National Aeronautics and Space Administration

Effects of Laser Wavelength on Ablator Testing

Susan White

NASA Ames Research Center

NASA Program support:

Hypersonics Entry Descent and Landing (HEDL)

Exploration Technology Development and Demonstration (ETDD)

Entry Descent and Landing Technology Development Project (EDL TDP)

2014 38th Annual Conference on Composites, Materials and Structures

Outline

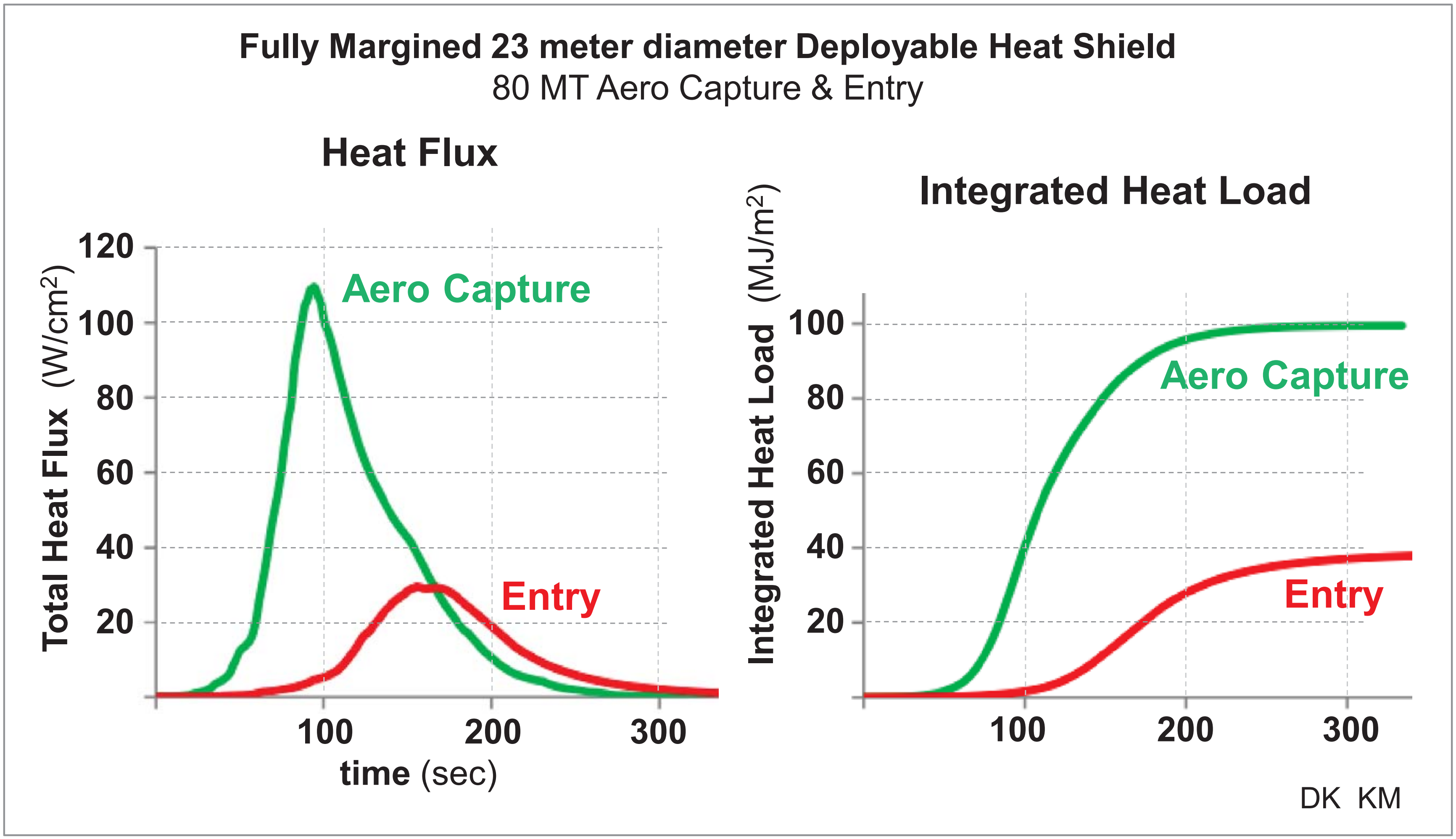
- Background / Motivation
- Approach
- Test Results
- Summary & Conclusions

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)

