Arc Jet Testing of Thermal Protection Materials: 3 Case Studies

NSMMS
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Arc Jet Testing: TPS Case Studies

Arc Jet Testing

Other than an actual flight test, arc jet facilities are the best available tool for testing materials and systems in high speed entry environments.

Arc jets provide a controlled test environment that approximates the heat fluxes, surface temperatures, enthalpies, pressures, flow, and shear experienced during high speed entries.

While arc jet facilities cannot duplicate all of the relevant parameters in any single test, a well designed test matrix in concert with material modeling and analysis can offer Mission teams confidence in validating the performance of their thermal protection materials and systems.
The following presentation discusses three illustrative cases involving material issues identified during arc jet testing.

**Background**

**Case 1: PICA & MSL**
Testing identifies material issue

**Case 2: Advanced TUFROC**
Test article or material?

**Case 3: Conformal PICA**
Testing guides material development
Arc Jet Testing: TPS Case Studies

ArcJet Basics

High Energy Flow
Mach 5 - 7 at exit
Bulk Temp ~ 7,000°K

Sealed Test Chamber
Capable of simulating extreme upper atmosphere (1 - 5 Torr)

Interchangeable Nozzles

Constrictor Segment
electrically isolated

test gas
(e.g. air, nitrogen)

cooling water
99.99% pure copper

cut-away cross-section
Arc Jet Testing: TPS Case Studies

NASA Ames Arc Jet Complex

- **Nation's highest powered** (150 MW DC) arc-heated hyper-thermal test facility
  - Aerodynamic Heating Facility (AHF) 20 MW
  - Turbulent Flow Duct (TFD) 20 MW
  - Panel Test Facility (PTF) 20 MW
  - Interactive Heating Facility (IHF) 60 MW

- **Unique capabilities enable development of advanced TPS materials and concepts**

- **Large test articles** (2.5 cm up to 60 x 60 cm)

- **Pre-mixed test gas with continuous high enthalpy flows** (2 - 40 MJ/kg in air)

- **Plasma flow expands through selectable nozzles to hypersonic speeds**

- **Enthalpies similar to planetary entries**

- **Spectroscopic / LIF diagnostic capability**

*Every NASA flown thermal protection system has been tested in some capacity in the Ames Arc Jet Complex*
Arc Jet Testing: TPS Case Studies

Outline

Case 1: PICA & MSL
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* Phenolic Impregnated Carbon Ablator
** Mars Science Laboratory
Objective of NASA's Mars Science Laboratory (MSL) program was to place an SUV size rover (Curiosity) safely on the surface of Mars.

Too heavy for airbags, MSL utilized a Sky Crane for a powered descent.

Curiosity rover:
- 3 m (long) x 3 m (wide) x 2 m (tall)
- 900 kg, 6 wheels, 90 m/hr
**MSL Entry, Descent, and Landing (EDL) Phase**

17 minutes of excitement

1. Entry Vehicle separation from Cruise Stage
2. Balance devices separation
3. Entry Interface
4. Peak heating
5. Peak deceleration
6. Hypersonic aero-maneuvering
7. Parachute deployment
8. Heat shield separation
9. Radar ground mapping
10. Backshell separation
11. Retro-propulsion
12. Tethered descent
13. Touchdown and cable separation
14. Sky Crane fly-away

**Guided Entry**
- 125 km
- 5.8 km/s

**Parachute Descent**
- 1.8 km
- 100 m/s
- 10 km
- 500 m/s

**Landing**
- 8 m, 1 m/s

**Approximate, non-linear time scale**
- T = 0
- 2 min
- 10 min
- 14 min
- 15 min
- 16 min
- 17 min
Prior to MSL, the heaviest Mars entry vehicle (EV) was Viking (980 kg). MSL (3380 kg) expected to be more than triple the EV mass of Viking.

Curiosity rover ~ 5 times the mass of MER Spirit / Opportunity rovers.

