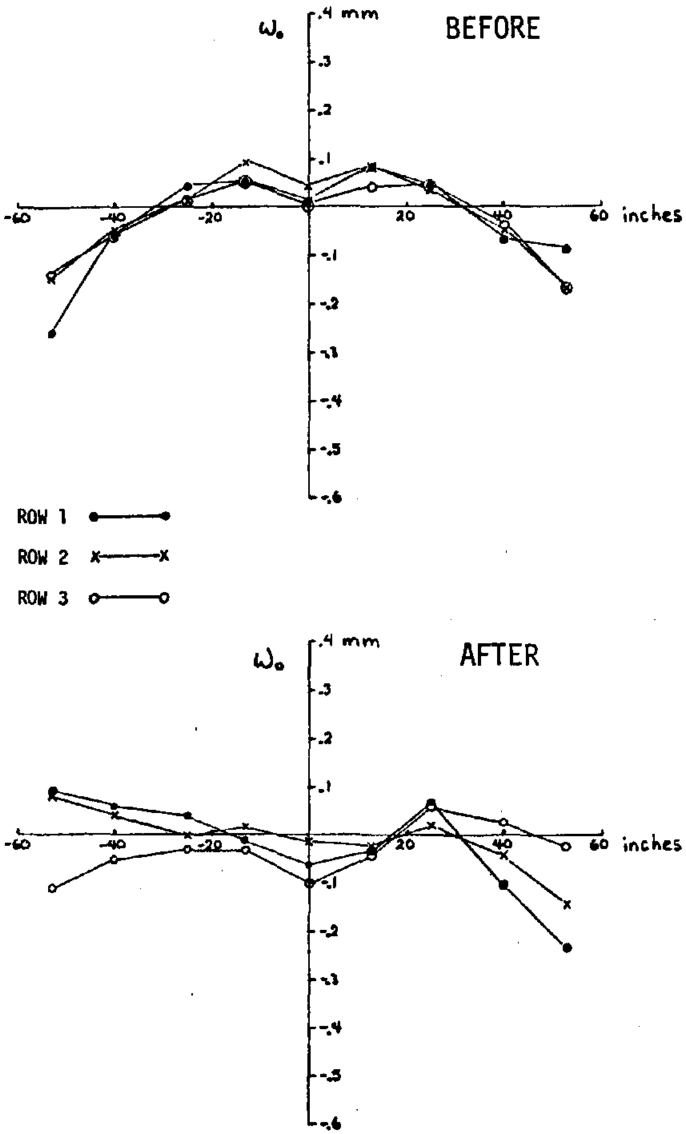



Figure 29. Contour ($w_o$) of Mirror Module 3 Before and After 236 Temperature Cycles

