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PROGRAM - PROJECT - JOB

Advanced Light Source - Beamlines

TITLE

Thermal and Structural Analysis of Beamline 7.3.3 M1 Focusing Mirror

Introduction

The Beamline 7.3.3 M1 Focusing Mirror is a silicon block 75mm x 75mm in cross section and 700 mm long, with an approximate clear aperture of 48mm x 600mm (although it was modeled as 56mm x 616mm, for purposes of even node spacing in the model). Supported by stainless steel S-benders, the mirror is subject to distortion from gravity sag as well as thermal expansion due to the incident beam. The reflecting surface of the mirror, which is cut into an 87mm saggital radius, absorbs 5.1 Watts of power (3 milliradians horizontal acceptance, with 1.7 Watts/ horizontal mrad absorbed power). In order to determine whether radiative cooling alone would be sufficient to keep the mirror within the slope error tolerance, we created an ANSYS Finite Element Analysis model of the mirror and S-benders. The bender dimensions, taken from a preliminary spreadsheet analysis, were set at 6.3mm (1/4") x 75mm x 268mm (10.5") (length as measured from the surface of the mirror).

Model

The mirror model, shown in Figure 1, was constructed using 8-node brick elements to represent the conductive and structural behavior of the mirror and benders (SOLID45 and SOLID70 ANSYS elements, respectively). Overlaid on these brick elements was a matching layer of 3-D surface elements (SURF22 elements) used to represent the radiative behavior of the materials. The top and side surfaces of the mirror were modeled as silicon with a uniform emissivity of 1, while the bottom, platinum coated reflecting surface was modeled with an emissivity of 0.03. The stainless steel benders were given an emissivity of 0.25. All of the surface elements were referenced to a common "space node", which represented the environment as a black body absorber constrained at room temperature (in this case defined as 298K). A heat flux load was applied to the nodes spanning the mirror's approximate clear aperture. The ends of the stainless benders were constrained at 298K and the whole model was given an initial room temperature condition.

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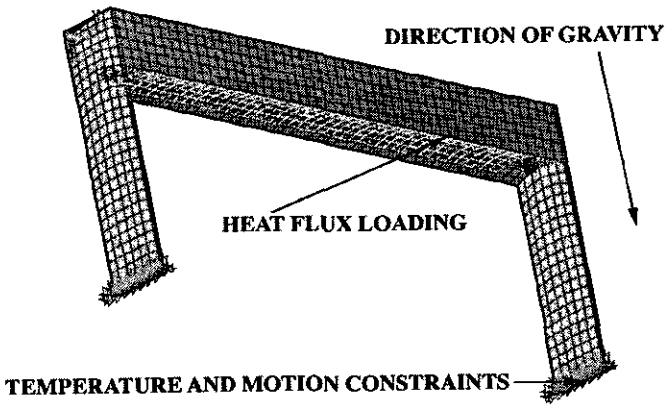

FIGURE 1: Mirror Model with Loads and Constraints

Analyses

We performed three types of analyses with the M1 Mirror model: thermal analyses of the temperature distribution due to radiative cooling, structural analyses of the mirror's deformation due to the combined effects of temperature distribution and gravity loading, and structural analyses studying the mirror's behavior when subjected to curvature adjustment with the benders.

The model was solved first with thermal loading, in order to determine the resulting temperature distribution, which was then applied to the structural model along with gravity loading in order to determine the mirror deformation. As a test for model consistency, and to verify the model's linearity, it was run once with only gravity and once with only thermal loading. The resulting deformations were added together and compared to the deformations of a model run with both thermal and gravity loading applied. As expected, the two sets of deformation data matched closely, and the summed and modeled responses to the thermal and gravity loading were found to be, on average, within less than 1 percent of each other.

It should also be noted that the radiation loading on the reflective surface of the mirror was modeled as uniform, while in reality the incident radiation falls in a gaussian distribution with the intensity at the ends about 25% lower than at the center. To check the accuracy of the constant heat load assumption, we discretized

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the gaussian heat flux distribution and applied the resulting array of heat fluxes to the surfaces of the mirror elements. The resulting deformations can be seen in Figure 2, and the average deviation between the models with and without the constant heat flux assumption was found to be roughly 1 percent. More importantly, the RMS slope error attributable to the constant heat flux assumption was found to be less than 0.05 microradians, which is well within the accuracy of the model.

