



THERMAL ANALYSIS OF A FINITE ELEMENT MODEL IN A RADIATION DOMINATED ENVIRONMENT

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ABSTRACT

This paper presents a brief overview of thermal analysis, evaluating the University of Arizona mirror design, for the Next Generation Space Telescope (NGST) Pre-Phase A vehicle concept. Model building begins using Thermal Desktop™, by Cullimore and Ring Technologies, to import a NASTRAN bulk data file from the structural model of the mirror assembly. Using AutoCAD® capabilities, additional surfaces are added to simulate the thermal aspects of the problem which, for due reason, are not part of the structural model. Surfaces are then available to accept thermophysical and thermo-optical properties. Thermal Desktop™ calculates radiation conductors using Monte Carlo simulations. Then Thermal Desktop™ generates the SINDA input file having a one-to-one correspondence with the NASTRAN node and element definitions. A model is now available to evaluate the mirror design in the radiation dominated environment, conduct parametric trade studies of the thermal design, and provide temperatures to the finite element structural model.

INTRODUCTION

The NGST, Figure 1, is NASA's planned successor to the Hubble Space Telescope. NGST is being designed as a large imaging and spectroscopic instrument capable of observing sources in the near infrared (IR) wavelengths. Marshall Space Flight Center's (MSFC) role in this evolving program includes feasibility studies and technology development demonstrations for the optical telescope assembly (OTA). MSFC's Thermal Control Systems Group also supports the program office at Goddard Space Flight Center (GSFC) as a member of the integrated analysis team. The University of Arizona (UofA) is one of several participants in the NGST Mirror System Demonstrator contracts developing technology for large, lightweight optics. Each of the participant's mirror designs will eventually be evaluated for relative performance by the integrated analysis team using a baseline Telescope design commonly referred to as the "yardstick" design.

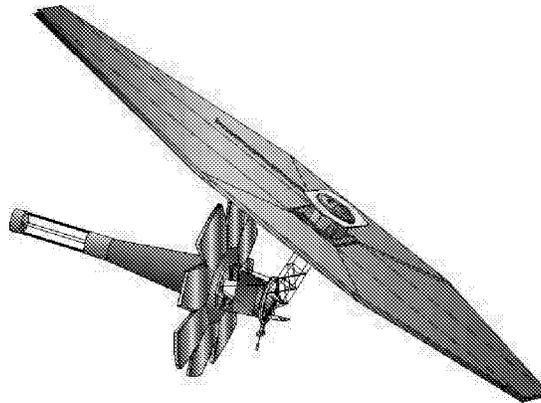


Figure 1: GSFC Pre-Phase A NGST conceptual design ¹

TELESCOPE DESCRIPTION

The NGST Telescope is composed of four major subsystems, Figure 2, which include the Sunshade, Primary Mirror (PM) Assembly, Secondary Mirror (SM) with mast, and the Integrated Scientific Instrument Module (ISIM). The Sunshade is a deployable structure basically acting as multi-layer insulation (MLI) to block direct solar energy from the OTA. The PM assembly is also a deployable structure too large to launch in a fixed position. The central petal is fixed and surrounded by deployable petals. Once deployed, the PM assembly has a diameter of approximately 8.5 meters. The SM is mounted at the end of a composite mast attached to the central petal of the PM.

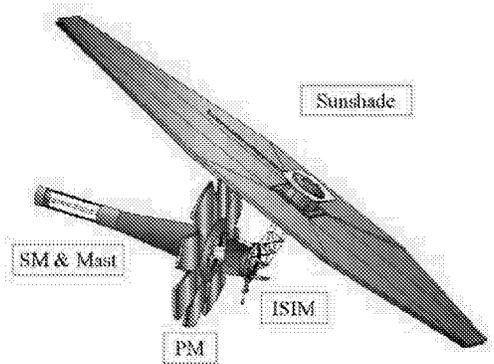


Figure 2: NGST Major Subsystems

Since the Telescope investigates near IR sources, the primary mirror must be maintained at stable temperatures near 35 Kelvin. The NGST baseline orbit is at the 'L2' Lagrangian point, Figure 3. The L2 point is located at an altitude of approximately 3 times the distance from the earth to the moon. It remains on the anti-sun side of the earth. This orbit, along with the Sunshade, provides a cold environment at very stable conditions

