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 *no*t 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.

Thermal Protection System Development and Certification

Donald M. Curry
NASA Johnson Space Center

Tutorial on Ablative TPS
2nd International Planetary Probe Workshop
August 21-22, 2004

TPS Certification Approach

- **Certification of Thermal Protection System Has Historically Been Accomplished By Analysis Supported By Appropriate Ground Test Data**

- **Analysis is Used as Flight Conditions Can Not Be Accurately Simulated on the Ground and It Is Not Feasible to Test for the Entire Spectrum of Flight Environments**

Factors That Influence TPS Design

- Maturity
- Density
- Aerothermal (Temperature)
- Strength (Airloads/Vibroacoustic)
- Outgassing
- Oxidation Resistance
  - Atomic
  - Diatomic
- Damage Tolerance/Impact Resistance
- Repairability
- Refurbishment
- Long Term Space Exposure
- Multi-use
- Man-rated
- Size Limits - Fabrication

COMPARISON OF SHUTTLE AND INTERPLANETARY TPS REQUIREMENTS

	Shuttle	Lunar Return	Mars Entry/Return
• PEAK CONVECTIVE HEATING (BTU/FT^2-SEC)	60	200	50 – 300
• PEAK RADIANT HEATING (BTU/FT^2-SEC)	<2	200	40-200
• PEAK VELOCITY (KM/SEC)	7	11	7-13
• PEAK DYNAMIC PRESSURE (PSF)	300	1000	250-1000
• TURBULENT HEATING	YES	YES	YES
• ENTRY HEATING TIME (SEC)	1200	<400	<400
• EXPOSURE TO ADVERSE ENVIRONMENTS			
- RAIN/WEATHER	YES	NO	NO
- AEROACOUSTICS (dB)	160+	146	146
- DEBRIS IMPACT			
- LAUNCH	YES	NO	NO
- ON-ORBIT/IN-FLIGHT	LESS	MORE	MORE

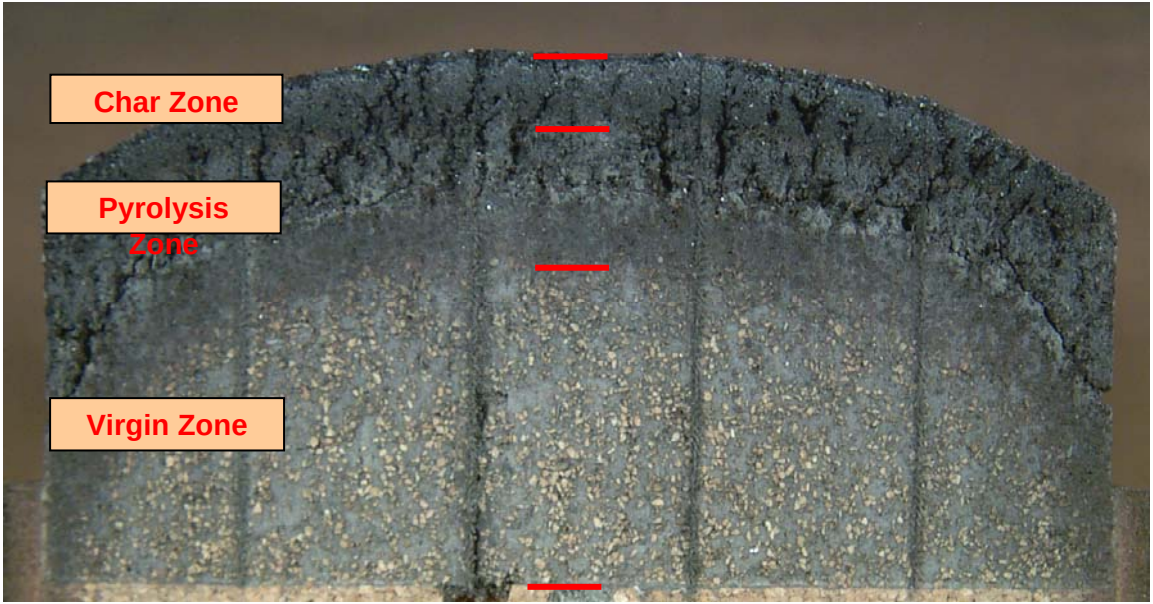
TPS Development Activities

- Material Screening
  - Used to select/evaluate materials and processes for further development
    - Arc jet survivability tests
    - Radiant heat thermal performance tests
    - Room-temperature material characterization tests