Given MSL's mass, geometry, and trajectory - turbulent flow was predicted on the primary heat shield (first for a Mars entry)

→ Entry heating projected to be 2x that of any previous Mars mission
## CASE 1: PICA & MSL

### Comparing MSL (design) with Prior Mars Entry Vehicles

<table>
<thead>
<tr>
<th>U.S. Mars Missions Entry Vehicles</th>
<th>Viking 1 &amp; 2</th>
<th>Pathfinder</th>
<th>MER A &amp; B*</th>
<th>Phoenix</th>
<th>MSL (design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry mass (kg)</td>
<td>980</td>
<td>585</td>
<td>840</td>
<td>570</td>
<td>5.6</td>
</tr>
<tr>
<td>Entry speed (km/s)</td>
<td>4.5</td>
<td>7.6</td>
<td>5.5</td>
<td>5.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Heat shield diameter (m)</td>
<td>3.5</td>
<td>2.65</td>
<td>2.65</td>
<td>2.65</td>
<td>4.5</td>
</tr>
<tr>
<td>Heat shield (TPS) material</td>
<td>SLA-561V</td>
<td>SLA-561V</td>
<td>SLA-561V</td>
<td>SLA-561V</td>
<td>SLA-561V</td>
</tr>
<tr>
<td>TPS thickness (cm)</td>
<td>1.3</td>
<td>1.9</td>
<td>1.6</td>
<td>1.4</td>
<td>TBD</td>
</tr>
<tr>
<td>Peak heat flux (W/cm²)</td>
<td>20</td>
<td>120</td>
<td>50</td>
<td>55</td>
<td>200</td>
</tr>
<tr>
<td>Turbulent (at peak heat flux)?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Peak pressure (atm)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.08</td>
<td>0.37</td>
</tr>
</tbody>
</table>

**KEY** denotes MSL not in class with prior Missions

*Spirit & Opportunity*
SLA Stagnation Testing for MSL

- **MSL baselined SLA-561V**, which performed well in stagnation arc jet testing and was heatshield material for all previous Mars missions
- Glass vaporization allowed material to withstand **heat fluxes > 300 W/cm²**
- **No failures observed**
- High fidelity SLA-561V material model matched stagnation arc jet tests

**MSL Stagnation Test Articles (SLA-561V)**

- 30 W/cm²
- 90 W/cm²
- 150 W/cm²
- 210 W/cm²
- 270 W/cm²
- 300 W/cm²
CASE 1: PICA & MSL

SLA Shear Testing for MSL

- Arc jet testing in shear environments yielded catastrophic material failures
  - Recession rate was 20+ times predicted values
  - Filler material seemed to disintegrate and evacuate the cells
  - Not a melt-fail; not correlated to shear force

- Material failure reproducible at certain conditions
Program Decision

- **Failure identified** in Sep 2007 after Critical Design Review and ~ 23 months before launch

<table>
<thead>
<tr>
<th>Option A</th>
<th>Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re-design mission to within heritage heat fluxes / pressures</td>
<td>Flight qualify alternate heat shield TPS material</td>
</tr>
<tr>
<td>Limits landing sites</td>
<td>PICA best candidate</td>
</tr>
<tr>
<td>Impact on science objectives?</td>
<td>Tiled ablator design never flown</td>
</tr>
<tr>
<td>Require more propellant</td>
<td>Leverages Orion PICA development</td>
</tr>
<tr>
<td>Adversely affect entry guidance robustness</td>
<td>MSL cost &amp; schedule at risk if any major technical issues arise</td>
</tr>
</tbody>
</table>

- MSL went with **Option B**, selecting PICA material
  - Leveraged past and ongoing PICA development by the CEV Orion project
  - MSL PICA testing would also expand Orion's PICA database
CASE 1: PICA & MSL

PICA consists of carbon substrate* impregnated with phenolic resin

![Diagram of PICA and MSL process]

- Carbon Fibers Pre-Impregnation: low density, randomly arranged
- Phenolic Resin: impregnation + curing
- PICA: Low phenolic loading matrix uniformly distributed throughout the substrate material
- Carbon Fibers Post-Processing: connected via 'fluffy' phenolic

High surface area resin morphology yields desirable thermal performance
CASE 1: PICA & MSL

Go-Forward Plan

• Design, develop, test, build, and qualify a PICA heat shield for an April 2009 delivery ( < 18 months from start!)

