Federal Aviation Administration

COE CST Second Annual Technical Meeting: Ultrahigh Temperature Composites for Thermal Protection Systems (TPS)

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Overview

- Team Members
- Purpose of Task
- Research Methodology
- Results
- Next Steps
- Contact Information

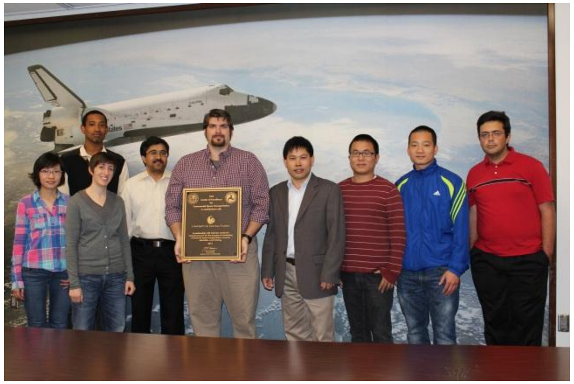
Team Members

Principle Investigators

- **Jan Gou -** Composites design and manufacturing, composites mechanics
- **Jay Kapat -** Heat transfer, film cooling, aerodynamics testing
- **Ali Gordon -** Mechanical property characterization, fatigue and fracture

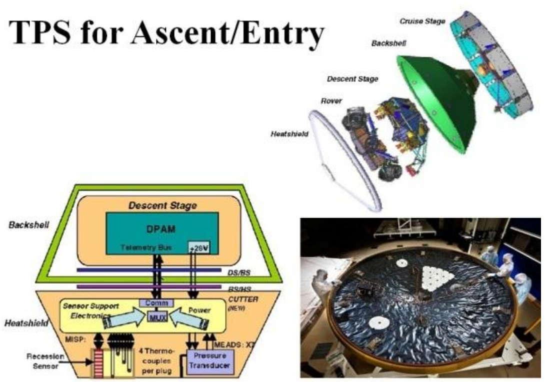
Graduate Students

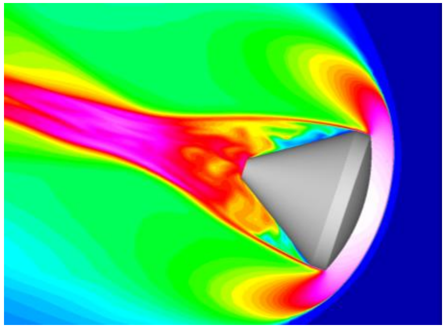
- **Donovan Lui/J. Gou**: Composites TPS design and manufacturing, ablation testing
- **Cassandra Carpenter/J. Kapat**: Aerothermal modeling
- **Steven Craft/A. Gordon**: Thermal-mechanical testing and characterization



