Simulation of Thermo Mechanical Behavior of a Ballistic Missile Model

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ABSTRACT

Thermo mechanical modeling and simulation of ballistic missile assumes importance due to the increased interest in assessing the potential of such attacks. Effective and innovative methods are sought in assessing the structural integrity of such structural components. In this study, we present modeling and simulation aspects of a generic missile loaded by high energy laser beam. We present an application of MSC software in modeling thermo-mechanical behavior, both steady state and transient behavior of missile structures. Thermal energies used for simulation correspond to high energy laser flux available at low earth orbits as reported in literature. A brief review of the concepts of laser energy involved is outlined. The analysis is performed under several scenarios that include critical thermal failures due to steady state as well as transient thermal exposures. The thermal exposure times and locations are varied to assess typical failure modes of the structure. Analysis is done in order to define suitable material thicknesses that will make a ballistic missile hardened enough to withstand these specific amounts of energy. Other parameters of interest pertaining to this study are the pulse width, and resulting transient phenomena affecting the behavior. Temperature gradients as well as resulting thermal stresses are reported in the paper.

INTRODUCTION

In an epoch of major technological advancements ballistic missiles have been transformed into a major destructive weapon system and so numerous studies have been done in recent years in order to minimize the destructive effects of an offensive ballistic missile.

In this study we thermal energies needed to debilitate an intercontinental ballistic missile, especially during boost or mid course phases. We have performed a detailed open literature review of ground based directed energy weapons and related laser energy that is required to be delivered on orbit to destruct incoming ballistic missiles.

Moreover, we have explored using state-of-the-art simulation methodologies to investigate thermo-mechanical analysis of ballistic missiles exposed to laser energy from Ground Directed Energy Weapons. Also, specific failure modes have been determined for ballistic missiles exposed into the above referred incoming energy. The study develops approaches for risk-mitigation of thermo-mechanical vulnerabilities and susceptibilities of ballistic missiles.

In the present analysis, different materials have been selected and temperature distributions on external surfaces exposed to different laser energy levels is computed. After assessing the thermal vulnerabilities, thermo-mechanical analysis is performed to yield thermal deformations and stresses for various energy inputs, giving us a clear idea of what is the appropriate laser energy input we have to use in order to be sure that killing mechanisms will be applied to the incoming ballistic missile.

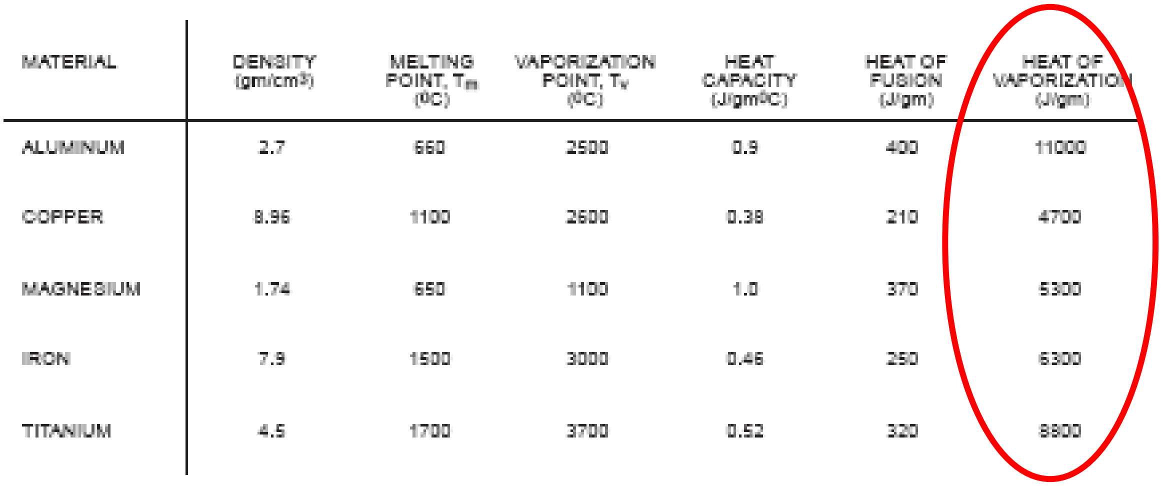
Finally, we have developed a parametric design space of laser energy input and design variables such as weight, thickness, strength and thermal properties suitable for addressing survivability and vulnerability issues in the design.

BACKGROUND

Albert Einstein is considered to be the first that discovered laser in 1916. There were no major technological advancements done until 1960. Theodore Maiman of Hughes Aircraft Corporation invented the laser machine. That was, essentially, the first important step in the beginning of laser era. Since then, thousands of people are dealing with lasers daily and laser applications have altered our lives for good. Today, in the engineering world, NASA is doing advanced research in laser applications for space. In the military arena, the united states air force (USAF) reports a new doctrine that Ground Based Lasers have to be used in the future for nation’s robust defensive control.

Based on open information resources, as most of it is highly classified, we only refer here a few examples of the use of laser energy against satellites in the recent years. In 1997, the USAF used a 30 watt chemical laser to blind a satellite at 425 km altitude [Ref 1]. The US Army used the giant laser MIRACL and shot a satellite, which failed to download data during the lasing period [Ref. 2]. Taking into account the above examples, we can deduce that laser energy can be used effectively to debilitate satellites. Similar application onto incoming ballistic missiles is also being pursued. This led to our motivation for the present study to investigate energy requirements to debilitate and study parametric design space for incoming ballistic missiles during initial phase of the flight.

