THERMAL AND STRUCTURAL ANALYSIS
OF A ROCKETBORNE EXPERIMENT

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Abstract

The MIT Lincoln Laboratory High Powered–Missile Alternative Range Target Instrument (HP-MARTI) program will design and operate an optical-sensor module (OSM) onboard an expendable rocket. The HP-MARTI program will test and characterize the effects of a megawatt airborne laser on a missile during its boost-phase. This project provides a survivability analysis of the HP-MARTI OSM and considers the effects of aerodynamic heating, laser heating, and aerodynamic loading on the rocket and OSM structure, through a coupled thermal and structural numerical analysis. Results show that at 40,000 feet the structure of the rocket and the OSM withstands the increased thermal and structural stresses, allowing enough time for the optical sensors to collect data before failure.
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**Acronyms**

ABL – Airborne Laser

CAD – Computer Aided Design

CG – Center of Gravity

COIL – Chemical Oxygen Iodine Laser

FEA – Finite Element Analysis

FEM – Finite Element Model

HEL – High Energy Laser

HP – High Powered

IR – Infrared

LASER – Light Amplification by Stimulated Emission of Radiation

LP – Low Powered

MARTI – Missile Alternative Range Target Instrument

OSM – Optical Sensor Module

RADAX – Radial-Axial
Chapter 1. Introduction

The High Powered Missile Alternative Range Target Instrument (HP-MARTI) is a program currently under development at Massachusetts Institute of Technology, Lincoln Laboratory. HP-MARTI is designed to test and characterize the Airborne Laser (ABL) by gathering optical data. The Airborne Laser is a system of 3 lasers affixed to a retrofitted Boeing 747 Freighter. The ABL is designed to acquire and track missiles and perform boost-phase missile interceptions. Once the missile is tracked the ABL directs a lethal, megawatt class laser beam onto the missile body until the missile fails.

The Missile Alternative Range Target Instrument (MARTI) program consists of three main components that integrate an optical sensor package into an expendable rocket to simulate ballistic missile conditions; the components are the vehicle, ground stations, and payload. The vehicle is a 2-stage Terrier Black-Brant rocket; the ground station serves as a data acquisition and calibration point. The payload contains three stacked optical sensor modules (OSM) and a fourth module containing a telemetry box; an overall schematic is shown in Figure 1. In order to quantify the performance characteristics of the ABL, each OSM has 512 optical sensors designed to measure the intensity of different wavelengths of the infrared spectrum. The MARTI Program involves two similar modules, the low power (LP) and high power (HP). Essentially, the difference between these is the LP uses a non-lethal surrogate high energy laser and the HP uses the lethal high energy laser. This

Figure 1: MARTI ascending into the atmosphere.
project considers the impact of the high energy laser and other atmospheric effects on the performance of the optical sensors.

1.1 HP – MARTI Thermal Environment

The HP-MARTI thermal environment will greatly affect its survival. Just as any system, the thermal environment abides by the conservation of energy

\[ \sum Q = mC_p \Delta T \]  

(DeWitt and Incropera, 2002). Although this is true at all locations, the energy conservation is most interesting at the surface where several components affect the thermal environment. Both aerodynamic heating and the megawatt laser will influence the thermal and structural stresses on the module. Although the effects of the laser are much more substantial than the aerodynamic heating, it is important to characterize both heating mechanisms.

1.1.1 Aerodynamic Heating

The estimated window of opportunity for the ABL to acquire the HP-MARTI module is between altitudes of 40,000 ft and 100,000 ft. When flying at these altitudes at a high velocity, the HP-MARTI is subject to extremely high surface temperatures caused by aerodynamic heating. At high speeds, i.e. Mach number > 2.5, viscous forces can generate a significant amount of heat; as a result, structural temperatures can rise dramatically (“A Manual for Determining Aerodynamic Heating,” 1959). Aerodynamic heating occurs when viscous and heat transfer effects at the body’s surface cause an
increase in surface temperature, with the potential to reduce material strength. Although materials are chosen and developed to withstand high temperatures and aerodynamic heating, the skin temperature rise needs to be quantified.

1.1.1.1 Boundary Layers

Aerodynamic heating is the heating of a body as it passes through a fluid and often occurs within a boundary layer. A boundary layer is, essentially, a thin fluid layer affixed to the surface of the body. Viscous forces are present only in the boundary layer; furthermore, the fluid outside of the boundary layer can be assumed inviscid. At the body’s leading edge, the boundary layer is ordered, or laminar. At some distance from the leading edge, the laminar boundary layer transitions to random motion and rapid growth, or turbulent. The region in between is characterized by a transition boundary layer. It is important to identify the laminar, transition, and turbulent boundary layers because the shear stresses and, thus, heat transfer rates differ between these three regimes.

As fluid flows over a solid surface, there is a frictional force between the surface and the fluid. These viscous shearing stresses do work on the fluid and cause the fluid temperature to rise. This viscous force also retards the motion of the fluid relative to the surface. This retardation causes a fluid velocity profile, where the fluid velocity gradually decreases until fluid adjacent to the surface stagnates, i.e. $V_{rel} = 0$. As the fluid motion diminishes, the fluid loses kinetic energy and some kinetic energy is converted into thermal energy. The thermal energy is transferred from the high temperature flow field to the surface.
1.1.1.2 Modes of Heat Transfer

Aerodynamic heating occurs with the boundary layer due to a combination of heat transfer processes: convection, conduction, and radiation. We will review the important characteristics of these modes of heat transfer.

**Convection**

Convection is the transfer of heat between a solid and an adjacent fluid. It is induced by fluid motion and, more specifically, motion of the fluid within the boundary layer. Forced convection occurs when fluid circulation is influenced by some driving force. Aerodynamic heating is caused by forced convection when viscous forces drive the fluid motion.

The temperature difference between the surface and fluid cause the development of a thermal boundary layer. This temperature gradient causes the fluid and body to exchange energy to attain thermal equilibrium. The convective heat transfer rate across the boundary layer can be defined by

\[ h = \frac{-k \frac{\Delta T}{\Delta y}}{T_s - T_{\text{fluid}}} \]  

(1-2)

In the above expression, \( h \) is the convective heat transfer coefficient, \( k \) is the thermal conductivity of the fluid, \( \Delta T / \Delta y \) represents the temperature gradient within the boundary layer, and \( T_s \) and \( T_{\text{fluid}} \) are the surface and boundary layer fluid temperature, respectively (DeWitt and Incropera, 2002).
Conduction

Heat conduction occurs through a solid, multiple adjacent solids, or a fluid with no relative motion adjacent to a solid. Heat transfer occurs where a temperature gradient exists, transferring energy from high temperature areas to low temperature areas. The heat transfer rate for one-dimensional heat conduction is characterized by

\[ q'' = -k \frac{\Delta T}{\Delta x} \]  (1-3)

where \( q'' \) is the conductive heat flux, \( k \) is the thermal conductivity, \( \Delta T \) is the temperature gradient, and \( \Delta x \) is the material thickness (DeWitt and Incropera, 2002).

Within the HP-MARTI aerodynamic heating, conduction occurs at the missile surface. Because the flow field at the surface is stagnated and a temperature variance exists between the free-stream and missile surface, the above equation is appropriate for the heat flux at the HP-MARTI surface because there is no fluid motion; the energy exchange between the stagnated fluid and the surface is dictated by conduction.