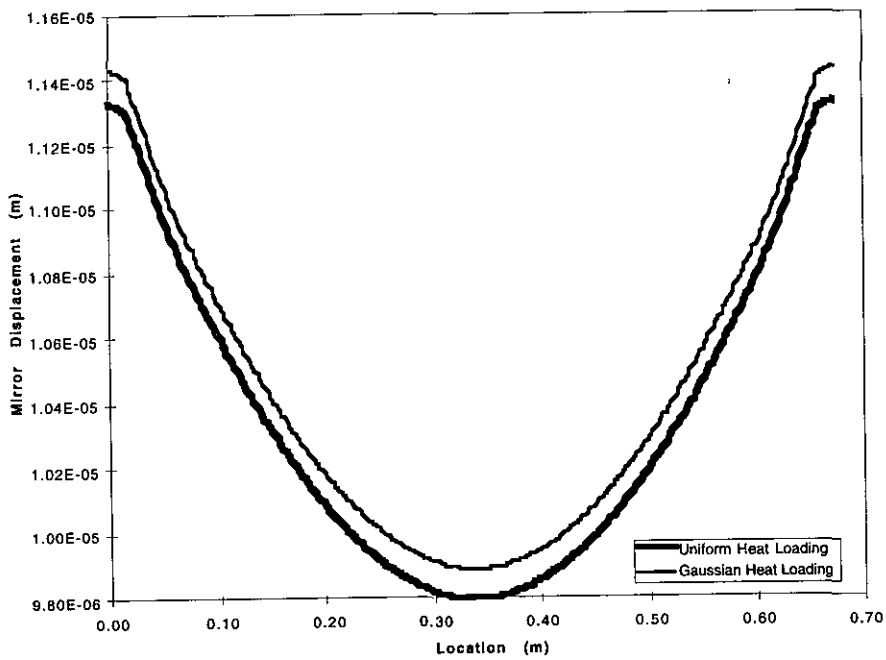

FIGURE 2: Mirror Centerline Deflection with Gaussian and Uniform Heat Loading

The final set of analyses investigated the effect of bender end displacements on the curvature of the mirror. This was accomplished by running the model with the bottom of one bender displaced in the mirror's longitudinal direction. We used these end displacements to successfully approximate the desired mirror curvature (a radius of roughly 2.9 km).

Results

The temperature distribution in a cross-section of the mirror is shown in Figure 3, and the maximum temperature difference from the front to the back surface of the mirror was found to be about 0.05 Kelvin. Figure 4 illustrates the mirror centerline deformation due to gravity and this thermal loading, as well as the deformations caused by each of the loading modes individually. The large gross

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motion of the mirror in the upward direction is caused by the linear thermal expansion of the relatively long bender springs. As can be readily observed, the mirror curvature due to the temperature loading is a relatively small part of the overall curvature. In fact, the RMS slope error (local deviation from horizontal) due to thermal loading, 1.3 μrad, is roughly one fourth of the overall RMS slope error of 5.4 μrad (the maximum errors are proportioned similarly). Fortunately, much of this slope error can be corrected by adjusting the mirror's bender positions.

