Hypersonic Materials and Structures

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Outline

- Introduction
- Vehicle components
- Technical challenges
- Concluding remarks
## Rockets vs. Airbreathers

<table>
<thead>
<tr>
<th><strong>Rockets</strong></th>
<th><strong>Airbreathers</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>♦ Don’t like the atmosphere</td>
<td></td>
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<tr>
<td>● Accelerate only</td>
<td></td>
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<tr>
<td>● Get out quick</td>
<td></td>
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<tr>
<td>● Tend toward vertical launch</td>
<td></td>
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<tr>
<td>● Low ISP</td>
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<tr>
<td>♦ Drag</td>
<td></td>
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<tr>
<td>● High drag not a problem on ascent, desirable on descent for deceleration</td>
<td></td>
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<tr>
<td>● Blunt leading edges</td>
<td></td>
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<tr>
<td>♦ Weight critical</td>
<td></td>
</tr>
<tr>
<td>● Mass fraction ~ 10% of GTOW</td>
<td></td>
</tr>
<tr>
<td>● Requirement to be weight sensitive</td>
<td></td>
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<tr>
<td>♦ Engine in back</td>
<td></td>
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<tr>
<td>● Weight drives components to be clustered near engine</td>
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<tr>
<td>● Tail heavy</td>
<td></td>
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<tr>
<td>● Hard to get forward $c_g$</td>
<td></td>
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<tr>
<td>● Highly compressive loaded structure</td>
<td></td>
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<tr>
<td>♦ Like the atmosphere</td>
<td></td>
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<tr>
<td>● Accelerate and cruise in atmosphere</td>
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<tr>
<td>● Tend toward horizontal launch</td>
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<tr>
<td>● High ISP</td>
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<tr>
<td>♦ Drag</td>
<td></td>
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<tr>
<td>● Optimize for low drag</td>
<td></td>
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<tr>
<td>● Thin, slender body, low thickness/chord</td>
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<tr>
<td>♦ Volume critical</td>
<td></td>
</tr>
<tr>
<td>● Mass fraction ~ 30% of GTOW</td>
<td></td>
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<tr>
<td>● Requirement to be volume sensitive, volume drives drag</td>
<td></td>
</tr>
<tr>
<td>♦ Engine in mid-body</td>
<td></td>
</tr>
<tr>
<td>● Stability easier</td>
<td></td>
</tr>
<tr>
<td>● Easier to control $c_g$</td>
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</table>
Structural Differences Between Rockets and Airbreathers

♦ Tanks
  ● Cylindrical, since vehicle is weight sensitive and volume insensitive

♦ TPS
  ● Driven by descent
  ● Low heat load due to short ascent

♦ Leading edges
  ● Blunt, due to desire for descent drag
  ● High heat flux

♦ Structure
  ● Lightly loaded wings
  ● Propulsion and airframe not highly integrated

♦ Tanks
  ● Conformal, since vehicle is drag, and thus volume, critical

♦ TPS
  ● Driven by ascent
  ● High heat load due to long ascent time

♦ Leading edges
  ● Sharp, due to low drag, low thickness/chord
  ● Severe heat flux

♦ Structure
  ● Highly loaded wings (some air breathers)
  ● Hot wings and control surfaces due to thin cross sections and high heat flux/load
  ● Propulsion and airframe highly integrated

Drag is the big driver for hypersonics
Hypersonic Vehicles

♦ Goal
  • Speed
  • Range

♦ Propulsion
  • Provide thrust

♦ Aerodynamics
  • Provide lift
  • Control the vehicle
  • Minimize drag

♦ Structures and materials
  • Minimize weight
  • Survive required mission
    ▪ Thermal / structural
    ▪ Acceleration
    ▪ Acoustic / vibration
    ▪ Environmental

♦ Weight reduction
  • High specific strength materials (high strength, low density)

♦ Drag reduction
  • Thin vehicle cross-sections
    □ Insulating a cold structure adds cross-sectional area
  • Sharp leading edges
  • Smooth surfaces

Thrust

Lift

Weight

Drag

Hot structures
Flight Vehicle Thermal Management

- Apollo
- Ablators
- Mercury
- Insulation Shuttle
- Heat Sink
- x-15
- Hot Structure
- promi
- SR-71
- Hot structure Insulation Active cooling

Exposure Time, hr

T, K

3000
2000
1000
0
1
2
History Shows That New Material Systems Help Enable the Vehicle

