Thermo-Mechanical Analysis of Ground Based Directed Energy Weapons on 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 involved is outlined. The analysis is performed under several scenarios that include 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 will be 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.
Objectives

• Perform Literature Survey DEWs (Laser Energy) required to kill an ICBM.

• Explore methodology for thermo-mechanical analysis of BMs exposed to DEWs.

• Determine the failures modes that laser energy can impose on BMs.

• Predict temperature distribution on external surfaces for selected materials.

• Predict thermal deformations and thermal stresses for various energy inputs.

• Develop parametric design space of laser energy input and design variables such as weight, thickness, strength and thermal properties etc., useful for vulnerability and survivability studies.
Presentation Outline

- Literature Review
- Failure Modes for ICBM’s
- Atmospheric Propagation Losses
  - Absorption
  - Scattering
  - Turbulence
  - Thermal Blooming
  - Diffraction
- Classification OF Lasers
  - Chemical Oxygen Iodine Laser
  - Hydrogen Fluoride Laser
  - Deuterium Fluoride Laser
  - High Power Microwaves
  - Free Electron Laser
Presentation Outline

• Taepoondong Characteristics
• Ballistic Missile Model Characteristics
• Problem Definition
• Material Characteristics
• Loads / Boundary Conditions
• Failure Criteria
• Thermal – Structural – Stress Analysis and Results
• Conclusions
Literature Review

- Albert Einstein World War II discovered laser
- Theodore Maiman 1960 Hughes Aircraft Corporation first manufactured a laser machine
- NASA Glenn Research Center – Geoffrey Landis
- U.S. Air Force: GBL’s for robust defensive control

- **TEST’s**
- U.S.A.F. 1997: 30 watt chemical laser temporarily blind a satellite at 425 km altitude*
- US Army: MIRACL shoot a satellite
  - failed to download data during lase*
  - *(Limited access to information resources as most of it is highly classified)*
Damage Criterion for ICBM’s

- **Factors**: Anticipated target - Engagement range
- **Energy Deposited**: capacity to vaporize almost everything
- **$10^4$ Joules** = capacity to vaporize a gram of almost anything