Radiation

Radiation, much like convection and conduction, occurs due to an existing temperature gradient between a body and its surroundings. Bodies constantly radiate heat, reducing their internal energy, to obtain thermal equilibrium with their surroundings. The thermal radiation heat flux can be described by

\[ q'' = \varepsilon \sigma \left( T_{\text{surf}}^4 - T_{\text{surr}}^4 \right) \]  (1-4)
where \( q' \) is the heat flux, \( \varepsilon \) is the material emissivity, \( \sigma \) is the Stephan-Boltzmann constant \((5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4})\), and \( T_{\text{surf}} \) and \( T_{\text{surr}} \) are the temperatures of the surface and the surroundings, respectively (DeWitt and Incropera, 2002).

The emissivity is a material property that characterizes how effectively the material radiates heat. More importantly, a material’s emissivity dictates surface temperature due to radiation. Aside from boundary layer heat transfer, solar radiation significantly affects the aerodynamic heating. A National Advisory Committee for Aeronautics (NACA) report illustrates in Figure 2 the relationship between emissivity and surface temperature for a flat plate of different materials. Using materials with higher emissivities is one method used to decrease surface temperatures.

![Figure 2: Effect of emissivity on surface temperature.](image)

1.1.2 Laser Effects

Because HP-MARTI is designed to characterize the Airborne Laser, the greatest contributor to its thermal environment is the megawatt laser. The sensing modules will be
illuminated by the high energy laser causing an increase in skin temperature that can greatly affect the material strength and, thus, the HP-MARTI durability.

1.1.2.1 Laser Properties

Light Amplification by Simulated Emission of Radiation (LASER) is the process of creating a light source of a defined wavelength. A typical laser emits light in a narrow, steady beam. Lasers consist of three parts: a pump source, a gain medium, and an optical resonator. The pump source provides the energy to the laser. The energy is “pumped” into the gain medium causing its optical properties to change. The gain medium determines the wavelength of the laser. The light illuminates within an optical resonator that has a partial reflector. During resonation the light is amplified by stimulated emission by reflecting between optics. The partial reflector allows the light to be emitted from the optical cavity.

1.1.2.2 Laser Heating

When the high energy laser illuminates HP-MARTI, some of the energy emitted will be reflected and the rest will be absorbed by the skin. The absorbed energy will heat the skin and cause its surface temperature to rise. The absorption of laser radiation by the surface is caused by radiation.

Figure 3: HEL illuminating HP-MARTI.
The laser absorption heats the surface; heat then conducts away from the surface into the solid by conduction. The heating of the material is described by the relationship for energy and temperature difference

\[ E = mC_p\Delta T \] (1-5)

where \( E \) is the energy, \( m \) is the mass, \( C_p \) is the specific heat, and \( \Delta T \) represents the temperature difference (DeWitt and Incropera, 2002).

### 1.2 HP – MARTI OSM Structure

The OSM shell is a double walled aluminum skin. The outer skin is a heat shield to protect the inner components and is, essentially, expendable. The inner skin carries the structural loading that is transferred through the module. The skins are connected together at a RADAX joint. The outer skin is bolted to the inner skin with a 0.3cm spacer that allows for an air gap between the two layers of aluminum. The radax joints are the connecting points for each of the HP-MARTI module sections and are further discussed in the next section. The total diameter of the OSM is 0.56m, and the final length including a male and female radax joint at each end is 1 meter. The 512 optical sensors that lace the inner and outer skins of the OSM are radially spaced (around the module centerline) at 11.25°. The axial spacing between each hole is 0.06m.

![Figure 4: 1 meter OSM section.](image)
1.2.1 Radial-Axial Joints

The radial-axial (RADAX) joints are connecting pieces of the HP-MARTI assembly. Their function is to transfer all the forces along the modules that they connect, including other sections of the rocket. The radax joints provide both axial and radial loading support. These joints will be the connecting points between all the separate sections of the rocket. Figure 5 shows the union between these female and male radax joints.

![Figure 5: Mated radax joints with loading indicators.](image)

The green arrow shows the axial support of the loading from the radax joints. At this location, the surfaces normal to the axial loads are in direct contact with the next surface. This allows the loading to be transferred from the one section through the radax joint to
the next section. Additionally the red arrow illustrates the location of the “shear shoulder” that provides radial support of the loading between the radax joints. Finally a bolt will pre-stress the joint so that there will be an initial load that will prevent the likelihood of the radax joint becoming dislodged.

1.2.2 Aluminum Skin

The HP-MARTI skins are constructed of anodized Aluminum Alloy 6061 T-6. This series of aluminum alloys are made up primarily of aluminum, magnesium, and silicon. The temper treatment, T-6, denotes that the alloy has been solution heat treated and artificially aged. This heat treatment process on the alloy gives it larger yield and tensile strengths. This alloy is used for the HP-MARTI skin because of the increased strengths of this treated material as the module will endure severe launch loads and thermal stresses.

1.3 Possible Structural Failure Mechanisms

The HP-MARTI anodized aluminum structure will endure a combination of thermal stresses and aerodynamic loads. When the high energy laser hits the missile, the energy will be absorbed by the missile’s skin, and it will begin heating. Due to the high energy that the laser transmits, the rocket will undergo severe thermal and structural stresses. The increase in thermal energy will cause the aluminum outer skin to expand and/or melt.

The optical sensors are composed of a ceramic designed to withstand these harsh conditions and will not fail. However, the structural integrity of the HP-MARTI structural
integrity could be compromised by a variety of mechanisms, especially melting and thermal expansion, caused by the thermal and structural environments. Very likely, a combination of these mechanisms will lead to increased thermal and structural stresses and cause structural failure.

1.3.2 Melting

The thermal energy transferred from the laser and due to aerodynamic effects increase the MARTI outer skin temperature. The solid to liquid transition for Aluminum 6061 is at 582°C (or 855K). With the megawatt class laser illuminating the target, the amount of energy transferred to the aluminum is very high. Because the rocket rotates, the laser beam’s energy will be distributed in a ring around the outer skin. Increased exposure to the HEL will cause the surface of the HP-MARTI module to achieve very high temperatures that will eventually the material to melt. When the material melts, the shell could melt away and no longer protect the sensors or cover the sensors.

1.3.1 Thermal Expansion

Rising temperatures cause a material’s volume to increase, i.e. thermal expansion. The amount of expansion is dependent on the specific nature of the material; each material has a unique coefficient of thermal expansion, $\alpha$; for Aluminum 6061, $\alpha = 23.6 \, \mu m/m^{\circ}C$ at room temperature (Boyer and Gall, 1990). Using a simple thermal expansion equation, we can determine the thermal expansion ratio

$$\frac{L_f}{L_i} = 1 + \alpha \Delta T$$  \hspace{1cm} (1-6)
where $L_f$ is the final length, $L_i$ is the initial length, $\alpha$ is the CTE, and $\Delta T$ represents the temperature difference. It is assumed that only the length expansion is significant and the

CTE varies with temperature. Figure 6 illustrates the theoretical thermal expansion of the HP-MARTI shell. Knowing this ratio will help determine the expected deformation with respect to the rising temperatures. Ultimately, the concern is not that the aluminum shell expansion will compromise sensor performance by over stressing the sensor assemblies.

1.4 Project Objectives and Methodology

HP-MARTI’s requirement for survivability specifies that the optical sensors must be able to gather sufficient optical data. To gather this data, the missile must follow a specified trajectory for a given amount of time. The structural integrity of the shell
directly impacts the optical sensor alignment, which affects their calibration. This change will compromise the optical sensor’s capability to gather accurate and adequate data.

With respect to the HP-MARTI survivability requirement, the objectives of this MQP are to:

1. Determine the durability of the HP-MARTI structure with respect to its survivability requirement by analytically modeling the aerodynamic heating and laser conditions to evaluate the structural integrity of the HP-MARTI shell.