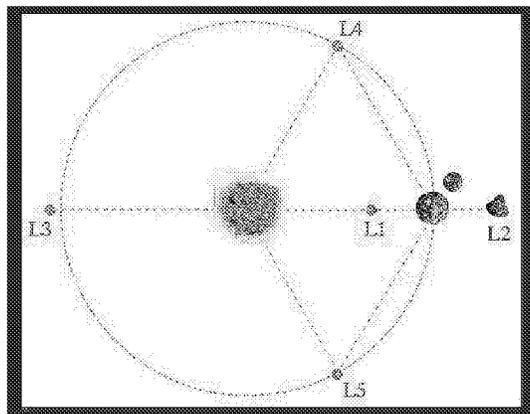


Figure 3: Lagrangian Points relative to the sun and earth orbit ¹

The NGST attitude is defined relative to the solar vector. Figure 4 shows how the attitude changes from having the Sunshade normal to the solar vector, which is the hottest attitude, by slewing to as much as $\pm 27^\circ$ off axis, which is the coldest attitude.

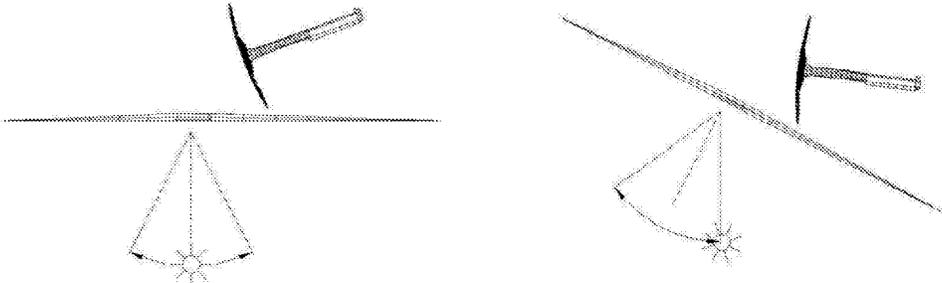


Figure 4: NGST slew maneuver

Figure 5 shows the UofA demonstrator mirror design for a single petal. The mirror is hexagonal shaped. Structural models of this mirror are scaled up to about 3 m flat-to-flat to fit the “yardstick” Telescope design. The front mirror surface is glass approximately 2 mm thick. The glass is held in place by a complex assembly of linkages attached to the backside of the mirror on one end and the actuators on the other end. Behind the glass mirror is the Reaction Structure. The Reaction Structure is an open-cell honeycomb composite. It includes a front and back face but remains open-cell as an assembly. Actuators are mounted inside the cells of the reaction plate.