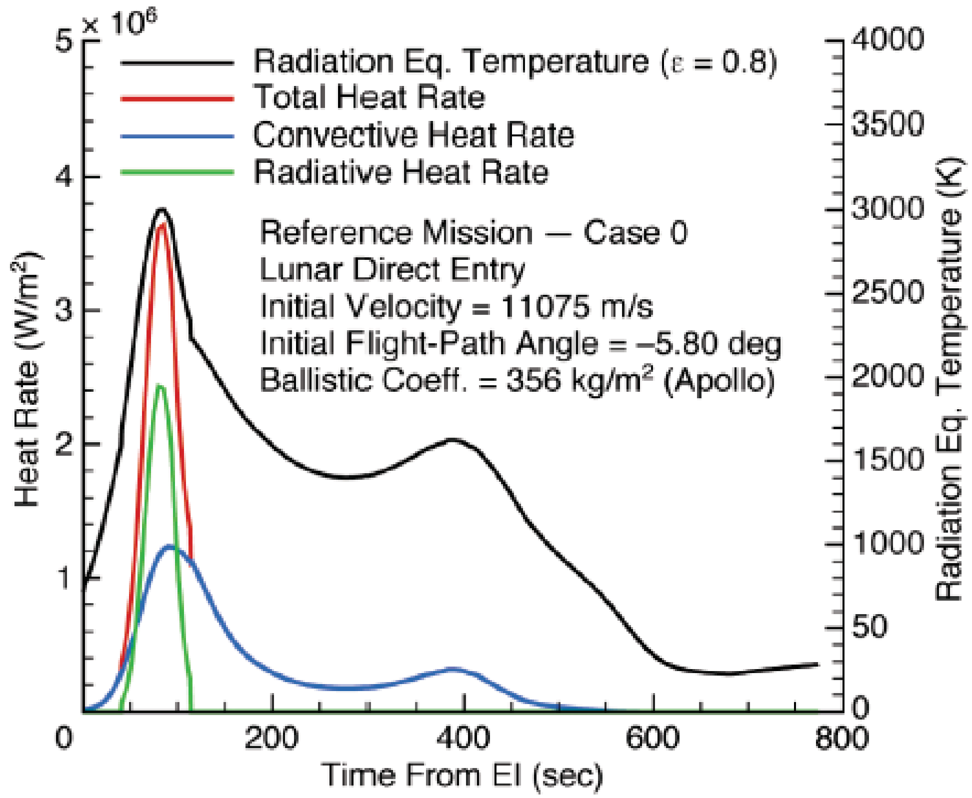


Flexible Ablator TPS Program

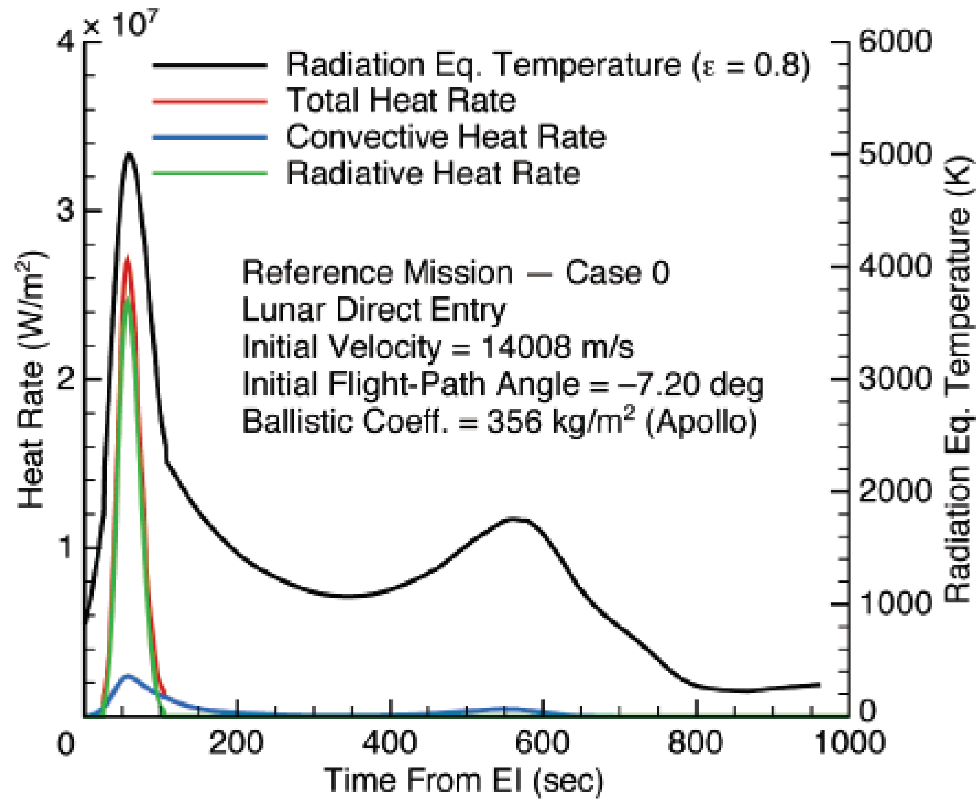
Flexible Ablator Technology Development, FY 10 - 14

- **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 (LHMEL)
  - 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



Moon-Earth nominal direct entry



Mars-Earth nominal direct entry

Radiative heating depends on size and speed –

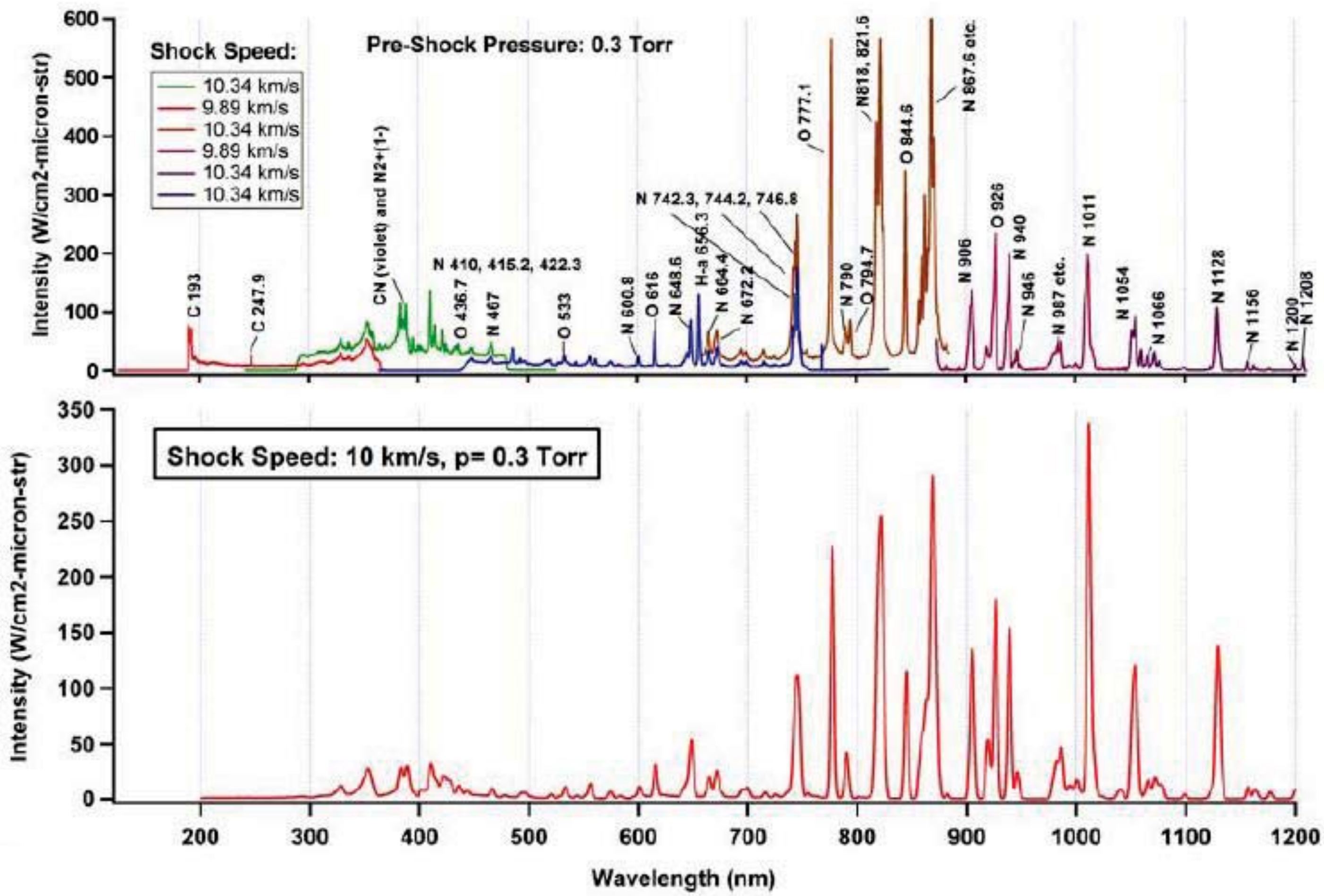
- the larger the entry vehicle, the higher the radiative heating,
- the higher the entry velocity, the higher the radiative heating

Robinson, J.S., and Wurster, K.E., and Mills, J. C., "Entry Trajectory and Aeroheating Environment Definition for Capsule-Shaped Vehicles", JOURNAL OF SPACECRAFT AND ROCKETS, Vol. 46, No. 1, January–February 2009

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.

Reference: "Analysis and Model Validation of Shock Layer Radiation in Air", Bose, D., McCorkle,, E., Thompson, C., Bogdanoff, D. , Prabhu, D.K. , Allen, G., And Grinstead, J., AIAA 2008-1246, 46th AIAA Aerospace Sciences Meeting and Exhibit., 7 - 10 January 2008, Reno, Nevada

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 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