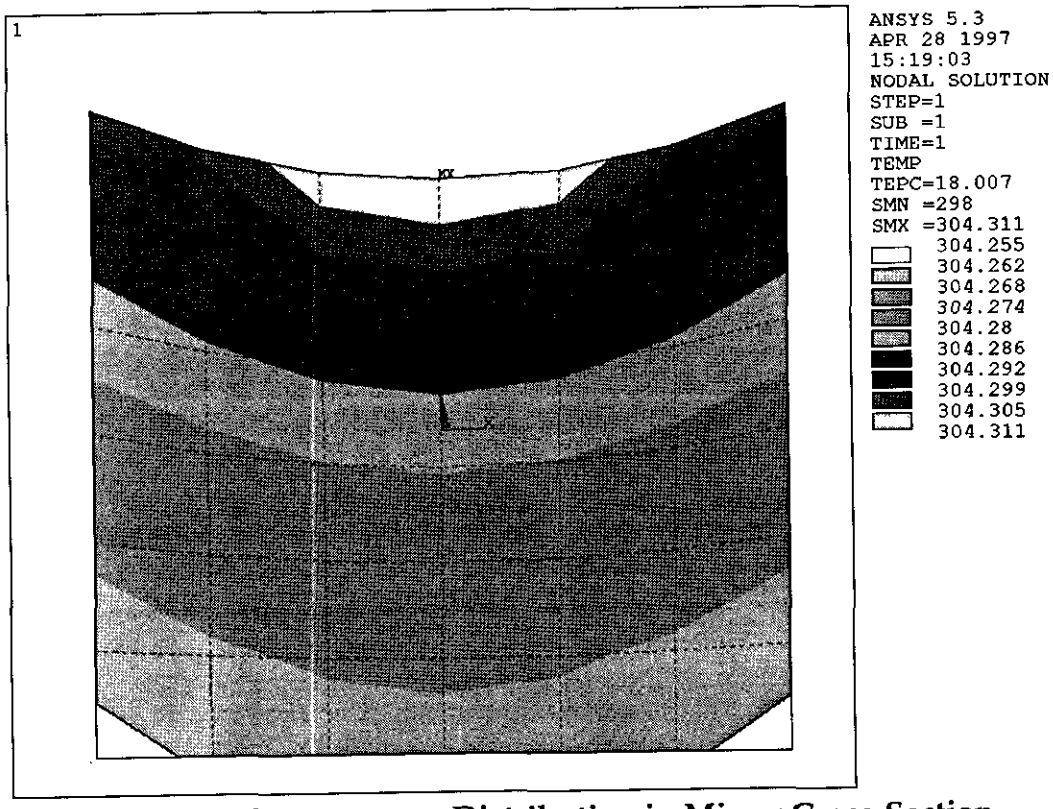

Figure 3: Temperature Distribution in Mirror Cross-Section

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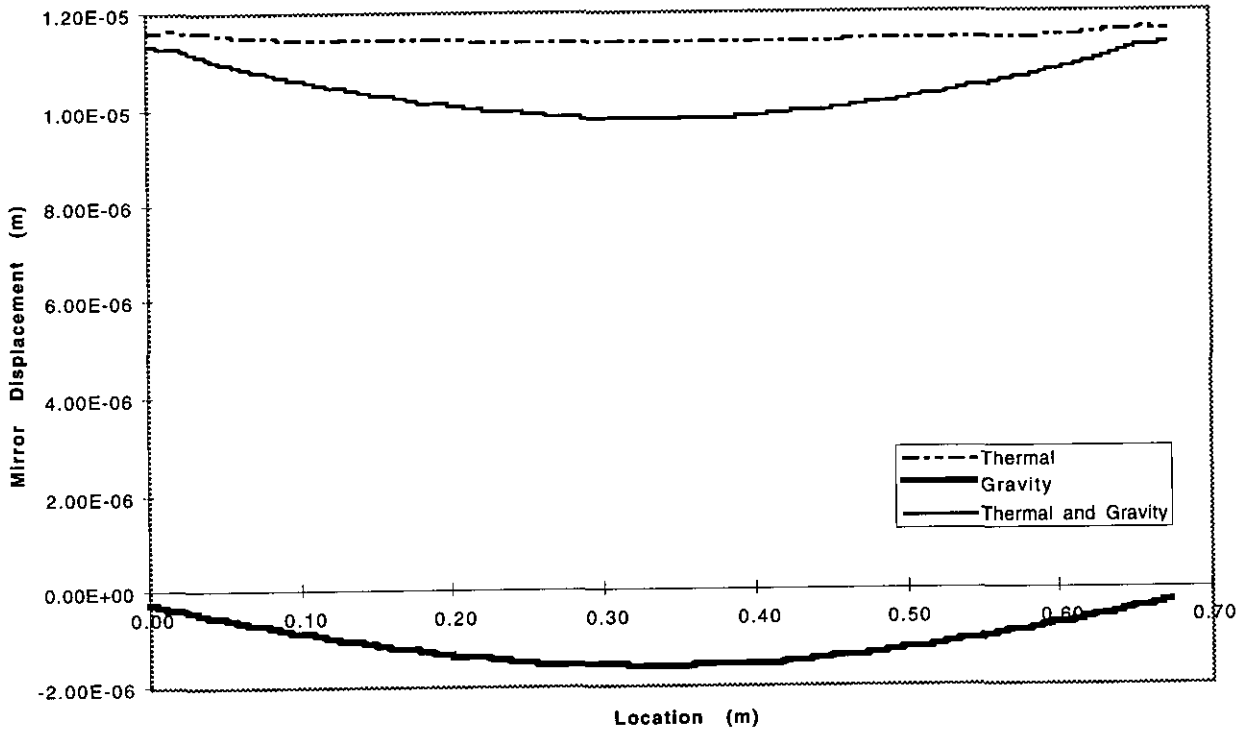