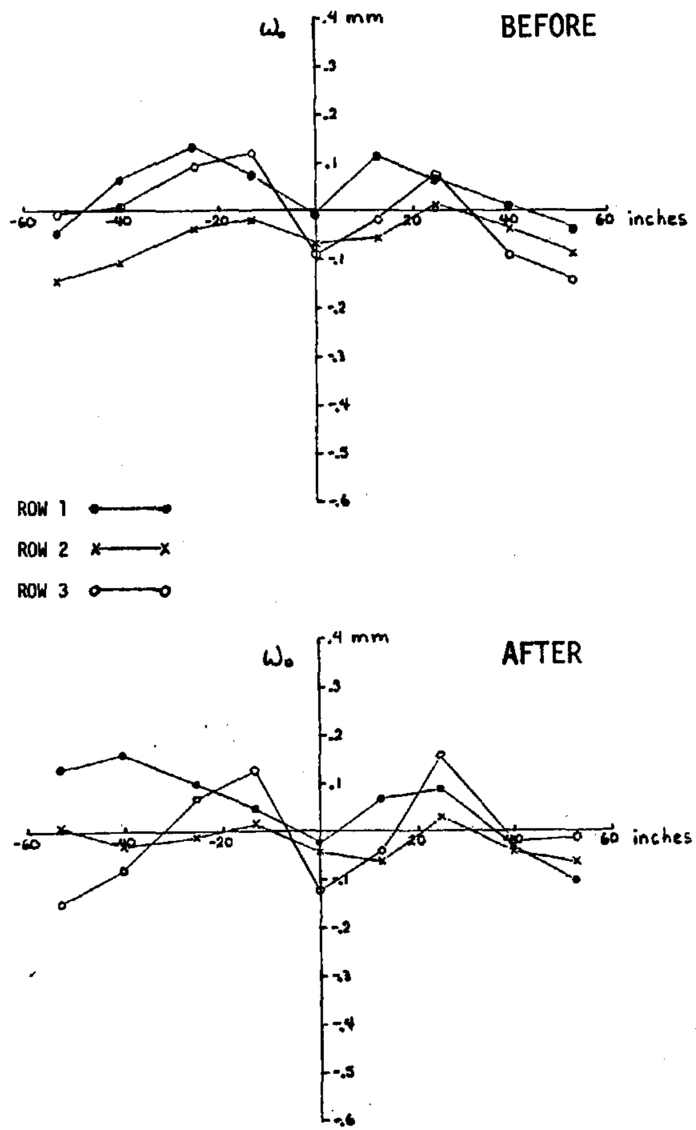



Figure 30. Contour ($w_o$) of Mirror Module 5 Before and After 236 Temperature Cycles

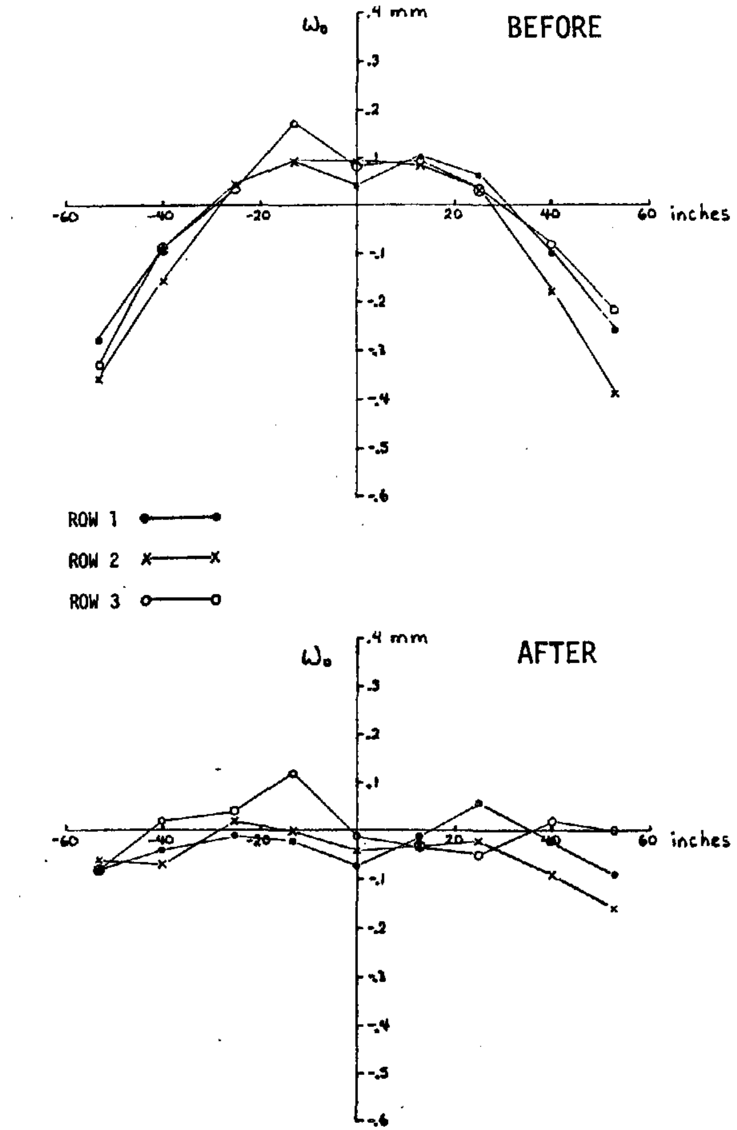



Figure 31. Contour $(w_o)$ of Mirror Module 7 Before and After 236 Temperature Cycles