First and foremost, we decide on the factors needed to consider achieving our objectives of the study. We need to assume the type of target and approximate ranges of the target. The answer to the above will determine the solution of our problem and therefore, the energy required to debilitate a given target. The Table 1 [Ref.3] shows various properties including heat of vaporization for selected materials that are currently in wide use by the ballistic missile manufacturers. 10^4 Joules is seen to be adequate energy to vaporize a gram of almost most materials indicated in the table.



MATERIAL	DENSITY (gm/cm^3)	MELTING POINT, T_m (°C)	VAPORIZATION POINT, T_v (°C)	HEAT CAPACITY (J/gm°C)	HEAT OF FUSION (J/gm)	HEAT OF VAPORIZATION (J/gm)
ALUMINUM	2.7	660	2500	0.9	400	11000
COPPER	8.96	1100	2600	0.38	210	4700
MAGNESIUM	1.74	650	1100	1.0	370	5300
IRON	7.9	1500	3000	0.46	250	6300
TITANIUM	4.5	1700	3700	0.52	320	8900

Table 1: Thermo-mechanical Characteristics of Selected Materials,[Ref.3]

With this information in mind we can easily set up a damage criterion, where a 10^4 Joules/ cm² incoming heat flux will be sufficient to generate a hole of 1 cm onto a ballistic missile external surface, as depicted in Figure 1. [Ref. 3]

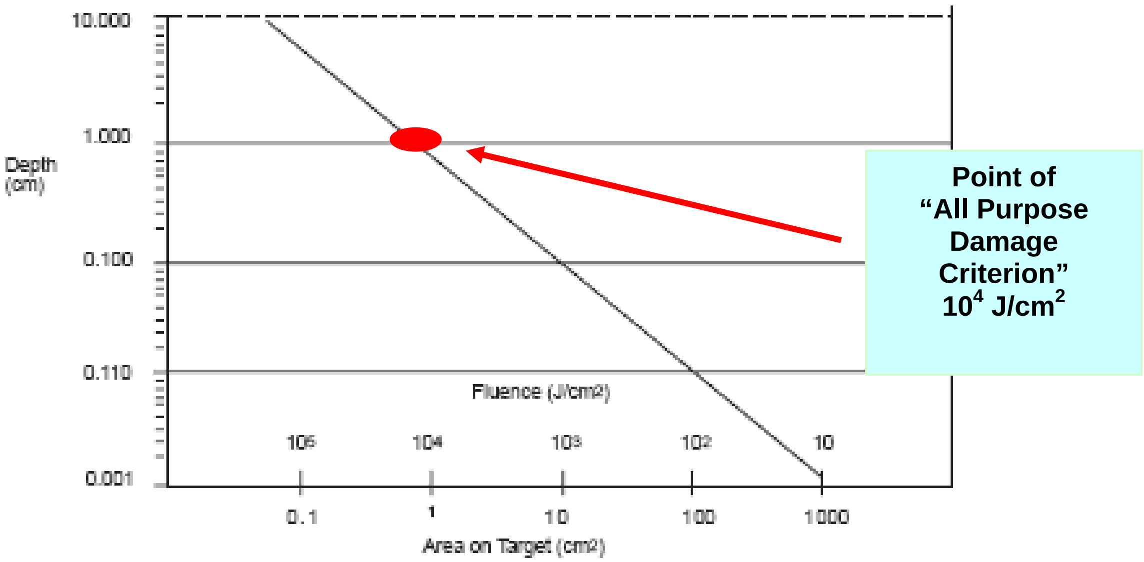


Figure 1: Damage Criterion for Ballistic Missiles,[Ref.1]

Restated, if the thicknesses of a ballistic missile are in the order of centimeters and we wish to create a hole of 1 cm in the external shell, laser energy of 10^4 Joules/ cm^2 is adequate to produce destruction. This is one of the damage criterion used in our evaluation process.

Finally, before we present the modeling and analysis, we discuss some perilous effects that atmospheric propagation losses cause on the energy delivered in a desired orbit. In design and analysis phase these losses need to be considered for achieving the required margins.

We list some atmospheric propagation losses that have to be taken into account:

- Absorption
- Scattering
- Turbulence
- Thermal Blooming
- Diffraction

These atmospheric losses influence the selection of appropriate use of the most applicable and capable laser to deliver the specified amount of heat flux on orbit and score a hit on the ballistic missile.

It is seen from the Table 2 that there is a huge variety of directed energy weapons available and only a select few may be used as ground based lasers (GBL). These are highlighted in red.

Type of laser	Wavelength	Output Power Ranges	Atmospheric Losses	Optics	Area of application	Literature Review
COIL	1.3 μ	Megawatts	Large	Small	**GBL** ABL	Partially Classified
HF	2.7-2.9 μ	Megawatts	Large	Medium	SBL	Partially Classified
DF	3.4-4 μ	Megawatts	Small	Large	**GBL**	Partially Classified
SSL	Electrical Energy	Up to 100 kilowatts	N/A	Depends on the application	Terrestrial	Partially Classified
HPM	0.1-0.01 μ	Megawatts	Highly diffractive	Small	Terrestrial ABL, SBL	Partially Classified
FEL	Tunable	Kilowatts	Optimum	Depends	**Possibly GBL**, ABL, SBL	Partially Classified

Table 2: Classification of Lasers

MODELING

In this study we decided to model and simulate a publicly available ballistic missile of practical relevance, namely Taepondong being developed by North Korea. Its total mass is reported to be 33,406 kg approximately, in the two stage version and it consists of four propellant tanks, an adapter between the stages and a nose cone. The first stage cylinder has diameter of 1.8m and length of 12m and the second stage cylinder has diameter of 0.96m and length of 12m respectively [Ref.4]. The missile is shown in Figure 2 [Ref.4].