FIGURE 4: Mirror Centerline Vertical Deflections

To initially simulate the correction of the mirror's figure using the benders, we subtracted the best fit 2nd order polynomial from the mirror deformation data, since a quadratic function closely represents the large-radius circular errors that can be removed with the benders. Figure 5 shows the mirror's deformed shape and the difference between this and the best fit quadratic polynomial (i.e. the mirror's "corrected shape"). We then calculated the slope along the mirror in both its "corrected" and uncorrected forms. These slope errors are plotted in Figure 6 (the roughness in the figure is due to the fact that slope errors were calculated discretely). In the case of combined gravity and thermal loading, the RMS slope error within the clear aperture were found to be 5.4 μrad for the uncorrected mirror, and 1.6 μrad for the "corrected" mirror. The slope error is even less if the end effects (the 10 cm. on either end) are ignored. Within this smaller aperture, the RMS slope error was found to be about 0.3 μrad.

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As can be seen in Figure 7, the RMS slope errors due to thermal loading alone are 1.6 μrad for the uncorrected mirror and 0.7 μrad for the "corrected" figure. (Note that the unusually high slope error at the mirror's ends is due to the material discontinuity at the junction between the mirror and the benders, and that this area lies outside the clear aperture). In actuality, only around half of the thermal errors can be removed due to the thermal cycling caused by the periodic fills and the subsequent current decay in the storage ring. For example, if the mirror is set at a nominal position for minimum slope error at "average" beam current and the load on the mirror decays to the minimum, the thermally induced error will vary half as much as was modeled here. That said, the thermal loading still has a much smaller contribution to the overall slope error than the gravity loading, though it is not negligible.