- **CO_2 Laser:** 10.6 microns

  LHMEL I

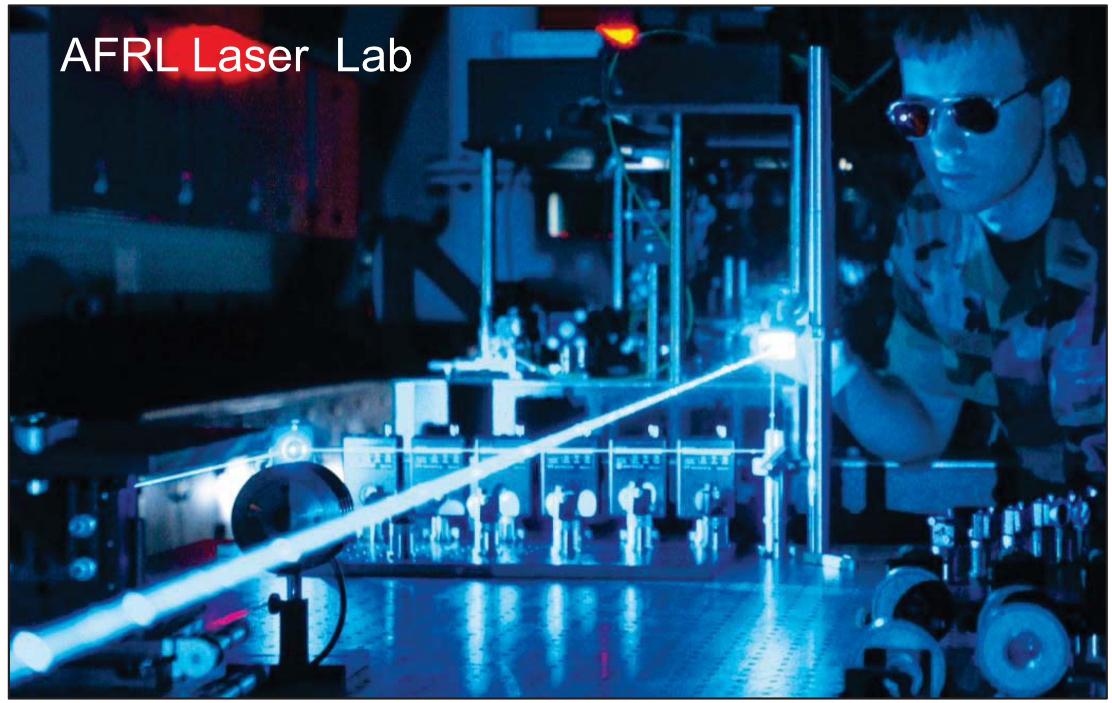
  15 kW CO_2 laser

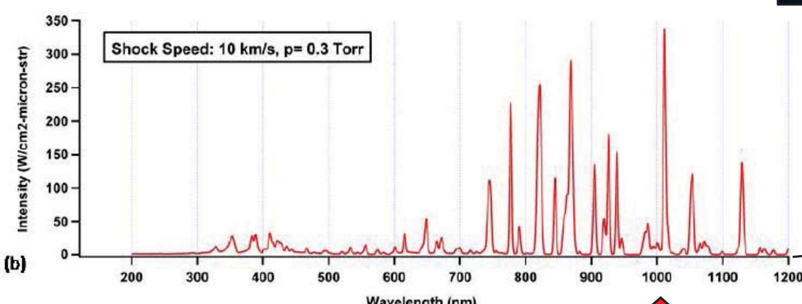
  (150kW LHMEL II not used)

- **Fiber Laser:** 1.07 microns

  IPG Photonics

  10 kW Fiber Laser (new)





Workhorse CO_2 Lasers 10.6 microns

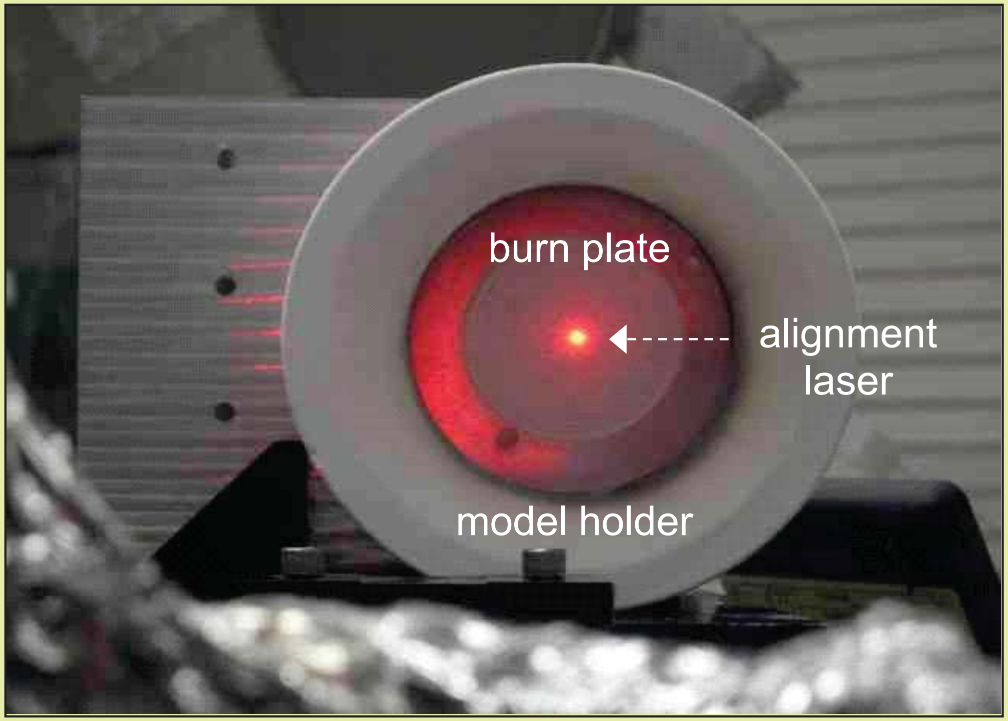
1 micron

(not to scale)

Test Set-Up

CO_2 (LHMEL 1) & Fiber Laser Setup

Nitrogen purged test box



Laser alignment, burn plate, and model holder

Tests conducted in inert environment

- Nitrogen (N_2) purged test box
- N_2 gas crossflow to prevent beam blockage

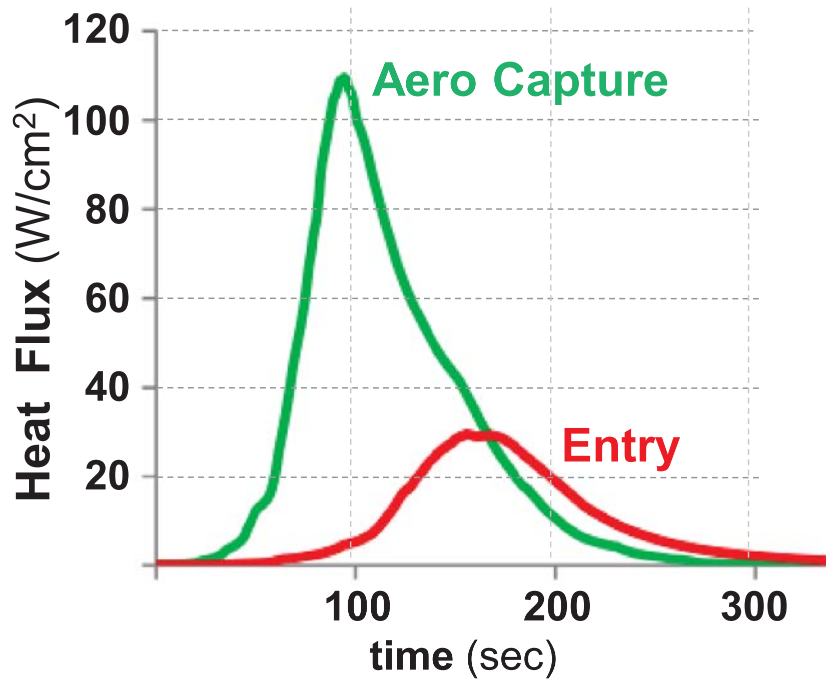
Burn plates used to verify exposed area, homogeneity

Test Conditions: 115 W/cm^2 30 seconds CW (non-pulsed)

Materials: a Subset of Flexible Ablators

2011 Screening Test Matrix

Flexible Ablator Screening Test Test Matrix	NOMINAL HEATING			HIGH HEATING	
	CO2 Laser		Fiber Laser	CO2 Laser	
Test Material	Aero Capture	Entry	Aero Capture	Aero Capture	Entry
Morgan-Phenolic					
FMI-Phenolic-F					
FMI-Phenolic					
Morgan-S-T					
FMI-S-T					
FMI-S-B					
FMI-S-T-A1					
FMI-S-T-A2					
BFFAB Carbon Felt-silicone					
AFRSI-S-B					
Refrasil-S-B					
SIRCA (as Reference)					
Carbon/PBI-P-T					
PBI-S-B					
LM3S Silica Felt Blanket					
LM2Z Zirconia Felt Blanket					
BFFA Impregnated Nextel					



Fully Margined 23 meter diameter Deployable Heat Shield (80 MT Aero Capture & Entry per NASA 2008 study)

Parameters of Interest

- **Mass Loss**
- **Char Layer Thickness**
- **Max Bondline Temperature**
- **Time to Max Bondline Temp**

Test Materials used to compare Results of Laser Tests

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.