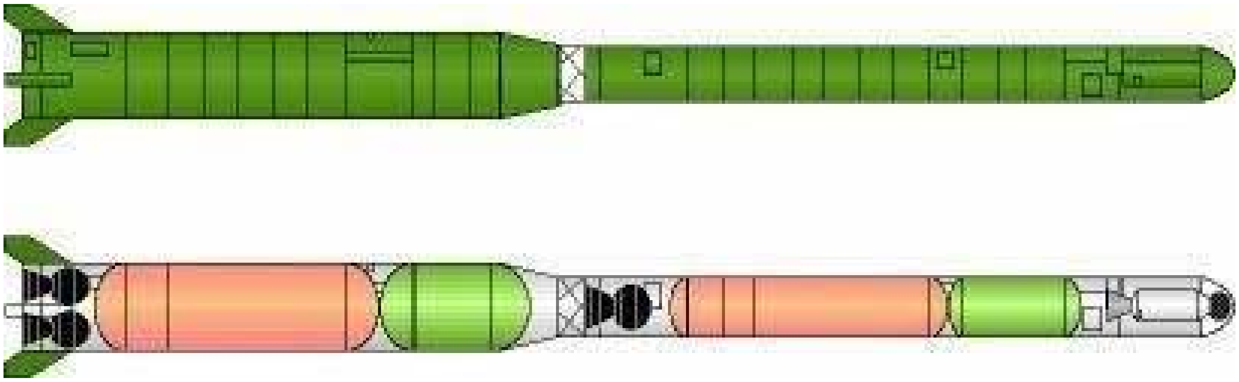


Figure 2: Schematic of Taepondong Ballistic Missile, [Ref. 4]

Using MSC software computer aided engineering analysis tools, MSC Patran, we created an idealized ballistic missile model which is consisted of the following parts:

- Stage 1 External Cylinder
- Stage 1 Bottom Fuel Tank
- Stage 1 Top Fuel Tank
- Stage 2 External Cylinder
- Stage 2 Bottom Fuel Tank
- Stage 2 Top Fuel Tank
- Adapter
- Nose Cone

The detailed model characteristics and parts are shown in Figures 3 and 4.

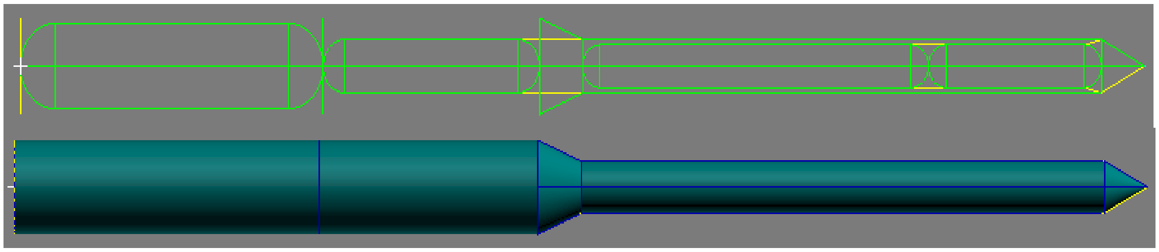
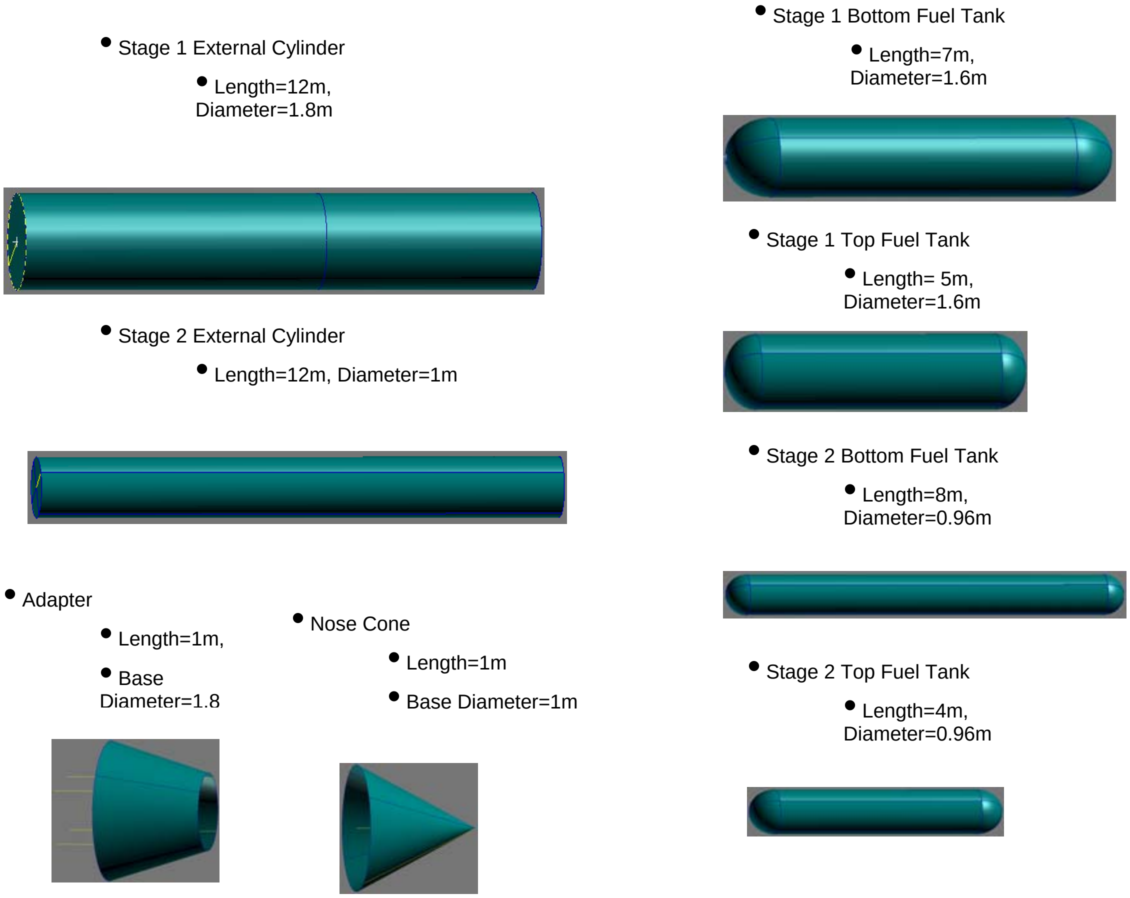