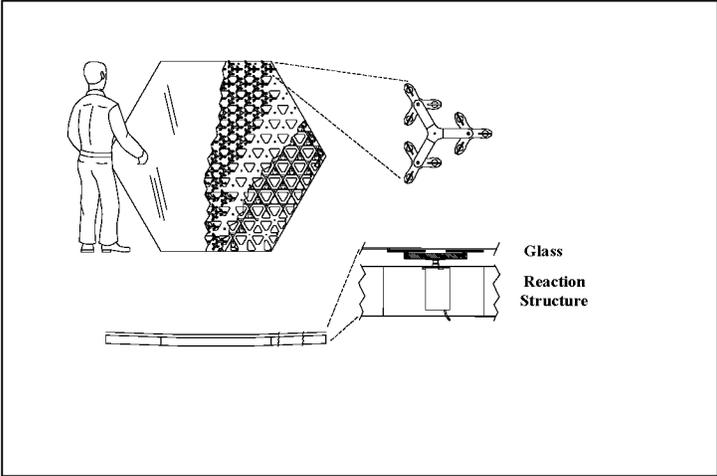


Figure 5: University Of Arizona NGST Demonstrator Mirror²

ANALYTICAL OBJECTIVES

Mirror temperature effects are integrated into stress analysis, along with dynamic loading. The combined effects are inputs to the optical analysis which evaluates performance of the individual petals and overall assembly. This integrated analysis effort is used to compare relative performance of the various mirror designs, requirements for individual components such as the actuators, and effects of other subsystem conceptual designs such as the SM mast and ISIM. This effort also evaluates the necessity for cryo-figuring, effects of material selection, and effects of mounting techniques.

More specifically, the first objective for the thermal analysis is to determine the maximum mirror temperatures during the hot case attitude. This data is used to determine mirror deformations from ambient conditions and evaluate the requirement for cryo-figuring. The second major objective is to determine the mirror temperature response to a slew maneuver from the hot case attitude to the cold case attitude. This data is used to evaluate mirror performance following the slew to determine when perturbations to the optical performance stabilize. The data is also used to determine the required travel for actuators to correct for thermal deformations. Another major objective is to compare temperatures and eventually stress magnitudes, dynamic response, and optical performance between the detailed petal and the corresponding simplified petal. This data is used to determine the amount of surface detail necessary in the integrated model to accurately evaluate overall performance criteria among the various disciplines.

In order to meet these objectives, the thermal analysis process follows a simple path. Sunshade temperatures are provided as boundary conditions from GSFC for the hot and cold attitudes. The NASTRAN FEM model is imported into Thermal DesktopTM and converted to thermal entities. Thermophysical properties, thermo-optical properties, and surface thicknesses are defined. Surfaces/solids are added as necessary. The SINDA thermal network is constructed and radiation conductors calculated. Temperatures are calculated using SINDA. Steady-state temperatures are calculated at the hot attitude and then the boundary conditions are changed to reflect the slew maneuver and a transient solution is completed. Temperatures are exported back to the NASTRAN FEM with a one-to-one correspondence between calculated temperatures and grid points. Although this is a simple path, the analytical process is not without significant challenges. These are discussed in the next section.

ANALYTICAL CHALLENGES

NGST performance and environmental requirements pose challenges to the integrated analysis effort that only a few years ago would have been insurmountable. Previous telescopes, with strict optical performance requirements, often chose to maintain mirror elements near ambient conditions with strict requirements on the thermal control system (TCS) design. Optical performance can then rely on stable temperatures that remain near manufacturing conditions of the mirror elements. Likewise, mirror elements are usually mounted inside a spacecraft structure allowing TCS designs to dampen temperature excursions due to environmental changes. Such luxuries are not afforded NGST. Due to NGST IR imaging requirements, optical elements must be near 35 K during operation, thereby making thermal effects over a large temperature span play a major role in optical performance. NGST also requires a large mirror assembly which necessitates lightweight, deployable elements. Mirror elements are too large to be enclosed in a spacecraft structure. The thin surfaces, naturally, have large temperature gradients. In summary, integration analysis and most notably thermal analysis becomes much more important for the NGST design and performance evaluation.

Integration analysis passes thermal and dynamic responses to stress models which combine the various loads into final mirror deformations. The deformations are then passed on to optical models to evaluate final performance. Therefore, the stress model serves as the primary gateway of data sharing among disciplines. Several challenges exist for this integration. First, there must be a routine interface between the stress FEM and the thermal model to evaluate changing designs. There are many mirror designs, optical assembly designs, TCS designs, etc. Likewise, the use of structural FEM in thermal analysis almost always dictates a large number of surfaces and grid points/nodes. Second, the thermal model must evaluate temperatures of surfaces with specular optical properties, driven by a radiation dominated environment.