Test Material	Areal Wt (g/cm2)	Density (g/cc)
Carbon Felt Silicone		
Morgan-S-T	0.34	0.18
Fiber Morgan-S-T	0.34	0.18
FMI-S-T	0.34	0.20
Fiber FMI-S-T	0.34	0.20
FMI-S-B	0.39	0.21
Fiber FMI-S-B	0.37	0.20
FMI-S-T-A2	0.43	0.22
Fiber FMI-S-T-A2	0.42	0.22
Glass Fiber w Silicone		
Refrasil-S-B	0.66	0.27
Fiber Refrasil-S-B	0.59	0.25
SIRCA	0.34	0.26
Fiber SIRCA	0.34	0.26

- Background / Motivation
- Approach
- Test Results
- 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.

pre-test **post CO_2 laser** **post Fiber laser**

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 CO_2 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

pre-test **post CO_2 laser** **post Fiber laser**

Refrasil was thicker, more insulative, than the other felts. Mostly smooth appearance from the CO_2 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_2 and Fiber laser @ 115 W/cm^2 for 30 sec

Preliminary Results

Post-test visual inspection showed no apparent differences between the carbon felt materials

Carbon felt materials with silicone resin

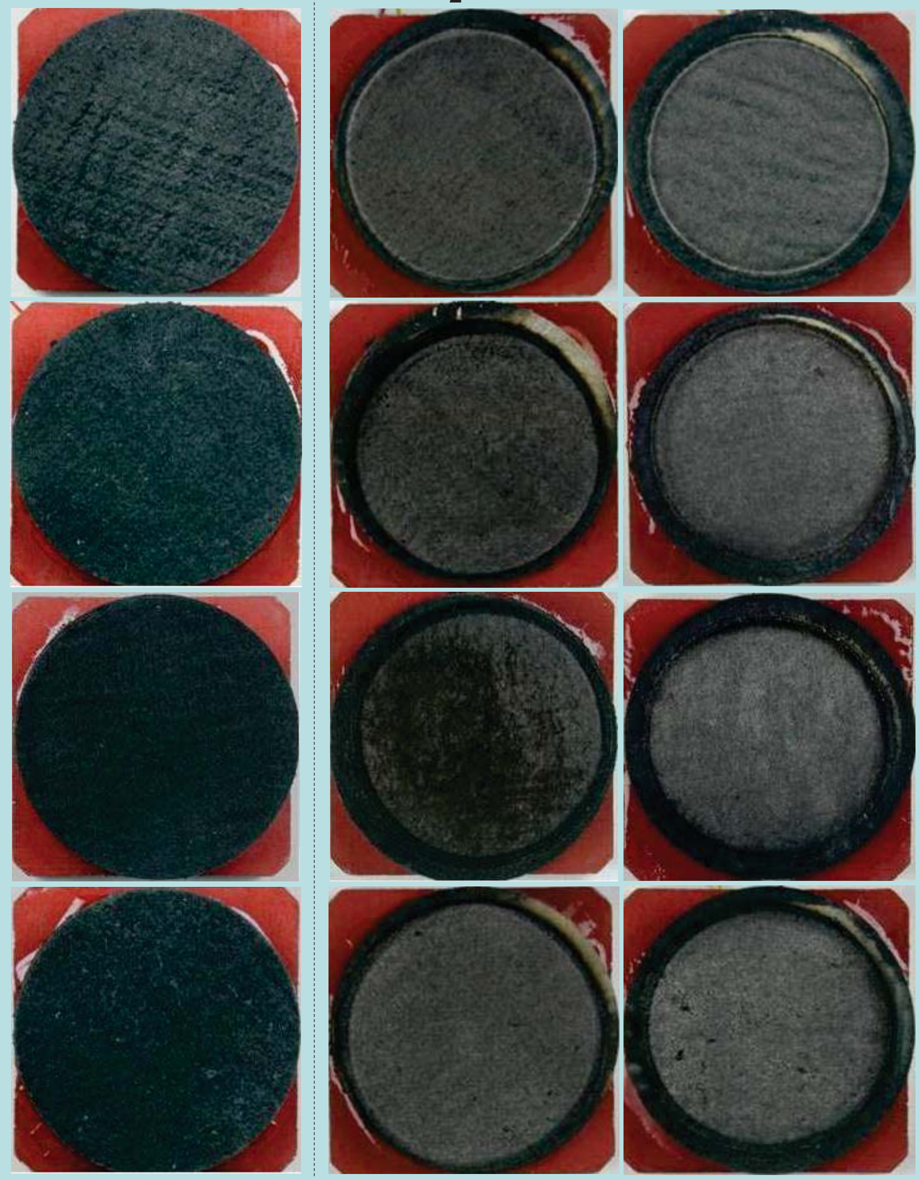
pre-test | post-test: CO_2 laser | Fiber laser

Morgan-S-T
Morgan C-felt
Silicone resin
T processing

FMI-S-T
FMI C-felt
Silicone resin
T processing

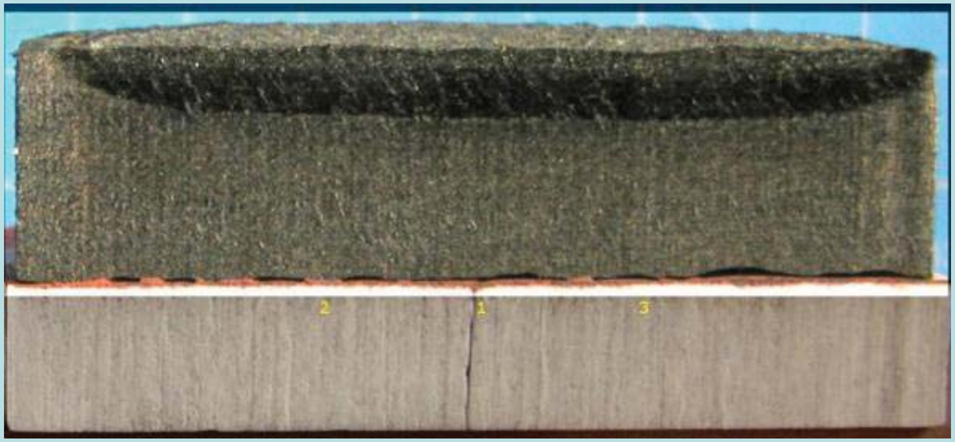
FMI-S-B
FMI C-felt
Silicone resin
B processing