Figure 3: Idealized Ballistic Missile Model.



- Stage 1 External Cylinder
  - Length=12m, Diameter=1.8m
- Stage 2 External Cylinder
  - Length=12m, Diameter=1m
- Adapter
  - Length=1m,
  - Base Diameter=1.8
- Nose Cone
  - Length=1m
  - Base Diameter=1m
- Stage 1 Bottom Fuel Tank
  - Length=7m, Diameter=1.6m
- Stage 1 Top Fuel Tank
  - Length= 5m, Diameter=1.6m
- Stage 2 Bottom Fuel Tank
  - Length=8m, Diameter=0.96m
- Stage 2 Top Fuel Tank
  - Length=4m, Diameter=0.96m

Figure 4: Parts of the Ballistic Missile Model.

For the simulation and modeling procedures MSC Patran was used extensively for the following:

- Creation of Geometry
- Material Characteristics Definition
- Thermal Modeling
  - Heat Conduction
  - Heat Radiation
  - Heat Flux loading
  - Temperature Loading
- Thermo-Mechanical Loading
- Post-processing

After modeling, MSC Nastran solver was used for:

- Thermal Analysis
    - Steady State Analysis
    - Transient Analysis
- Structural Analysis
    - Nonlinear Analysis

ANALYSIS

At this point we need to define the initial design parameters, and relate the results with the assumptions that we were made in the assessment and interpretation of the results and conclusions.

In this study, we used titanium, steel and aluminum for the parts of the ballistic missile and for consistency the thicknesses will be fixed for every part to be 0.0254 m (1 inch). The material characteristics are shown in Table 3:

Material	**ALUMINUM 6061-T6**		**STEEL C-1020**		**TITANIUM B120 VCA**	
Units	**SI**	**EU**	**SI**	**EU**	**SI**	**EU**
Elastic Modulus (E)	**7.31e10 Pa**	**10.5e6 psi**	**2.03e11 Pa**	**29e6 psi**	**1.02e11 Pa**	**16e6 psi**
Poisson Ratio(ν)	**0.33**		**0.313**		**0.27**	
Density (ρ)	**2700 kg/m^3**	**0.101 lbm/m^3**	**7850 kg/m^3**	**0.283 lbm/m^3**	**4850 kg/m^3**	**0.16 lbm/m^3**
Thermal Expansion Coefficient, (α)	**24.3e-6 m/m ºC**		**11.34e-6 m/m ºC**		**9.36e-6 m/m ºC**	
Thermal Conductivity (k)	**155.8 W/mºC**		**46.73 W/mºC**		**7.442 W/mºC**	
Minimum Yield Strength	**275 MPa**	**40000 psi**	**520 MPa**	**36000 psi**	**830 MPa**	**120000 psi**
Melting Point	**660°C**	**1220 ºF**	**1375 ºC**	**2507 ºF**	**1675 ºC**	**3047 ºF**

Table 3: Material Characteristics

The external stage 1 cylinder is assumed to be exposed with the directional heat flux load for the following cases:

- 100 W/m²
- 10e4 W/m²
- 10e5 W/m²
- 10e6 W/m²

The stage 1 external cylinder application area is only representative and the procedures may easily be extended to other exposure areas of the missile. We specify radiation parameters as follows:

- Absorptivity: 0.5
- Emmisivity: 0.5
- Ambient Temperature: 20 °C
- View Factor: 1

It is also to be noted that no convection has been considered but only thermal conduction and radiation in the present analysis. Figure 5 shows the distribution and application of the directional heat load and the radiation parameters on the ballistic missile model as it is shown by the graphical interface of the MSC Patran tool.