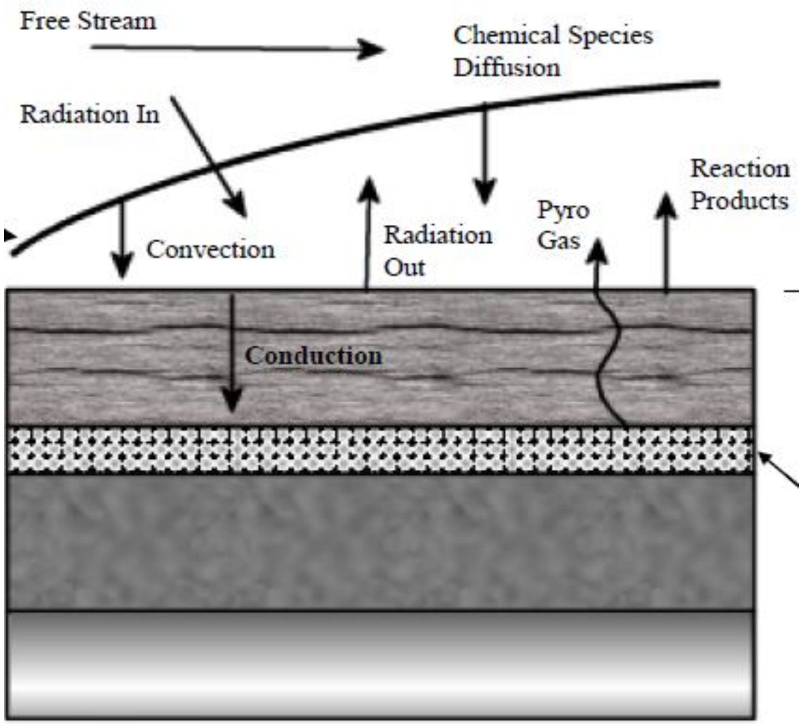
Purpose of Task

Develop **ultrahigh temperature**, **light weight**, **low erosion**, and **cost effective** ablative thermal protection systems with embedded health monitoring for inherent safety and real-time assessment of TPS performance in hypersonic space vehicles



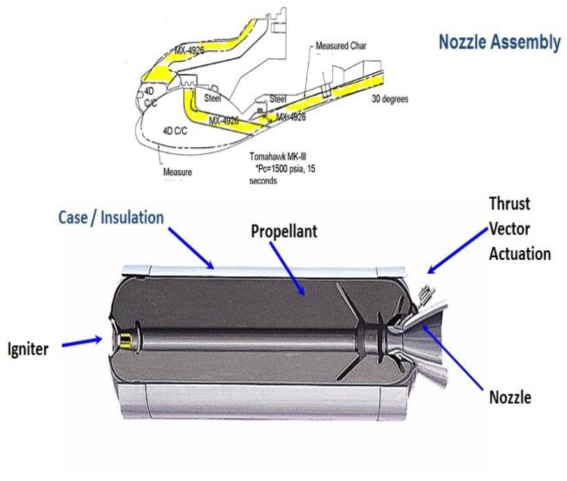


Reentry Vehicles

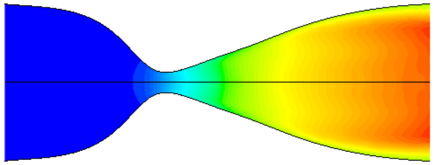


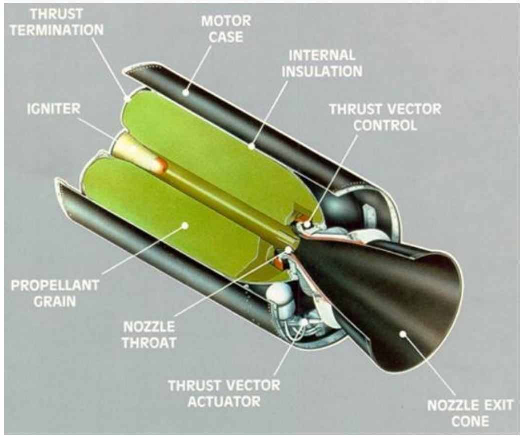
Purpose of Task (Cont'd)

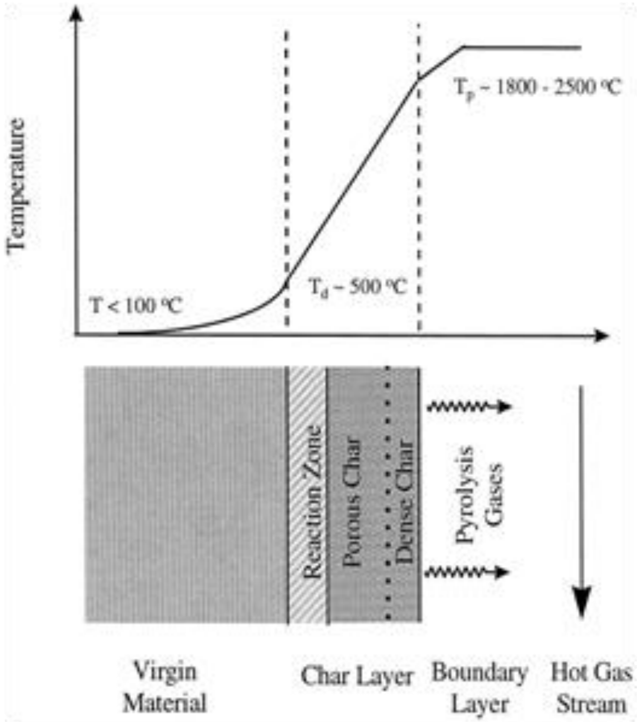
Develop **ultrahigh temperature**, **light weight**, **low erosion**, and **cost effective** ablative thermal protection systems with embedded health monitoring for inherent safety and real-time assessment of TPS performance in hypersonic space vehicles