FMI-S-T-A2
FMI C-felt
Silicone resin
T processing
A2 additive



Comparison of Representative cross sections

Cross sections of one test material after laser testing

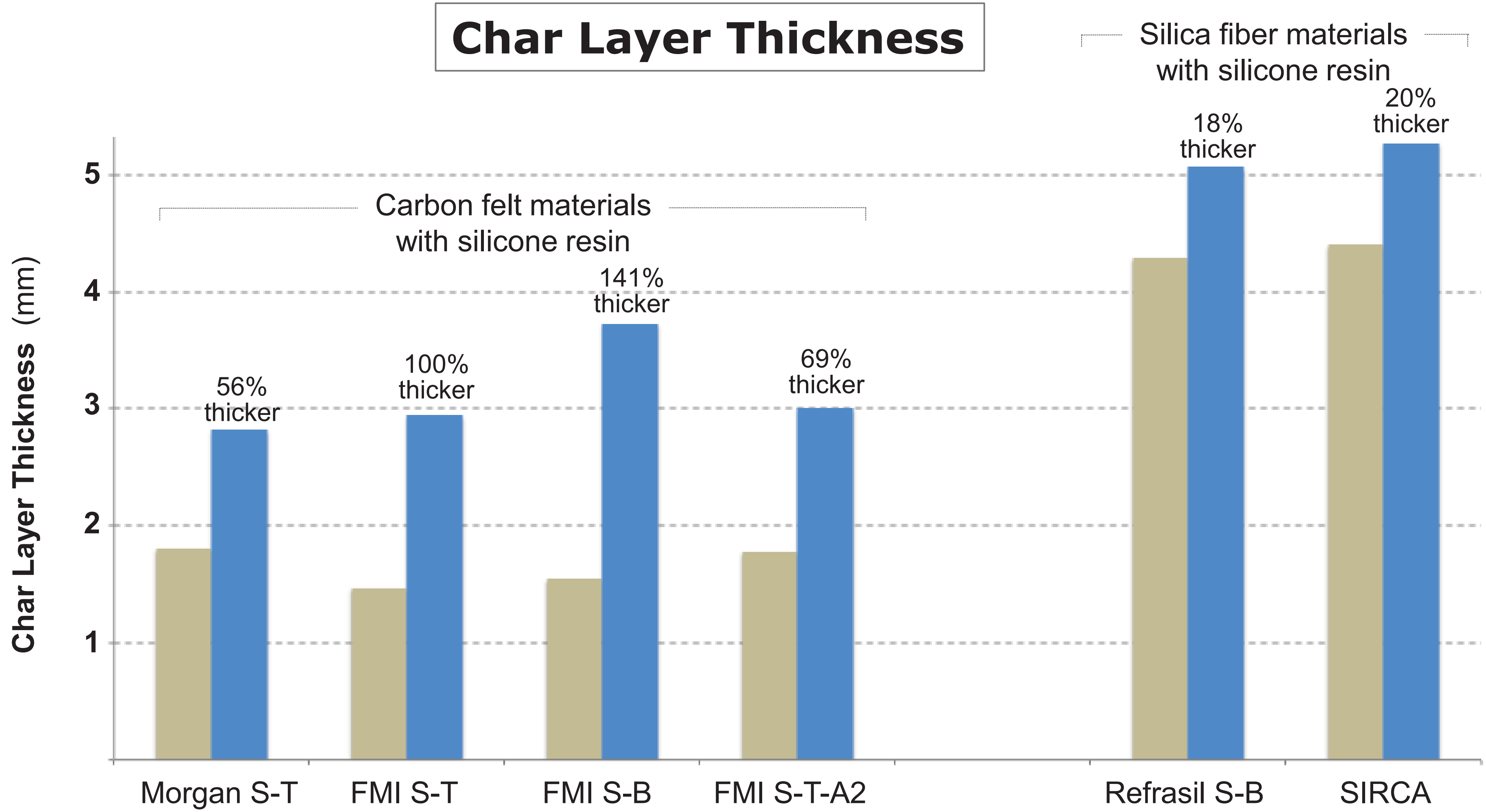


post CO_2 laser

post Fiber laser

- Char zone is created when enough energy is absorbed in depth to produce the temperature required to pyrolize 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