- Titanium
- Inconel
- Ceramic tiles and blankets
- C/C leading edges
- Ceramic Matrix Composites (CMC’s)
CMC’s are the material system that will provide the required strength at elevated temperature.
CMC Hot Structure Weight Savings

♦ **Space Shuttle Orbiter Body Flap (AIAA-1983-913)**
  - Baseline 1460 lb, insulated cold structure
  - ACC body flap 1207 lb (253 lb, 17% weight savings)

♦ **HSR (NASA High Speed Research program) SiC/SiC Combustor Liner**
  - Projected 30% weight savings
  - Reduced NOx and CO emissions due to higher temp

♦ **X-38 C/SiC Hot Structures**
  - Bearings 50% lighter weight than traditional bearings
  - Body flap 50% less than insulated cold structure (5.25 ft x 4.6 ft, 150 lb)
  - Rudder (different design temperature)
    - PM-1000 with Ti inner structure and insulation: 133 lb with growth factor of ~ 5%
    - CMC: 97 lb with higher growth factor (27% weight savings)

♦ **Aircraft brakes**
  - 500-1000 lbs per plane weight savings

♦ **Actively cooled CMC combustor (French study, AIAA-2011-2208)**
  - 30% weight savings over metallic

Rule of thumb, ~ 25% weight savings with CMCs
Key Point – Drag Reduction

♦ Reentry vehicles (most of our prior experience), want drag to reduce velocity as they reenter.

♦ Cruise vehicles must minimize drag as they cruise through the atmosphere.
  ● Surface and cross-section

♦ Hot structure is the preferred approach (rather than TPS over cold structure)
  ● Large, smooth, hot airframe has not been addressed
A Few General Thoughts

♦ Weight is always critical

♦ High risk ≠ high payoff
  ● Might be, but not an automatic

♦ Requirements have a significant impact on TRL
  ● Number of cycles
  ● Mechanical loads
  ● Pressure (oxidation)
  ● Heat flux
  ● Etc.

TRL = f(requirements)
Can’t change requirements and expect to keep TRL the same

♦ Thinking of how much it will cost to develop a technology is often a better gage of how far away we are than asking how long it will take
Leading Edges

♦ State of the art
- Space shuttle orbiter RCC
- Hyper-X coated C/C
- HTV-2 oxidizing C/C

♦ Requirement
- Multi-use
- Light weight
- Durable
- Sharp

♦ Technical challenges
- Manufacturing
- Life
- Thermal stress
- High heat flux / temperature
- Environmental durability
Typical Ascent Leading-Edge Heat Flux for SSTO

In comparison, Shuttle Orbiter leading edge ~ 80 W/cm², CEV heatshield ~ 800 W/cm²
Leading-Edge Radius Effect on Stagnation Heat Flux

Heat flux \( \propto \frac{1}{\sqrt{\text{radius}}} \)

- 1 cm radius, 500 W/cm\(^2\)

Heat flux, W/cm\(^2\)

Radius, cm

1 cm radius, 500 W/cm\(^2\)
Sharp leading edges produce intense, localized heating.
Active Oxidation of Si-Based Materials

◆ Transition from passive to active oxidation function of
  ● Temperature
  ● Oxygen partial pressure
  ● Plasma speed
  ● Degree of dissociation

◆ Destroys protection of Si containing system
  ● C/SiC
  ● SiC/SiC
  ● Coated C/C
  ● UHTC
  ● … etc.

Arc-jet test of MT Aerospace C/SiC in the German PWK2 facility

Arc-jet test of DLR C/C-SiC for X-38 at NASA JSC
Heat-Pipe-Cooled Leading Edges

Heat pipe results in an isothermal leading edge.
NASP Heat-Pipe-Cooled Wing Leading Edge

- Carbon/carbon (C/C) structure
- Mo-Re container

Challenges
- Material compatibility, $f(t,T)$
- Thermal stresses

- Mo-Re embedded in C/C
- Li working fluid
- D-shaped heat pipes
Control Surfaces

☀ State of the art
  ● Space shuttle orbiter (insulated)
  ● X-38 (CMC hot structure)
  ● HTV-2 C/C
  ● NASA X-37 evaluated C/C and C/SiC

☀ Requirement
  ● High strength at elevated temperature
  ● Light weight

☀ Technical challenges
  ● Volume constrained
  ● Manufacturing
  ● Recession / stressed oxidation
  ● Thermal stress
  ● High heat flux / temperature
  ● High heat load
  ● Heat conduction into vehicle / insulation
Types of Control Surfaces