Solid Rocket Motor







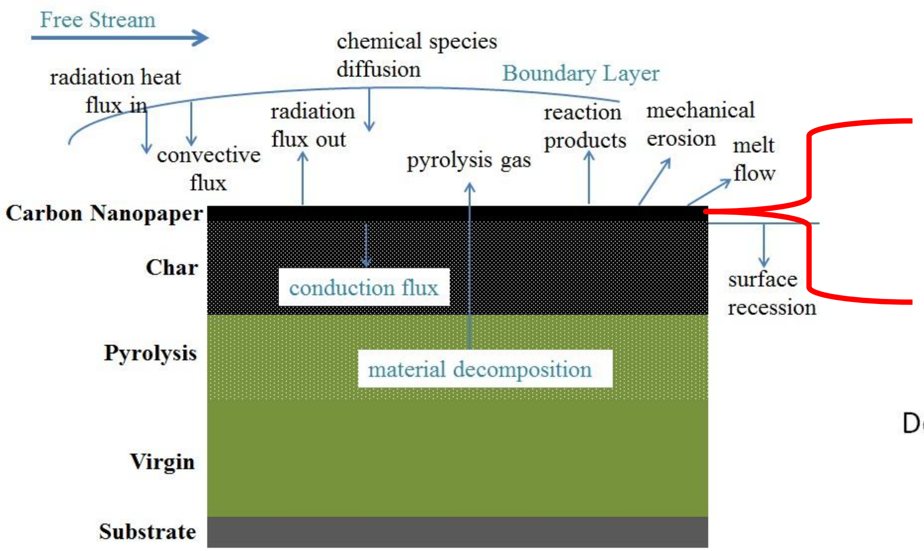
Current Approach

- PICA: Phenolic Impregnated Carbon Ablator
- SICA: Silicone Impregnated Carbon Ablator
- Carbon/Carbon Composites

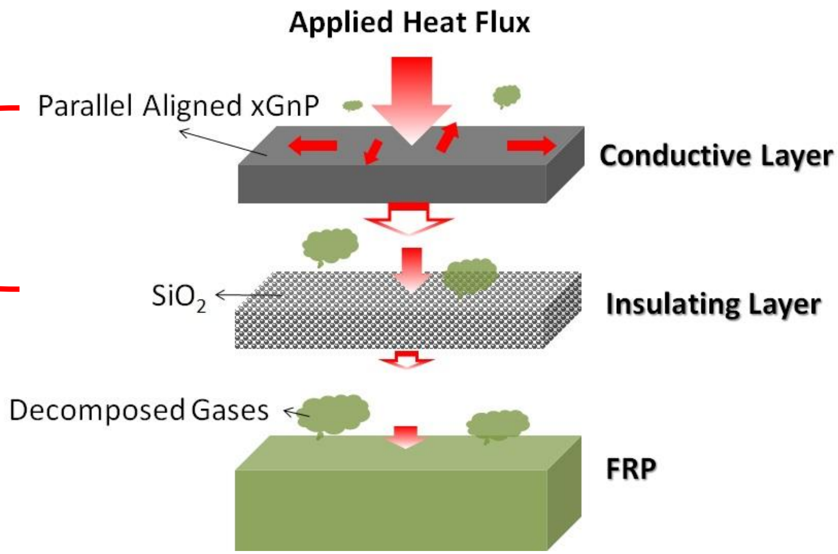
Problems

- The resulting chars are structurally weak and susceptible to mechanical erosion, severely reducing the lifetime of the TPS. Reducing spallation or erosion of the char can enable use of less ablative materials thereby reducing the total weight of TPS.
- The evaluation of ablation performance needs to consider the structural integrity of TPS structures
- Recession monitoring is most important measurement to the aerothermal analysis of the TPS structure. This measurement provides critical information about how the TPS mass and shape changes during the fight.