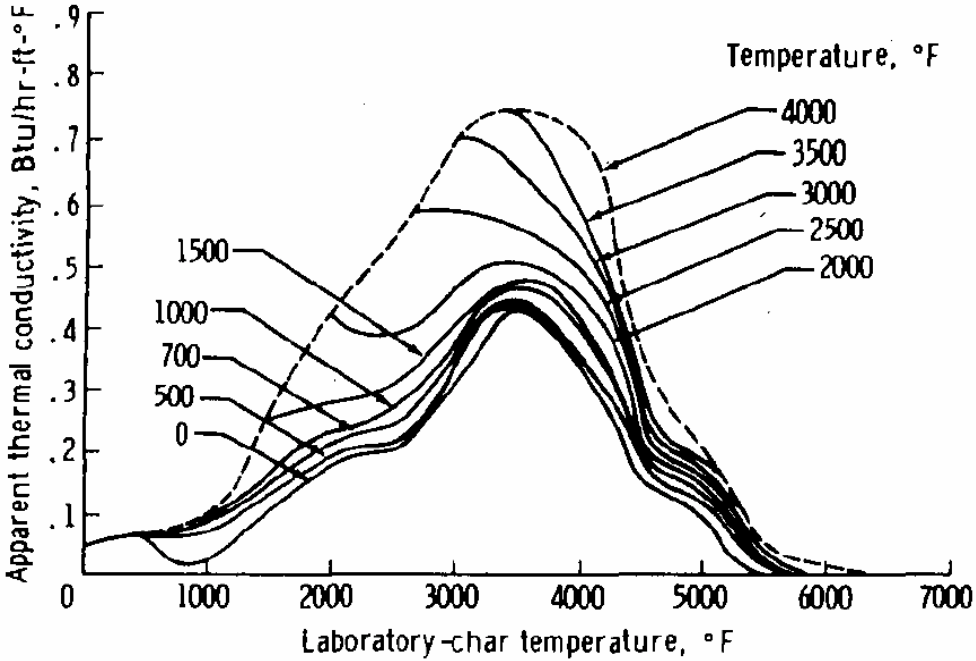
Material Development/Selection

- Environment Definition
  - Induced
    - Nominal
    - Abort
  - Natural
- Material Characterization (Virgin/Char)
  - Thermophysical Properties
    - Density
    - Thermal conductivity
    - Specific heat
    - Emittance
    - Thermogravimetric test (Arrhenius constants)
    - Pyrolysis gas specific heat/composition
    - Heat of pyrolysis

