Hypersonic Materials and Structures

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Outline

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

#### Rockets

- **Don’t like the atmosphere**
  - Accelerate only
  - Get out quick
  - Tend toward vertical launch
  - Low ISP

- **Drag**
  - High drag not a problem on ascent, desirable on descent for deceleration
  - Blunt leading edges

- **Weight critical**
  - Mass fraction ~ 10% of GTOW
  - Requirement to be weight sensitive

- **Engine in back**
  - Weight drives components to be clustered near engine
  - Tail heavy
  - Hard to get forward $c_g$
  - Highly compressive loaded structure

#### Airbreathers

- **Like the atmosphere**
  - Accelerate and cruise in atmosphere
  - Tend toward horizontal launch
  - High ISP

- **Drag**
  - Optimize for low drag
  - Thin, slender body, low thickness/chord

- **Volume critical**
  - Mass fraction ~ 30% of GTOW
  - Requirement to be volume sensitive, volume drives drag

- **Engine in mid-body**
  - Stability easier
  - Easier to control $c_g$
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

- **Thermal / structural**

- **Acceleration**

- **Acoustic / vibration**

- **Environmental**

- **Goal**

- **Propulsion**

- **Aerodynamics**

- **Structures and materials**

- **Weight reduction**

- **Drag reduction**

- **Thrust**

- **Lift**

- **Weight**

- **Drag**

- **Hot structures**
Flight Vehicle Thermal Management

- Apollo
- Ablators
- Mercury
- Insulation Shuttle
- x-15
- Heat Sink
- SR-71
- Hot Structure
- Insulation
- Active cooling
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)
- SR-71
- X-15
- Orbiter
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
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

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

Can’t change requirements and expect to keep TRL the same
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, $W/cm^2$

Radius, cm

Heat flux $\propto \frac{1}{\sqrt{\text{radius}}}$

1 cm radius, 500 W/cm²
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
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 (Sncema, 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

30 windward TPS panels on IXV

Sealing approaches

**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
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

DLR C/C-SiC test article

C/C-SiC hot surface, post test

Flow
Design and Manufacturing

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

Big difference!

♦ 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
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**
  - $f(T)$, $f(\text{processing})$, 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 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
- \[ TRL = f(\text{requirements} \div \text{loads}) \]  
  - 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