Effects of Laser Wavelength on Ablator Testing

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Entry Descent and Landing Technology Development Project (EDL TDP)

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Outline

- Background / Motivation
  - Approach
  - Test Results
  - Summary & Conclusions
Motivation: Need for Advanced TPS

NASA conducted study in 2008 to establish entry system technologies required to put 40+ metric tons* on the surface of Mars. *State-of-the-art ~ 1 MT

Heritage TPS / Entry Systems (5 m, 1 MT) do not meet requirements

Concepts included ablative flexible thermal protection systems (TPS)

[Graph showing heat flux and integrated heat load over time for aero capture and entry.]
Flexible Ablator Technology Development, FY 10 - 14

- **Determine evaluation criteria** to define successful development
- **Identify promising materials** with flexible matrices / substrates
  - carbon, silica, and polymer based felts / cloths
  - organic / inorganic blended materials
- **Investigate resins, additives, solvents** for flexible composites
- **Utilize lower cost screening tests** to determine viability
  - Aerothermal screening in NASA Ames X-jet plasma torch
  - Thermal screening in radiant environment at Wright-Patterson AFB Laser Hardened Materials Evaluation Laboratory (LHMELE)
  - Aerothermal screening in NASA Johnson TP2 arc heater
  - Fold testing for stowability effects
- **Downselect materials** for further technology (TRL) maturation
Shock Layer Radiation can significantly impact Spacecraft Heat Flux

Radiative heating depends on size and speed –
- the larger the entry vehicle, the higher the radiative heating,
- the higher the entry velocity, the higher the radiative heating

Experiment vs. Predicted Air Shock Layer Radiation Spectrum

Experimental data – measured in EAST facility

Theoretical predictions - from NEQAIR simulations of shock layer in Air

Shock layer radiation is concentrated in narrow spectral bands characteristic of atmospheric chemistry.

Shocklayer Radiation and TPS Testing

- Material response to radiation can depend strongly on wavelength. For example, your car window traps heat (infrared) but transmits light (visible).

- Unfortunately, existing convective arc jet test facilities are unable to simulate shock layer radiation at the desired wavelengths and levels.

- In addition, even for convective dominated heating environments, laser testing is less expensive per test and can be widely used for preliminary screening purposes.

- High-powered spectral radiation sources needed to assess radiation transport effects on TPS materials. Lasers are the best radiation sources to provide high levels of energy at specific wavelengths.

Example: Laser 1 radiant energy absorbed at or near surface (ideal). Radiant energy from Laser 2 travels further in-depth.
• Background / Motivation

• Approach

• Test Results

• Summary & Conclusions
Test Facility used for Spectral Radiation Heating

Laser Hardened Materials Evaluation Laboratory (LHMEL)
Reliable, calibrated, and economical laser test facility located at Wright-Patterson AFB and operated by the U.S. Air Force Research Lab

- **CO₂ Laser**: 10.6 microns
  - LHMEL I
  - 15 kW CO₂ laser
  - (150kW LHMEL II not used)

- **Fiber Laser**: 1.07 microns
  - IPG Photonics
  - 10 kW Fiber Laser (new)
Test Set-Up

CO$_2$ (LHMEL 1) & Fiber Laser Setup

Tests conducted in inert environment
- Nitrogen (N$_2$) purged test box
- N$_2$ gas crossflow to prevent beam blockage

Burn plates used to verify exposed area, homogeneity
Test Conditions: 115 W/cm$^2$ 30 seconds CW (non-pulsed)
# Materials: a Subset of Flexible Ablators