2. Measure the temperatures of aluminum squares under actual laser testing to compare to the analytical predictions of the HP-MARTI skin performance to validate the thermal model.

The methodology used to determine the HP-MARTI durability is described below:

1. Determine mechanisms that could jeopardize the HP-MARTI structural integrity. These include radiation, aerodynamic heating, laser-on conditions, melting, and thermal expansion.

2. Perform aerodynamic heating analysis using Gambit and Fluent, finite element codes designed to model fluid flow and heat transfer. Create an external flow field model in Gambit. The results of this analysis will be compared to analytical calculations and a more specific code, the ABRES Shape Change Code, to determine if the mesh is appropriate and verify thermal results. Deliver heat transfer coefficients and recovery temperatures for thermal analysis.

3. Perform a thermal analysis by incorporating the aerodynamic heating results and simulating the high energy laser on the rotating HP-MARTI surface. Develop a
thermal model in ABAQUS/Standard™ that simulates the vehicle roll and the laser. Deliver the temperature values for structural analysis.

4. Evaluate the structural integrity of the HP-MARTI shell via a coupled thermal and structural analysis. Construct a structural model in ABAQUS/Standard™ incorporating the launch and aerodynamic loads, temperatures, and rotational loads.

5. Evaluate results of the structural model to determine the HP-MARTI durability.

The methodology used to experimentally measure the HP-MARTI skin performance is described below:

1. Create and run an aluminum square model in ABAQUS/Standard™. These results will determine the optimum thermocouple locations.

2. Configure test equipment. This includes assembling thermocouples, drilling the aluminum squares, and peening thermocouples to the squares. Also, determine the laser aperture radius and location. Develop a heat shield for thermocouples located on front surface of squares.

3. Design a test matrix. This matrix includes several tests that will evaluate the squares at select laser irradiances and material absorptivities.

4. Compare experimental temperature and computational thermal model results to verify model accuracy.
Chapter 2. Aerodynamic Heating Modeling and Data Analysis

2.1 Aerodynamic Heating Modeling Software

The complexity of the aerodynamic heating analysis requires the use of computational fluid dynamics computer analysis. The software packages used for the aerodynamic heating analysis were Fluent™, Gambit™, and the ABRES Shape Change Code.

Fluent™, a general purpose computational fluid dynamics software, is used to analyze the model created in Gambit™, a model and mesh generation tool. Using Gambit, it is simple to appropriately mesh a created geometry using boundary layer meshing and sizing functions. Fluent is a very robust program as it has an array of turbulence models that approximate turbulent effects in a variety of flow fields. Most importantly, Fluent is designed with the capability to approximate the boundary layer transition from laminar to turbulence; however, Fluent has not been able to accurately determine the boundary layer transition.

The ABRES Shape Change Code (ASCC) is primarily used to assess nose-tip heating and ablation. ASCC uses integral boundary layer equations to generate approximate solutions for shocks and boundary layer conditions over the body. ACSS is a finely tuned code that can accurately characterize these conditions (King, et al., 1986). Fluent is a more comprehensive code; thus, it is desired to determine if Fluent can be applied to a specific purpose, i.e. shock and boundary layer conditions. Comparison of the ACSS and Fluent solutions will not only verify the accuracy of the results but also lead to a correlation between the two codes.
2.2 Modeling Procedures and Analysis

To simplify the viscous solution, the model is divided into two sections: the solid boundary, MARTI, and the external flow field, the atmosphere. Because the geometry, material, and boundary conditions are symmetric about the MARTI axis, the missile can be modeled and analyzed as axisymmetric. To further simplify the model, the MARTI boundary includes only the necessary segment of the rocket, the nose-tip to the end of the payload modules. For the purposes of aerodynamic heating analysis, an external flow field model is created, appropriately modeling the MARTI geometry, boundary layers, and an extensive external flow field. Generating a suitable mesh is primarily dictated by the boundary layer, stagnation point, and changes in surface geometry inclination. For Fluent to accurately represent the boundary layer conditions, it is appropriate to make the mesh finer near the MARTI surface and at the stagnation point (nose-tip).

Figure 7: Segments modeled in MARTI boundary.

Figure 8: External flow field and mesh.
After generating the geometry and mesh, we ran initial laminar and turbulent boundary layer solutions. The appropriateness of the model and mesh was evaluated within the framework of existing models (ASCC) and analytical approximations. Because the HP-MARTI analysis is an on-going project at MIT Lincoln Labs, we used previous data from ASCC for comparison to the Fluent results. Also, the flow field conditions, i.e. high velocity and high Mach number, allowed us to assume that the MARTI surface is comparable to a flat plate. The most significant difference between the MARTI surface and a flat plate is the shock at the nose-tip and at the diameter change; nevertheless, flat plate heat transfer approximations are valid for comparison to the Fluent solution for the MARTI surface.

We evaluated the laminar solution to determine the anticipated boundary layer transition to turbulence. Due to the complexity of the problem, we are only able to calculate the surface heat flux at the stagnation point. Because the nose-tip conditions are of greatest concern when assessing aerodynamic heating, it is very important that the nose-tip heat flux is calculated correctly. Thus, for the purposes of this analysis, calculating only the stagnation point heat flux is sufficient; furthermore, this value represents the highest heat flux attained on HP-MARTI. As seen on Figure 9, the Fluent
and ASCC solutions show a good match. The laminar Fluent solution should also agree with the calculated stagnation point heat flux. The stagnation point heat flux for axisymmetric flow is specified as

\[ q^* = 0.763 \Pr^{-0.6} \left( \frac{\rho_t \mu_t K}{\rho_w \mu_w} \right)^{0.5} \left( \frac{\rho_w H_w}{\rho_t H_t} \right)^{0.1} C_p \left( T_t - T_w \right) \]  

(2-1)

where \( \Pr \) is the Prandtl number, \( \rho \) is the density, \( \mu \) is the viscosity, \( K \) represents the local velocity gradient, \( C_p \) is the specific heat capacity, and \( T_t - T_w \) represents the temperature gradient between the stagnation temperature and the initial wall temperature (White, 1974). To calculate the heat flux, we must first derive the stagnation properties. Simple incompressible calculations can determine the stagnation temperature from
\[
\frac{T_2}{T_1} = \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{-1} \quad (2-2)
\]

using \( \gamma = 1.4, M = 3.9, \) and \( T_1 = 200.5 \text{K} \), we find that \( T_1 = 810.42 \text{K} \). At the nose-tip, the flow field experiences a shock. Thus, the density must utilize relations from the Normal Shock Tables for \( M = 3.9 \) \( \frac{\rho_2}{\rho_1} = 4.516 \) and \( \frac{T_2}{T_1} = 3.893 \) (Anderson, 2007).

From these relations, we determine that the density at the wall is \( \rho_2 = 1.0694 \frac{\text{kg}}{\text{m}^3} \), and the relationship between the wall density and stagnation density is obtained from

\[
\frac{\rho_2}{\rho_1} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma - 1}} \quad (2-3)
\]

From these relations we determine that the stagnation density is \( \rho_1 = 1.22 \frac{\text{kg}}{\text{m}^3} \).