♦ Insulated
- Suitable for very large structures
- Minimal thermal expansion issues
- Heavy
- Little thermal margin
- Thick cross section

♦ Hybrid
- Affordable manufacturing for large structures
- May not require TPS on upper surface
- Thermal growth mismatch between metal/PMC and CMC
- Weight increase 30-40% over all CMC

♦ Hot Structure
- Lowest weight and thin cross section
- Minimal thermal expansion mismatch problems
- Thermal margin
- High manufacturing/tooling costs for box structure
- Challenging for very large structures
X-38 Hot Structures

♦ C/SiC nosecap, skirts & chin panel
  - Nosecap provided by DLR (Germany)
  - Nose skirts (2) provided by Astrium (Germany)
  - Chin panel provided by MT Aerospace
  - Nose assembly has undergone full qualification (qual units)
    - Vibration
    - Thermal (radiant)
    - Mechanical

♦ C/SiC body flaps
  - Provided by MT Aerospace
  - Qualified for flight
Dutch Space Metallic Hot Rudder

♦ X-38 hot rudder

- Fabricated and tested a PM-1000 rudder to 2192°F (1200°C) in 1 yr
- Requirements changed
- Qualified Ti/ceramic tile rudder (1 yr)
- Planned Ti/CMC rudder for crew return vehicle (CRV)
MT Aerospace Integrated Fabrication Approach

♦ Advantages
  ● Fewer joints
  ● Better mechanical performance

♦ Disadvantages
  ● Complex tooling and associated fabrication expense
  ● Risk of damage during fabrication

♦ Fabrication
  ● 2-D prepreg of carbon fabric
  ● Cured and pyrolyzed
  ● Further densified with CVI SiC
  ● No fasteners (less mass)

MT Aerospace Pre-X body flap
Acreage TPS / Hot Structure Aeroshell

♦ **State of the art**
  ● Ceramic tiles and blankets
  ● Ablators
  ● Oxidizing C/C hot structure

♦ **Requirement**
  ● Durable
  ● Thin cross section
  ● Smooth OML
  ● Insulate interior (keep the heat out)

♦ **Technical challenges**
  ● Manufacturing
  ● Durability
  ● High temperatures
  ● Large heat load due to extended duration flight
  ● High temperature insulation
  ● Combined loads
Trade studies required on how to best meet requirements and optimize performance – need to keep trade space wide open.
Windward CMC Standoff (Shingle) TPS (Sneca, IXV)

- **Total mass of CMC shingle system**
  - ~3 lb/ft² (15 kg/m²) (very much f(req.))
  - Not optimized

- **Attachment system design**
  - Mechanically attach panel to structure
  - Transfer loads from panel to structure
  - Enable expansion differences
  - Prevent large OML deformation through sufficient stiffness
  - Participate in thermal protection of structure
  - Easily replaced

**C/SiC pressure ports**
- 10 windward

**Sealing approaches**

**Figure 12:** Influence of the TPS panels gap on seal permeability

**Figure 13:** TPS panels stiffeners geometries

3.5 Sneak flow tests.
This test is complementary to the permeability test and aims at characterizing the sneak-flow, which is the hot gas infiltration under the panels of the TPS, which overheats the cold structure in a convective way [06]. In addition, a sneak flow characterization approach is developed. 3 panels representative of TPS panels will be assembled in a test chamber. A gas flow will be injected in the test chamber, and two main configurations will be tested. For the first configuration, an added wall, which will be on the second panel, will force the gas flow to go through the gap between the first two panels and exit through the second gap. For the second configuration, there will be no added wall so that the amount gas going outside or inside the gap will depend solely on the gas flow and test sample configuration (see Figure 14.) These test results will be used, along with venting tests results and permeability tests results, as input data for TPS sneak flow calculation, which will assess the cold structure temperature increase due to sneak flow.

- **30 windward TPS panels on IXV**
- **Curved C/SiC panel**
  - IXV side panel
- **C/SiC pressure ports**
  - 10 windward
- **Attachment approach**
- **Curved C/SiC panel**
  - (IXV side panel)
Internal Insulation

♦ Light-weight
♦ Flexible
♦ Non load-bearing
♦ Non-oxidizing
♦ Reflective foils or no foils
♦ High volumetric heat capacity
♦ Low effective thermal conductivity
♦ Capable of long duration flight at elevated temperatures

Nextel fabric
Reflective Foils
fibrous insulation
Propulsion Structures

♦ **State of the art**
  - Passive heat sink
  - Actively cooled superalloy

♦ **Requirement**
  - Light weight
  - High heat flux/temperature
  - Reduced fuel