• Fortunately, to date Orion had conducted 125 arc jet tests of PICA
  - Tested to more severe environments (heating, pressure, shear)
  - Various gap filler designs
  - Material characterization (material property tests) performed
  - High fidelity model developed for in-depth thermal and recession response

• MSL could simplify design because the aeroshell structure was composite (vs metallic for Orion)
  - CTE agreement was better
  - Lower deflections in MSL enabled direct bonding to structure and filled gaps
CASE 1: PICA & MSL

Not much time!

• MSL PICA design worked in parallel with PICA manufacturing
  - Maximum allowable gap size originally based on Orion tests
  - Gap size then refined via thermal/structural analysis; verified through tests

• TPS sizing selected at 1.25" (3.175 cm) without detailed testing or analysis
  - Conservative over-design
  - 1.25" based on maximum mass allowed by spacecraft mass budget

• Symmetric heat shield selected to minimize aero-torques

• Tiled architecture driven by
  - PICA processing limitations
  - Aerothermal environments
  - Thermal-mechanical requirements
PICA Stagnation Testing

• Gap-filled specimens simulated cruise-to-entry effects
  - Low and high heat fluxes
  - With and without pre-cooling

• Tests using in-depth instrumentation verified PICA thermal response model

• Predicted recession rates within 20% of measured values from arc jet tests
  - MSL-relevant conditions
  - Predictions not as good at low heat rates
  - TITAN: 2D thermal response model
PICA Shear Testing

- Shear tests conducted at Ames and AEDC with wedges, swept cylinders
  - Comparison of tested PICA to thermal response model predictions
  - Effects of fiber direction
  - Gap filler response
  - Damaged or flawed acreage / gaps
  - Repair methods
  - Coating behavior

- Long gaps tested in Panel Test Facility (PTF), Turbulent Flow Duct (TFD)
PICA Test Results

- Extensive PICA arc jet test series utilized 100+ test articles

- PICA material robust at all tested conditions including those where SLA-561V experienced failures

- RTV-560 filled gaps performed well

- Recession rates varied from model predictions, but could be modeled and bounded conservatively

- Heat Shield thickness
  - Up front, program decision was to set it at 1.25”
  - Analysis and margining process yielded a thickness of 0.94"
  - So, as built vehicle had 0.31” extra thermal protection material / margin
CASE 1: PICA & MSL

MSL PICA Heat Shield

19 PICA lots manufactured for testing, development, production
⇒ 114 PICA billets ⇒ 113 PICA tiles (with 27 different tile geometries)
CASE 1: PICA & MSL

MSL Team Accomplishment

• Developed, designed, tested, built and qualified a 4.5-m tiled ablative heatshield in 18 months

• NASA’s first tiled, ablative (flight hardware) heat shield
MSL Mission Success

• MSL launched on 26 Nov 2011

• **6 Aug 2012:** successfully entered Mars atmosphere @ 5.8 km/s

• **Curiosity safely landed in Gale Crater,** within 3 km of the target after a 563,000,000 km journey

• **Curiosity has been producing valuable science on the surface of Mars for 1000+ days**

Top View of the MSL Heat Shield image taken by Curiosity 3 sec (50 ft) after separation from the descent Capsule
Arc Jet Testing: TPS Case Studies

Outline

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Case 2: Advanced TUFROC*
Test article or material?

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Testing guides material development

* Toughened Uni-piece Fibrous Reinforced Oxidation Resistant Composite
While the Space Shuttle was a technical marvel, there remains a national need for low cost, reliable access to and from Earth orbit.

- DoD Missions
- Space Station support
- Commercial access (satellite servicing, tourism, manufacturing)

**Major technical gap:** low cost, reusable TPS for high temp surfaces
In 1998, NASA established the Future-X Pathfinder program to develop 2\textsuperscript{nd} generation reusable launch systems.

In 1999, MSFC led the X-37 project was established with Boeing as the prime contractor.

Parallel research and development of the TUFROC concept started in 1998.