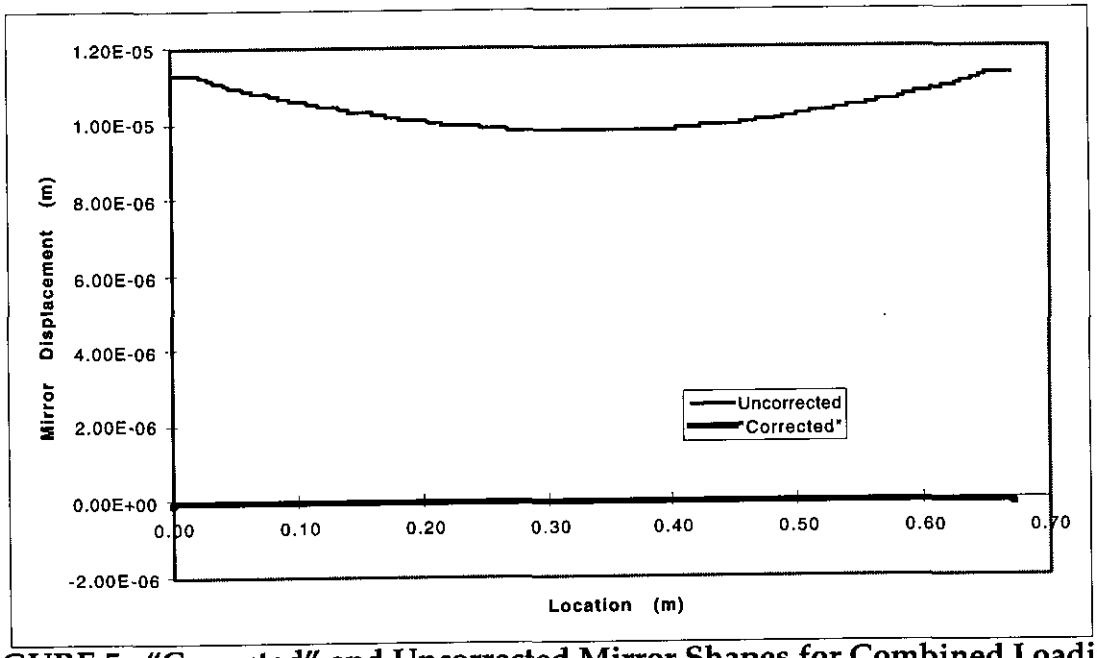

FIGURE 5: "Corrected" and Uncorrected Mirror Shapes for Combined Loading

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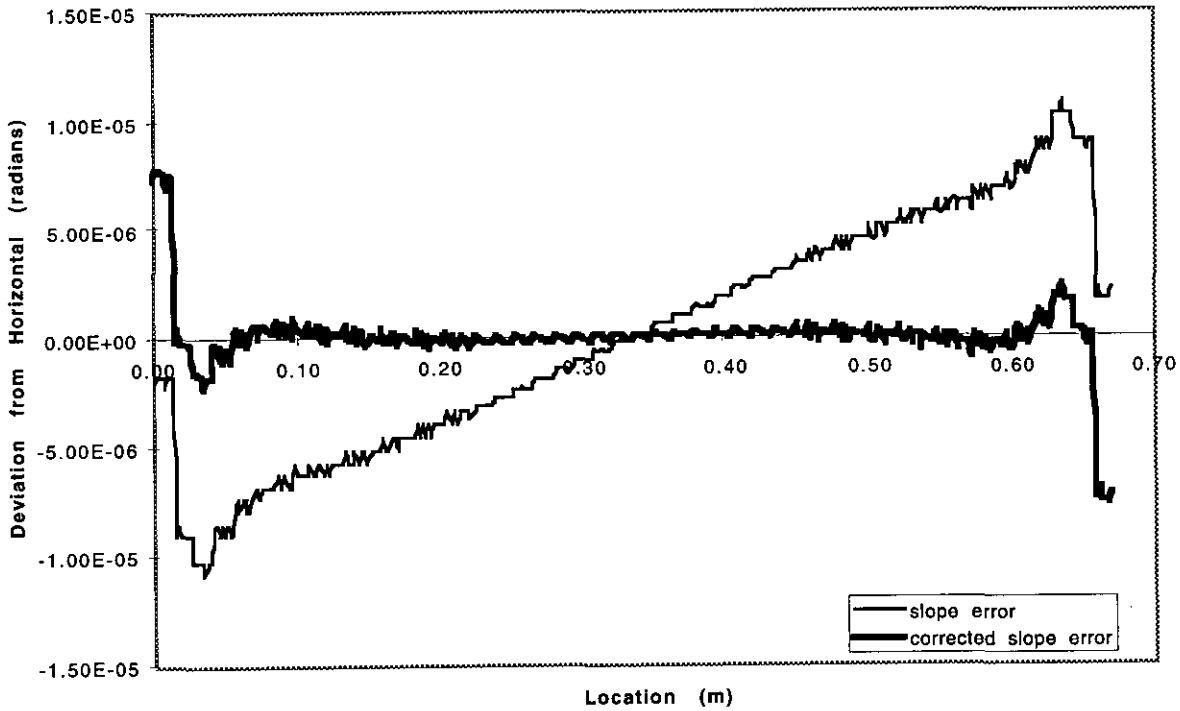

FIGURE 6: Slope Errors in Mirror in "Corrected" and Uncorrected Conditions under Combined Loading

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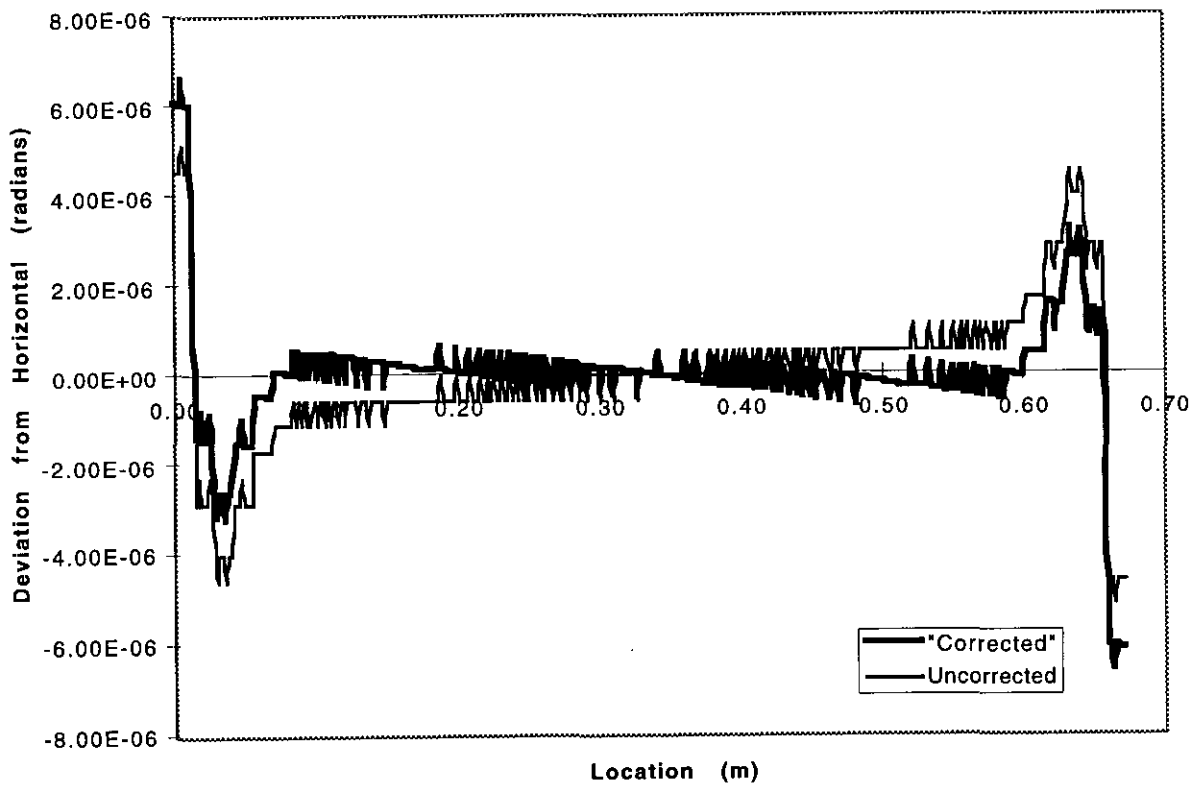

