Hypersonic Materials and Structures

SAMPE
Baltimore, MD
May 18-21, 2015

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Outline

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

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

Hot structures
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.

  \[ \text{TRL} = f(\text{requirements}) \]
  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

Space shuttle orbiter leading edge

X-43 leading edge
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, \( W/cm^2 \)

1 cm radius, 500 W/cm²

Heat flux \( \propto \frac{1}{\sqrt{\text{radius}}} \)
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 DLR C/C-SiC for X-38 at NASA JSC

Arc-jet test of MT Aerospace C/SiC in the German PWK2 facility
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)
**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)
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 (Snecma, IXV)

- **Total mass of CMC shingle system**
  - \(~3 \text{ lb/ft}^2 (15 \text{ kg/m}^2)\) (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**

- **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
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
  - \( q = 1000 \text{ psf} \) (479 hPa)
  - \( H = 793 \text{ Btu/lb} \) (1.846 MJ/kg)

- **Hydrogen fuel**

- **4 tests**
  - \( M \sim 6 \text{ enthalpy} \)
  - 20 sec tare (no fuel)
  - 3 x 44 sec fueled tests

**C/C-SiC Panel #1 Post Test**

- 4 tests
- \( M \sim 6 \text{ enthalpy} \)
- 20 sec tare (no fuel)
- 3 x 44 sec fueled tests

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**DLR C/C-SiC test article**
Design and Manufacturing

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!
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

We can’t simulate this in ground tests

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 $\neq$ mechanical failure
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 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