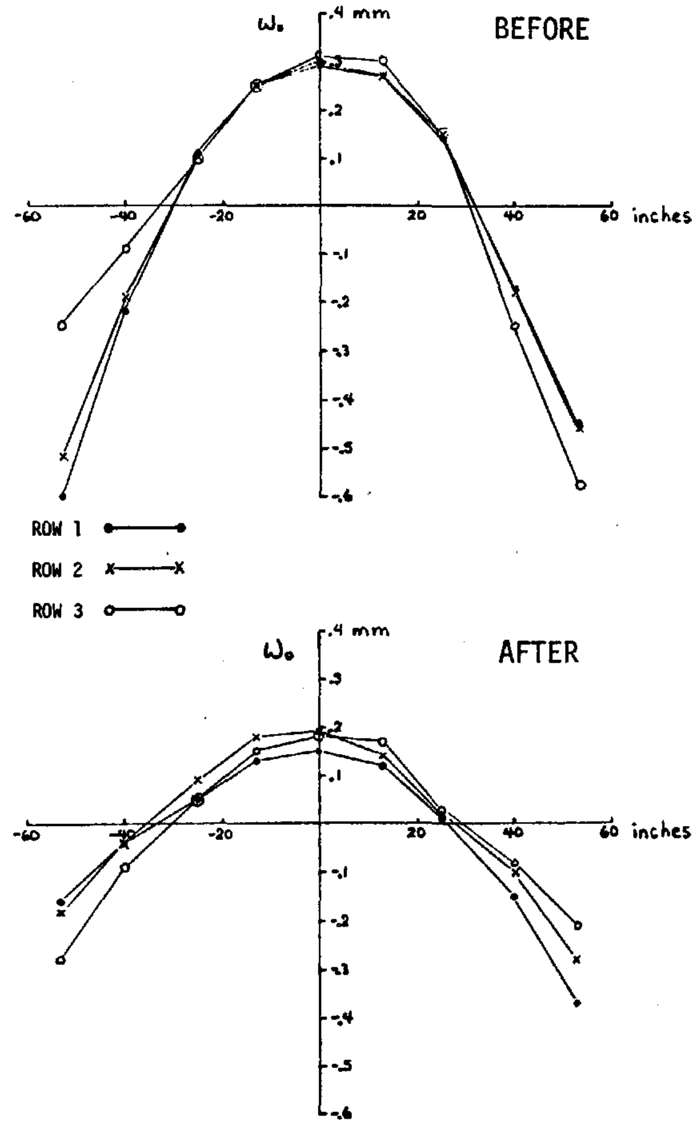



Figure 32. Contour $(w_o)$ of MDAC Mirror Module S/N 07 Before and After 208 Temperature Cycles

mirror modules suffered some minor damage where the overlapping metal lip of the edge cap pulled away from the mirror face of one module and the back face of another. Both of these gaps occurred at the downward facing long edge and it is possible that water which condensed on the mirror module dripped into a region where the edge cap was not completely sealed and subsequently expanded after successive thaw-freeze cycles. No damage was observed in the MDAC module which had no overlapping lips on the edge caps (see Figure 2).

## Adhesive Creep and Cure

The contours of two 2-in. mirror modules (9 and 10) were measured every two weeks for several months after fabrication to determine whether creep occurs in the adhesive of newly made modules. This test was performed because of the characteristic tendency of polyurethane adhesives to undergo stress relaxation (creep) over a period of time and because of the time required for the adhesive to cure completely at room temperature (four months).

Mirror module #9 was fabricated and then stored vertically on edge for two weeks. After this time, it was placed face up horizontally on a table where it was left for the remainder of the test. The mirror contour ($w_1$) was measured initially and at several times over the following six months. The results shown in Figure 33 indicate that little or no creep occurred.