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<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>DENSITY (gm/cm³)</th>
<th>MELTING POINT, $T_m$ (°C)</th>
<th>VAPORIZATION POINT, $T_v$ (°C)</th>
<th>HEAT CAPACITY (J/gm°C)</th>
<th>HEAT OF FUSION (J/gm)</th>
<th>HEAT OF VAPORIZATION (J/gm)</th>
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<tbody>
<tr>
<td>ALUMINUM</td>
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<td>660</td>
<td>2500</td>
<td>0.9</td>
<td>400</td>
<td>11000</td>
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<td>COPPER</td>
<td>8.96</td>
<td>1100</td>
<td>2600</td>
<td>0.38</td>
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<td>4700</td>
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<td>MAGNESIUM</td>
<td>1.74</td>
<td>650</td>
<td>1100</td>
<td>1.0</td>
<td>370</td>
<td>5300</td>
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<tr>
<td>IRON</td>
<td>7.9</td>
<td>1500</td>
<td>3000</td>
<td>0.46</td>
<td>250</td>
<td>6300</td>
</tr>
<tr>
<td>TITANIUM</td>
<td>4.5</td>
<td>1700</td>
<td>3700</td>
<td>0.52</td>
<td>320</td>
<td>8800</td>
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</tbody>
</table>
```

“Philip E. Nielsen, Effects of Directed Energy Weapons, 1997”
Damage Criterion ICBM’s (cnt’d)

- “1 cm depth hole is sufficient to damage almost anything on any target”
- Define: Heat Flux = 10^4 J/cm²
  - Satellites: Thicknesses on the order of mm
  - ICBM’s: Thicknesses on the order of cm

“Philip E. Nielsen, Effects of Directed Energy Weapons, 1997”
Atmospheric Propagation Losses

- **Absorption**

- Occurs due to **water**, **dioxide**, **diatomic oxygen** and **ozone** absorption of electromagnetic radiation

- **Solution**: Use of specific wavelengths

"Professor R. Olsen notes, Remote Sensing from Air and Space, NPS"
Atmospheric Propagation Losses

- **Scattering**
  
  "Professor R. Olsen notes, Remote Sensing from Air and Space, NPS"

  - Occurs due to scattering of electromagnetic radiation on
  - **water droplets, clouds and aerosols**
  - **Solution:** Use of specific wavelengths
Atmospheric Propagation Losses

- **Turbulence**
- Occurs due to **density** and **temperature fluctuations** of the atmosphere
- Least during the darkness hours when there is no solar heating to increase inhomogenieties
- **Solution:** Use of adaptive optics technology

“Professor R. Olsen notes, Remote Sensing from Air and Space, NPS”
Atmospheric Propagation Losses

- **Thermal Blooming**

  When high power optical beam travels through atmosphere increase temperature, increase air’s density, increase index of refraction and finally beam is distorted

- **Solutions:** Reducing the intensity of the beam
  Use of adaptive optics technology

“Philip E. Nielsen, Effects of Directed Energy Weapons, 1997”
Atmospheric Propagation Losses

• **Diffraction**

When light travels through a given D aperture there is spreading and divergence of an angle \( \theta \) which is related to wavelength.

• **Solution**: Choice of smaller wavelengths and larger apertures results in longer propagation

“Professor R. Olsen notes, Remote Sensing from Air and Space, NPS”
# Classification of Lasers

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

- North Korean Ballistic Missile
- Total mass: 33,406 Kg
- Stages = 2
  - Stage 1 dimensions: Diameter: 1.80 m. Length 12 m
  - Stage 2 dimensions: Diameter: 0.96 m. Length 12 m
- Parts = 4 Propellant Tanks, Adapter, Nose Cone
Idealized Model Characteristics

- **Total Mass:** 32,100 kg
- **Model 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
Idealization for Simulation

- **MSC Patran for Modeling**
  - Geometry
  - Material Definition
  - Thermal Modeling
    - Heat Conduction
    - Heat Radiation
    - Heat Flux loading
    - Temperature Loading
  - Thermo-Mechanical Loading
  - Post-processing

- **MSC Nastran**
  - Thermal analysis
    - Steady State
    - Transient Analysis
  - Structural Analysis
    - Nonlinear
Pictures of Ballistic Missile Model

- **Stage 1 External Cylinder**
  - Length=12m, Diameter=1.8m

- **Stage 1 Bottom Fuel Tank**
  - Length=7m, Diameter=1.6m

- **Stage 1 Top Fuel Tank**
  - Length=5m, Diameter=1.6m

- **Stage 2 External Cylinder**
  - Length=12m, Diameter=1m

- **Stage 2 Bottom Fuel Tank**
  - Length=8m, Diameter=0.96m

- **Stage 2 Top Fuel Tank**
  - Length=4m, Diameter=0.96m

- **Adapter**
  - Length=1m, Base Diameter=1.8, Top Diameter=1m

- **Nose Cone**
  - Length=1m, Base Diameter=1m
Problem Definition

- Nodes ~ 25,342
- Elements ~ 25,533
- Degrees of Freedom: 76,026
- Materials: Titanium, Steel, Aluminum
- Finite Element Model with 0.1 Global Length

- Displacement Constraints (123) = Zero Translations in selected points
- Performed Model Static and Modal analysis
Problem Definition

- **Properties of Ballistic Missile**

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adapter</td>
<td>Titanium</td>
<td>0.0254</td>
</tr>
<tr>
<td>Nose Cone</td>
<td>Steel</td>
<td>0.0254</td>
</tr>
<tr>
<td>Stage 1 External Cylinder</td>
<td>Titanium</td>
<td>0.0254</td>
</tr>
<tr>
<td>Stage 1 Bottom Fuel Tank</td>
<td>Steel</td>
<td>0.0254</td>
</tr>
<tr>
<td>Stage 1 Top Fuel Tank</td>
<td>Steel</td>
<td>0.0254</td>
</tr>
<tr>
<td>Stage 2 External Cylinder</td>
<td>Titanium</td>
<td>0.0254</td>
</tr>
<tr>