## 2011 Screening Test Matrix

<table>
<thead>
<tr>
<th>Test Material</th>
<th>CO2 Laser</th>
<th>Fiber Laser</th>
<th>CO2 Laser</th>
<th>Fiber Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morgan-Phenolic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FMI-Phenolic-F</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>FMI-Phenolic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morgan-S-T</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>FMI-S-T</td>
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<tr>
<td>FMI-S-B</td>
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<tr>
<td>FMI-S-T-A1</td>
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</tr>
<tr>
<td>FMI-S-T-A2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BFFAB Carbon Felt-silicone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFRSI-S-B</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Refrasil-S-B</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>SIRCA (as Reference)</td>
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<td></td>
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<td></td>
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<tr>
<td>Carbon/PBI-P-T</td>
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<tr>
<td>PBI-S-B</td>
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<tr>
<td>LM3S Silica Felt Blanket</td>
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</tr>
<tr>
<td>LM2Z Zirconia Felt Blanket</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>BFFA Impregnated Nextel</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**Parameters of Interest**

- Mass Loss
- Char Layer Thickness
- Max Bondline Temperature
- Time to Max Bondline Temp
### Test Materials

**Carbon fiber felts** (non-woven) impregnated with silicone resin

**Silica fiber felts** impregnated with silicone resin

**SIRCA used** as a reference.

Comparable in:
- substrate felt commercial manufacturing
- processing
- density

Each pair of two samples for the CO$_2$ and Fiber laser had similar thickness, but Refrasil was thickest and had highest areal weight compared to other materials.

<table>
<thead>
<tr>
<th>Test Material</th>
<th>Areal Wt (g/cm$^2$)</th>
<th>Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Felt Silicone</td>
<td>0.34</td>
<td>0.18</td>
</tr>
<tr>
<td>Morgan-S-T</td>
<td>0.34</td>
<td>0.18</td>
</tr>
<tr>
<td>Fiber Morgan-S-T</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td>FMI-S-T</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td>Fiber FMI-S-T</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td>FMI-S-B</td>
<td>0.39</td>
<td>0.21</td>
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<tr>
<td>Fiber FMI-S-B</td>
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</tr>
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<td>FMI-S-T-A2</td>
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<td>0.22</td>
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<tr>
<td>Fiber FMI-S-T-A2</td>
<td>0.42</td>
<td>0.22</td>
</tr>
<tr>
<td>Glass Fiber w Silicone</td>
<td></td>
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</tr>
<tr>
<td>Refrasil-S-B</td>
<td>0.66</td>
<td>0.27</td>
</tr>
<tr>
<td>Fiber Refrasil-S-B</td>
<td>0.59</td>
<td>0.25</td>
</tr>
<tr>
<td>SIRCA</td>
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<td>0.26</td>
</tr>
<tr>
<td>Fiber SIRCA</td>
<td>0.34</td>
<td>0.26</td>
</tr>
</tbody>
</table>
• Background / Motivation

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• Summary & Conclusions
Comparison of Silica, Glass Fiber-based Materials

SIRCA
Rigid Silica fiber matrix impregnated with silicone resin, used as the reference material for these tests.

Interference patterns visible in the photographs correspond to patterns seen in witness burn plates used to characterize the beam. Concentric circles are characteristic of the LHMEL I CO₂ laser, whereas the Fiber laser has a smaller scale mottled pattern of interference peaks.

Refrasil felt-silicone resin
Refrasil-S-B
Refrasil silica-felt
Silicone resin
B processing

Refrasil was thicker, more insulative, than the other felts. Mostly smooth appearance from the CO₂ laser testing, but the Fiber laser testing of Refrasil resulted in a mottled, uneven surface.
Comparison of Carbon felt-based materials

Material samples
- 2 different carbon felts
- impregnated with silicone resin
- processed with different methods and additives

Laser tests
*Materials were tested with both a CO\textsubscript{2} and Fiber laser @ 115 W/cm\textsuperscript{2} for 30 sec*

Preliminary Results
*Post-test visual inspection showed no apparent differences between the carbon felt materials*
Char zone is created when enough energy is absorbed in depth to produce the temperature required to pyrolyze the silicone resin.

Note that char zones resulting from laser tests are generally different thicknesses from arc jet test chars, even at equal heat fluxes (convective char ≠ radiative char).