Historically, thermal software packages that interface with FEM's cannot perform full radiation analysis to calculate radiation conductors, orbital heating, and add surfaces as part of the TCS design. Some do not provide a means to calculate non-linear temperature responses. In addition, most of these packages do not provide an interface to SINDA which remains the tried and true workhorse of thermal analysts throughout NASA. The packages that do provide an interface are sometimes not viable for continuously changing designs or designs driven by radiation. Therefore, a gap results which greatly hinders integrated thermal analysis.

Within recent years a very few software packages have evolved that do provide, to one degree or another, interfaces to FEM's used by other analytical disciplines, interfaces to CAD packages used by designers, and finally, they are capable of full thermal analysis with radiation. Thermal Desktop™, which runs within AutoCAD®, is one of the most notable developments that does provide these capabilities. Thermal Desktop™ is used for NGST because of its capability to import NASTRAN FEM's, calculate radiation conductors for a very large number of surfaces, add thermal design features, quickly change material properties and geometry, evaluate surfaces with specular properties, and post-process temperatures for direct export back to NASTRAN. There are many other features within the package that are not used for NGST analysis. Some of the more notable features are the capability to evaluate articulating surfaces and the capability to reduce the number of surfaces in the model while maintaining the original interface to FEM's grid points.

THERMAL/STRUCTURAL MODEL

With the Sunshade added, the NASTRAN FEM has 2,015 elements (surfaces) and 1,466 grid points (nodes) once imported into Thermal Desktop™, Figure 6. The detailed mirror has 785 elements (surfaces) while the simplified mirrors have only 26 elements (surfaces) per petal. The FEM includes the Sunshade, PM Petals, SM Mast, and SM. The FEM also includes the Reaction Structure for the detailed petal. This NASTRAN FEM serves as the basic model used to share data among the various disciplines conducting integrated analysis. Post-processed results from the thermal analysis provide temperatures for each of these grid points in the NASTRAN FEM. The ISIM is not included in this model because the baseline model used for comparison had no ISIM. This model does not include elements for the Reaction Structure behind the simplified petals.

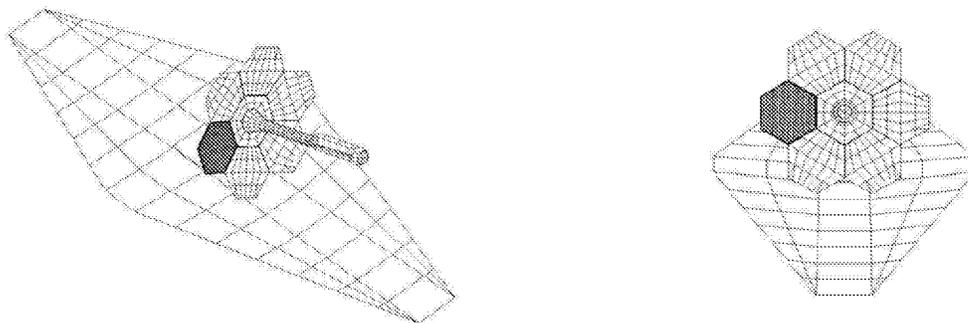


Figure 6: NASTRAN FEM of NGST with the UofA mirror design

Thermal analysis must consider radiation between the mirror petals and Reaction Structure and between the Reaction Structure and Sunshade, Figure 7. Modeling the open-cell structure is discussed below. Using AutoCAD® features, the simplified petal surfaces are copied and translated behind the mirror providing new surfaces for a simplified Reaction Structure with identical detail, Figure 8. Using Thermal Desktop™ the new surfaces are put in a separate submodel. Once the simplified Reaction Structure is added, the thermal model has 2,219 surfaces and 1,689 nodes.