Temperature greatly affects the air’s viscosity. Using the Sutherland’s formula, we can determine the viscosity of air at various temperatures; the total viscosity is obtained from

\[
\mu_i = \mu_{\text{ref}} \left(\frac{T_{\text{ref}} + C}{T_1 + C}\right) \left(\frac{T_1}{T_{\text{ref}}}\right)^{\frac{3}{2}} \quad (2-4)
\]

with \( \mu_{\text{ref}} = 18.27 \times 10^6 \text{Pa} \cdot \text{s} \), \( T_{\text{ref}} = 291.15 \text{K} \), and \( T_1 = 810.42 \text{K} \) (DeWitt and Incropera, 2002); thus, the total viscosity is \( \mu_i = 3.75 \times 10^6 \text{Pa} \cdot \text{s} \). Similarly, the viscosity at the wall can be obtained from the Sutherland’s formula with \( \mu_{\text{ref}} = 18.27 \times 10^6 \text{Pa} \cdot \text{s} \), \( T_{\text{ref}} = 291.15 \text{K} \), and \( T_2 = 780.5 \text{K} \). The viscosity at the wall is \( \mu_w = 3.66 \times 10^6 \text{Pa} \cdot \text{s} \).

The heat transfer within the boundary layer depends heavily on the value \( K \) that characterizes the local velocity gradient and is derived from the free-stream conditions (White 1974). The following equation defines \( K \)
Using $V_\infty = 1108 \text{ m/s}$, $\rho_\infty = 0.2368 \text{ kg/m}^3$, $\rho_t = 7.778 \text{ kg/m}^3$, and $D = 0.0254 \text{ m}$, we find that $K = 54360 \text{s}^{-1}$. The Prandtl Number relates the momentum and thermal diffusivity and is a function of the free-stream conditions. It can be evaluated using $C_p = 1004.77 \text{ J/kg} \cdot \text{K}$, $\mu_\infty = 1.33 \times 10^{-5} \text{ kg/m} \cdot \text{s}$, and $k = 0.018 \text{ W/m} \cdot \text{K}$ in the equation below

$$Pr = \frac{C_p \mu}{k}$$

(2-6)

to find that $Pr = 0.742$. Finally, we can evaluate the stagnation point heat flux as

$$q^* = 7.27 \times 10^5 \text{ W/m}^2 = 0.0727 \text{ kW/cm}^2$$. The Fluent result for the stagnation point heat flux is $7.02 \times 10^5 \text{ W/m}^2$, which is within 3.5% of the calculated heat flux.

Fluent is designed with a “transitional flows” capability; ideally, this function would allow Fluent to solve for the laminar, turbulent, and transitional flows in a single run. This transitional analysis works for simple flat plate problems; however, more complex problems, such as HP-MARTI, cannot be solved using this functionality as the code assumes the entire boundary layer as turbulent. Thus, a method used to attempt to solve for the entire boundary layer was dividing the external flow field into two sections. The forward section would model the laminar boundary layer and the aft, the turbulent boundary layer. To determine the location of the division, we used known critical Reynolds numbers for flat plates. In a flat plate analysis, it is assumed that the boundary layer transitions to turbulence at some critical Reynolds number between 100,000 and
3,000,000 (DeWitt and Incropera, 2002). Using the atmospheric conditions to solve for the transition location,

\[ x = \frac{\text{Re} \cdot \mu}{\rho V} \]  

(2-7)

the boundary layer begins to transition between 0.005m and 0.15m from the nose-tip. Using a value of \( x=0.15 \)m, we separated the external flow field and ran several iterations.

**Figure 10**: Fluent transitional flow results.

Fluent was able to assess the entire boundary layer, both laminar and turbulent; however, there was an inconsistency in the transition layer, as indicated in Figure 10. Additionally, the stagnation point heat flux is low, \( 6.31 \times 10^5 \frac{W}{m^2} \) in comparison to the calculated heat flux, \( 7.27 \times 10^5 \frac{W}{m^2} \).
Because of this inconsistency, we decided to use only the turbulent aerodynamic heating results for the thermal and structural analyses. The entire missile is approximately 18 meters in length; thus, when determining the boundary layer conditions and aerodynamic heating, it is justified to assume the vast majority of the boundary layer is turbulent. For the purposes of providing the HP-MARTI aerodynamic heating conditions

![Figure 11: Fluent turbulent solution.](image)

to the thermal and structural analyses, the entire boundary layer over the payload modules is turbulent. The turbulent solution also agrees with the ASCC results. At position 2.2m from the nose-tip, there is an inclination in the HP-MARTI geometry. As seen in Figure 11, the surface heat flux increases. This increase in heat flux is caused by a shock at the
geometry inclination. The differences in heat flux between the Fluent and ASCC results are due to this geometry. ASCC uses a more crude geometry, and Gambit is very specific.

2.3 Aerodynamic Heating Results

The surface temperatures derived from the aerodynamic heating analysis are used in the thermal and structural models. Figure 12 exhibits the OSM surface temperatures. The aerodynamic heating model assumes the initial surface temperature is 30°C. The temperature reached at 40,000 ft is 255°C; the aluminum melting point is 582°C. Thus, the aerodynamic heating alone will not cause material failure.

![Temperature vs Altitude graph](image)

**Figure 12:** Surface Temperature Resulting from Ascent Heating.

Between 5000 and 20,000 feet, the aerodynamic heating does not increase linearly. This occurs because MARTI utilizes a 2 stage Black Brant IX rocket. In a multi-stage rocket,
each stage contains its own fuel and engines. The stages are configured in series but burn sequentially. The first stage acts during lift-off and, when all the fuel is expelled, is released from the vehicle. Between 0 and 20,000 feet, the first stage provides the thrust, and the vehicle velocity increases rapidly. The first stage provides the thrust for the rocket through the thickest part of the atmosphere. After the stage expels its fuel, it takes some time to be released from the rocket. Aerodynamic heating is a function of velocity and altitude as the density decreases, as the heat generated by the viscous forces increase with increasing velocities.
Chapter 3. Thermal Modeling and Data Analysis

3.1 Thermal Analysis

The thermal environment analysis coupled the aerodynamic heating with the laser-on conditions and simulated the vehicle roll to assess the thermal expansion and stresses on HP-MARTI payload. To achieve an accurate representation of the thermal heating that will occur when the rocket is in flight a Finite Element Analysis (FEA) was needed to simulate the effects of the aerodynamic and laser heating.

Complete modeling and analyzing all heat transfer modes using any Finite Element (FE) codes requires large amounts of time and massive amounts of computing power. In order to shorten the time and decrease the computing power needed, a simplified model was developed.

The aerodynamic heating conditions from Fluent were used as the initial thermal conditions for the laser to hit. A model was generated using ABAQUS/CAE™ software. A time-stepped method was developed to model the vehicle roll. The ABAQUS/Standard™ solver code was used for the thermal analysis.

The selected location to apply the laser beam heat spot was semi-arbitrary as there are many different locations to where the laser can hit the OSM. This location was selected because the laser energy will be deposited on the surface of the skin and the radax joint. This analysis therefore, provides preliminary data on the performance of both the skin and the radax joint under the laser radiation.

Simple, conservative analytic calculations of each of the modes of heat transfer will provide estimates the heat flux. To perform these simplified analytical calculations,
equations for convective, conductive, and radiating heat transfer were applied to the thermal environment that the HP-MARTI module is expected to experience. Comparing these values of each mode to the energy of the laser, we quantified each mode’s contribution to the overall thermal environment. This allowed for simplification of the thermal model by excluding the negligible factors.

3.2 Evaluation of Heat Transfer Effects

Several heat transfer mechanisms affect the HP-MARTI thermal environment. They include the high energy laser (HEL), aerodynamic heating, surface radiation, and convection between the outer inner HP shell structure. Although it is valid and justified to assess the various heat transfer mechanisms affecting the HP-MARTI shell, only the HEL will significantly contribute to the HP-MARTI shell’s rising temperatures. The high energy laser heat flux is on the order of $10^{3}$ kW cm$^{-2}$. The following sections compare the aerodynamic heating, surface radiation, and convection between the inner and outer shell with the heat flux due to illumination.