Photographs show thicker char and pyrolysis zones developed after exposure to the shorter wavelength Fiber laser.

Photos visually demonstrate that the material absorbs energy deeper in depth at 1.07 microns than at 10.6 microns.
Test Results of Carbon & Silica Fiber-based Materials

Comparing char layer thickness results from the Fiber laser vs CO₂ laser tests
- Carbon felt chars were on average 92% thicker
- Silica fiber chars were thick & on average 19% thicker
Test Results of Carbon & Silica Fiber-based Materials

Comparing the mass loss of pyrolysis & vaporization from the Fiber laser vs CO₂ laser tests:
- Carbon felt materials lost on average 20% more mass from Fiber to CO₂ laser test.
- Silica fiber materials lost on average 160% more (but less overall: start at high reflectance)
Data ordered by increasing density of the carbon and silica (glass) felt materials

Higher bondline temperatures for each material.

Note Refrasil was thicker, insulative.

*Materials subjected to 115 W/cm² for 30 sec
Test Results of Carbon & Silica Fiber-based Materials

Comparing the time to max bondline temp for the Fiber laser vs CO₂ laser tests
- Carbon felt materials peaked on average 15% faster
- Silica felt materials peaked ~22% faster
• Background / Motivation

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Summary and Conclusions

- Overview: Experimental data was compared from tests in two non-pulsed lasers with widely separated wavelengths, at irradiances of 115 W/cm² for 30 sec. These low-density ablators incorporated silicone resin in commercial refractory felt substrates, and were comparable in processing and density.

- The carbon and silica substrate materials gave

<table>
<thead>
<tr>
<th>General Test Results</th>
<th>CO₂ Laser</th>
<th>Fiber Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Bondline Temperature</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>Time to Max Bondline Temp</td>
<td>slower</td>
<td>faster</td>
</tr>
<tr>
<td>Mass Loss</td>
<td>less</td>
<td>more</td>
</tr>
<tr>
<td>Char Layer Thickness</td>
<td>thinner</td>
<td>thicker</td>
</tr>
</tbody>
</table>

- Numerical modelling (not shown) shows lower extinction (i.e. greater penetration and forward scattering of energy) at 1 micron than at 10 microns. Test results are consistent with greater in-depth absorption from 1.07 versus 10.6 micron radiation (i.e. more efficient surface absorption at the 10.6 versus 1.07 micron radiation).

- Even for carbon-fiber-dominated porous composite materials, wavelength-dependent (i.e. spectral) radiation effects can have an impact on the material’s response to intense shock layer radiation!
Acknowledgements

• This work was supported by the EDL TDP of the Exploration Technology Development and Demonstration (ETDD) Program, managed at NASA-Glenn Research Center.

• Robin Beck and Matt Gasch, project managers

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• Test materials described herein were from NASA Ames. The vendors Boeing, Lockheed Martin and Textron supplied materials for related testing not described here.

• John Bagford and Dan Seibert from the LHMEL facility.

• S-C Lee of Applied Sciences Laboratory for fiber radiation scattering theoretical modelling & consultation.
Effects of Laser Wavelength on Ablator Testing