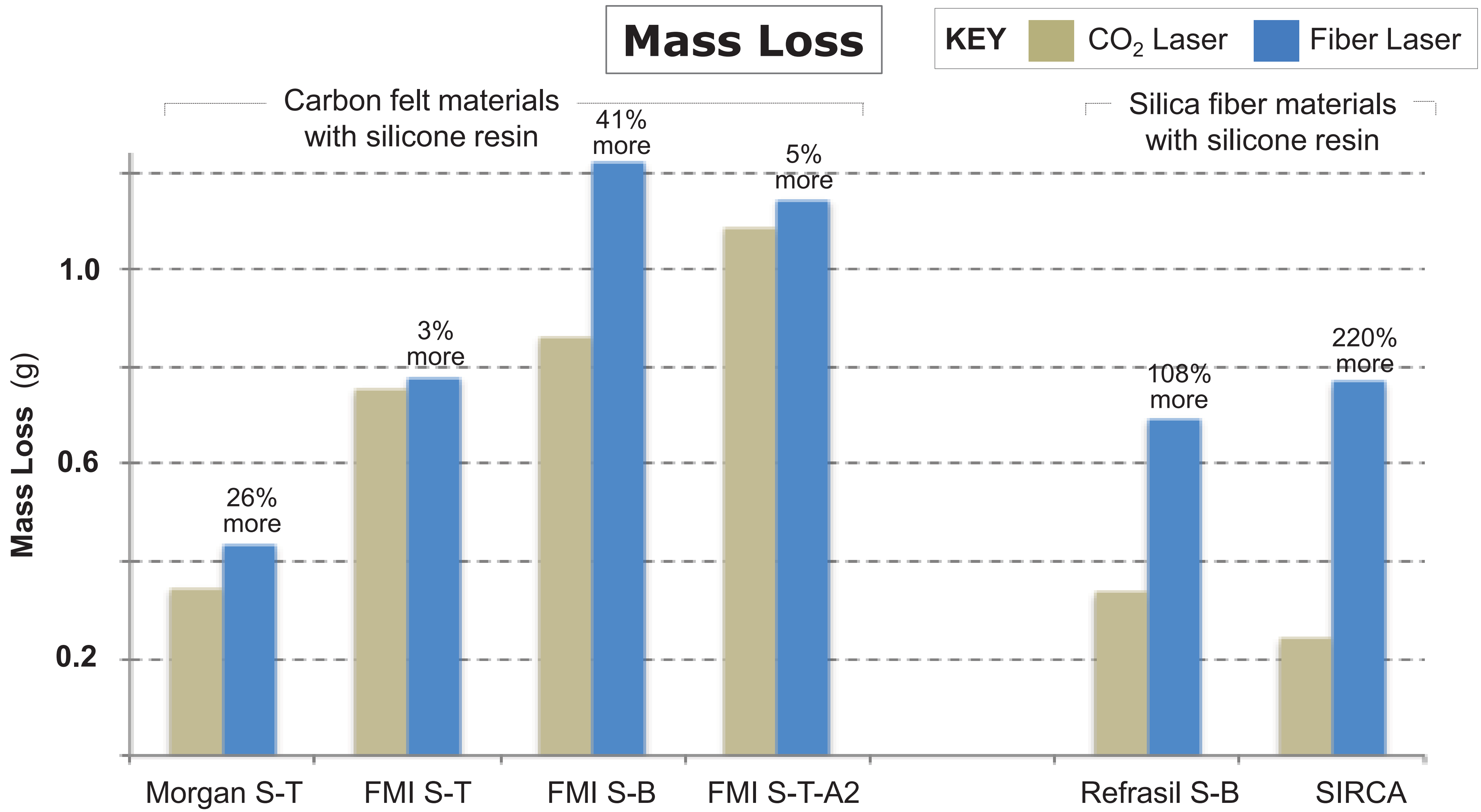


Comparing char layer thickness results from the Fiber laser vs CO_2 laser tests

- 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

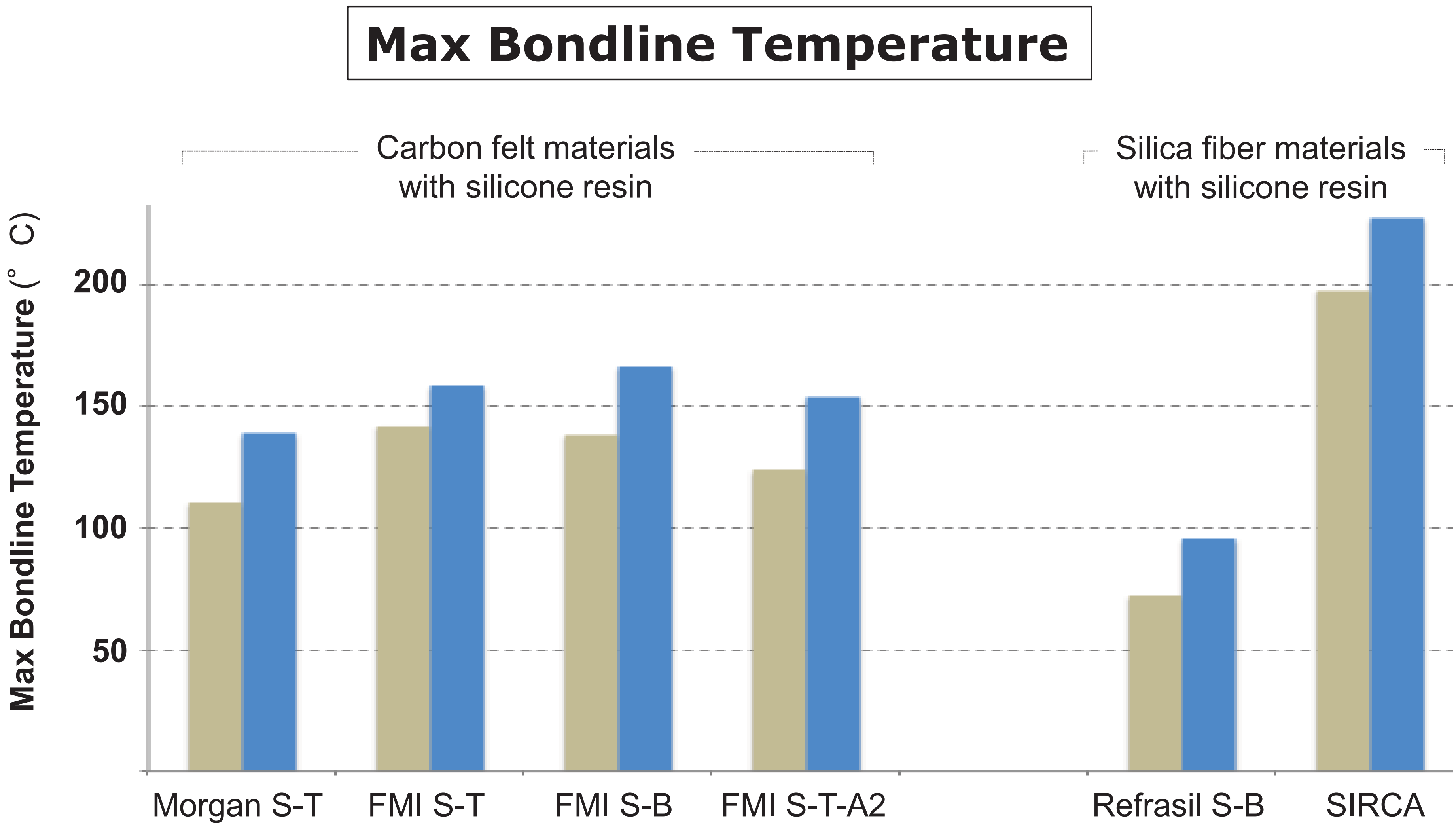


Comparing the mass loss of pyrolysis & vaporization from the Fiber laser vs CO_2 laser tests

- Carbon felt materials lost on average 20% more mass from Fiber to CO_2 laser test.

- Silica fiber materials lost on average 160% more (but less overall: start at high reflectance)

Test Results of Carbon & Silica Fiber-based Materials



Data ordered by increasing density of the carbon and silica (glass) felt materials

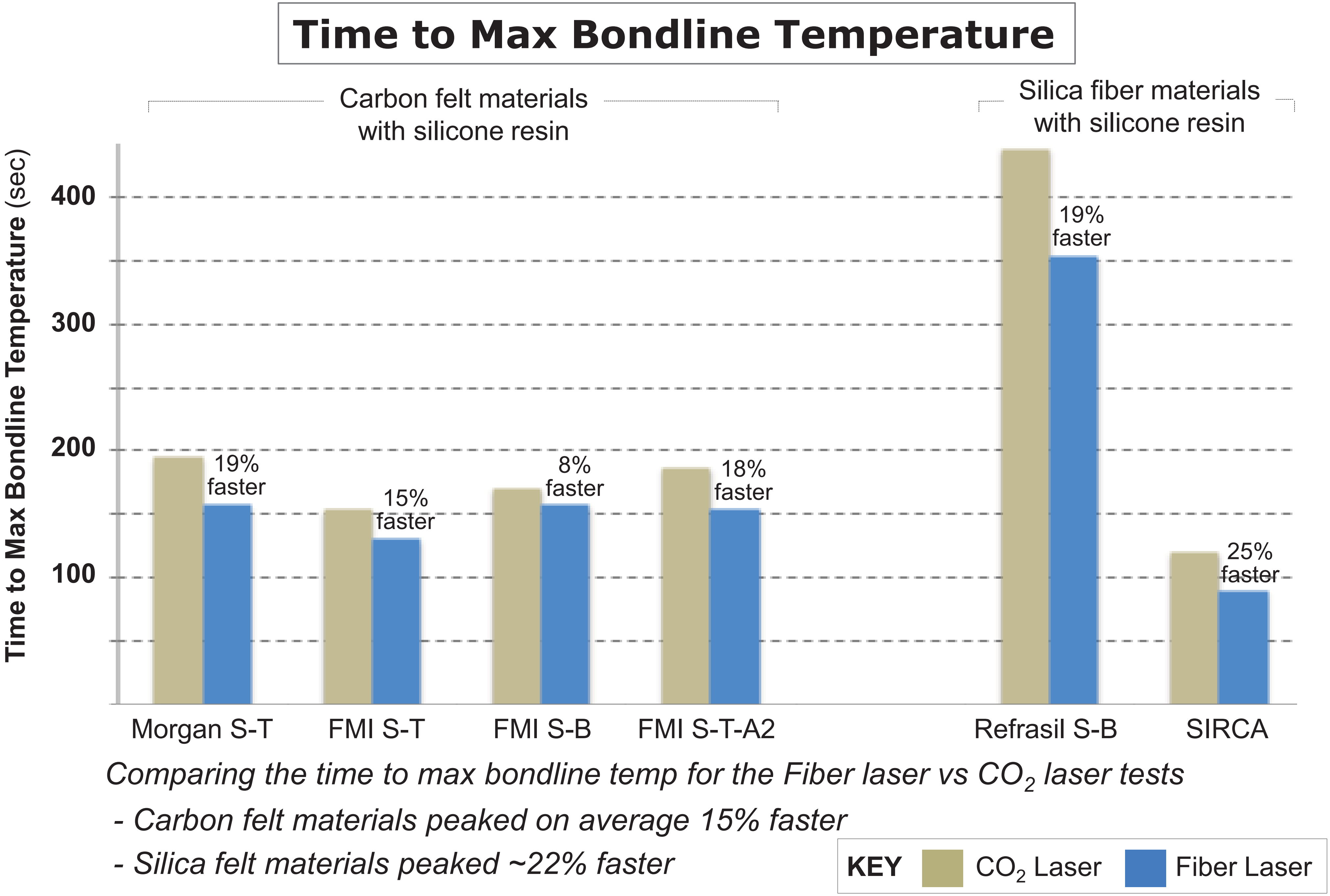
Higher bondline temperatures for each material.