Mirror module #10 was tested in the same manner as #9 except that after fabrication it was placed on edge in an environmental chamber and subjected to an elevated temperature cure at 135°F for two weeks. This curing cycle should have been equivalent to four months at room temperature and should have resulted in a complete cure of the adhesive. After that, this mirror module was placed face up on a table and its contour was measured initially and several times over the following four months. The results are shown in Figure 34. It appears that between the first and second measurements a small amount of contour flattening occurred. The second and third contour measurements taken two months apart are essentially identical.

It can be concluded from this test that the creep which occurs in the mirror modules under gravity loading at room temperature is insignificant. It was also shown that an elevated temperature cure of the mirror modules has no effect on room-temperature creep.

## Hailstone Survival

Mirror module #4 was impacted with simulated hailstones (ice balls) to determine whether damage is inflicted by 3/4-in. hail impacting the glass at 65 ft/sec or by 1-in. hail impacting the back side of the module at 75 ft/sec (heliostat stowed face down).

The simulated hailstones were ice balls frozen in spherical molds at 0°F. The ice balls were accelerated to the required speed by a slingshot made with surgical tubing. The speed was measured when the ice ball passed

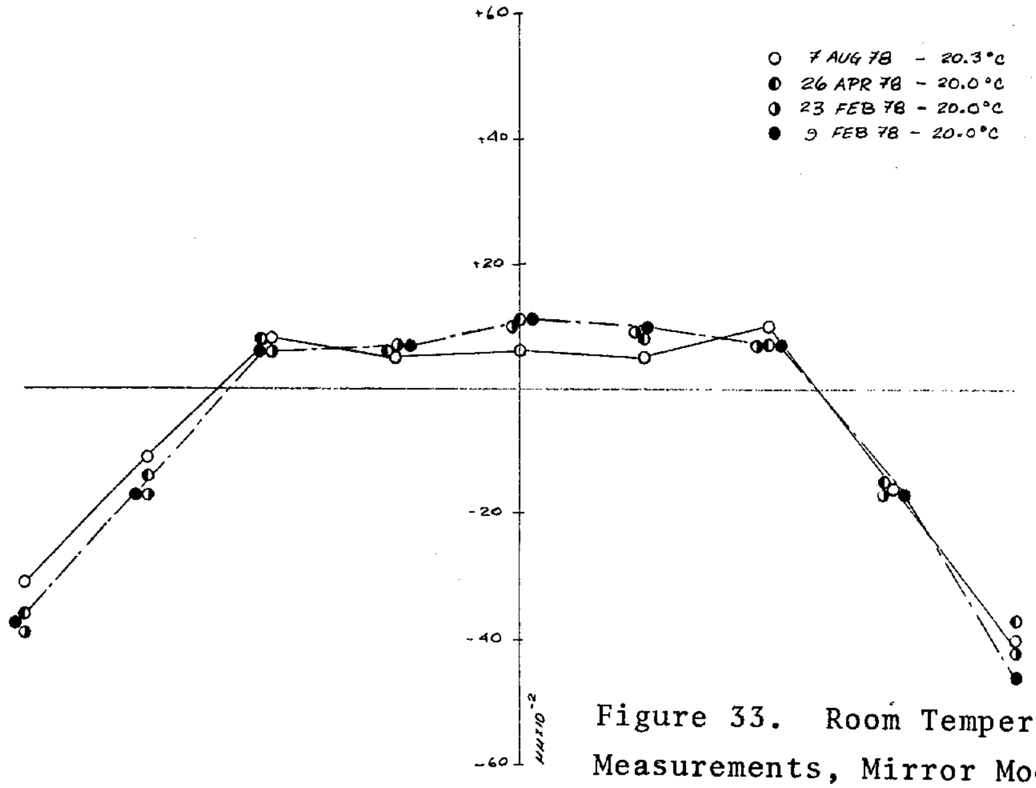



Figure 33. Room Temperature Creep Measurements, Mirror Module 9 (No Elevated Temperature Cure)