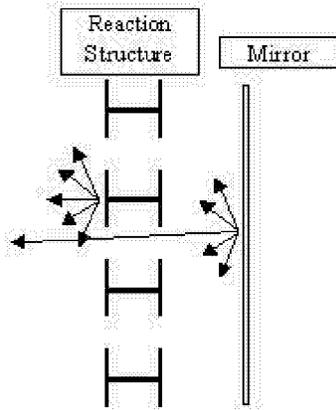


Figure 7: Radiation interchange toward the backside of the Mirror

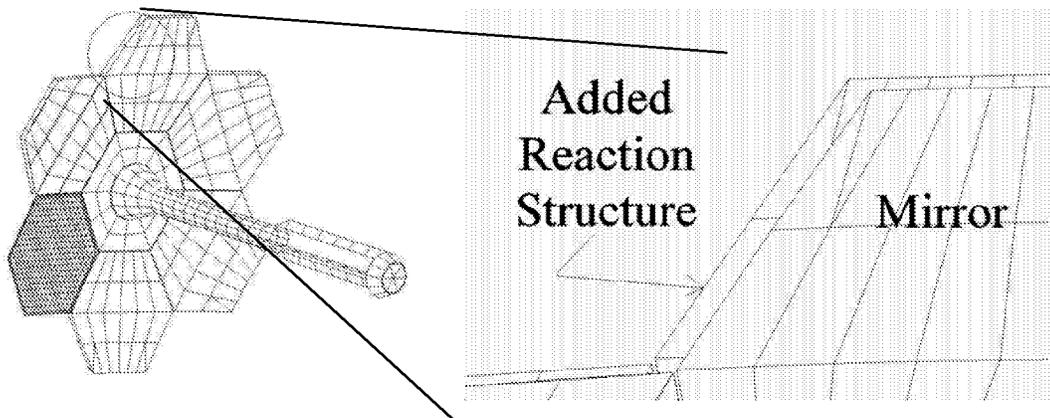


Figure 8: Reaction Structure surfaces added to the thermal model

The next step in developing the thermal model is defining thicknesses and material properties of the various planer surfaces. Thicknesses and material properties are used to calculate nodal thermal capacitance and linear conductors to adjacent nodes. Surfaces are selected using a multitude of options within either AutoCAD[®] or Thermal Desktop[™]. The PM is borasilicate glass while the Reaction Structure and SM Mast are laminated composites. Properties are given in Tables 1 & 2. If material properties near 30 K are available they are used. Otherwise, properties are set to those used in the “yardstick” analysis. The PM surfaces are set to the actual glass thickness of 2 mm. The SM Mast surfaces are set to the actual thickness of 3 mm. The Reaction Structure surfaces are set to the actual thickness of the single facesheet toward the PM which is 0.76 mm. This simplifies the honeycomb assembly and provides conservative predictions on lateral temperature gradients. However, the material density of the Reaction Structure is increased to include the total thermal capacity of the two facesheets and honeycomb webs. This maintains accuracy for the transient analysis.

Material	Thermal Conductivity (W/m/K)	Density (kg/m ³)	Specific Heat (J/kg/K)
Borosilicate	0.15	2352.8	37.6
Composite	8.72	2155.4	10.04
Reaction Structure	8.72	11324.3	10.04

Table 1: Thermophysical Properties

Surface	Material	Emissivity
Sunshade	VDA	0.03
Primary Mirror	Coating?	0.03
Secondary Mirror	Glass	0.03
Reaction Structure	Composite @40 K	0.4
Composite	Composite @40 K	0.4

Table 2: Surface Emissivity

The next step before beginning calculations is selecting the necessary surfaces to be included in the radiation analysis and defining optical properties for those surfaces. This is a simple task for all structures except one. A difficult situation exists with the honeycomb Reaction Structure. The structure is open-cell. Therefore, the backside of the PM glass “sees” through the Reaction Structure to the Sunshade, Figure 7. A detailed model of each individual cell would require too many surfaces to handle in the radiation analysis. As a common alternative, simplifying assumptions are used. Optical properties for this structure include 11% transmissivity in the IR wavelength. The transmissivity value is determined by importing design drawings of the facesheet. Again, using AutoCAD® techniques, the relative surface area of the open-cells to facesheet is calculated.