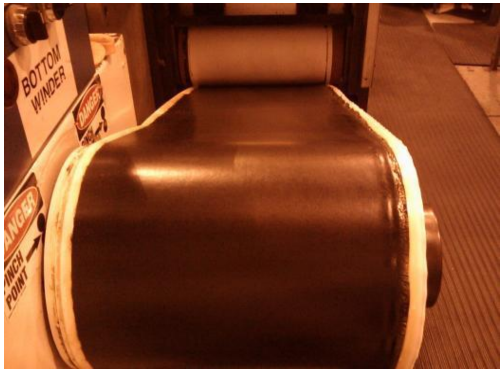
Ablative TPS Design - Nanocomposites Approach



TPS Materials Design



Bi-layer thermal protective coating

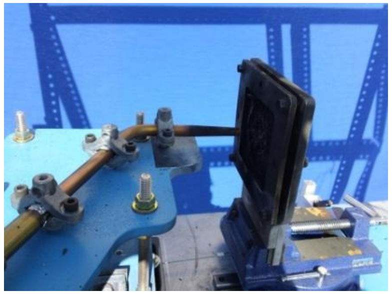


Nanocomposite prepreg systems

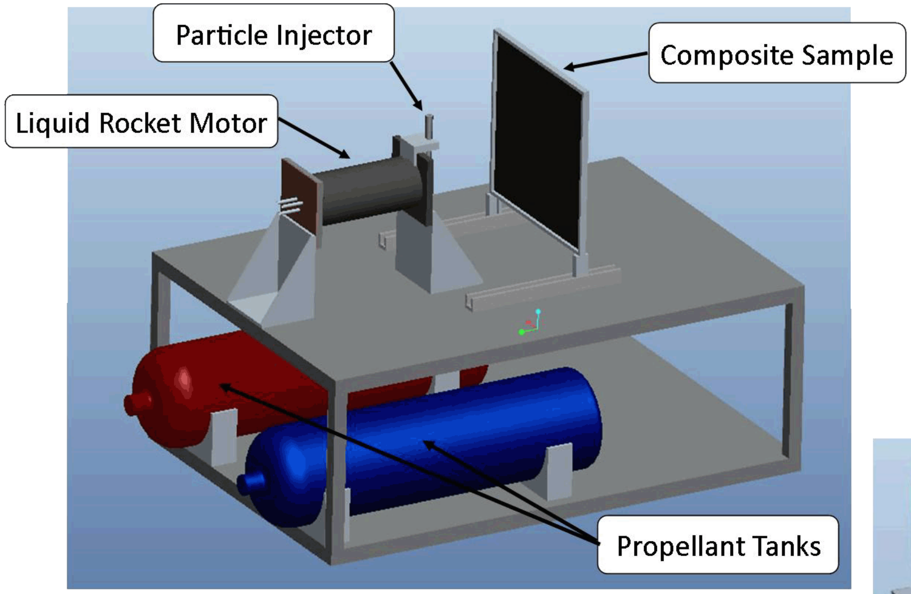
Nanocomposite thermal protective coating