Leadership transitioned to DARPA in 2004 to support a U.S. Air Force vehicle – X-37b.

In 2003, a focused 18 month activity took TUFROC from research TPS to flight ready – Standard TUFROC.
CASE 2: Advanced TUFROC

Flight Proven Standard TUFROC

TUFROC spans USAF X-37b wing leading edge
- NASA developed Standard TUFROC and transferred it to X-37b Prime - Boeing
- Enabling technology for critical USAF Program
- 3 successful missions, 4th mission in progress

Reusability of Standard TUFROC? ⇒ Advanced
**2 Piece Approach**

*Re-radiate enough heat so that conduction through*
- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

**ROCCI Carbonaceous Cap**
- Silicon-oxycarbide phase slows oxidation
- HETC, treatment near surface slows oxidation and keeps emissivity high ($\varepsilon \sim 0.9$)
- Coated with borosilicate reaction cured glass (RCG) for oxidation resistance

**AETB Silica Insulating Base**
- Solved thermo-structural issues by adding boron oxide ($\text{B}_2\text{O}_3$) and alumino-borosilicate fibers, which also improved mechanical strength
- Increased temp capability to 2500+ °F by adding alumina ($\text{Al}_2\text{O}_3$) fiber

**CASE 2: Advanced TUFROC**

<table>
<thead>
<tr>
<th>Max Temp (°F)</th>
<th>VEHICLE STRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>AETB Insulating Base</td>
</tr>
<tr>
<td>2500</td>
<td>significantly reduces heat conducted to the vehicle</td>
</tr>
<tr>
<td>400</td>
<td>max temp: 2600 °F</td>
</tr>
<tr>
<td>200</td>
<td>ROCCI Cap</td>
</tr>
<tr>
<td></td>
<td>maintains outer mold line</td>
</tr>
<tr>
<td></td>
<td>max temp: 3000 °F</td>
</tr>
</tbody>
</table>

**re-radiation $\propto \varepsilon T^4$**
Advanced TUFROC

2 Piece Approach

*Re-radiate enough heat so that conduction through*
- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

**ROCCI Carbonaceous Cap**
- Silicon-oxycarbide phase slows oxidation
- High temp HETC surface treatments that helps mitigate ROCCI – RCG CTE issues
- Improved, higher viscosity RCG to handle repeated cycles at higher temperatures

**AETB Silica Insulating Base**
- Solved thermo-structural issues by adding boron oxide (B$_2$O$_3$) and alumino-borosilicate fibers, which also improved mechanical strength
- Increased temp capability to 2500+ °F by adding alumina (Al$_2$O$_3$) fiber

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**Re-entry Heating**

\[ re-radiation \propto \varepsilon T^4 \]

Max Temp (°F)

3000 2500

ROCCI Cap

maintains outer mold line
max temp: 3100 °F

---

heat conduction

AETB Insulating Base

significantly reduces heat conducted to the vehicle
max temp: 2600 °F

---

**Vehicle Structure**
Series of Arc jet tests conducted to evaluate modified HETC, RCG.
Blunt cone provides uniform temps across stagnation region of the model
(more useful for evaluating different surface treatments / coatings than blunt wedges)

**AHF T-257** (Jul 2007) Blunt cones at 0.04 atm and 78 W/cm²

<table>
<thead>
<tr>
<th>Model</th>
<th>1st Exposure 5 min</th>
<th>2nd Exposure 5 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1025</td>
<td>3080 °F</td>
<td>3100 °F</td>
</tr>
<tr>
<td>Model 1028</td>
<td>3070 °F</td>
<td>3090 °F</td>
</tr>
<tr>
<td>Model 1030</td>
<td>3095 °F</td>
<td>3060 °F</td>
</tr>
</tbody>
</table>
CASE 2: Advanced TUFROC

Sphere cone provides a heat flux distribution more similar to WLE flight conditions

AHF Test Series: T-284, March 2009

Sphere Cone Pre-Test Model

1st Exposure
5 min

Test Conditions
\( H_{eo} = 17.3 \text{ MJ/kg} \)
\( P_O = 0.02 \text{ atm} \)
\( q_{HW} = 61 \text{ W/cm}^2 \)