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• Appendix
<table>
<thead>
<tr>
<th>Test Material</th>
<th>Areal Wt (g/cm²)</th>
<th>Density (g/cc)</th>
<th>Peak Bondline Temp (°C)</th>
<th>Time to Peak Temp (sec)</th>
<th>Mass loss (g)</th>
<th>Virgin (mm)</th>
<th>Char (mm)</th>
<th>Char+Pyro (mm)</th>
<th>Recession (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Felt Silicone</td>
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</tr>
<tr>
<td>Morgan-S-T</td>
<td>0.34</td>
<td>0.18</td>
<td>110</td>
<td>195</td>
<td>0.34</td>
<td>13.18</td>
<td>1.81</td>
<td>4.03</td>
<td>0.2</td>
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<tr>
<td>Fiber Morgan-S-T</td>
<td>0.34</td>
<td>0.18</td>
<td>139</td>
<td>157</td>
<td>0.43</td>
<td>11.24</td>
<td>2.81</td>
<td>7.70</td>
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<tr>
<td>FMI-S-T</td>
<td>0.34</td>
<td>0.20</td>
<td>142</td>
<td>154</td>
<td>0.75</td>
<td>8.77</td>
<td>1.47</td>
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<td>0.34</td>
<td>0.20</td>
<td>158</td>
<td>131</td>
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<td>166</td>
<td>158</td>
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<td>7.06</td>
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<td>FMI-S-T-A2</td>
<td>0.43</td>
<td>0.22</td>
<td>124</td>
<td>187</td>
<td>1.09</td>
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<td>1.78</td>
<td>8.38</td>
<td>-1.0</td>
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<tr>
<td>Fiber FMI-S-T-A2</td>
<td>0.42</td>
<td>0.22</td>
<td>154</td>
<td>154</td>
<td>1.14</td>
<td>8.08</td>
<td>3.01</td>
<td>10.90</td>
<td>2.5</td>
</tr>
<tr>
<td>Glass Fiber w Silicone</td>
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<tr>
<td>AFRSI-S-B</td>
<td>0.54</td>
<td>0.23</td>
<td>80</td>
<td>408</td>
<td>0.43</td>
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<td>4.16</td>
<td>8.39</td>
<td>1.0</td>
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<tr>
<td>Fiber AFRSI-S-B</td>
<td>0.54</td>
<td>0.23</td>
<td>80</td>
<td>346</td>
<td>0.55</td>
<td>14.06</td>
<td>5.30</td>
<td>9.40</td>
<td>-0.7</td>
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<td>Refrasil-S-B</td>
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<td>0.27</td>
<td>72</td>
<td>438</td>
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<td>SIRCA</td>
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<td>Fiber SIRCA</td>
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<td>90</td>
<td>0.77</td>
<td>4.34</td>
<td>5.27</td>
<td>9.04</td>
<td>2.0</td>
</tr>
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</table>

This table shows the areal weight and density before testing, the peak bondline temperatures and the time taken to reach the peak bondline temperature beneath the test specimen, the mass loss, the char thickness and the combined char plus pyrolysis zone thickness. In the table, the following naming convention is used to describe the materials: the samples used for the Fiber laser test include the word Fiber in the test material name, the carbon felts were procured from FMI or Morgan, the S stands for silicone, and the designations after the S refer to different chemical alterations and processing methods. Each test material gave higher bondline temperatures from the Fiber laser test than the CO₂ 10.6 micron laser test. The absorption of energy in the material leads to mass loss, due to resin being pyrolyzed, and water and residual solvent being vaporized, whereas spallation and vaporization were minimal in these tests. All the test material listed gave shorter times to peak temperature, greater mass loss, and thicker zones heated to pyrolysis or char temperatures, when irradiated at the 1.07 micron fiber laser wavelength than at the CO₂ 10.6 micron laser. The glass-silicone materials started with higher reflectance when they were virgin materials, which would lead to lower energy absorption rather than higher energy absorption if a significant fraction of energy were reflected away from the surface, however, the test materials quickly charred during testing, reducing differences in reflectance.
Comparison of Fiber and CO2 laser tests

<table>
<thead>
<tr>
<th>Test Material</th>
<th>Bondline Temperature Increase (°C)</th>
<th>Time to Peak Temperature Change (%)</th>
<th>Mass Loss Change (%)</th>
<th>Char Thickness Change (%)</th>
<th>Char + Pyrolysis Zone Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morgan-S-T</td>
<td>28</td>
<td>-22</td>
<td>26</td>
<td>56</td>
<td>43</td>
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<tr>
<td>FMI-S-T</td>
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<td>-17</td>
<td>3</td>
<td>100</td>
<td>38</td>
</tr>
<tr>
<td>FMI-S-B</td>
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<td>-9</td>
<td>41</td>
<td>141</td>
<td>75</td>
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<tr>
<td>FMI-S-T-A2</td>
<td>30</td>
<td>-20</td>
<td>5</td>
<td>69</td>
<td>626</td>
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<tr>
<td>Refrasil-S-B</td>
<td>23</td>
<td>-20</td>
<td>106</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>SIRCA</td>
<td>29</td>
<td>-30</td>
<td>220</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