Results - Ablation Testing with Oxyacetylene Torch

Initial Testing on October 28, 2012 at UCF, Orlando, FL

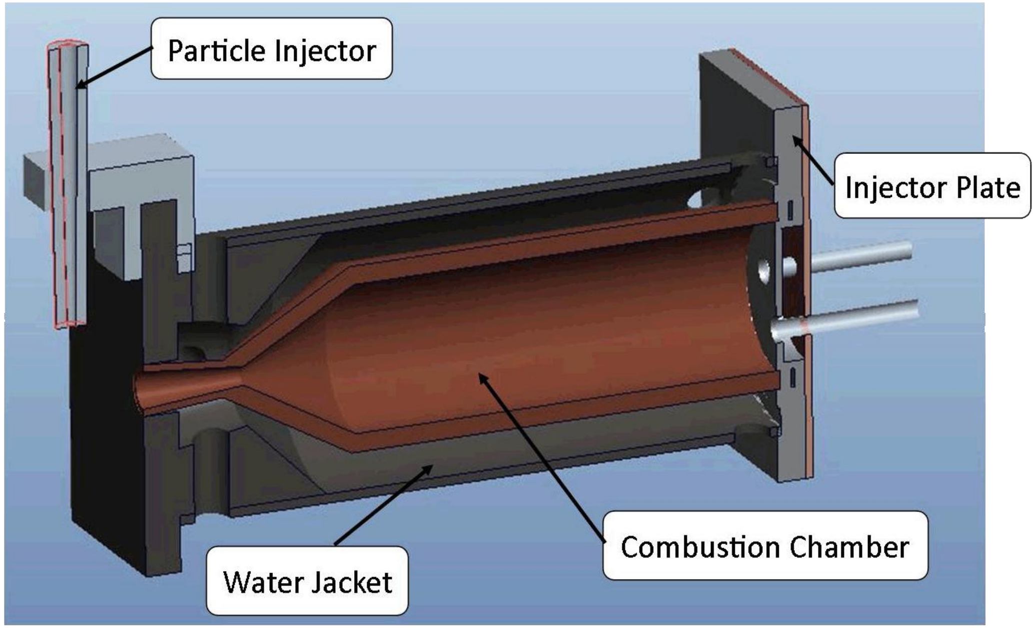


Results - Ablation Testing with SSRM



Ablation Performance

- Surface Temperature
- Backside Temperature - backside heat soaked temperature
- Ablation rate – peak erosion depth

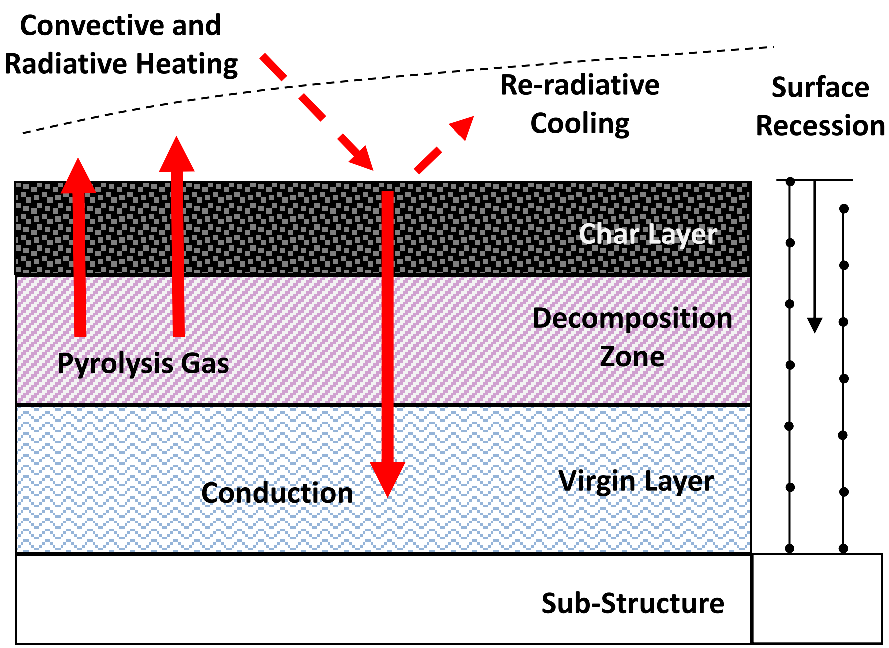


- Simulated Solid Rocket Motor (SSRM) is a small scale, liquid-fueled rocket burning kerosene and oxygen.
- Heat flux of 700 W/cm^2 at 1 inch from the nozzle
- Support sample size of 12”x12”
- Minimum burning time of 10 seconds
- Particle injection mass flow rate of ~ 20 lb/hr
- High exhaust velocity

Results - Ablation Modeling

1-D Material Model

- Acknowledges two material states: virgin and charred
- A mixture law used to interpolate intermediate states



The developed material response code predicts the 1-D thermal distribution, material decomposition, pyrolysis gas generation and the resulting surface recession rate from heat flux and surface temperature values calculated by the commercial solver.