Figure 13: HP-MARTI thermal environment.
3.2.1 Aerodynamic Heating

Although aerodynamic heating can cause serious damage to the ascending missile, its effects are small in comparison to megawatt class lasers. Figure 14 details the ratio of heat fluxes,

\[
\text{%Heat Flux} = 100 \times \frac{\text{Stagnation Point Aerodynamic Heating}}{\text{Megawatt Laser}}
\]

for several laser heat fluxes. The aerodynamic heating is greatest at the nose-tip, i.e. the stagnation point. Figure 14 illustrates the relationship between the stagnation point heat flux and various heat fluxes due to the megawatt laser. Comparing the aerodynamic heating to a laser heat flux of magnitude \(10 \text{ kW/cm}^2\), Figure 14 shows that the aerodynamic heating at the stagnation point, \(0.0727\text{ kW/cm}^2\), is very small in comparison to the megawatt

---

**Figure 14:** Aerodynamic heating in relation to megawatt class lasers.
laser. Although the aerodynamic heating effects serve as the initial conditions for the laser-thermal environment, any detriment to the HP-MARTI shell will ultimately be caused by the high energy laser.

### 3.2.2 Radiation

The laser heating causes the aluminum skin temperatures to rise and the surface to radiate heat in order to attain thermal equilibrium. Using the melting temperature as the OSM surface temperature, we evaluated the “worst case” radiation heat flux.

![Figure 15: Radiation in relation to megawatt class lasers.](image)

We determined the radiation heat flux using

\[ q^\prime = \varepsilon \sigma \left( T_{\text{surf}}^4 - T_{\text{surr}}^4 \right) \]

(3-2)
At 40,000ft, the radiation heat flux is $0.0037 \text{ kW cm}^{-2}$. This value remains fairly constant for several altitudes. Similar to the aerodynamic heating comparison, Figure 15 illustrates the ratio of heat fluxes for several laser heat fluxes. The radiation heat flux is only 0.037% of a $10 \text{ kW cm}^{-2}$ laser heat flux. Thus, when analyzing the effects of the megawatt laser, any radiation between the MARTI surface and the surrounding atmosphere is negligible.

### 3.2.3 Convection Between Inner and Outer Shells

Each module has an inner and outer shell. These shells are separated by a layer of air; thus, convection heat transfer occurs within the two layers of the HP-MARTI structure. Convection heat transfer is described by

$$ q'' = h(T_s - T_\infty) $$

where $h$ is the convection heat transfer coefficient, $T_s$ is the surface temperature and is unknown, and $T_\infty$ is the free-stream temperature. The convection heat transfer coefficient dictates the magnitude of the convection heat flux.

The Nusselt number is used to nondimensionalize the heat transfer coefficient, $h$, and represents the heat transfer through a fluid by comparing the convection and conduction heat transfer by (Cengel, 2003)

$$ Nu = \frac{hL}{k} = C(Gr_L \text{ Pr})^{\frac{n}{2}} = CRa_L^n $$

(3-4)

From this relation, the Rayleigh number is defined as

$$ Ra_L = Gr_L \text{ Pr} $$

(3-5)
Recall from the Aerodynamic Heating Modeling Procedures and Analysis that $Pr = 0.742$. The Grashof number, or the ratio of buoyancy to viscous forces, is

$$Gr_L = \frac{g \beta (T_s - T_\infty) L^3}{\nu^3}$$  \hspace{1cm} (3-6)

Assuming $T_s = 773.5K$ (or 500°C), $T_\infty = 200.5K$, $\beta = \frac{1}{530.6}$, $L = 1m$, and

$$\nu = 14.6 \times 10^{-6} \frac{m^2}{s},$$

we find that $Gr_L = 4.96 \times 10^{10}$. Using the definition of the Rayleigh number, we find that $Ra_L = 3.71 \times 10^{10}$. We can now use the relation for Nusselt number

$$Nu = \left\{ 0.825 + \frac{0.38Ra_L^{1/6}}{1 + (0.492/Pr)^{9/6}} \right\}^{2}$$  \hspace{1cm} (3-7)

and the previously calculated Rayleigh and Prandlt numbers to find that $Nu = 327.15$.

Knowing the value of the Nusselt number, the convection heat transfer coefficient is

$$h = \frac{kNu}{L} = 6.70 \frac{W}{m^2K}.$$ Using equation (3-3) and assuming $T_s = 773.5K$ (or 500°C) and $T_\infty = 200.5K$, we find that, at 40,000ft, the convection heat flux is

$$q'' = 3.84 \frac{W}{m^2} = 3.84 \times 10^{-5} \frac{kW}{cm^2}$$  \hspace{1cm} (3-8)

This convective heat flux, therefore, is negligible in comparison to the heat flux from a 10 $\frac{kW}{cm^2}$ laser.
3.3 Thermal Structural Finite Element Software

Analyzing the complicated thermal environment requires the use of advanced finite element analysis. In order to solve the numerous equations of the finite element model, the aid of computers and finite element software will be needed. The software of choice is ABAQUS™. ABAQUS is an advanced finite element solver that has the capability to solve non-linear and large scale linear dynamics. Most notably, ABAQUS has the ability to conduct both thermal and structural analysis. ABAQUS supports a wide variety of features that can simplify the problem and reduce computational time, such features include axisymmetric analysis and both 2D and 3D element types. All of these features are in a graphical interface known as CAE which allows the user to interact with the software more efficiently.

The ABAQUS software suite will be used to conduct the thermal analysis of the OSM with the aerodynamic heating and the laser beam illumination. Those results will be imported into another ABAQUS model that is setup to conduct the structural analysis. Lastly, ABAQUS will be used to model the axisymmetric aluminum squares to support the laser testing.

3.4 Thermal Environment Modeling Procedures

The first step in modeling the HP-MARTI module is to simplify the actual CAD model. All the internal features were removed as they did not contribute to the thermal environment. Next, the radax joint was simplified into a square. This is possible because the bolt connections connecting the skins to the radax joints are pre-stressed, causing the joint and the skins to be in direct contact making it a rigid structure.
A finite element model of HP-MARTI was generated with correct dimensions and with all the optical sensors as previously detailed. In order to reduce the time and computing resources it takes to build the FEA geometry, we took into account that the HP-MARTI module is symmetric. That allowed us to generate one part of it and use the symmetry features of ABAQUS to pattern this part and construct the entire module. This process is illustrated in Figure 16.

Once the model was generated the next step was meshing. To reduce the amount of work, the thermal model that was generated for the thermal analysis was also used for the structural analysis. Because the model was used for two different analyses, the model had to be carefully meshed to insure accuracy for both analyses. Unlike ordinary thermal analysis that does not require structured meshing; the structural analysis that was performed had a mesh linearity requirement. For the structural mesh to be accurate, load
paths from the top of the module have to be linear to the bottom of the module. This allowed the loads to be transferred accurately without the likelihood of skew as with non-linear meshing techniques. Since there is no cross-body lateral loading, there was no need to linearly constrain the mesh in the lateral orientation. However, with all the holes in built into the module for the optical sensors, the meshing algorithms were unable to mesh the geometry with linear longitudinal load paths. This was addressed by creating partitions along each of the patterned sections that make up the HP-MARTI assembly. These partitions laid tangent to the holes and constrained the load paths allowing the meshing algorithm to correctly mesh the geometry. After the meshing was completed, we were then able to simply change the thermal loads to structural loads for the structural analysis. In addition, these partitions set the time steps for the laser surface heat flux.