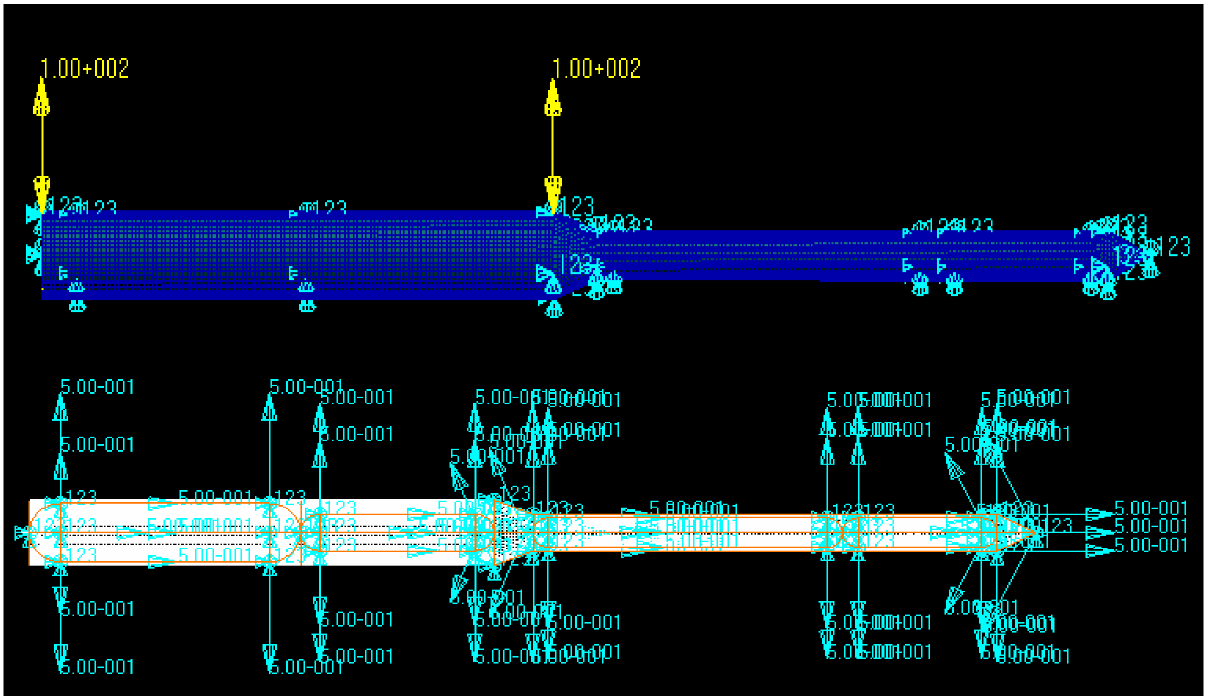


Figure 4: Heat Flux and Radiation Parameters of the Ballistic Missile Model.

For our ballistic missile model specific failure modes have been defined as follows:

- **deformations** greater than the original thickness.
- **temperatures** greater than the melting point of the materials.
- **stresses** greater than the yield stress of the materials.
- **deformations, temperatures, stresses** greater than other mission critical parameters.

If any of the defined parameters are violated, then we can conclude that the ballistic missile model has failed or that we have made it vulnerable to the laser exposure

After several trials and preliminary validation analysis, the final finite element model for the present analysis the following model data-

- Nodes ~ 25,342
- Elements ~ 25,533
- Degrees of Freedom: 76,026

RESULTS

In the ballistic missile model thermal analysis was performed initially with the results that are shown in the following Table 4:

Parts	100 W/m²	10e4 W/m²	10e5W/m²	10e6W/m²
Stage 1 External Cylinder	**35.1 °C**	**380 °C**	**880 °C**	**3370 °C FAILURE**
Stage 1 Bottom Fuel Tank	**20.1 °C**	**21.7 °C**	**23.3 °C**	**101 °C**
Stage 1 Top Fuel Tank	**20.1 °C**	**21.7 °C**	**23.3 °C**	**101 °C**
Adapter	**25.5 °C**	**212 °C**	**569 °C**	**2500 °C FAILURE**

Table 4: Thermal Analysis Results

We can easily see that with 10^6 W/ m^2 applied heat flux to the titanium stage 1 external cylinder raises temperatures up to 3370 °C, which exceeds the melting point temperature of the material. This condition qualifies as a failure as defined earlier. Similarly, results for the adapter which is an adjacent part to the stage 1 external cylinder also scores a failure.

The above results is shown graphically in the Figure 5 where the points on the curves are the parametric design and analysis points and also these curves depict the nonlinearity of the applied heat flux versus received temperatures in the selected ballistic missile parts. The figure captures results from several analysis with different exposures to thermal energies.