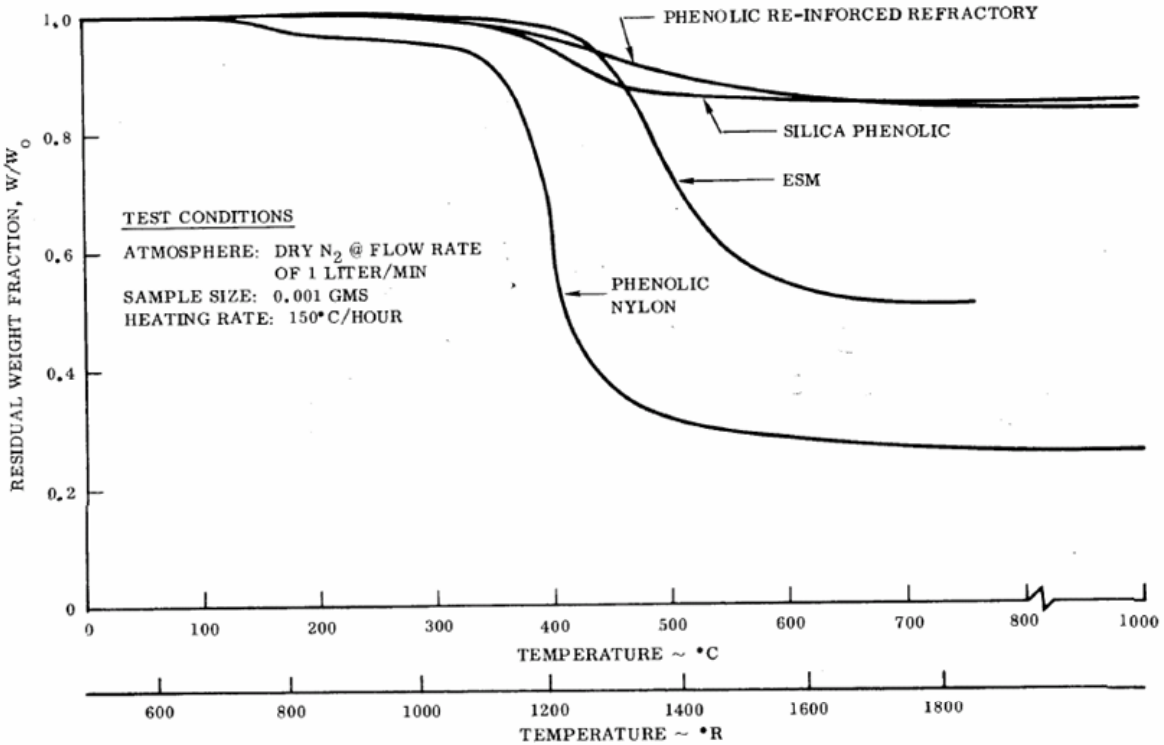
Typical Charring Ablator Cross-Section



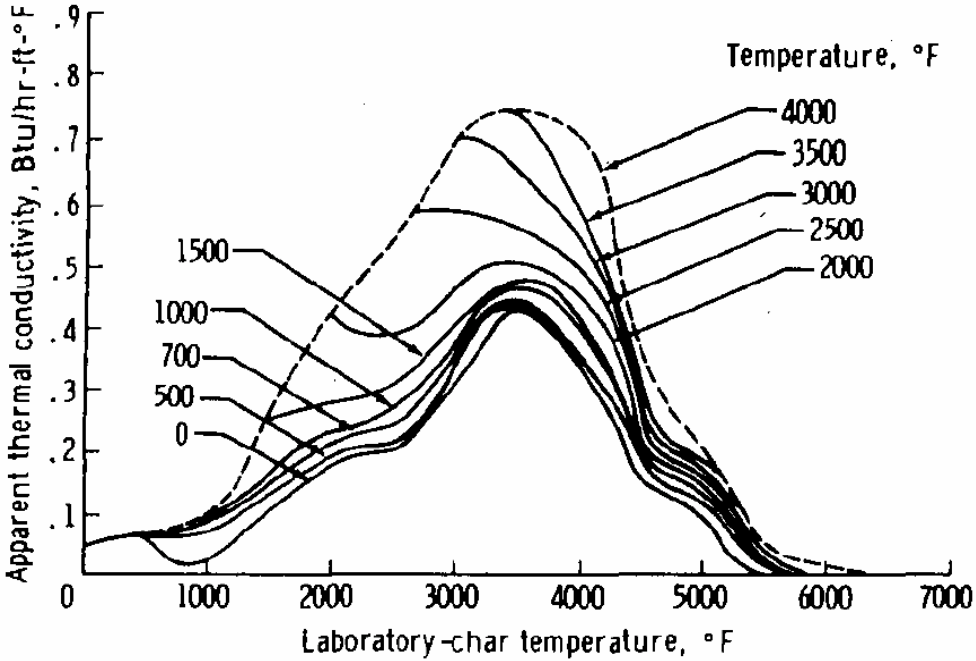