Note Refrasil was thicker, insulative.

KEY CO_2 Laser* Fiber Laser*

* *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 CO_2 laser tests

- Carbon felt materials peaked on average 15% faster

- Silica felt materials peaked ~22% faster

- Background / Motivation
- Approach
- Test Results
- Summary & Conclusions

Summary and Conclusions

- Overview: Experimental data was compared from tests in two non-pulsed lasers with widely separated wavelengths, at irradiances of 115 W/cm^2 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

General Test Results	CO_2 Laser	Fiber Laser
Max Bondline Temperature	lower	higher
Time to Max Bondline Temp	slower	faster
Mass Loss	less	more
Char Layer Thickness	thinner	thicker

- 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
- The entire NASA Ames EDL/TDP materials team (Parul Agrawal, Jim Arnold, Al Covington, Wendy Fan, Matt Gasch, Howard Goldstein, Bernie Laub, Joe Mach, Frank Milos, Steve Sepka, Mairead Stackpoole, Jeremy Thornton)
- 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

- Background / Motivation
- Approach
- Test Results
- Summary & Conclusions
- Appendix

Key Results Table

Test Material	Areal Wt (g/cm^2)	Density (g/cc)	Peak Bondline Temp (C)	Time to Peak Temp (sec)	Mass loss (g)	Virgin (mm)	Char (mm)	Char+Pyro (mm)	Recession (mm)
Carbon Felt Silicone									
Morgan-S-T	0.34	0.18	110	195	0.34	13.18	1.81	4.03	0.2
Fiber Morgan-S-T	0.34	0.18	139	157	0.43	11.24	2.81	7.70	0.0
FMI-S-T	0.34	0.20	142	154	0.75	8.77	1.47	8.20	0.1
Fiber FMI-S-T	0.34	0.20	158	131	0.78	7.68	2.94	9.89	-0.8
FMI-S-B	0.39	0.21	138	171	0.86	10.07	1.54	8.52	0.5
Fiber FMI-S-B	0.37	0.20	166	158	1.22	7.06	3.72	12.17	-0.2
FMI-S-T-A2	0.43	0.22	124	187	1.09	10.79	1.78	8.38	-1.0
Fiber FMI-S-T-A2	0.42	0.22	154	154	1.14	8.08	3.01	10.90	2.5
Glass Fiber w Silicone									
AFRSI-S-B	0.54	0.23	80	408	0.43	14.17	4.16	8.39	1.0
Fiber AFRSI-S-B	0.54	0.23	80	346	0.55	14.06	5.30	9.40	-0.7
Refrasil-S-B	0.66	0.27	72	438	0.34	17.27	4.29	5.85	0.0
Fiber Refrasil-S-B	0.59	0.25	95	353	0.69	15.32	5.06	6.55	0.0
SIRCA	0.34	0.26	198	120	0.24	3.88	4.40	8.75	0.3
Fiber SIRCA	0.34	0.26	227	90	0.77	4.34	5.27	9.04	2.0

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 CO_2 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 CO_2 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.

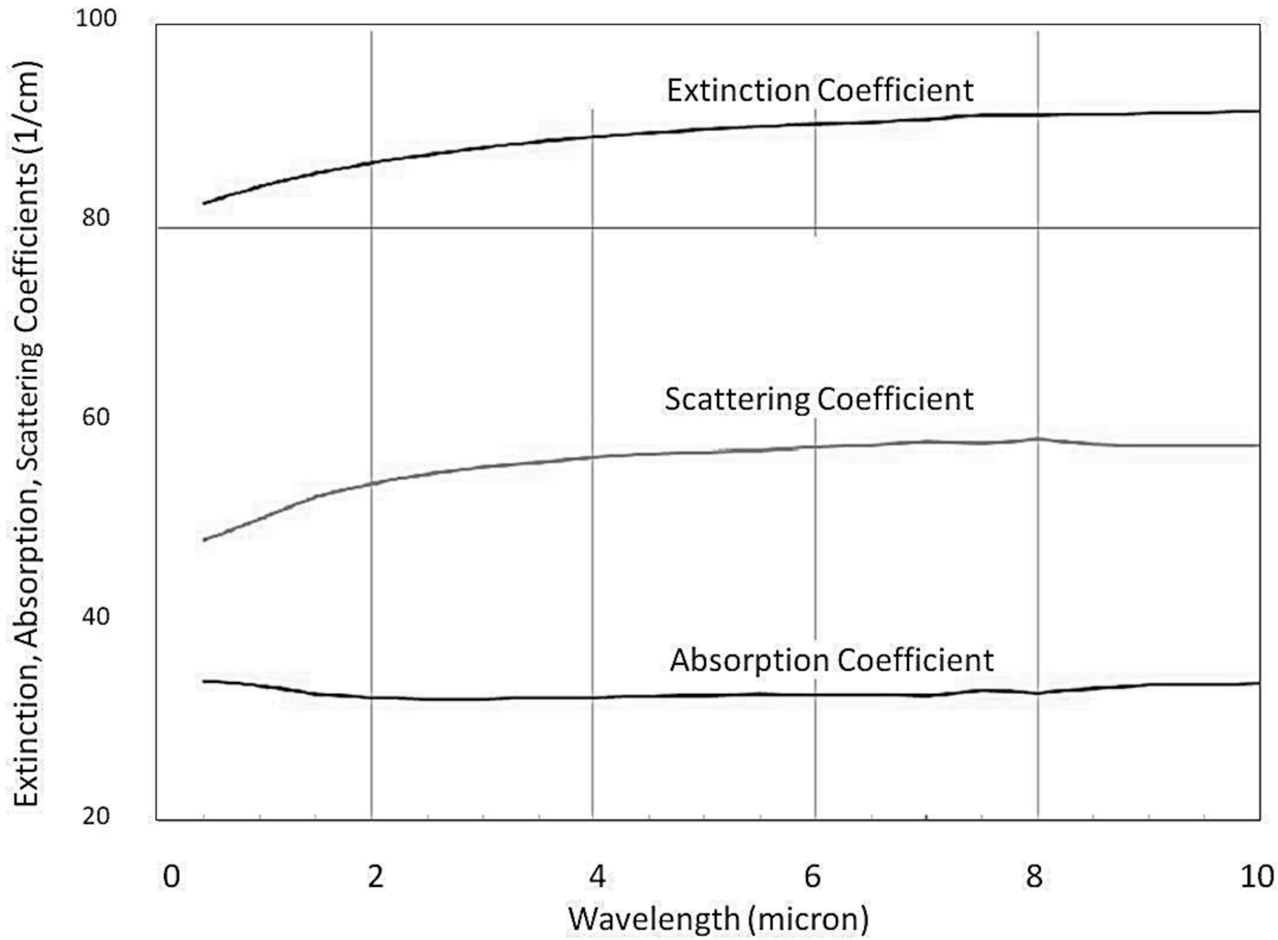
Comparison of Fiber and CO2 laser tests

Test Material	Bondline Temperature Increase (C)	Time to Peak Temperature Change (%)	Mass Loss Change (%)	Char Thickness Change (%)	Char + Pyrolysis Zone Change (%)
Morgan-S-T	28	-22	26	56	43
FMI-S-T	16	-17	3	100	38
FMI-S-B	28	-9	41	141	75
FMI-S-T-A2	30	-20	5	69	626
Refrasil-S-B	23	-20	106	18	18
SIRCA	29	-30	220	20	20