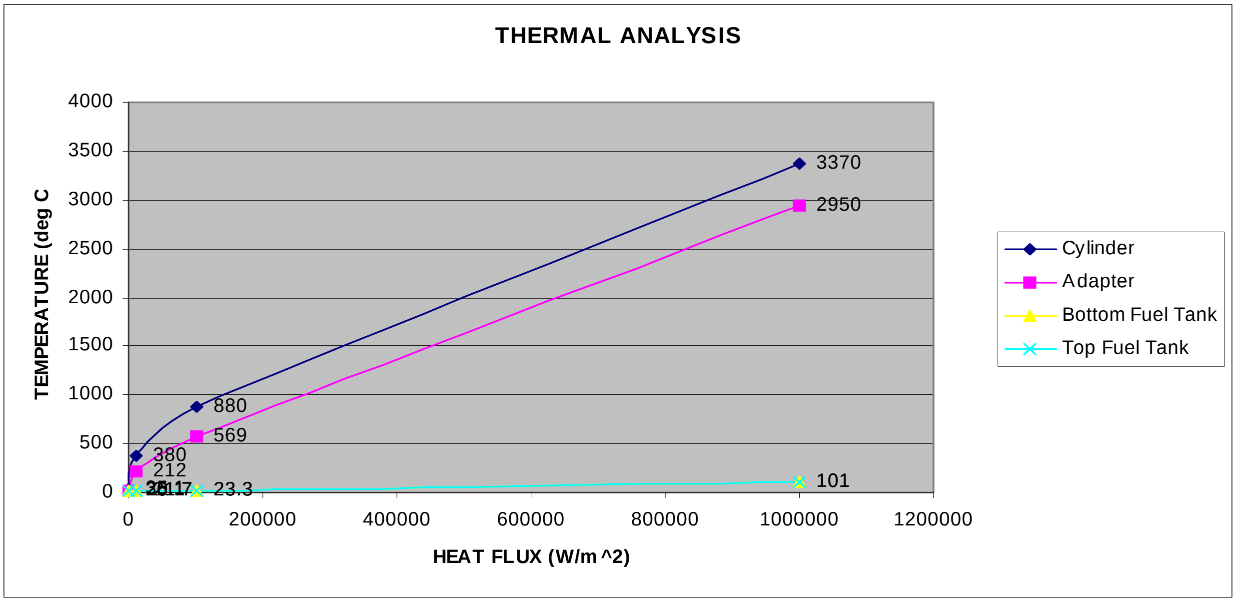
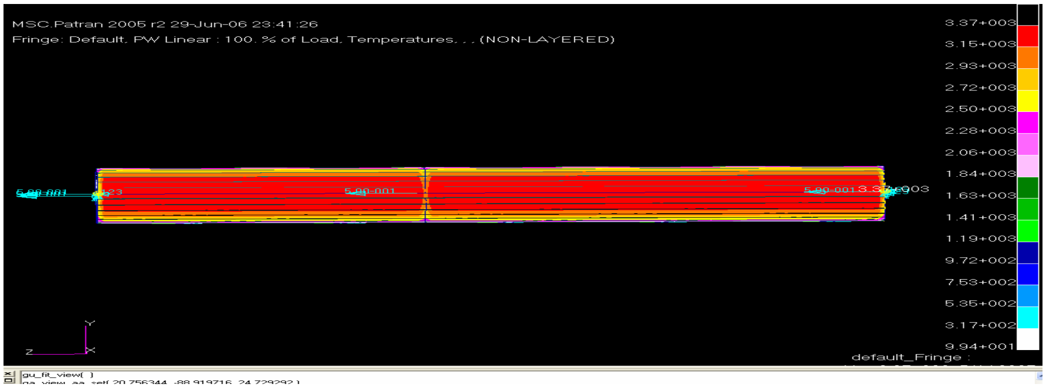


Figure 5: Temperatures versus Heat Flux Results.

In the following Figure 6 temperature distribution are shown as obtained from the graphical interface of MSC Patran for the case of 10^6 W/ m^2 applied heat flux to the stage 1 external cylinder.



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Fringe: Default, PW Linear : 100. % of Load, Temperatures, , , (NON-LAYERED)

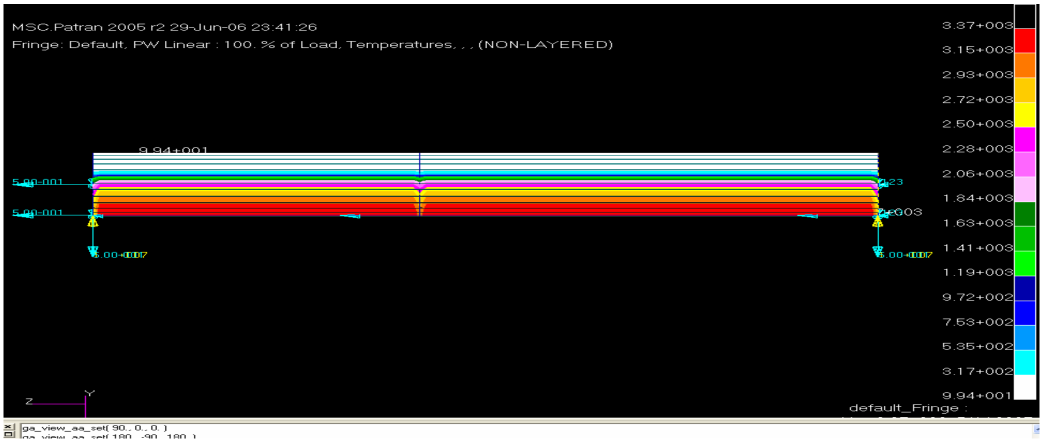

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Figure 6: Temperature Distribution Pictures for Heat Flux of 10^6 W/ m^2

The next step was to perform the structural analysis in which we used as inputs the temperature distributions we obtained from the thermal analysis. The results are shown in Table 5 and Figures 7 and 8. Table 5 shows that the maximum deformation for the applied heat flux of 10^6 W/ m^2 is 0.0472 m and the initial thickness of the cylinder was 0.0254m. In accordance with our failure modes criteria, the cylinder has deformed substantially and scored a failure.