Char Thermal Conductivity



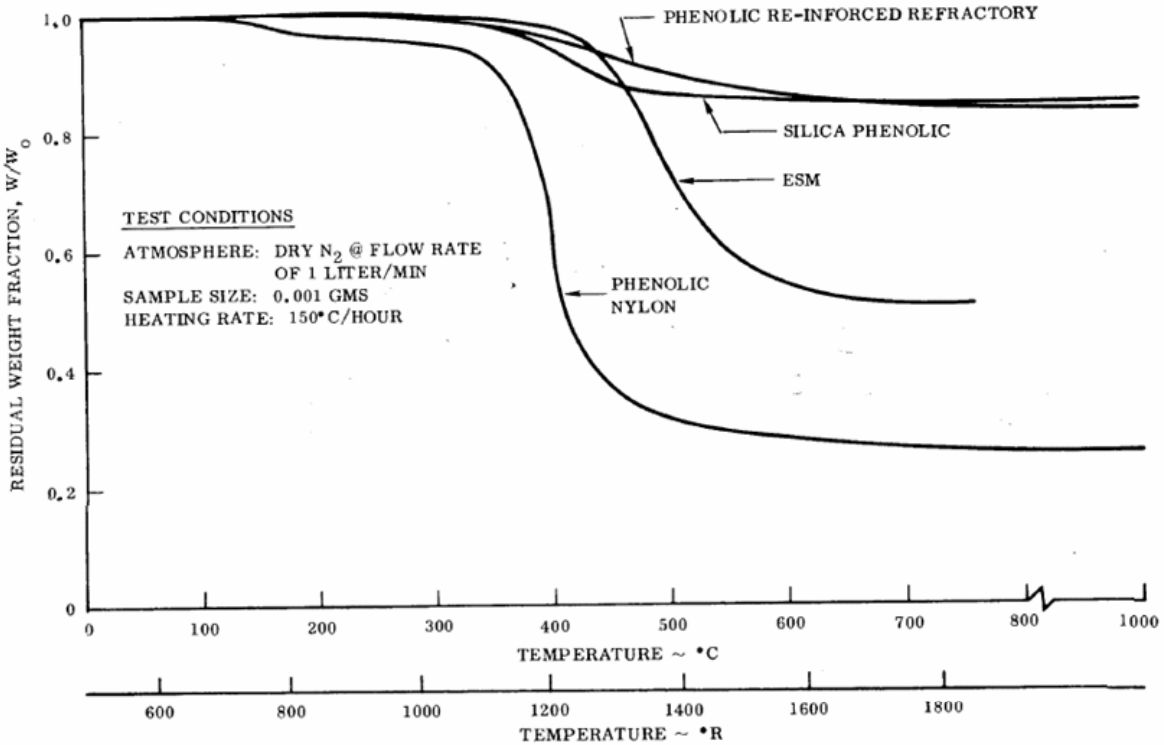
Thermogravimetric Results of Typical Ablators