FIGURE 7: Slope Errors in Mirror in "Corrected" and Uncorrected Condition under Thermal Loading

Finally, we applied bender end displacements in the ANSYS 3-D model to better simulate the use of the benders in correcting the mirror's figure (see Figure 8). We simulated the bending of the mirror into its toroidal shape, and attained a roughly 2900 meter radius with a 7mm bender end displacement. The mirror's centerline shapes resulting from the bending study along with the uncorrected "nominal" mirror figure, are shown in Figure 9, and the corresponding slope errors in Figure 10. The slope error in the mirror is found to have an RMS value of 1.9 μrad over the entire mirror surface, and 0.4 μrad if the end effects are ignored.

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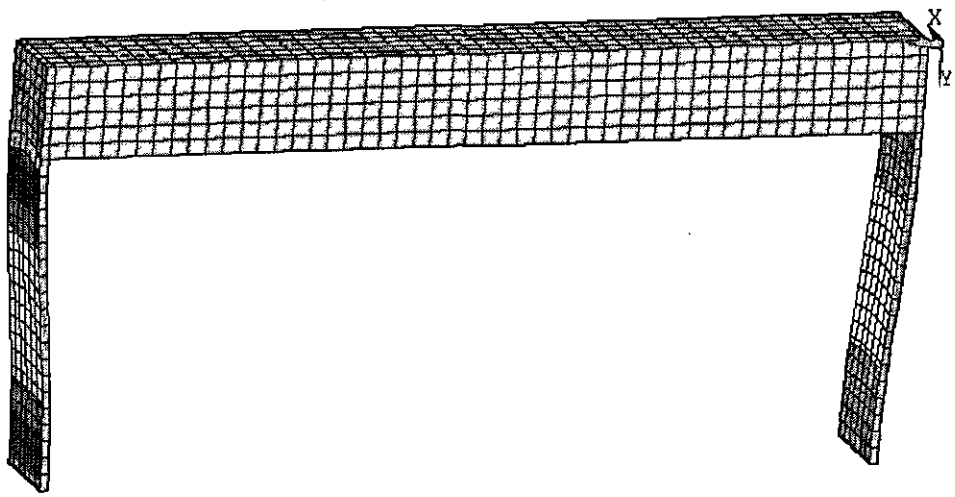