- For each test material shown, all the non-layered carbon and silica materials gave:
  - higher peak bondline temperatures,
  - decreased penetration times,
  - greater mass loss,
  - and thicker zones heated to pyrolysis or char temperatures.
Why? Carbon fiber extinction depends on wavelength

- Theoretical Modelling or low-powered laboratory transmission measurements can provide insight into material behavior at different wavelengths.

- Carbon fiber modeling in the figure shows lower extinction and scattering, higher absorption at ~ 1 (Fiber Laser Wavelength) vs. 10 microns (CO₂ Laser Wavelength)

- Silica (glass) fibers are already known to respond like this.

- But Carbon... it’s unexpected!

Carbon fiber matrix radiative properties based on theoretical absorbing fiber scattering model by S-C. Lee (Applied Sciences Laboratory)
Radiative heat transfer with the diffusion approximation
(Ref: Theoretical model by S-C Lee, Applied Sciences Laboratory)

\[ q_r = -\lambda_r \frac{\partial T}{\partial z} \]

\[ \lambda_r = \frac{16n^2 \sigma T^3}{3} \int_0^\infty \frac{1}{k_{e\lambda} (1 - G_\lambda)} \frac{dI_{b\lambda}}{dI_b (T)} d\lambda \]

\[ G_\lambda = \frac{1}{k_{e\lambda}} \int_0^1 \int_0^1 \left\langle k_{s\lambda} p_\lambda (\mu, \mu') \right\rangle \mu' d\mu' d\mu \]

\[ \left\langle k_{s\lambda} p_\lambda (\mu, \mu') \right\rangle = \frac{2 f_v \lambda}{\pi^4} \sum_{i=1}^N x_i \int_0^{2\pi} \int_0^{\pi/2} \frac{i_\lambda (\eta, \phi, r_i) \cos \phi}{\sqrt{(1 - \cos \eta)(1 + \cos \eta - 2 \sin^2 \phi)}} d\phi d\omega \]

- For optically thick materials, radiative heat transfer can be modeled using the diffusion approximation in the radiative transfer equation – with the effective radiative conductivity for scattering and absorbing fibers.
Spectra of Available Radiation Sources

- CN radiation at Titan ($10^2$) (RED)
- Mercury-Xenon lamp radiation ($10^3$) (BLUE)
- Solar (6000 K source) (GREEN)
- Xenon lamp (5800 K source) (BLACK)
- LASERS (PURPLE)
  - Excimer lasers (pulsed)
  - Nd:YAG (line doubled/pulsed)
  - Nd:YAG COIL
- HF

High speed Earth atmospheric entry includes significant energy in the UV/
Accurate thermal prediction and analysis requires proper modeling of the char and pyrolysis zones – including reaction kinetics.

- **Char Zone**: Recessed material - vaporization, sublimation, spallation or shrinkage. Highest temperature outer mold line (OML) region. Coking, other reactions may occur. Organics have burned out, leaving substrate material or a refractory compound (e.g. C, SiO₂, Si-C).

- **Pyrolysis Zone**: Sufficient temperature for chemical decomposition of pyrolyzing components, which vary by type (e.g. phenolic, silicone) and processing.

- **Virgin TPS Material**: Original material, thermally and chemically unchanged, typically consisting of a substrate and resin.

- **Vehicle Structure**: Inner mold line (IML) interface between TPS and vehicle structure. Temperature and heat load limits of the vehicle structure drive TPS requirements and sizing with margins.