Radiation conductors are now calculated and a SINDA network file is generated. The final analysis uses a total of 414,945 radiation conductors and 5,179 linear conductors.

RESULTS

As a checkout procedure, the temperatures are first calculated using only the radiation network. In this case only the front mirror surface is active. This helps evaluate the radiation network and gives a quick comparison of the detailed petal, to the left, and simplified petal, to the right. Mirror temperatures, Figure 9, show symmetry across the PM assembly along a vertical axis as expected. It also shows good agreement between the detailed and simplified petal. There is a shadow of the SM Mast toward the top of the PM assembly as it blocks radiation from the warmer Sunshade below.

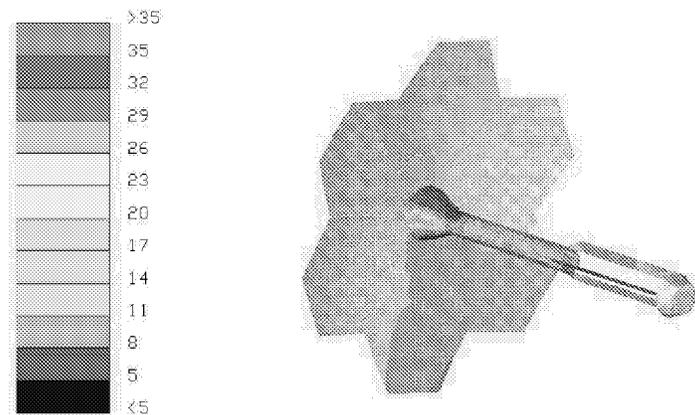


Figure 9: Results from a checkout run with radiation only

With the checkout complete the conduction network is added to the SINDA model. Calculations for the hot case attitude show a maximum mirror temperature around 32 K, Figures 10 & 11. The temperature gradient across the PM assembly is about 10 K. The central petal has the largest gradient of any single petal.