<td>Stage 2 Bottom Fuel Tank</td>
<td>Titanium</td>
<td>0.0254</td>
</tr>
<tr>
<td>Stage 2 Top Fuel Tank</td>
<td>Steel</td>
<td>0.0254</td>
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</table>
# Material Characteristics

<table>
<thead>
<tr>
<th>Material</th>
<th>ALUMINUM 6061-T6</th>
<th>STEEL C-1020</th>
<th>TITANIUM B120 VCA</th>
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<tbody>
<tr>
<td>Units</td>
<td>SI</td>
<td>EU</td>
<td>SI</td>
</tr>
<tr>
<td>Elastic Modulus (E)</td>
<td>7.31e10 Pa</td>
<td>10.5e6 psi</td>
<td>2.03e11 Pa</td>
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<tr>
<td>Poisson Ratio (ν)</td>
<td>0.33</td>
<td>0.313</td>
<td></td>
</tr>
<tr>
<td>Density (ρ)</td>
<td>2700 kg/m^3</td>
<td>0.101 lbm/m^3</td>
<td>7850 kg/m^3</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient, (α)</td>
<td>24.3e-6 m/m °C</td>
<td>11.34e-6 m/m °C</td>
<td>9.36e-6 m/m °C</td>
</tr>
<tr>
<td>Thermal Conductivity (k)</td>
<td>155.8 W/m°C</td>
<td>46.73 W/m°C</td>
<td>7.442 W/m°C</td>
</tr>
<tr>
<td>Minimum Yield Strength</td>
<td>275 MPa</td>
<td>40000 psi</td>
<td>520 MPa</td>
</tr>
<tr>
<td>Melting Point</td>
<td>660°C</td>
<td>1220 °F</td>
<td>1375 °C</td>
</tr>
</tbody>
</table>
Loads / Boundary Conditions

• Applied HEAT FLUX for the following cases:
  • 100 W/m²
  • 10e4 W/m²
  • 10e5 W/m²
  • 10e6 W/m²

• Directional Heat Load

• Representative Application Area: Stage 1 External Cylinder (Titanium)
Loads / Boundary Conditions

- Radiation Parameters for the whole Ballistic Missile:
  - Absorptivity: 0.5
  - Emmissivity: 0.5
  - Ambient Temperature: 20 °C
  - View Factor: 1
Failure Modes

• Typical Failure Modes for our Ballistic Missile:

• **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
## Thermal Analysis - Results

<table>
<thead>
<tr>
<th>Parts</th>
<th>100 W/m²</th>
<th>10e4 W/m²</th>
<th>10e5W/m²</th>
<th>10e6W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 External Cylinder</td>
<td>35.1 °C</td>
<td>380 °C</td>
<td>880 °C</td>
<td>3370 °C</td>
</tr>
<tr>
<td>Stage 1 Bottom Fuel Tank</td>
<td>20.1 °C</td>
<td>21.7 °C</td>
<td>23.3 °C</td>
<td>101 °C</td>
</tr>
<tr>
<td>Stage 1 Top Fuel Tank</td>
<td>20.1 °C</td>
<td>21.7 °C</td>
<td>23.3 °C</td>
<td>101 °C</td>
</tr>
<tr>
<td>Adapter</td>
<td>25.5 °C</td>
<td>212 °C</td>
<td>569 °C</td>
<td>2500 °C</td>
</tr>
</tbody>
</table>

*FAILURE*
Temperature Vs. Heat Flux

Heat Flux (W/m^2) vs. Temperature (deg C)

- Cylinder
- Adapter
- Bottom Fuel Tank
- Top Fuel Tank

Thermal Analysis

Temperature and heat flux data for different components of a fuel tank system.
Temperature Distribution
## Structural Analysis - Results

- **Deformations**

<table>
<thead>
<tr>
<th>Parts</th>
<th>100 W/m²</th>
<th>10e4 W/m²</th>
<th>10e5W/m²</th>
<th>10e6W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 External Cylinder</td>
<td>4.87e-4</td>
<td>5.12e-3</td>
<td>1.22e-2</td>
<td>4.72e-2</td>
</tr>
<tr>
<td>Stage 1 Bottom Fuel Tank</td>
<td>5.5e-4</td>
<td>5.52e-4</td>
<td>5.53e-4</td>
<td>2.72e-3</td>
</tr>
<tr>
<td>Stage 1 Top Fuel Tank</td>
<td>2.92e-4</td>
<td>2.94e-4</td>
<td>2.96e-4</td>
<td>1.45e-3</td>
</tr>
<tr>
<td>Adapter</td>
<td>2.57e-4</td>
<td>7.44e-4</td>
<td>1.5e-3</td>
<td>4.4e-3</td>
</tr>
</tbody>
</table>

FAILURE
Deformation Vs. Heat Flux

![Graph showing deformation vs. heat flux for different components: cylinder, bottom fuel tank, top fuel tank, and adapter.](image)
Thermal Deformation

- 10e6 W/m²

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

- Adapter
  - Max Deformation: 4.4e-3 m
## Stress Analysis - Results

### Stresses

<table>
<thead>
<tr>
<th>Parts</th>
<th>100 W/m²</th>
<th>10e4 W/m²</th>
<th>10e5W/m²</th>
<th>10e6W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 External Cylinder</td>
<td>5.48e 7</td>
<td>4.8e 8</td>
<td>1.2e 9</td>
<td>5.19e 9</td>
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<tr>
<td>Stage 1 Bottom Fuel Tank</td>
<td>1.67e 8</td>
<td>1.55e 8</td>
<td>3.06e 8</td>
<td>1.01e 9</td>
</tr>
<tr>
<td>Stage 1 Top Fuel Tank</td>
<td>1.16e 8</td>
<td>1.55e 8</td>
<td>3.06e 8</td>
<td>1.01e 9</td>
</tr>
<tr>
<td>Adapter</td>
<td>5.47e 8</td>
<td>4.52e 8</td>
<td>1.2e 9</td>
<td>5.19e 9</td>
</tr>
</tbody>
</table>

*FAILURE*
Stress Vs. Heat Flux

![Stress vs. Heat Flux Diagram](image)

- **Stresses Analysis**

  - **X-axis**: Heat Flux (W/m^2)
  - **Y-axis**: Stresses (Pa)

  - **Legend**:
    - Blue circles: cylinder
    - Pink squares: bottom fuel tank
    - Yellow triangles: top fuel tank
    - Cyan crosses: adapter

  - The graph shows the relationship between heat flux and stresses for different components of the fuel tank system.
Conclusions

• A multidisciplinary methodology based on MSC.Software was developed for thermo-mechanical analysis of ballistic missiles exposed to DEWs
• A preliminary survey of published available energy levels was performed
• Thermal analysis of a model ballistic missile is presented
• Critical energy levels are identified for thermal failure modes of BM
• Thermo-mechanical analysis was performed for the model BM
• Critical energy levels are identified for the mechanical failure modes of BM
• Critical parametric design space is generated for the BM design
References

- Professor R. Olsen notes, *Remote Sensing from Air and Space*, NPS
Questions?