Parts	**100 W/m²**	**10e4 W/m²**	**10e5W/m²**	**10e6W/m²**
Stage 1 External Cylinder	**4.87e -4**	**5.12e -3**	**1.22e -2**	**4.72e -2** **FAILURE**
Stage 1 Bottom Fuel Tank	**5.5e -4**	**5.52e -4**	**5.53e -4**	**2.72e -3**
Stage 1 Top Fuel Tank	**2.92e -4**	**2.94e -4**	**2.96e -4**	**1.45e -3**
Adapter	**2.57e -4**	**7.44e -4**	**1.5e -3**	**4.4e -3**

Table 5: Deformation Results

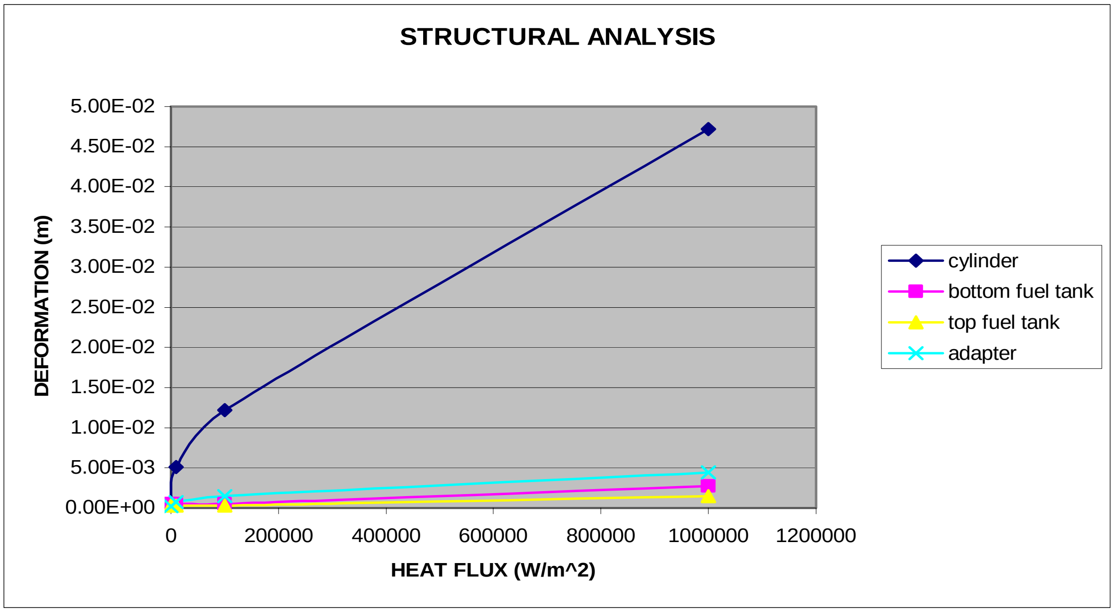
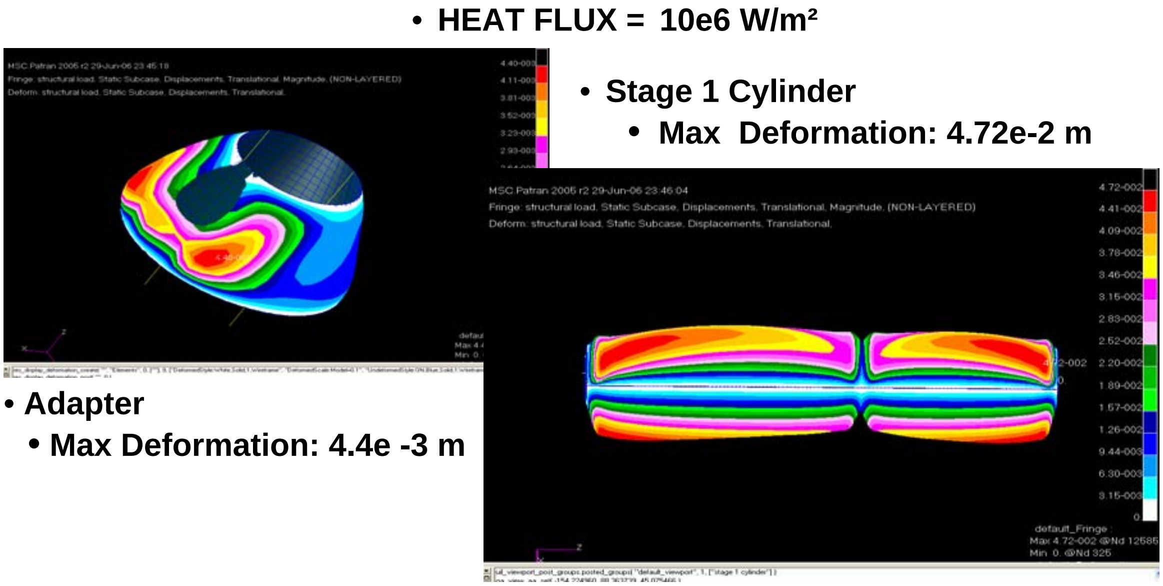


Figure 7: Deformation versus Applied Heat Flux Results



- **HEAT FLUX = 10e6 W/m²**

- **Stage 1 Cylinder**
  - **Max Deformation: 4.72e-2 m**

- **Adapter**
  - **Max Deformation: 4.4e -3 m**

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Fringe: structural load, Static Subcase, Displacements, Translational, Magnitude, (NON-LAYERED)
Deform: structural load, Static Subcase, Displacements, Translational,
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Figure 8: Thermal Deformations Results as shown in MSC Patran

Finally, thermal stress distributions are shown in Table 6 and in Figure 9. The failure occurs when we applied heat flux greater than 10^5 W/ m^2.