![Figure 17: Mesh of the pattern for modeling of HP-MARTI.](image)
The next step incorporated the aerodynamic heating data simulated with Fluent™ into the model. Because the aerodynamic heating varies as a function of altitude which is time dependent in the trajectory, the convective coefficient and recovery temperatures have to be specified in a table as a film condition on the outer skin surface. The initial conditions for this analysis came from the aerodynamic heating results in the form of recovery temperatures as a function of time (see Figure 12).

Finally the effects of the laser on the module are modeled. The first assumption is that the laser beam is a flat profile commonly known as a top-hat profile. Essentially, the laser will be irradiating a flat surface evenly. However, there is also the curvature of the module to account. It was assumed that this curvature is small enough to be negligible, and design our model to be more conservative by allowing the full irradiance on the surface. If this were not the case a cosine function would have to be derived to compensate for the module’s curvature. The following equation details the cosine function for the heat flux over a curved surface such as the cylindrical OSM.

\[
\text{Heat Flux} = \alpha \times I \times \cos \left( \arcsin \left( \frac{x}{r} \right) \right)
\]

(3-1)

Where \( \alpha \) is the absorptivity, \( I \) is the irradiance, \( x \) is the radial distance from the center along the curvature, and \( r \) is the radius of the beam size.

When the laser illuminates the surface, the rocket will be rotating at approximately 2 Hz. To account for this, a time step as previously mentioned was
modeled. The total time of the run was divided into 96 partitions, allowing the laser heat flux to be distributed more accurately with respect to time.

### 3.5.1 Thermal Results

The results from the thermal analysis shown in Figure 19 details the temperature profile of both the inner and outer aluminum skins of the HP-MARTI optical sensor module. Figure 19 indicates that the outer skin will be reaching melting temperatures during the time that it will be illuminated. As the outer skin becomes hotter during the ascent, the heat is transferred through the radax joint into the inner skin. However, the inner skin does reach temperatures close to melting during the aerodynamic heating. The maximum defined solid temperature of the aluminum 6061 alloy is 582 °C. Figure 20 plots the temperatures at the center of the laser beam spot around the circumference of the beam path. As seen in Figure 20 the maximum temperature achieved by the outer aluminum skin is 533 °C at the end of a 0.5 second pulse of laser on the rotating OSM. This temperatures shows that the aluminum 6061 T-6 outer shell approaches the end of the solid state and will be entering the liquid state. At these temperatures the structural integrity of the aluminum is severely compromised. However, this occurs only at 0.5 seconds under the HEL illumination and provides enough time to gather sufficient data to characterize the airborne laser.
Figure 19: Thermal profile of aluminum skins after aerodynamic heating.

Figure 20: Surface temperatures versus circumferential location.

Even with the thermal model showing temperatures under the liquid phase, the sudden increase in temperature due to the laser will induce thermal stresses and cause the
aluminum shells to strain. These thermal strains will be modeled in the structural model using ABAQUS.
Chapter 4. Laser Testing

4.1 Laser Testing Procedure

The laser testing is designed to validate the thermal model results. A sample aluminum square affixed with several thermocouples was the target for the laser tests. Thermocouples are temperature sensors that convert temperature difference into and electrical potential difference. Essentially, a thermocouple is the junction of two dissimilar materials. Any temperature variance from a reference temperature, room temperature, will cause the thermocouple voltage to change. To determine the locations to place the thermocouples, a temperature profile of the squares must be generated. A computer model of the squares was generated using ABAQUS. These models accounted for the different absorptivities of the surfaces.

Figure 21 and Figure 22 show the ABAQUS results for the temperature profile of the aluminum squares with absorptivity 0.65. The maximum temperature achieved by this squares after 6 seconds is 615°C. The center front surface experiences a dramatic temperature rise. As the laser continues to illuminate the surface, the heat conducts through the material and outwards from the center.

Figure 21: Contour plot of 0.65 absorptivity Al squares @ 6secs.
The temperatures of the front and back surfaces converge as a function of radial distance from the center at approximately 5 mm, as seen in Figure 22. In order to confirm these curves, thermocouples were placed 2.54 mm and 4.445 mm from the center. Using these locations enables us to compare the testing data to the expected thermal results from the computer model. Also, a thermocouple was placed on the other edge of the aluminum squares as a final reference point. The schematic of the thermocouple locations are shown in Figure 23. The thermocouples are located on the front and the back at 2.54 mm and 4.445 mm from the center on two axes. Because this is an axisymmetric problem, putting thermocouples on two axes provided redundancy. This redundancy helped alleviate any
error in the thermocouple location. The back also has one thermocouple at the center of the square as well as a reference point.

A 350 W infrared laser illuminated the squares. This infra-red laser’s 930 nm wavelength is similar to the wavelength of the HEL on the ABL. However, there was concern that the laser power illuminate the squares would be above the 5 percent threshold of the thermocouples. If the power striking the squares was greater than 5 percent of the total power of the laser, the thermocouples would be under severe thermal loads. This would affect the reliability and life of the thermocouples during the experiment. In order to determine the amount of energy that would be deposited on the thermocouples, a correlation between power, irradiance and radial distance must be made. The first equation used is to determine the maximum irradiance

\[ P_{tot} = I_o \times \frac{\pi}{2} \times \omega_o^2 \]  

(4-1)

where \( P_{tot} \) is the peak power, \( I_o \) is the peak irradiance, and \( \omega_o \) is 86% power as a function of \( e^2 \). Once the peak irradiance has been determined, it can be used to determine the irradiance as function of radial distance from the center in the following equation:
\[
\frac{I(r)}{I_o} = e^{\left(\frac{-2r^2}{\alpha_o^2}\right)}
\]  
(4-2)

where \( r \) is the radius and \( I(r) \) is the irradiance as a function of the radius. Finally the power as a function of radial distance from the center must be calculated using

\[
P(r) = P_{tot} \left(1 - e^{\frac{-2r^2}{\alpha_o^2}}\right)
\]  
(4-3)

where \( P(r) \) is the power as a function of the radius. Plotting the irradiance and power as a function of radius of will give us the amount of power that we expect the thermocouples will receive. Figure 23 shows the normalized plot of the calculated values of irradiance and power as a function of radius.

**Figure 24:** Plot of Irradiance versus Power in the radial direction.
From Figure 24, we can extrapolate the amount of power that the thermocouples will receive from the laser. The amount is far less than 5%; therefore, the thermocouples will not require any shielding from direct laser illumination.

4.2 Laser Testing Results

The results of the data gathered by the thermocouples are shown in plotted in Figure 25 below. This plot shows that the center back thermocouple reached the highest temperature. This is because the spot size of the beam on the surface of the aluminum square is small enough so that the heat conducted through the material was faster than the heat conducted radially from the center.

![Thermal Response of Aluminum Squares - 207W](image)

**Figure 25:** Thermal response of thermocouples at 207W laser power.
The initial slope of the temperature response from the thermocouples is similar to the initial temperature slopes of the computer model. This rapid temperature increase occurs because the sudden impact of energy on the aluminum squares causes a temperature gradient to spread through and out from the center of the aluminum square. However, this state does not last as there is convection, radiation, and conduction of the energy from the square to the room and through itself. Eventually, the entire aluminum square’s temperature increases such that the bulk temperature will rise while keeping the gradient throughout the aluminum square. The square constantly radiates heat, and convection cells around the square also help remove the heat. Lastly, aluminum has a high thermal conductivity causing the material to rapidly transfer the thermal energy evenly throughout the square.

