Hypersonic Materials and Structures

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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>
</tr>
<tr>
<td>- Accelerate only</td>
<td>- Accelerate and cruise in atmosphere</td>
</tr>
<tr>
<td>- Get out quick</td>
<td>- Tend toward horizontal launch</td>
</tr>
<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>
</tr>
<tr>
<td>- High drag not a problem on ascent, desirable on descent for deceleration</td>
<td>- Optimize for low drag</td>
</tr>
<tr>
<td>- Blunt leading edges</td>
<td>- Thin, slender body, low thickness/chord</td>
</tr>
<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>
<td></td>
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</tbody>
</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

Thrust

Lift

Drag

Weight

Thermal / structural

Acceleration

Acoustic / vibration

Environmental
Flight Vehicle Thermal Management

- Ablators
- Mercury
- Insulation Shuttle
- Heat Sink
- Apollo
- x-15
- SR-71

Hot Structure
Insulation
Active cooling

Exposure Time, hr
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.

♦ 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, $\alpha \frac{1}{\sqrt{\text{radius}}}$

1 cm radius, 500 W/cm$^2$
Sharp leading edges produce intense, localized heating.

Sharp LE, hypersonic vehicle

Blunt LE, Shuttle Orbiter

Chordwise position, in.

Heat Flux

S>0  S=0  S<0
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

Leading Edge
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
Hot Structure Versus TPS Over Cold Structure

**Shuttle orbiter** (Al load-bearing airframe with tiles and blanket TPS)

**Falcon HTV-2** (C/C aeroshell primary load bearing structure)

**HyFly** (load shared between C/C combustor / nozzle assembly and Ti tank, which carried most of the load, ablative TPS)

Trade studies required on how to best meet requirements and optimize performance – need to keep trade space wide open
Windward CMC Standoff (Shingle) TPS (Snece, 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

- **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 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

- DLR C/C-SiC test article
- C/C-SiC hot surface, post test

- Flow

<table>
<thead>
<tr>
<th>#</th>
<th>Δt</th>
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<tbody>
<tr>
<td>1</td>
<td>0 mm</td>
</tr>
<tr>
<td>2</td>
<td>0.051 mm</td>
</tr>
<tr>
<td>3</td>
<td>0.026 mm</td>
</tr>
<tr>
<td>4</td>
<td>0.026 mm</td>
</tr>
<tr>
<td>5</td>
<td>0 mm</td>
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<tr>
<td>6</td>
<td>0.025 mm</td>
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<tr>
<td>7</td>
<td>0.026 mm</td>
</tr>
<tr>
<td>8</td>
<td>0 mm</td>
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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

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
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