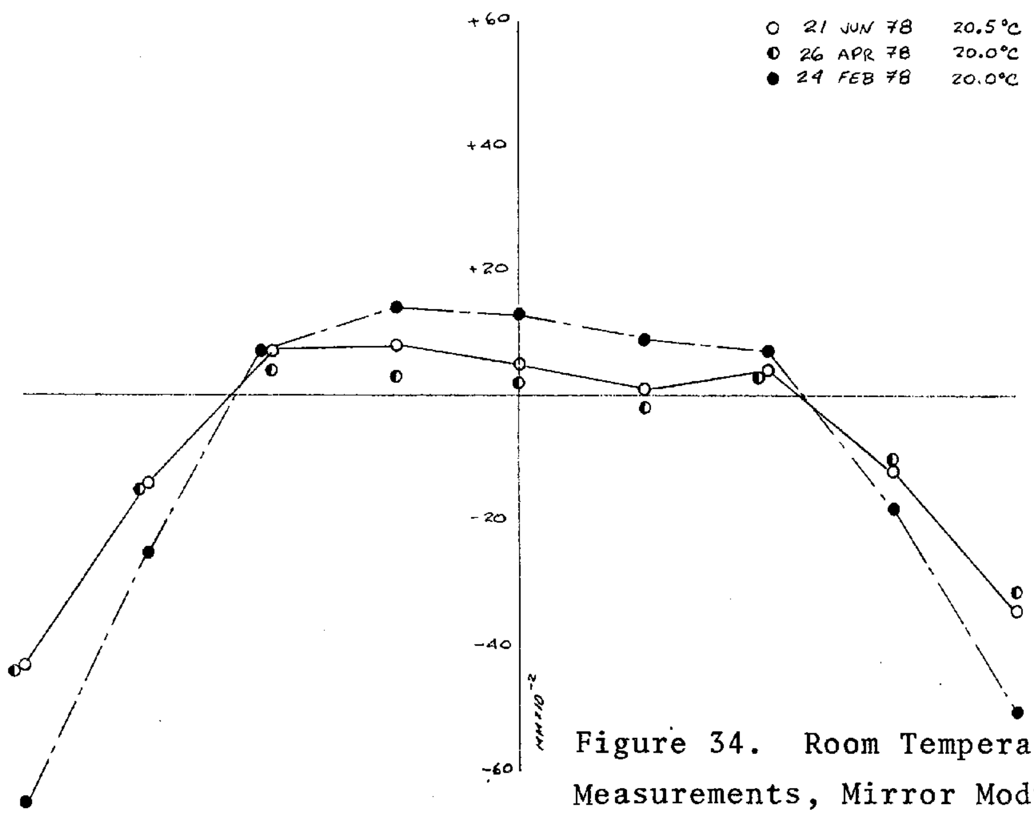



Figure 34. Room Temperature Creep Measurements, Mirror Module 10 (Two Weeks at 135°F Elevated Temperature Cure)

through two light beams directed at photodiodes. The slingshot was calibrated for various speeds for the two sizes of ice balls, and these speeds were found to be very repeatable.

The 3/4-in. ice balls were first impacted on the glass of mirror along the edges and at a corner as well as away from the edges with no effect. Next, 3/4-in. ice balls at speeds up to 80 ft/sec were impacted on a previously damaged (due to handling) portion of the glass. Ice balls impinged around and at the termination of existing cracks without extending them. Finally, 1-in. ice balls were impacted on the glass; a 50% failure rate occurred when the balls impacted the glass edge. One-in. ice balls at 80 ft/sec did no damage to the back side of the mirror module.

Because of the interest in thinner glass, a 4 x 4 ft piece of 0.060-in. Corning 0317 fusion glass was bonded with 4-in. thick Styrofoam and 26-gage galvanized sheet steel into a half-sized mirror module and subjected to hail testing. Initially this mirror module had no edge caps around the edges. When 3/4-inch ice balls impacted the glass edge at 65 ft/sec, a high percentage of failures resulted. The addition of an edge cap reduced the glass breakage rate only slightly.