Model 1044
3120 °F

Model 1043
3000 °F

2nd Exposure
5 min
(same conditions)

Total exposure = 600 sec

Model during arc jet exposure
CASE 2: Advanced TUFROC

Arc jet test exposed corner issue with the sphere cone model

AHF Arc-Jet Exposure on Test Article 1043 (Mod IV)

\[ T_w = 3,000^\circ F \quad H_{e0} = 17.5 \text{ MJ/kg} \quad P_0 = 0.02 \text{ atm} \]

Test article issue or a material issue relevant to flight hardware?

- \( T_w \) - wall temperature
- \( H_{e0} \) - enthalpy at the boundary layer edge
- \( P_0 \) - pressure at the stagnation point
**CASE 2: Advanced TUFROC**

**Aerothermal & Thermal-Mechanical Analysis**

Heating Distribution* over Test Article

Surface Heat Flux

- Surface heating for 5 min with a 10 min cool-down

Thermal stresses** caused by velocity gradient near sonic line at shoulder

Stresses concentrated by mechanical attachment (interlocking tab)

⇒ Test article design issue

Not representative of flight hardware. Not a material issue.

*DPLR solution from Gokcen; **FEM analysis from Squire
CASE 2: Advanced TUFROC

Original Interlocking Tab Mechanical Attachment
CASE 2: Advanced TUFROC

Re-designed Interlocking Tab Mechanical Attachment
CASE 2: Advanced TUFROC

Sphere-cone arc jet test model

AHF Test Series: T-284 & T-290
Single 5 min exposures

- Original interlocking tab attachment
  - Test Series: T-284
  - March 2009
  - Ames Model 1043
  - 3000 °F
  - $H_\infty = 17.5 \text{ MJ/kg}$
  - $P_0 = 0.02 \text{ atm}$
  - $q_{HW} = 70 \text{ W/cm}^2$

- Re-designed interlocking tab attachment
  - Test Series: T-290
  - Feb 2010
  - Ames Model 1048
  - 3175 °F
  - $H_\infty = 22.8 \text{ MJ/kg}$
  - $P_0 = 0.034 \text{ atm}$
  - $q_{HW} = 85 \text{ W/cm}^2$

⇒ arc jet results confirmed
no issue with material
CASE 2: Advanced TUFROC

Corner issue resolved, modified HETC & RCG testing continued

**AHF T-293**
Nov 2010

**1st Exposure**
8 min

Test Conditions

\[
\begin{align*}
H_e &= 19.1 \text{ MJ/kg} \\
P_O &= 0.03 \text{ atm} \\
q_{HW} &= 70 \text{ W/cm}^2
\end{align*}
\]

3000 °F

**AHF T-301**
May 2012

**Model 1056**

**2nd Exposure**
8 min

Test Conditions

\[
\begin{align*}
H_e &= 16.7 \text{ MJ/kg} \\
P_O &= 0.03 \text{ atm} \\
q_{HW} &= 61 \text{ W/cm}^2
\end{align*}
\]

2900 °F

**Model 1056**

**3rd Exposure**
8 min

Test Conditions

\[
\begin{align*}
H_e &= 16.7 \text{ MJ/kg} \\
P_O &= 0.03 \text{ atm} \\
q_{HW} &= 61 \text{ W/cm}^2
\end{align*}
\]

Total Exposure = 24 minutes

2900 °F
CASE 2: Advanced TUFROC

AHF Test Series: T-301 May 2012  (24 minutes, total exposure time)  Model H-1087

1st 8 min Exposure
2900 °F

\[ H_{eo} = 19 \text{ MJ/kg} \]
\[ P_O = 0.02 \text{ atm} \]
\[ q_{HW} = 62 \text{ W/cm}^2 \]

2nd 8 min Exposure
3000 °F

\[ H_{eo} = 20 \text{ MJ/kg} \]
\[ P_O = 0.025 \text{ atm} \]
\[ q_{HW} = 70 \text{ W/cm}^2 \]

3rd 8 min Exposure
3000 °F

\[ H_{eo} = 20 \text{ MJ/kg} \]
\[ P_O = 0.025 \text{ atm} \]
\[ q_{HW} = 70 \text{ W/cm}^2 \]
CASE 2: Advanced TUFROC

TUFROC R&D Success!