The results of the experimental data from the laser testing were compared to the results generated from the computer simulation of the same 0.65 absorptivity aluminum square. Figure 26 shows the temperature as a function of time from a computer simulated aluminum square with 0.65 absorptivity. Similar to the experimental testing results in the

![Computer Model Results](image_url)

**Figure 26:** Computer Simulation results of aluminum square, 0.65 absorptivity.
initial temperature rise is very steep due to the sudden impact of energy on the aluminum squares. Again, once the thermal profile has been established, the bulk temperature will begin to rise while maintaining the thermal profile.

Both of these plots show similar results in their thermal data. Their initial temperature rises are very drastic and begin to stabilize as the heat has spread from the center of the square to the rest of the material. However, there are subtle differences between the experimental data and the computer simulated data. Several inaccuracies caused by surface absorptivity, time, location of thermocouples, and several effects not included in the model result in the differences between the experimental and analytical models. First is the rate of the temperature raise. The experimental data shows a larger temperature raise when compared to the computer generated results. This may be due to the alignment of the laser relative to the thermocouples. If the thermocouples are closer to the laser beam, there will be more energy deposited closer to the thermocouple thus causing the thermocouples to report such a large temperature change in the shorter amount of time. Secondly, when the temperature curves of the laser experiment stabilize, they plateau. The computer simulation shows a continuous linear temperature curve. Unlike the experimental data the system of computer model is closed. There is only one heat source, the laser, illuminating an aluminum square that will only conduct heat through itself and can only rise in bulk temperature. However, in the real life there are heat leaks, due to convection cells around the aluminum squares and surface radiation into the surround air.
Chapter 5. Structural Analysis

5.1 Structural Modeling Procedures

Because the outer skin is directly connected to the inner skin via the radax joint, all thermal stresses that the outer skin experiences will be transferred to the inner skin. Likewise, the aerodynamic loading of the accelerating rocket will be transferred from the inner to the outer skin. This understanding was used to simply the thermal model and was again used to reduce the complexity of the structural model. Two structural models were generated for the understanding of the mechanical stresses that the OSM will undergo.

The first model was a simplified structural model that was generated to understand the boundary conditions of the OSM. This simplified model allowed us to fully grasp all the loading conditions without having to work with complex geometries. The simplified model consisted of a hollow cylinder that has the same dimensions as the OSM. However, the differences will be that it will not have the 512 optical sensor holes through the two skins. Secondly, the laser beam spot will be stationary in the middle of the OSM instead of rotating around the edge encompassing the outer skin and the radax joint. This simplified model was accompanied by an exact thermal model with coincidental node locations. Working with two analogous models, meant that the structural model provided accurate results. However, the thermal model for this structural analysis did not include the aerodynamic heating data and the structural model did not include the launch loads due to the time constraints of this project. The first structural model was fully constrained in all degrees of freedom at that base of the OSM. The other end of the OSM was allowed to move freely.
Once the basic boundary conditions of the OSM were understood, the second model was generated. All the complexities that were removed for the first model were reintroduced into the second model. The first load added was the thermal loading from the aerodynamic heating and the laser-on condition. This allowed the thermal stresses to be extracted from the structural analysis. The next loads added were related to the launch and flight loadings. They consisted of the maximum 16.25 g loading from the initial liftoff and the rotational loading from the spinning of the rocket. In addition, the boundary conditions for the OSM were revised. A point mass was connected to the free end of the OSM. This point mass represented the combined masses of the components forward of the OSM that we modeled. It was located to the calculated center of gravity (CG) of the relative components. Table 1 show the weights and distances used for the CG calculation and Figure 27: MARTI illustrates the sections forward of the modeled OSM. The addition of the point mass was intended to yield more accurate structural results representing the actual loading conditions.

**Table 1**: Center of gravity for MARTI components.

<table>
<thead>
<tr>
<th>Section</th>
<th>Weight (lbs)</th>
<th>CG Station (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ogive + ORSA</td>
<td>225</td>
<td>32.00</td>
</tr>
<tr>
<td>Empty Transition</td>
<td>15</td>
<td>62.79</td>
</tr>
<tr>
<td>Empty Transition</td>
<td>30</td>
<td>74.78</td>
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<tr>
<td>Empty Transition</td>
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<td>88.75</td>
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<tr>
<td>Forward Transition</td>
<td>30</td>
<td>105.50</td>
</tr>
<tr>
<td>OSM1</td>
<td>250</td>
<td>135.44</td>
</tr>
</tbody>
</table>

**Figure 27**: MARTI
Figure 28 shown below illustrates the second model generated with all the optical sensor holes and the point mass above the OSM.

**Figure 28**: Complex FE model of OSM with a point mass connected to the radax joint.

## 5.2 Structural Results

The structural analysis used the temperatures from the thermal analysis to determine the thermal stresses on the OSM. Since the laser causes a large temperature
rise for the material that it is illuminating, the rest of the OSM will not experience the same large temperature changes due to the short amount of time that the laser is on the illuminated section relative to the thermal conductivity of the material. The thermal stresses shown in Figure 29 are predicted the edge of the laser beam spot due to the large temperature differences in that region.

The maximum Von-Mises stress experienced by the simplified model from the laser loading are predicted at 98 Mega-Pascals (MPa). The stress due to the laser loading is less than the tensile yield stress of aluminum 6061 T-6 which is 276 MPa as depicted in Figure 29 in red locations. These points are around the horizontal edges of the laser beam spot. As the laser heats the surface it will expand with the coefficient of thermal expansion for the particular material. In the case of the OSM, it is a thin walled cylindrical object that is axisymmetric around a centerline. The stresses of this cylinder can be broken up into two orientations of stresses. The first is the circumferential (Hoop stress) stress around the curvature of the cylinder. The second is the longitudinal (axial stress) stresses that is parallel to the centerline of the cylinder. The axial stress around the laser beam spot shown in Figure 29 is half that of the hoop stress which is in concordance with the equations for the thin walled pressure vessels (Hearn, 1997).
Figure 29: Maximum Von-Mises Stresses on Simplified OSM.

Figure 30: Maximum Displacement on Simplified OSM.
The OSM has 2 parallel aluminum skins that are evenly spaced. However, with the laser heating causing thermal stresses which lead to thermal expansion and strains, the two aluminums skins have shifted relative to each other. The maximum displacement depicted in Figure 30 is approximately 4.1 mm. This is a very small amount of displacement that would otherwise be negligible without the optical sensors. A cross section of the shift between the two shells shown in Figure 32 indicates the potential problems that may occur from this shifting. Depending on the amount of shift, the optical sensor stack up (Figure 31) within the sensor holes may be covered or misaligned, rendering them useless for the acquisition of optical data for characterizing the airborne laser. Further analysis of the second structural model with the aerodynamic heating, laser heating, launch loads and complex geometry is needed to accurately determine the structural integrity of the OSM under this combination of loadings.

Figure 31: Optical Sensor Stackup.
The second FE model that was generated was not complete due to the time constraints of the project. Using the second model as a framework for future analysis is described in section 6.5.4.

**Figure 32:** Cross Section of displacement between outer and inner aluminum skins.
Chapter 6. Summary & Recommendations

6.1 Aerodynamic Heating Modeling and Analysis

The objective of the aerodynamic heating analysis was to determine the effects of aerodynamic heating as well as the effects of other heat transfer mechanisms. This was accomplished through the following methods.

