Coatings and Surface Treatments for Reusable Entry Systems

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ICCCRD
Washington, D.C.
March 7, 2016
NASA & DoD Missions Requiring TPS

Peak heat flux (W/cm²) vs. Stagnation pressure (atm)

- Mars
- Saturn
- Venus
- Jupiter
- Ice Giants
- Ballistic RV
- Sample Return
- Earth Return
- Hypersonic Cruise
- LEO

Heat fluxes and pressures are approximate.
NASA & DoD Missions Requiring TPS

Peak heat flux (W/cm²) vs Stagnation pressure (atm)

- Earth Re-Entry
- Lunar
- Mars
- Jupiter
- Venus
- Saturn
- Ice Giants
- Sample Return
- LEO
- Hypersonic Cruise
- TUFROC
- SLA-561V
- PICA
- PICA-NU
- 3D-Woven
- Carbon Phenolic

KEY
- Flight Heritage TPS
- Arc Jet Tested TPS
- DoD Mission

RV Re-entry Vehicle

Heat flux and pressures are approximate.
Reusable TPS (definitions vary)

Material unchanged (mechanically, chemically) by the mission
TPS can be safely flown X number of times (with or without servicing)
TPS flew more than once

Ablators

Material is used up / depleted and recesses due to vaporizing, melting, subliming, spalling, erosion, and other ablative processes. Many ablative materials include constituents that pyrolyze and char, which help mitigates the heat load.

While any material can technically be reusable or an ablator – an effective TPS needs an optimized material stackup for all regions of the vehicle, factoring in all potential environments throughout the planned flight profiles and missions.

Note that many reusables can survive conditions beyond those for which they are designed and tend to fail
Energy management through storage and re-radiation — material unchanged

When exposed to atmospheric entry heating conditions, surface material will heat up and reject heat in the following ways:

• Re-radiation from the surface and internal storage during high heating condition
• Re-radiation and convective cooling under post-flight conditions
Reusable TPS Materials Requirements

- High temperature capability
- High thermal shock resistance
  (rapid heat-up with very large thermal gradients)
- Properties stable over many flights
- Surface property requirements
  - High emittance
  - Low catalycity
- Low thermal expansion coefficient
- Low thermal conductivity
- Minimum weight heat shield

AETB (35% Al₂O₃) Tile
Surface Treatments and Coatings

Coatings
Applied on top of a material, forming a separate layer

Surface Treatments
Deposited in the near surface forming an integrated or composite material

Surface treatments and coatings generally have the same goals
- high temperature capability to withstand nominal and abort environments
- high emissivity (> 0.9) except for areas where sunlight is the primary heat source
- low catalycity to avoid heating via chemical recombination of hot atmospheric/plasma constituents
- mechanically stable in the material system (high temperatures, thermal expansion, and thermal shock)

Water proofing is often desired for TPS that is exposed to water / high humidity
Original Space Shuttle TPS

Rigid Silica Tile* and Coating System, acreage TPS

RCC\(^1\) Nosecap

RCC\(^1\) Leading Edges

Rigid Silica Tile* and Coating System, acreage TPS

*Developed by Robert Beasley
Lockheed Martin Missiles and Space

\(^1\) Reinforced Carbon-Carbon
RSI Installation Configuration

1. Low Temperature Reusable Surface Insulation
2. High Temperature Reusable Surface Insulation
3. Inner Mold-Line
4. Room Temperature Vulcanizing
5. Reaction Cured Glass

Diagram: LRSI\textsuperscript{1} gap white tile glass coating RCG\textsuperscript{5} coating black tile gap HRSI\textsuperscript{2} densified IML\textsuperscript{3} surface strain isolation pad gap adhesive (silicone RTV\textsuperscript{4}) structure (koropon-primed) uncoated tile filler bar structure (koropon-primed)
**Description**: Black coating consisting of tetra-boronsilicide and low porosity borosilicate glass. Typically applied to top and sides to protect the porous silica. RCG is very effective on silica-based tiles up to 3000°F.

RCG-M is a modified version of RCG with a higher temperature capability (operates up to 3150°F).

**Typical Application/Heritage**: Most Shuttle tiles and many X-37b tiles were/are coated with RCG.
Surface Treatment: Toughened Unipiece Fibrous Insulation

Description: Consists of borosilicate glass ($\text{B}_2\text{O}_3\cdot\text{SiO}_2$), silicon-boride ($B_x\text{Si}$), and molybdenum disilicide ($\text{MoSi}_2$), yielding a stronger, tougher silica tile.

Heritage: Standard TUFI tiles were used on the Shuttle Orbiter's underside. White variants with higher impact resistance and conductivity were used on the upper body.

Surface Treatment: High Efficiency Tantalum-based Composite

Description: Similar to TUFI except that HETC includes tantalum disilicide ($\text{TaSi}_2$). Designed to operate at higher temps than TUFI and to mitigate higher thermal expansion differences between the substrate and coating.