FIGURE 8: Mirror Model with Benders in Displaced Position

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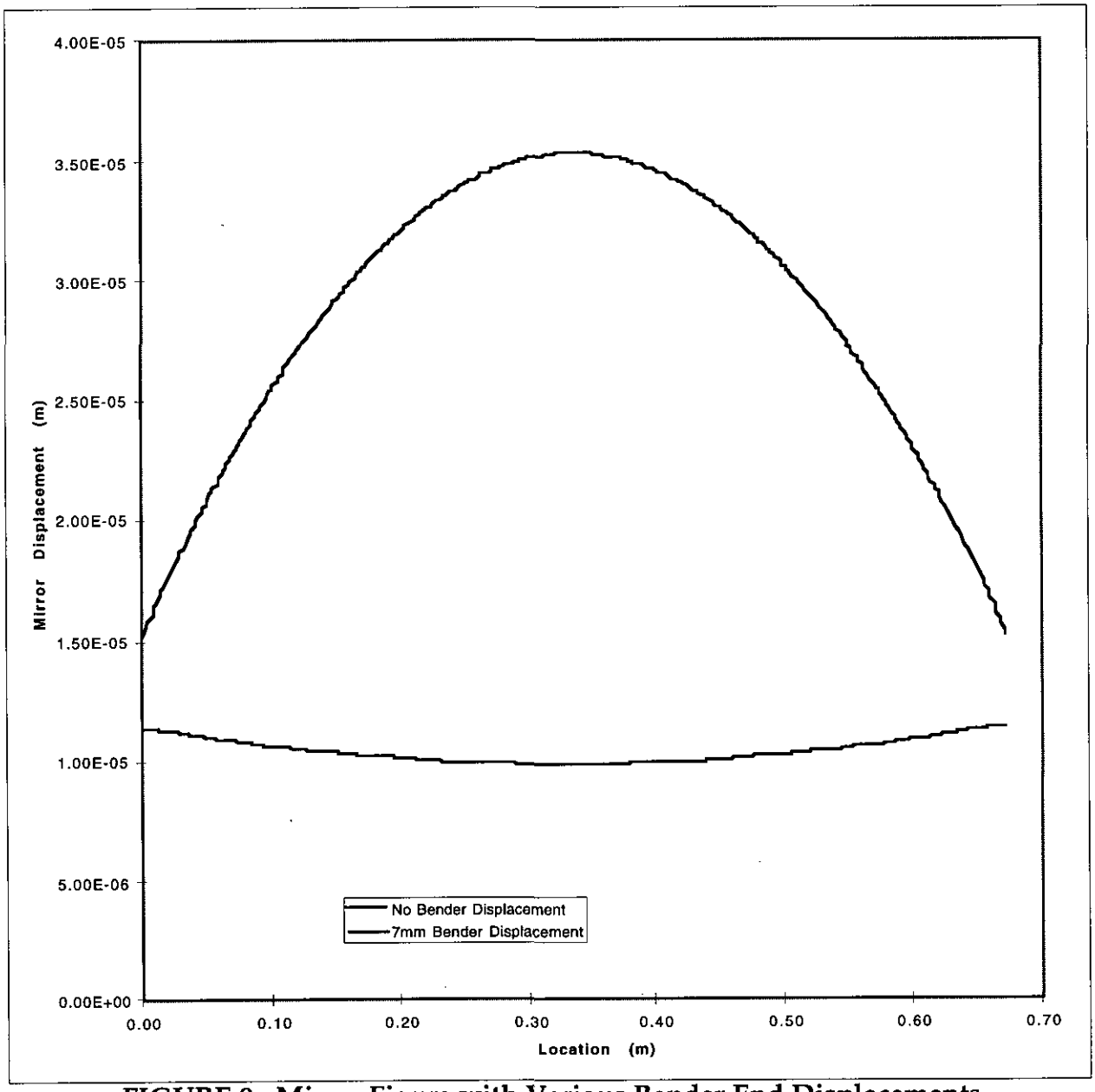