Results - Ablation Modeling (Cont'd)

Assume there is no volume change and enthalpy is a function of temperature only. The governing equation of the decomposition of PMC can be written as:

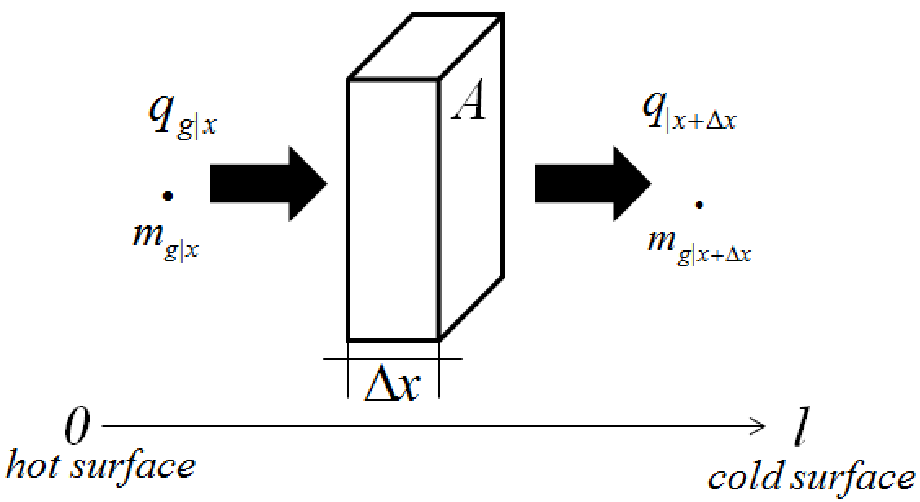
Change in the total energy

Conduction heat flux

Endothermic decomposition

$$\frac{\partial}{\partial t}(\phi.\rho_g h_g + \rho h) = \frac{\partial}{\partial x}\left[k_g \phi \frac{\partial T}{\partial x} + k(1-\phi)\frac{\partial T}{\partial x}\right] - \frac{\partial}{\partial x}(\dot{m}_g h_g) - Q\frac{\partial \rho}{\partial t}$$

Convection of energy resulting from the gaseous products flowing through the char structure



Results - Ablation Modeling (Cont'd)

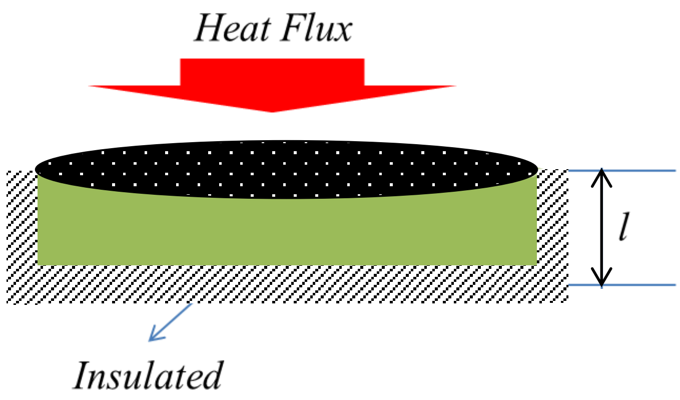
Conservation of mass: $$\frac{\partial \dot{m}_g}{\partial x} + \phi \frac{\partial \rho_g}{\partial t} = -\frac{\partial \rho}{\partial t}$$

Gas flowing out

Residual Char

Mass change of the composites

Gas flow(Darcy's Law): $$\dot{m}_g = -\frac{r\rho_g}{\mu}\frac{\partial P}{\partial x} \qquad P = \frac{\rho_g RT}{M}$$



Decomposition follows Arrhenius reaction:

$$\frac{\partial m}{\partial t} = -Am_v[(m-m_e)/m_v]^n \exp(E_a/RT)$$

Boundary conditions:

$$k_g\phi\frac{\partial T}{\partial x} + k(1-\phi)\frac{\partial T}{\partial x} = 0 \qquad \dot{m}_g = 0$$