Heritage: Three X-37b missions.
Reusable TPS: Tiles and Coatings

Density: 0.14 to 0.19 g/cm³

“Space Shuttle Tile”

- RCG is a thin dense high emittance glass coating on the surface of shuttle tiles
- Poor impact resistance

- TUF1 coatings penetrate into the sample
- Porous but much more impact resistant system

RCG Coating

TUF1 Coating

- Silica-based fibers
- Mostly empty space - >90% porosity
This system reduces the weight of TUFIT/LI-900 to an acceptable level by limiting the area where the surface treatment is applied while retaining the improved damage resistance of the TUFIT system.
3 decades of Space Shuttle experience led to the concept for an advanced reusable thermal protection system.

TUFROC is a 2 piece system that takes advantage of the high temperature capability of carbon for the cap.

with the insulating properties of silica based tiles for the base.
TUFROC TPS
(Toughened Unipiece Fibrous Reusable Oxidation Resistant Ceramic)

• Developed TUFROC for X-37 application
• Advanced TUFROC developed recently
• Transferred technology to Boeing and others
• System parameters:
  - Lightweight (similar to LI-2200)
  - Dimensionally stable at surface temperatures up to 1922 K
  - High total hemispherical emittance (0.9)
  - Low catalytic efficiency
  - In-depth thermal response is similar to single piece Shuttle-type fibrous insulation
TUFROC Background: Initial Concept

TUFROC 2-piece system

Basic Approach

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

Carbon Cap
Low density carbon with a high temp capability
- unprotected carbon will rapidly oxidize

Silica Insulating Base
Starting point was LI-900 Shuttle tile
- outstanding, low weight silica based insulator
- mechanically weak
- breaks down above 2300°F

Max Temp (°F)

Re-entry Heating

Re-radiation $\propto \varepsilon T^4$

Carbon-based Cap
Re-radiates most of the heat; absorbs and conducts the rest

Silica Insulating Base
significantly reduces heat conducted to the vehicle

Vehicle Structure

TUFROC 2-piece system

TUFROC Concept
TUFROC Background: Initial Concept

TUFROC 2-piece system

Basic 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 Carbon Cap
- Silicon-oxycarbide phase slows oxidation
- HETC treatment near surface slows oxidation and keeps emissivity high (ε ~ 0.9)
- Coated with borosilicate reaction cured glass (RCG) for oxidation resistance

AETB Silica Insulating Base
- Solved thermo-structural issues by adding boron-oxide (B₂O₃) and alumino-borosilicate fibers, which also tripled mechanical strength
- Increased temp capability to 2500+ ° F by adding alumina (Al₂O₃) fiber

TUFROC Design

R E - E N T R Y
H E A T I N G

re-radiation \( \propto \varepsilon T^4 \)

Max Temp
(° F)
3000
2500
200
400

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
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 ($\text{B}_2\text{O}_3$) 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

**RE-ENTRY HEATING**

- Heat conduction
- \(\text{re-radiation} \propto \varepsilon T^4\)

**Max Temp (°F)**
- **3000**
- **2500**
- **400**
- **200**

**AETB Insulating Base**
- Significantly reduces heat conducted to the vehicle
  - Max temp: 2600 °F

**ROCCI Cap**
- Maintains outer mold line
  - Max temp: 3100 °F
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

1st Exposure
5 min

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<th>Temperature</th>
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<td>3070 °F</td>
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<td>1030</td>
<td>3095 °F</td>
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2nd Exposure
5 min

<table>
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<th>Model</th>
<th>Temperature</th>
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<td>3090 °F</td>
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<td>1030</td>
<td>3060 °F</td>
</tr>
</tbody>
</table>

Total exposure = 600 sec
Description: Carbon cap attached to a silica based insulating tile base with HETC surface treatment and a modified RCG coating. Cap is typically < ½" thick and consists of carbon fiber substrate impregnated with silicon-oxysilane (aka ROCCl) that has a density of 0.57 g/cc. Silica base is AETB-like tile.

Typical Applications
Reusable TPS for LEO re-entry on wing leading edge, nose area, and control surfaces with environments < 3100° F. Higher heat fluxes and temperatures are possible if duration is limited to a few minutes or ablation/single use is acceptable.

Heritage: Three X-37b successful LEO re-entries. Baseline for SNC Dreamchaser wing leading edge, nose area, and control surfaces.

* winner of NASA's Invention of the Year
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
Summary

• Coatings and surface treatments on reusable TPS
  - RCG, TUFII used extensively on shuttle
  - Technology now being used for new materials system

• TUFROC
  - Uses refinements of coating and surface treatments from shuttle era to make a 2 piece material for leading edges

• Reusable materials still used on back shells and other low-heating areas of vehicles such as Orion.
TUFI tiles used on base heatshield of Shuttle to protect against damage from debris incurred during liftoff.

TUFI/AETB-8 Tiles Undamaged After Three Flights.