- Repeatable arc jet testing of the modified TUFROC demonstrated a multiple use capability
- Modified TUFROC material and processing specification frozen and branded as Advanced TUFROC
- Technology transfer of Advanced TUFROC has started with Boeing and Sierra Nevada Corporation

Standard TUFROC performed better than expected as demonstrated by a successful re-flight of X-37b wing leading edge tiles

X-37b, April 2015
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CASE 3: Conformal PICA

Motivation

• TPS integration is hard and expensive

• Current heat shield types all have issues / limitations
  - *Monolithic*: limited by size (< 1 m diameter)
  - *Tile*: complex with gap and seam issues
  - *Honeycomb*: complex with gore and curing issues
  - Compatibility with sub-structure (strain, CTE, etc.)

[Tiled SpaceX Dragon & Heat Shield (PICA-X)]
5 m diameter. 4 successful 8 km/s Earth re-entries 2010-13.

[Honeycomb Orion Heat Shield (Avcoat)]
5 m diameter. Successful Flight Test (EFT-1) Dec 2014

[Monolithic Stardust Capsule]
0.8 m diameter PICA Heat Shield
CASE 3: Conformal PICA

Conformal TPS

- Offers a promising solution to a number of challenges faced by traditional rigid (low strain-to-failure) TPS materials

- Compliant (high strain to failure) nature simplifies TPS integration on a wide range of aeroshell structures

- Also enables configuration of over large areas, thus reducing
  - part count
  - number of seams
  - installation complexity ⇒ time and cost
CASE 3: Conformal PICA

Initial Development

- Developed using commercially available low density rayon-based carbon felt from Morgan
- Demonstrated uniform fabrication of a sample 12-inch square and demonstrated conformability of the system over 3-inch radius
Initial Testing

- Initial formulation of Conformal TPS tested at:
  Heat Flux: 1000 W/cm²
  Pressure: 0.85 atm

- Conformal 1 appeared to recede 2x faster than PICA

- Testing identified erosive failure of material

- Work begun to reduce the recession difference between PICA and Conformal TPS
CASE 3: Conformal PICA

Redevelopment - Conformal PICA

- Work on Conformal 1 culminated in the development of Conformal PICA (CPICA)
  - Increased phenolic content and incorporated additives to increase char strength
  - CPICA recession still > PICA, but not 2x
  - Too much resin content causes delamination due to shrinkage stresses from resin cure
  - Higher density felt resolves this issue
CASE 3: Conformal PICA

Approach – Advanced Conformal TPS

• Investigated felt substrate density vs. effect on TPS ablation performance

• Used commercial needling to increase felt density and increase substrate toughness

• Areas of exploration
  - Required strength in the felt substrate?
  - Possible thickness?
  - Desired thickness?
  - Resin impregnation in denser felts?
  - Felt densification vs structural integrity?
CASE 3: Conformal PICA

Advanced Conformal TPS – Accomplishment

- Advanced CPICA substrate density increased substantially from previous generation of felt
- Arcjet tested 0.14 g/cm$^3$ felt infused with phenolic at 1850 W/cm$^2$ heat flux, 1.4 atm

- Recession of Advanced CPICA now less than both PICA and previous CPICA
Acknowledgements

* MSL Program & Helen Hwang*, Robin Beck*

* STMD Conformal Flexible Ablators Project & Matt Gasch*

* Tom Squire*, Mike Wright*, Tahir Gocken*

* NASA Ames Research Center
Arc Jet Testing: TPS Case Studies

Acronyms not identified in the charts
RCG  Reaction Cured Glass
AETB  Alumina Enhanced Thermal Barrier
HETC  High Efficiency Tantalum-based Composite
ROCCI  Refractory Oxidation-resistant Ceramic Carbon Insulation