Parts	100 W/m²	10e4 W/m²	10e5W/m²	10e6W/m²
Stage 1 External Cylinder	5.48e 7	4.8e 8	1.2e 9 FAILURE	5.19e 9 FAILURE
Stage 1 Bottom Fuel Tank	1.67e 8	1.55e 8	3.06e 8	1.01e 9 FAILURE
Stage 1 Top Fuel Tank	1.16e 8	1.55e 8	3.06e 8	1.01e 9 FAILURE
Adapter	5.47e 8	4.52e 8	1.2e 9 FAILURE	5.19e 9 FAILURE

Table 6: Stress Analysis Results

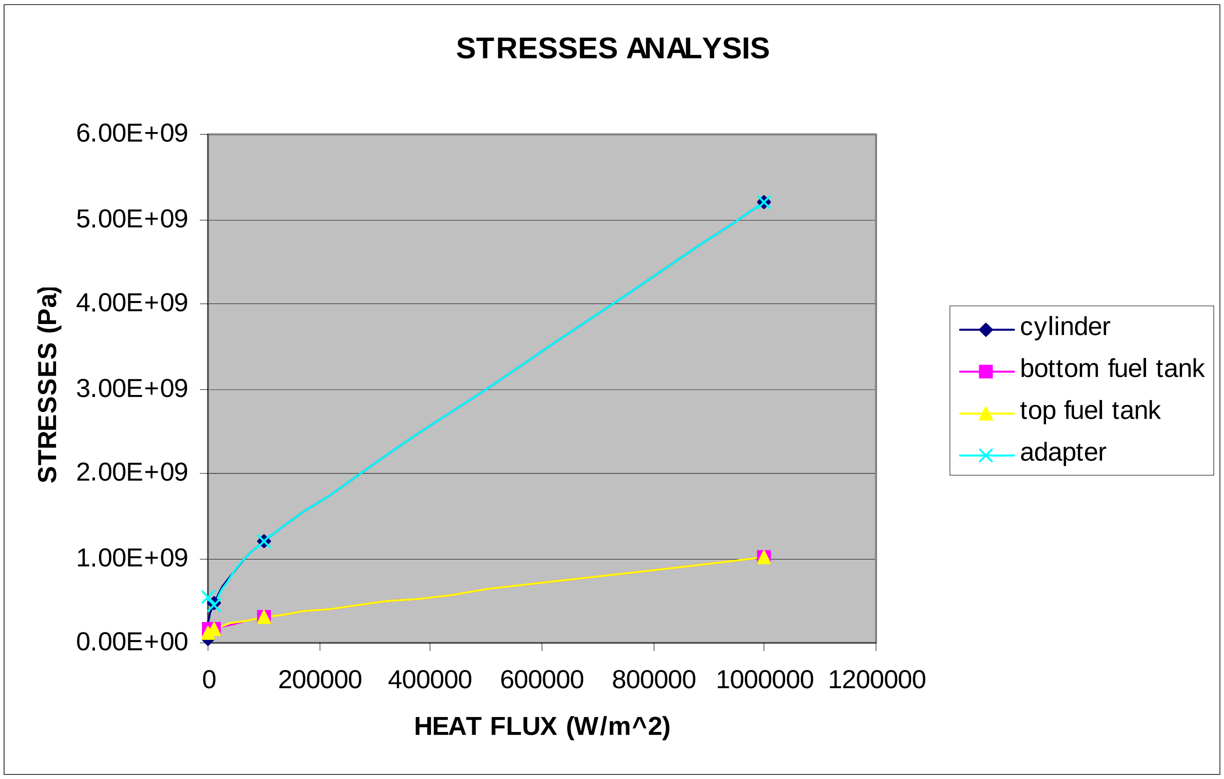

Figure 9: Stresses versus Applied Heat Flux Results

CONCLUSIONS

Some important conclusions that can be reached based on the detailed thermo-mechanical study. The design of ground based laser weapons should include careful modeling and simulation of the offensive ballistic missiles and effects of the laser thermal energy exposures.

The present study offers a multidisciplinary methodology based on MSC Software for thermo-mechanical analysis of ballistic missiles exposed to Directed Energy Weapons.

A preliminary survey of published available energy levels was performed and a thermal analysis of a model ballistic missile is presented in this paper. Critical energy levels are identified for thermal failure modes of a ballistic missile and also thermo-mechanical analysis was performed in order to construct the final temperature, deformation and stress curves versus the applied heat flux. This led us to predict critical energy levels for the prescribed mechanical failure modes. A critical parametric design space is proposed and generated through the above analysis which can be used as a ballistic missile design tool as well as for risk mitigation, vulnerability as well as survivability studies associated with missile defense.

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