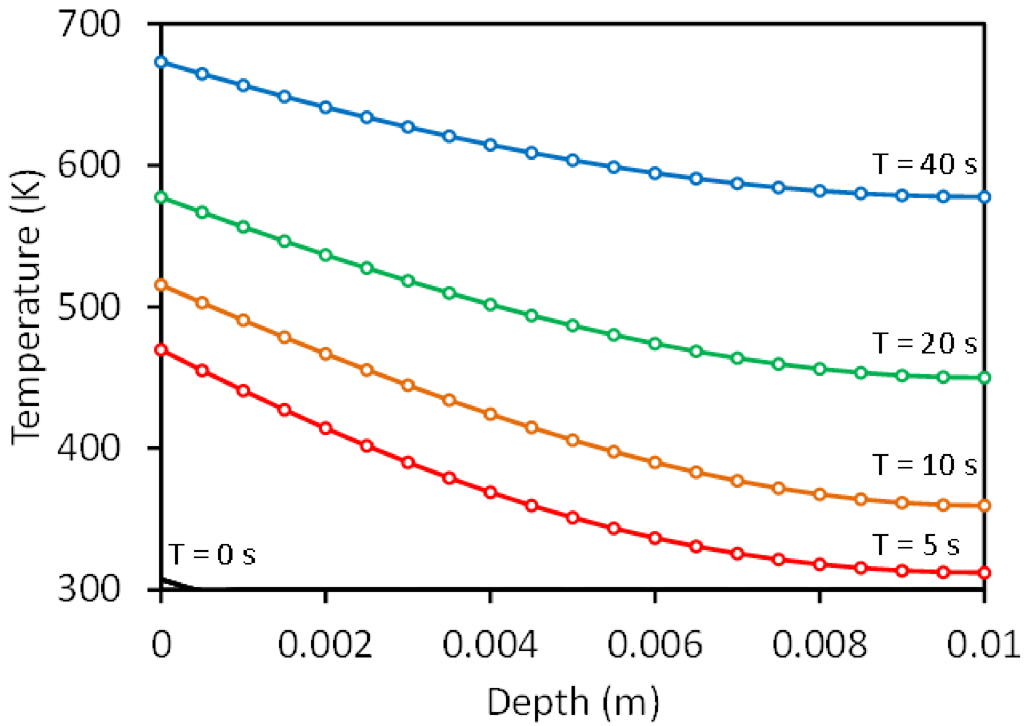
Initial conditions:

$\rho_g=0$, $T=T_0$, $\dot{m}_g=0$, $\rho=\rho_0$ for $0 \le x \le l$ at $t=0$

Results - Ablation Modeling (Temperature Profile)

T_0 = 300 K
q" = 750 kW/m^2
L = 0.01 m
ρ= 8000 kg/m^3
α =2.5x10-6 m^2/s

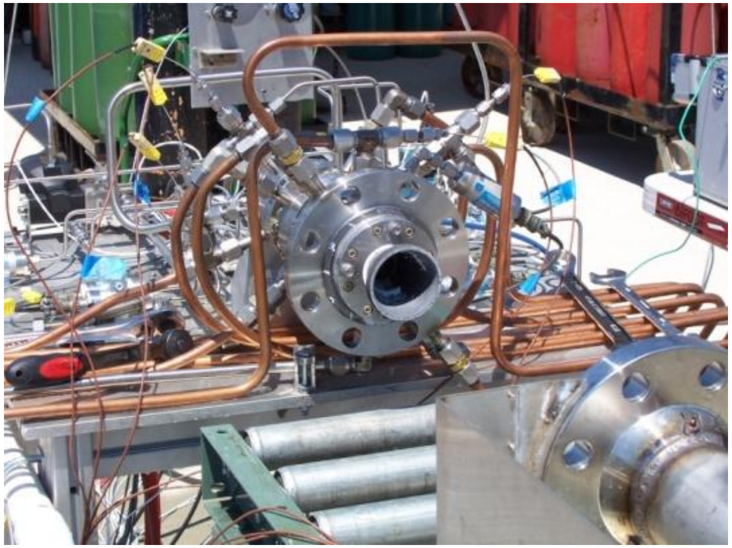
T	k, (W/m-K)	Cv, (J/kg-K)
300	10	500
1300	100	5000



In-depth decomposition ablation model can be coupled to a commercial CFD package to predict the 1-D response for any desired geometry where ablative TPS is applicable.