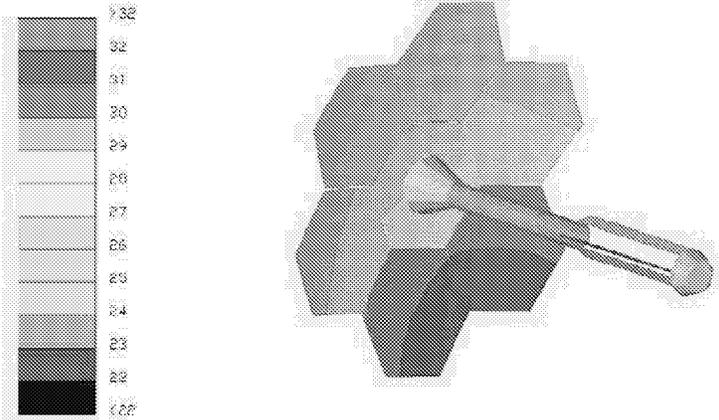


Figure 10: Final hot case results- isometric view

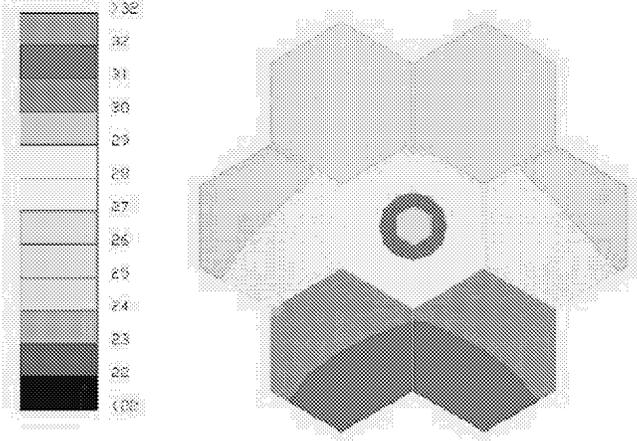


Figure 11: Final hot case results- front view

There is a large gradient at the interface between petals. Eventually, latches and/or hinges will be included that may have significant effects on these gradients. It should be noted that these temperatures are not considered the best possible with the UofA mirror design. Future analysis, to improve performance, should consider options to eliminate direct radiation from the backside of the Mirror to the Sunshade. Gradients can be easily reduced with the addition of insulation, for example. Temperatures for the entire vehicle are given in Figure 12.

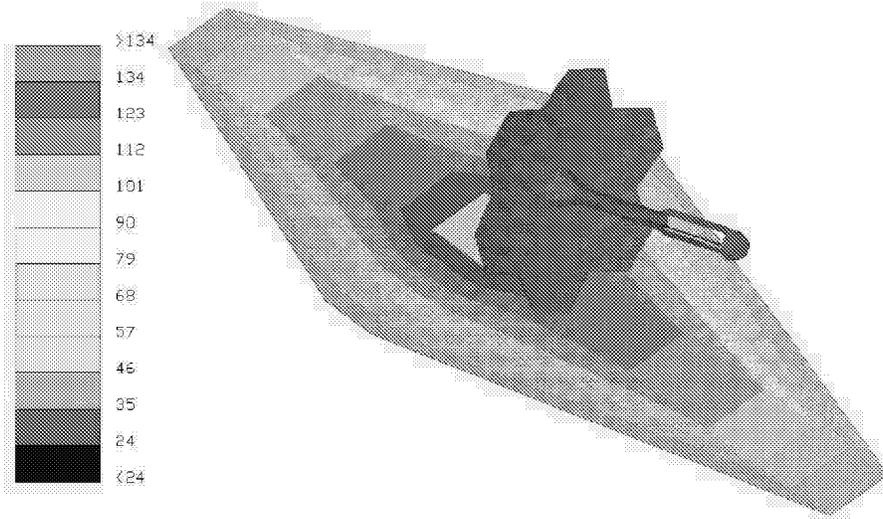


Figure 12: Final hot case results- entire vehicle

During the maximum slew maneuver Sunshade temperatures decrease about 2 K on average. Figure 13 shows how the Mirror and OTA structure respond to the different environment. Although the Mirror is lightweight, the radiation coupling to the Sunshade is small. Therefore, Mirror temperatures continue to decrease for a long time following the slew. Transient temperatures are used in the stress analysis to provide thermal deformations over a period of time following the slew. This information is used to determine when optical stability is achieved. Although Mirror temperatures continue to change many days following the slew, the rate of temperature change decreases a great deal after about 36 hours, Figure 14.

