Outline

- Why this tutorial?
- Ablative TPS - early studies
- Organic resin composites
- Surface recession mechanisms/modeling
- High fidelity model development
- **Testing approaches/requirements**
- Future needs

Philosophy

- What is the test objective?
  - Screening several candidate ablative materials for comparative performance
  - Evaluating ablation performance over broad range of conditions
  - Evaluating performance limits of a material (failure threshold)
  - Developing data base for thermal modeling
  - Developing data base for reliability assessment (design margin)
  - Validating performance of material interfaces (gaps, seals, penetrations, etc.)

Approach

- The test objective dictates the test approach, but raises the following issues:
  – Test facility
  – Test article design
  – Test conditions
  – Instrumentation
  – Post-test evaluation

Test Facilities[1] - 1

Radiative Facilities (radiant lamps)

- Useful for evaluating insulation performance of acreage TPS
  - Relatively low heat fluxes (10s of W/cm^2)
  - Large test articles
- Only meaningful if surface-boundary layer interaction effects are *negligible,* i.e., effects of surface catalycity, surface oxidation, transpiration, atmospheric composition, etc. are well-understood
  - Primary objective is to evaluate heat conduction (2-D, 3-D)
  - Must be cognizant of potential pressure effects on conduction
- Requires very accurate knowledge of:
  - Heat flux distribution across test article (diagnostics)
  - Spectral distribution of radiant energy (diagnostics)
  - Spectral (and directional) optical properties of test material
    - Can use surface coatings with know optical properties (if they won't blow off)
- For complex test article geometry, must be aware of potential for shadowing

Test Facilities[1] - 2

Radiative Facilities (CW lasers)

- Primary application is to obtain very high heat fluxes not attainable in other ground test facilities
- Requires very accurate knowledge of:
  - Heat flux distribution across test article (diagnostics)
  - Spectral optical properties of test material at the laser wavelength
    - Most materials are opaque at 10.6μm (CO_2 lasers)
- Tests with small spots are misleading (cavity effects)
  - Avoid spots smaller than ≈ 25 mm diameter
- Cannot simulate surface-boundary layer interaction effects
  - Many facilities employ a (cold) cross-flow across the target area
    - Primary purpose is to sweep ablation products out of the beam path, which is important to avoid complications of beam attenuation due to gas phase absorption
- Useful for studying potential spallation[2] phenomena at very high heat fluxes

Test Facilities[1] - 3

Combustion Facilities

- Useful for testing TPS materials in motor applications
  - Rocket nozzles, combustor liners
  - Well-suited for full scale systems-level tests
- Very limited utility for studying TPS performance in hypersonic flight at Mach > ≈ 8
  - Cannot simulate many important environmental parameters
  - Limitations in total temperature of combustion products (little flexibility)
    - Maximum gas temperature set by theoretical combustion limits (≈ 2800 K)
  - Limited, if any, surface visibility (diagnostics)
  - Chemical composition of test gases (gas-surface chemical reactions are *not* representative)
  - Absence of dissociated species (due to gas temperature limits) precludes use of such facilities for studies of surface catalycity of oxidation

Test Facilities[1] - 4

Arc Plasma Facilities

- Have been used for over 40 years to study TPS material performance
  - Two classes:
    - Low enthalpy, high pressure, high heat flux (high β vehicles)
    - High enthalpy, low pressure, low-moderate heat flux (lifting entry, aeroassist, aerocapture, planetary entry, etc., I.e., low β vehicles)
- Significant flexibility
  - Pressure: nozzle geometry, test article design. gas mass flow rate
  - Enthalpy: gas mass flow rate, electrical power
  - Gas composition: most facilities operate with air, but tests have been conducted with N_2, CO_2, H_2/He, etc. gas streams
- Amenable to sophisticated diagnostics
  - Surface visibility (film or video), surface pyrometry, PLIF, etc.
- Capability to *simultaneously* simulate conditions representative of flight (e.g., $H, \dot{q}, p$) is rare. Requires strategic test planning.
- Typically, cannot simulate time-varying conditions (trajectories)

Diagnostic Instrumentation

- Surface temperature
  - Pyrometry, radiometry to determine surface temperature is a critical requirement
    - Fundamental parameter used to determine validity of surface modeling
    - Critical parameter in evaluating surface ablation mechanisms
- Surface observation
  - Film or video of surface during exposure critical to understanding surface performance mechanisms (e.g., melting, flow, spallation, etc.)
- In-depth thermocouples
  - Critical data required for developing high fidelity subsurface thermal/ablation response models
  - Placement determined by material characteristics and exposure conditions (capture transient response over entire temperature range in char and pyrolysis zones)

Uncertainties

- Well-designed ground-test program should cover the range of conditions anticipated in flight
- Identification of surface response mechanisms and development of high fidelity model significantly reduces performance uncertainties in flight
- But, typically it is not unusual that ground tests cannot simulate some aspects of the flight environment
  - Turbulent flow
  - High shear
  - High pressure gradient
  - Combined convective/radiative heating
- Mechanism-based modeling allows extrapolation with some confidence
  - Remaining uncertainties can only be addressed through flight test with instrumented TPS

References

1. Laub, B., Balboni, J. and H. Goldstein, “Ground Test Facilities for TPS Development,” NASA TM-2002-211400, NASA Ames Research Center, Moffett Field, California, May 2002.
2. Koenig, J.R., Jackson, T.E., Stewart, D.J., Laughlin, W.T., “Evaluation of LHMEL Exposed Specimens”, Presented at the 1994 JANNAF RNTS Subcommittee meeting, Seattle Washington, 15-17 November 1994.

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