Collaboration with Dynetics, Inc.
Rocket Nozzle Testing

Kickoff meeting with Dynetics, Inc. at Solutions Complex on October 29, 2012 in Huntsville, AL



Collaboration with AAE Aerospace
Rocket Nozzle Manufacturing

Tape Wrapped Steel Mandrels

Next Steps

- Integration of nanocomposite thermal protective coating with PICA
- Oxyacetylene torch testing of composite panels
- Simulated solid rocket motor (SSRM) hot fire test
- Aerothermal analysis of TPS structures with curved geometry
- Thermo-mechanical characterization and testing for structural integrity evaluation

TASK 253. ULTRA HIGH TEMPERATURE COMPOSITES FOR THERMAL PROTECTION SYSTEMS (TPS)

- **PROJECT AT-A-GLANCE**
- AST RDAB POC: Demidovich, Nick
- AST RESEARCH AREA: 2.3 Vehicle Safety Systems & Technologies
- UNIVERSITY: University of Central Florida
- PRINCIPAL INVESTIGATOR: Dr. Jan Gou, Dr. Jay Kapat, Dr. Ali Gordon
- STUDENT RESEARCHER: Mr. Donovan Lui, Ms. Cassandra Carpenter, Mr. Steven Craft
- PERIOD OF PERF: Jan 1, 2011 - May 31, 2012.
- STATUS: Ongoing

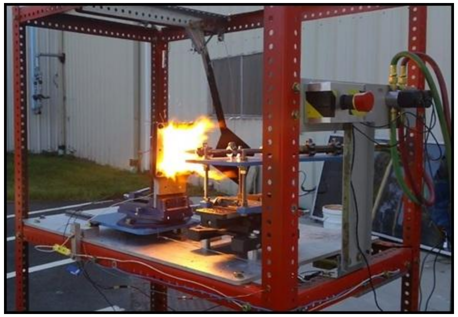
RELEVANCE TO COMMERCIAL SPACE INDUSTRY

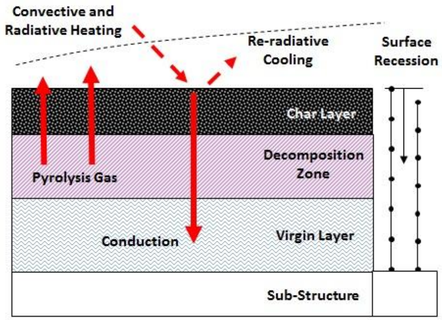
- Ultra-high temperature, light weight, low erosion, and cost effective thermal protection systems (TPS) are enabling technologies for viable commercial space transportation vehicles and their high-temperature systems.

STATEMENT OF WORK

- Develop nanocomposites TPS with embedded health monitoring for inherent safety and real-time assessment of hypersonic TPS applications.
- Provide an analysis tool for the aerothermal modeling of reentry vehicles and rocket propulsion.
- Provide an analysis tool for thermal degradation modeling of new ablative materials.
- Provide ablation sensing to monitor the structural health of the ablative thermal protection system.

ABLATION TESTING & THERMAL MODELING





STATUS

- Investigated 3 approaches: Phenolic Impregnated Carbon Ablator (PICA), Silicone Impregnated Carbon Ablator (SICA); Carbon/Carbon Composites.
- Manufactured nanocomposite thermal protective coating; ablation testing with oxyacetylene torch; thermal modeling of TPS structures by integrating self-developed code with Fluent.

FUTURE WORK

- Ablation Testing and Analysis: Simulated Solid Rocket Motor (SSRM) is a small scale, liquid-fueled rocket burning kerosene and oxygen
- Thermal Degradation Modeling and Ablation Sensing: Damage modeling and life prediction under thermal- and pressure-loading conditions; Integrated health monitoring with embedded sensors for real-time assessment

Funding Requirements – Five Years

- Gross received thru October 31, 2012
  - FY2011: $89K Research Funding, $11K Technical Oversight, $42K Stop Gap
  - FY2012: $114K
- Gross requested for five total years broken out by year
  - FY2011: $89K+$20K+$42K = $161K
  - FY2012: $114K
  - FY2013: $150K
  - FY2014: $150K
  - FY2015: $150K
- 1:1 Matching from Space Florida

Contact Information

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