1. Determined several mechanisms that could jeopardize the HP-MARTI structural integrity. This list includes radiation, aerodynamic heating, laser-on conditions, melting, and thermal expansion. Each of these mechanisms was evaluated in comparison to the high energy laser.

2. Created an axisymmetric external flow field model in Gambit to analyze the effects of aerodynamic heating. Performed thermal analysis of this model using Fluent. The results of the steady-state analysis were compared to analytical calculations for flow over a flat plate and the stagnation point heat flux. The Fluent results were also compared to results from a previous analysis from the ABRES Shape Change Code.

3. Determined that the Fluent model was able to predict the HP-MARTI aerodynamic heating conditions for the laminar and turbulent portions of the boundary layer. However, Fluent was unable to accurately characterize the boundary layer conditions over the entire body. It was decided to use the results from the turbulent boundary layer as the initial conditions for the thermal and structural analysis. The thermal and structural models include only the MARTI payload modules, and analysis of potential boundary layer transition locations proved that the boundary layer over the MARTI payload is entirely turbulent.
6.2 Thermal Modeling and Analysis

The thermal analysis of the HP-MARTI module was conducted to determine the effects of the aerodynamic heating coupled with the effects of the megawatt airborne laser. This was accomplished through the following methods.

1. Created a finite element model of an optical sensor module of the HP-MARTI payload, applying the aerodynamic heating data and the laser heat onto the rotating HP-MARTI module.

2. Evaluated the effects of aerodynamic heating, radiation between the surface and surroundings, and convection between the inner and outer shells in comparison to the megawatt laser. The analysis determined that these effects are insignificant when analyzing the effects of the laser. Although it was important to characterize these heat transfer effects, any deformation of the HP-MARTI structure would be caused by the high energy laser.

3. Ran the thermal model to the theoretical time that that the laser would first be able to engage the target. The result was in the form of temperatures achieved from the loading conditions described previously. Analysis showed that the temperatures of the aluminum shells did not reach the melting point (582 °C) of aluminum. This concludes that the HP-MARTI module will not melt or ablate during its ascent to 40,000 ft and when the laser is illuminating it for 0.5 seconds.
6.3 Structural Modeling and Analysis

Launch loads and thermal strains are the major contributing factors to the stresses that the module will undergo. To understand these stresses and displacements, a structural analysis was performed. This was accomplished through the following methods.

1. Created two structural finite element models. The first was an oversimplified model to understand boundary conditions. The second used the finite element model from the thermal analysis but added a point mass with the weight of the components above the OSM 2 at the total CG of those components. Incorporated the nodal temperature values to generate thermal stresses. Applied conservative launch loads of 16g’s and a rotational load of 2 Hz.

2. The results from the simplified structural analysis showed that the magnitude of the maximum stresses does not reach the material’s maximum yield stress. The total deformation from the thermal stresses was 4.1mm.

6.4 Laser Testing

Laser testing was used to verify the results of the thermal finite element model. This was accomplished through the following methods.

1. Instrumented aluminum squares by drilling aluminum squares and peened thermocouples to the front and back surfaces of the squares. Illuminated the squares using a 940 nm laser at various beam sizes and power levels.

2. Thermal data from the laser testing revealed the material’s response to sudden laser beam impact. The result shows that the aluminum square’s experimental data are similar to the computer implantation data. Both the aluminum from the
laser testing and from the computer simulation had a sudden increase in temperature when the laser illuminated the surface. After a very short time the heat began to spread throughout the aluminum and the heating rate decreased. In conclusion the data curves from the experimental testing resembled the data curves from the computer simulation thus validating the results of the computer simulation.

6.5 Recommendations

Due to time constraints at MIT Lincoln Laboratory, several analysis be performed before the project can be considered complete. The following details the analysis recommended for the thermal and structural environments of HP-MARTI.

6.5.1 Higher Altitude Considerations

The estimated window of opportunity for the ABL to acquire the HP-MARTI module is between altitudes of 40,000 ft and 100,000 ft. At 40,000 feet, the optical sensor module structure will survive long enough for the optical sensors to retrieve adequate data. The analysis outlined in this report considers the conditions at 40,000ft; higher altitudes should be considered. The thermal and structural analyses should be completed for the maximum altitude, 100,000ft, in order to best understand the OSM responses during the ABL window of opportunity.
6.5.2 Aerodynamic Heating Analysis: Boundary Layer Transition

As addressed in Chapter 2. Aerodynamic Heating Modeling and Data Analysis, we currently do not have the means to accurately predict the boundary layer transition in Fluent. Although the turbulent solution was used for the conditions over the OSM and the aerodynamic heating decreases as the altitude decreases, it is of interest to determine a method to accurately characterize the entire boundary layer. One method used during this project was separating the flow field into two sections, one characterizing the laminar flow and a second representing the turbulent flow. To determine this location, we used flat plate assumptions/calculations. In the future, using the momentum thickness will better approximate the transition location. The momentum thickness equation illustrates the decreasing momentum flux caused by the boundary layer:

\[
\delta_2 = \int_0^\infty \frac{\rho u}{\delta} \left( 1 - \frac{u}{u_\infty} \right) dy.
\]  

(6-1)

The difficulty with this method is defining the velocity gradient. As the boundary transitions and becomes turbulent, the velocity gradient is not as easily defined. After the transition location is determined, one would create a mesh within a certain region that is normal to the surface; the mesh in this area should be very fine. Separating the flow into two flow fields at this location will, ideally, lead to more accurate Fluent results for the entire boundary layer.

6.5.3 Thermal Heating Environment Future Work

The thermal condition that was analyzed could be modified for different scenarios of the laser hitting the optical sensor module. We originally modeled the laser
illuminating the edge of the OSM and the radax joint; this can be changed so that the laser will hit the center of the OSM. The illumination at the center is a completely different scenario because the radax joint is much farther away from the laser beam spot. This is significant because the radax joint allows for additional stiffness at the edge of the OSM. Because the stiffness is decreased in the center the likelihood of the outer skin shifting over the inner skin is higher. Figure 33 illustrates the locations along the length of the OSM where the laser loading can be applied.

![Figure 33: Possible locations along the length of the OSM to apply the laser loading.](image)

Also, different irradiances should be used when modeling the laser conditions. For example lower irradiance that has a longer duration may do more damage that a higher irradiance with a shorter duration. In addition, surface absorptivity plays a role in determining how much energy is absorb by the material. Varying the absorptivity will generate data that is more applicable to a range of different missile skins.
6.5.4 Structural Analysis Future Work

The structural model was simplified so that the radax joint was the connecting member that held the two skins together. The next step would be to fully model the radax joint with the bolts that connects the inner skin to the radax joint. Also the bolts that connect the inner skin to the outer skin should be modeled to find the stress concentrations and tear out forces at the bolt locations.

In addition to adding complexity to the radax joint, the detailed model should be completed with the mass of the components above the OSM modeled as a point mass at the total CG of the contributing components as illustrated in Figure 28. This higher detailed model will incorporate the thermal results from the aerodynamic heating, laser heating, and launch loads unlike the simplified model which only included the thermal stresses from the laser heating.

Also a dynamic structural analysis should be performed as future work instead of a static structural analysis. A dynamic analysis would yield stress data that is not only temperature dependent but also time dependent as the rocket ascends.

Lastly, a dynamic buckling analysis should be performed. Buckling is a type of sudden failure that is caused by high compressive stresses similar to those undergone by rocket during launch. In combination with the launch loads, there is also the laser that impacts the outer skin. With such great thermal stresses from the laser there may be localized buckling that is only predictable with FEA tools such as ABAQUS.
Bibliography