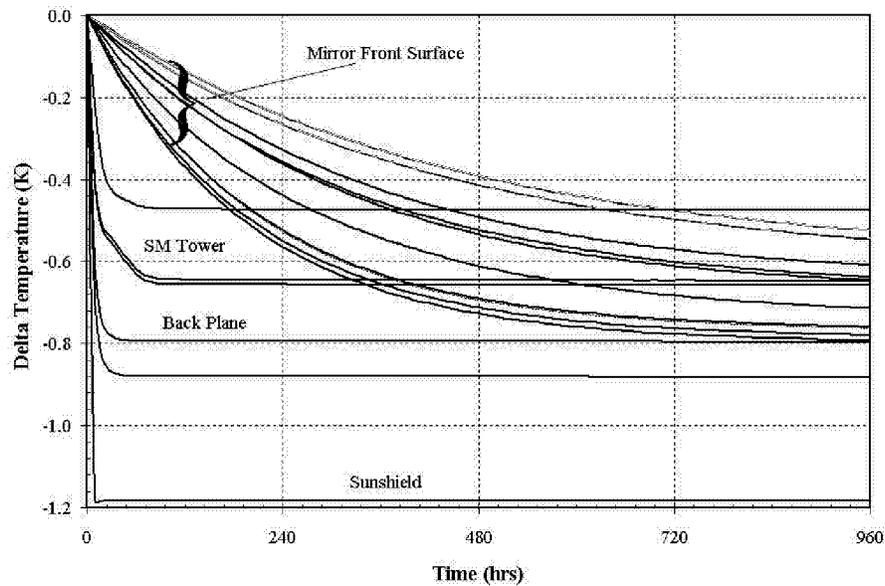


Figure 13: Slew Maneuver- Temperature Change From Initial Conditions

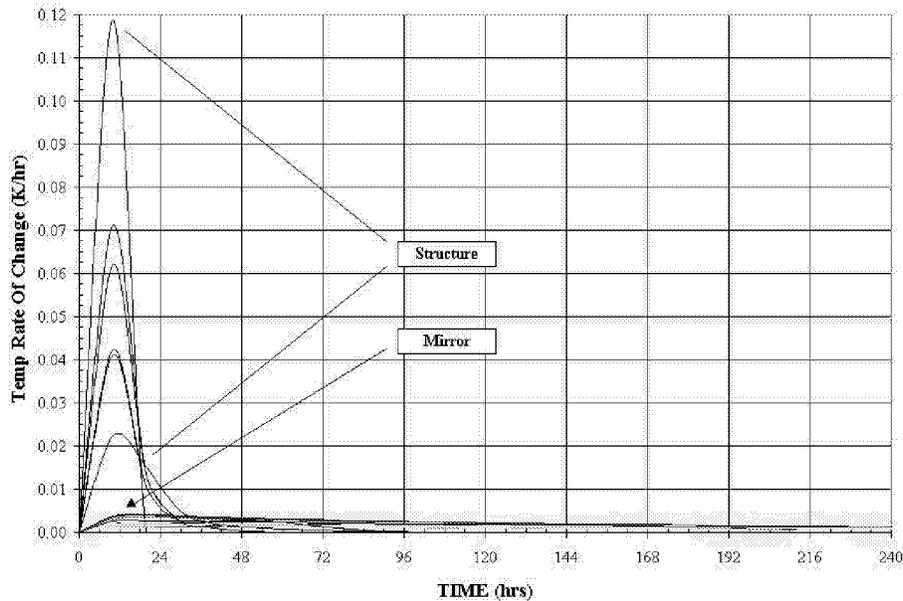


Figure 14: Slew Maneuver- Rate of Temperature Change

CONCLUSIONS

Initial calculations show that the L2 orbit combined with the Sunshade design result in Mirror temperatures at or below 32 K. Temperatures of the simplified petal show the same degree of fidelity in gradients as the detailed petal. Therefore, the simplified petals do reflect the required amount of detail to accurately evaluate temperatures. Mirror temperatures continue to decrease many days following a 27° slew maneuver. As a result of this effort, a thermal model now exists to conduct parametric trade studies that evaluate various design changes to reduce gradients and improve the optical performance. The thermal model can be quickly modified to reflect design changes as the project matures.

This effort also demonstrates that Thermal Desktop™ is a useful tool to perform thermal analysis on FEM models in an environment dominated by radiation interchange. The release of Thermal Desktop™ is a major advancement in tools available to the thermal analysis. Thermal analysis can now play a more active role in the integrated analysis and concurrent engineering design effort.

REFERENCES

- [1] National Aeronautics and Space Administration, Goddard Space Flight Center, Next Generation Space Telescope Internet Home Page.
- [2] University Of Arizona, Next Generation Space Telescope Mirror System Demonstrator Critical Design Review.