♦ **Technical challenges**
  - Hermetically sealed CMC with no tubes
  - Manifold

♦ **MBDA (France)**
  - Fuel cooled CMC combustor
  - No metallic tubes

♦ **NASA & AF (Teledyne Scientific)**
  - Last funding several years ago
  - No tubes

♦ **NASA (HyperTherm)**
  - SiC/SiC with refractory metal tubes
Passive CMC Combustor Material Evaluation

♦ Simulated Mach 6 conditions
  - Actual flow velocity ~ Mach 2
  - $q = 1000$ psf (479 hPa)
  - $H = 793$ Btu/lb (1.846 MJ/kg)

♦ Hydrogen fuel

♦ 4 tests
  - M ~ 6 enthalpy
  - 20 sec tare (no fuel)
  - 3 x 44 sec fueled tests

♦ C/C-SiC Panel #1 Post Test
  - 4 tests
  - M ~ 6 enthalpy
  - 20 sec tare (no fuel)
  - 3 x 44 sec fueled tests

Flow

<table>
<thead>
<tr>
<th>#</th>
<th>1</th>
<th>2</th>
</tr>
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<tbody>
<tr>
<td>$\Delta t$</td>
<td>0 mm</td>
<td>0.051 mm</td>
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<table>
<thead>
<tr>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
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<tbody>
<tr>
<td>$\Delta t$</td>
<td>0 mm</td>
<td>0.026 mm</td>
</tr>
</tbody>
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<thead>
<tr>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t$</td>
<td>0.025 mm</td>
<td>0.026 mm</td>
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DLR C/C-SiC test article

C/C-SiC hot surface, post test
Design for manufacturing
- Involve manufacturers in the process
- Don’t “throw it over the wall”

Properties in a complex structure are often different than material test coupons

Attachments and joints
- Different material systems
  - Severe thermal gradients in multiple directions
- Mechanical loads

Metrology often “required” for accurate fabrication and assembly
- Optical / laser devices
- Accuracy to < 0.001 in., f(size)

TRL = f(requirements / loads)
- Can’t change the requirements / loads and keep the TRL

Affordable, robust, & simple

A state-of-the-art material is not the same thing as a state-of-the-art structure

Big difference!
Testing

How do we qualify the vehicle for flight?

We are unable to test many components in relevant, combined loads, environments (even small scale)

- Thermal, mechanical, plasma, shear, oxygen partial pressure, vibration and acoustic, etc.
- Apply appropriate boundary conditions over entire structure
- Thermal gradients (spatial and temporal) from boundary layer transition

Thermally generated stress ≠ mechanically generated stress

Extensive testing is required

- Performance testing and benchmarking for analyses

Building block approach

Test as much as you can, and still include adequate margins for uncertainties
Thermal-Structural Analysis

♦ Adequate material properties
  ● $f(T)$, $f$(processing), etc.
  ● Adequate quantities (shape of curve and statistics)
  ● Capture non-linear behavior

♦ Boundary conditions
  ● Thermal, mechanical
  ● Boundary layer transition

♦ Mesh convergence

♦ Local / global models
  ● Apply global loads to local models

♦ Mechanical / thermal stresses

♦ Factors of Safety (FOS)

♦ Failure modes
  ● Biaxial stress interaction
  ● Thermal ≠ mechanical failure

Boundary layer transition
Failure modes
Thermal Stress

♦ Generated by restrained thermal growth
  ● Temperature gradients and/or different materials (CTE)

♦ Very different from mechanical stresses
  ● Driven by thermal gradients, not just high temperatures
  ● Thicker structure can make it worse
  ● Structurally connected, dissimilar materials, also drive thermal stress

♦ Complicated by different materials, 3-D thermal gradients, moving hot spots, asymmetric heating, etc.

SR-71 grows ~ 3 in. during flight

Thermal stress failure due to differential thermal expansion at uniform temperature

Thermal stress must be understood and accurately tested and modeled
Concluding Remarks

♦Reduction of weight and drag are key for all hypersonic vehicles

♦A state-of-the-art material is not the same thing as a state-of-the-art structure

♦TRL = f(requirements / loads)
  ● Can’t change the requirements / loads and keep the TRL

♦Long duration flight results in high integrated heat loads that impact design

♦Hot structure should be traded versus insulated (TPS) cold structure
  ● Open up the trade space

♦Thermal stress must be understood and accurately tested and modeled