- **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 (CO_2 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)

$$q_r = -\lambda_r \frac{\partial T}{\partial z}$$

$$\lambda_r = \frac{16 n^2 \sigma T^3}{3} \int_0^\infty \frac{1}{\kappa_{e\lambda}\left(1 - G_\lambda\right)} \frac{dI_{b\lambda}}{dI_b\left(T\right)} d\lambda$$

Rosseland mean approach…

for fiber scattering and absorption…

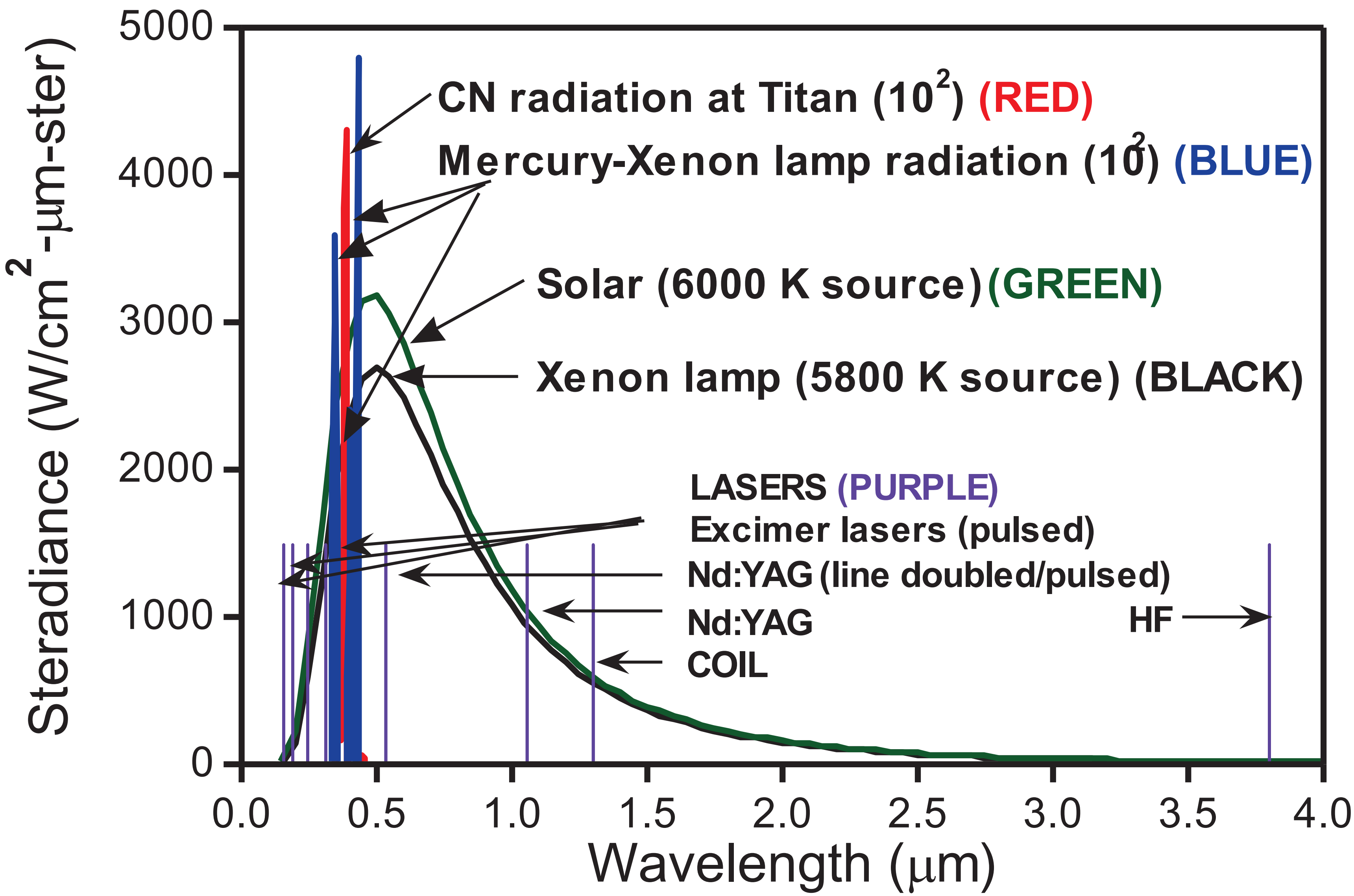
$$G_\lambda = \frac{1}{\kappa_{e\lambda}} \int_0^1 \int_{-1}^1 \left\langle \kappa_{s\lambda} p_\lambda\left(\mu, \mu'\right)\right\rangle \mu' d\mu' d\mu$$

The forward component is computed from the weighted phase function:

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

- 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.

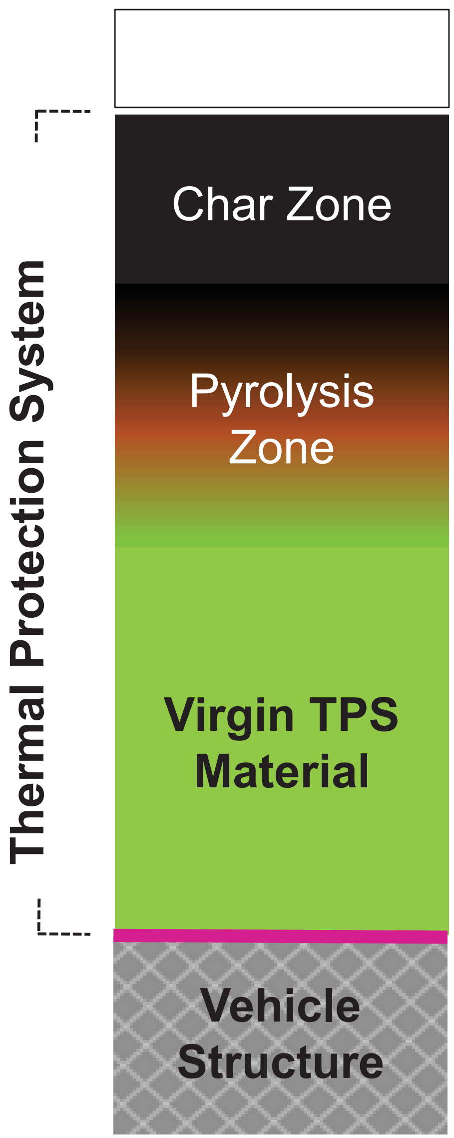
Spectra of Available Radiation Sources



High speed Earth atmospheric entry includes significant energy in the UV/

Background: In-depth Response of TPS Ablators

Accurate thermal prediction and analysis requires proper modeling of the char and pyrolysis zones – including reaction kinetics



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, SiO_2, Si-C).

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

Original material, thermally and chemically unchanged, typically consisting of a substrate and resin

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