FIGURE 9: Mirror Figure with Various Bender End Displacements

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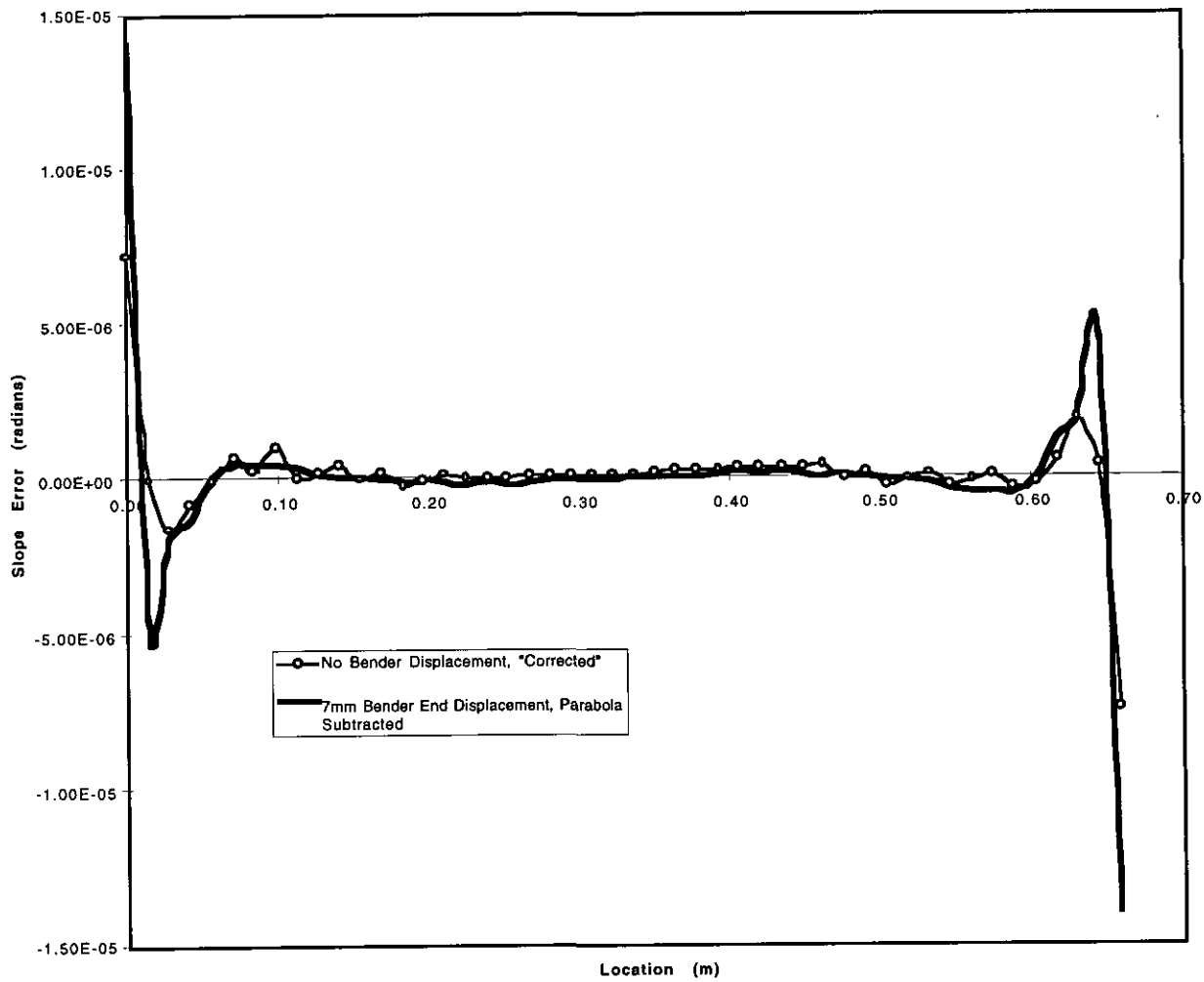

FIGURE 10: Mirror Slope Errors with Various Bender End Displacements

Conclusions and Suggestions for Further Analysis

As can be seen from the results of our models, the distortion caused by thermal loading is small. Gravity sag, on the other hand, is a more significant cause of slope error in the mirror. However, the bender displacement analyses show that the combined errors from gravity sag and thermal loading are around 1 μrad when the mirror is bent into its operating radius (and about half that, if a smaller clear

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aperture can be tolerated). Given a slope error tolerance of one fourth the angular subtense of the source (i.e. one fourth of 2.5 μrad, or .6 μrad), the mirror is within tolerance inside a reduced aperture of approximately 580mm. We can thus conclude that no additional cooling (beyond radiation) nor gravity sag correction is necessary.

Since the analyses that we performed assumed radiation to a black body absorber, a more rigorous analysis would be to model the mirror including radiation between the mirror and its chamber, which could conceivably raise the temperature distribution across the mirror's section. Also, it would be interesting to model the mirror with its back surface (i.e. opposite to the reflecting surface) coated with a material that exhibits the same emissivity as the reflecting surface. It is possible that this would cause the temperature gradient through the mirror to decrease and thus reduce the amount of thermally induced bending. While the deformation due to thermal loading for this mirror is relatively insignificant, for many mirrors it is not, and coating the back surface of the mirror may be a simple way to reduce thermal distortion under solely radiative cooling.

References

For a more detailed analysis of the power loading on the mirror, see Light Source Beamline Note:

"Absorbed Power on the 7.3.3 M1 Mirror," Padmore, H.A. March 30, 1997.