The conclusions of this test are:

1. Mirror modules with 1/8-inch float glass can withstand 3/4-in. hail at 80 ft/sec with no damage, even when struck at previously induced cracks.

2. The mirror modules sustain no damage on the back side from 1-in. hail at 80 ft/sec, but a high failure rate occurs when struck with 1-in. hail on the glass near the edges.

3. The 0.060-inch fusion glass mounted on Styrofoam cannot survive 3/4-in. hail at 65 ft/sec.

Cold Water Shock

Four mirror modules mounted on a heliostat in the hot sun were splashed with cold water to assess their ability to undergo washing without damage. A 2-in. and a 4-in. module built by Sandia and a 2-in. and a 4-in. module built by MDAC were tested. The front and back surfaces of the mirrors were 104°F and 99°F respectively, and the water was 57°F. Approximately one gallon of water was thrown on each of the mirrors with no effect.

In an attempt to create thermal gradients in the glass, tap water from a hose (68°F) was sprayed continuously on half the glass of one of the mirror modules. Again, no effect was seen.

It can be concluded that cleaning operations using cool liquids should not damage any unbroken mirror modules.

## Conclusions and Recommendations

This test program resolved several unanswered questions, confirmed some expected mechanical behavior, and identified two previously unknown potential problems concerning the Styrofoam-core mirror modules. Hailstone survival, creep at room temperature, cold water shock, and residual stress in the glass were all concerns which were put to rest by the testing. The changes in mirror module curvature due to temperature, gravity, and wind loading were each shown to behave as expected. The thaw-freeze cycling identified two areas of concern: the change in the mirror contours due to temperature cycling, and the slight damage done to the edge seal of two Sandia-built mirror modules.

One of the most important results of the testing is that there were no broken mirrors due to thermal stresses, either at extreme uniform temperatures (-20°F and 120°F) or due to thermal gradients or fatigue during temperature cycling. This is attributed to the mirror module design which applies minimal constraint to the expansion and contraction with temperature of the glass and thereby results in relatively low stresses. These stresses were measured at a $\Delta T$ of 50°F and found to be well below the recommended design level of 500 psi in the 2-in. thick mirror module.

A major concern identified during this testing program is that of mirror module performance, that is, the reflected beam quality as affected by the mirror module contour. Although the mirror modules exhibited little creep at room temperature, significant contour changes were observed after the thaw-freeze temperature cycling. It appears that the mirror modules cannot hold a fixed curvature when temperature cycled. This may prove to be a problem to MDAC, as they are presently planning to curve each mirror module to attain a focusing effect. A period of aging for the adhesive may be required. This problem deserves further study.

In summary, the Styrofoam-core mirror module design appears to be able to withstand the environmental effects of wind, hail, and temperature extremes. The effects of aging are yet to be determined. Also, the performance of the design has not been measured, and there is reason to suspect that thermal cycling-induced contour changes may be detrimental to reflected beam quality. The following work is recommended to resolve unanswered questions concerning the mirror modules:

1. The issue of mirror contour change with temperature cycling should be investigated further. It should be determined what effect this phenomenon would have under normally occurring temperature excursions.

2. Further temperature cycling should be performed to determine also whether the MDAC edge cap configuration prevents the type of damage observed on the edge caps of two of the Sandia-made mirror modules.

3. The original test plan included the measurement of the reflected beam quality of each mirror module. This test was not done because the test system at Sandia, Livermore for measuring the image of sunlight reflected from a mirror has not been completed. This test

should be performed as soon as possible to determine the performance capability of the Styrofoam-core design. Beam quality measurements should be compared with theoretical calculations and with the beam quality of other designs. The results of these measurements should be used with field performance calculations to determine whether the mirror modules perform as expected and how they compare with mirror modules of other designs. Field performance calculations should also be made for flat mirrors to determine the impact on performance if it turns out that the Styrofoam-core mirror modules do lose their focusing contour with time.

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