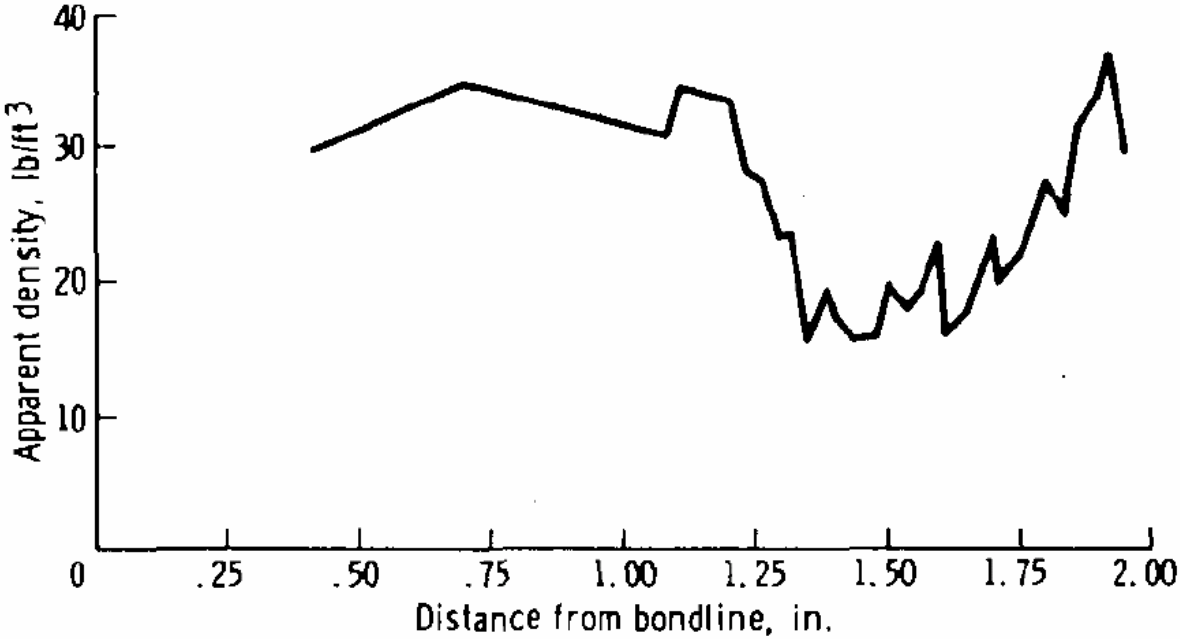
Char Thermal Conductivity



Thermogravimetric Results of Typical Ablators



Char Densification - Deposition



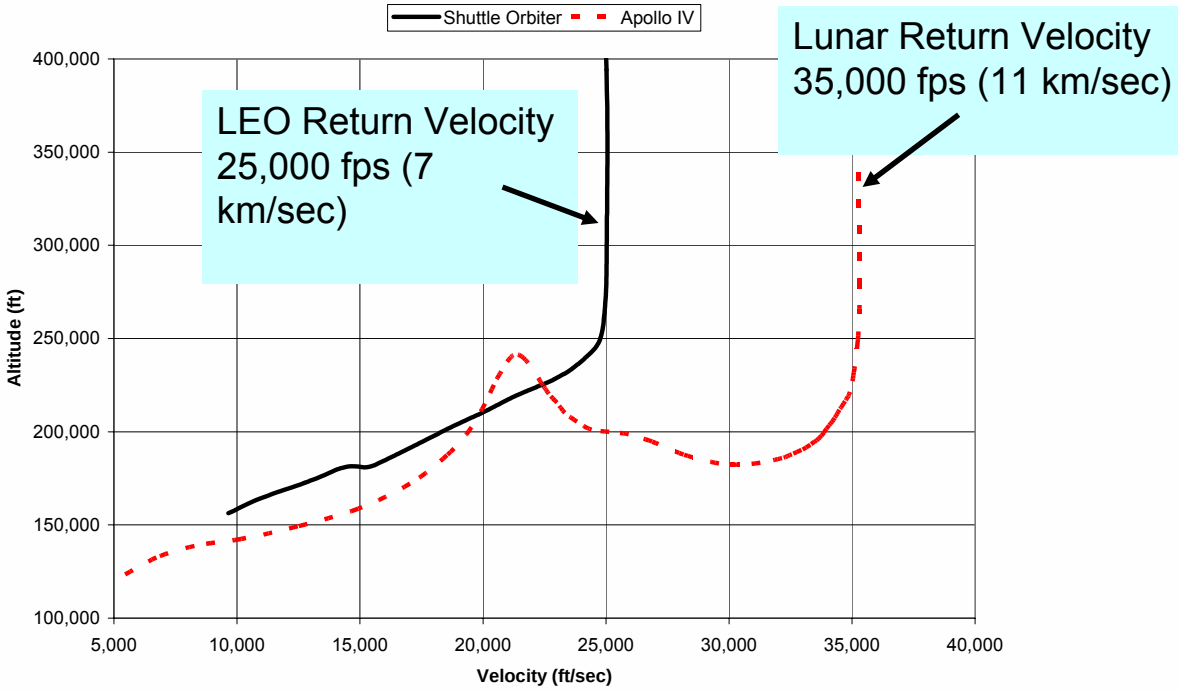
Material Development/Selection

- Mechanical Properties
  - Tension
  - Compression
  - Flexure
  - Shear
  - Coefficient of thermal expansion
  - Impact Resistance
- Plasma Arc/Radiant Testing
  - Surface Recession
    - Oxidation
      - Radiant
      - Convective
    - Mechanical
  - Catalytic characteristics
  - Material degradation
  - Heat flux/temperature limits
  - Pressure effects
  - Nominal/Abort conditions
  - Repairs

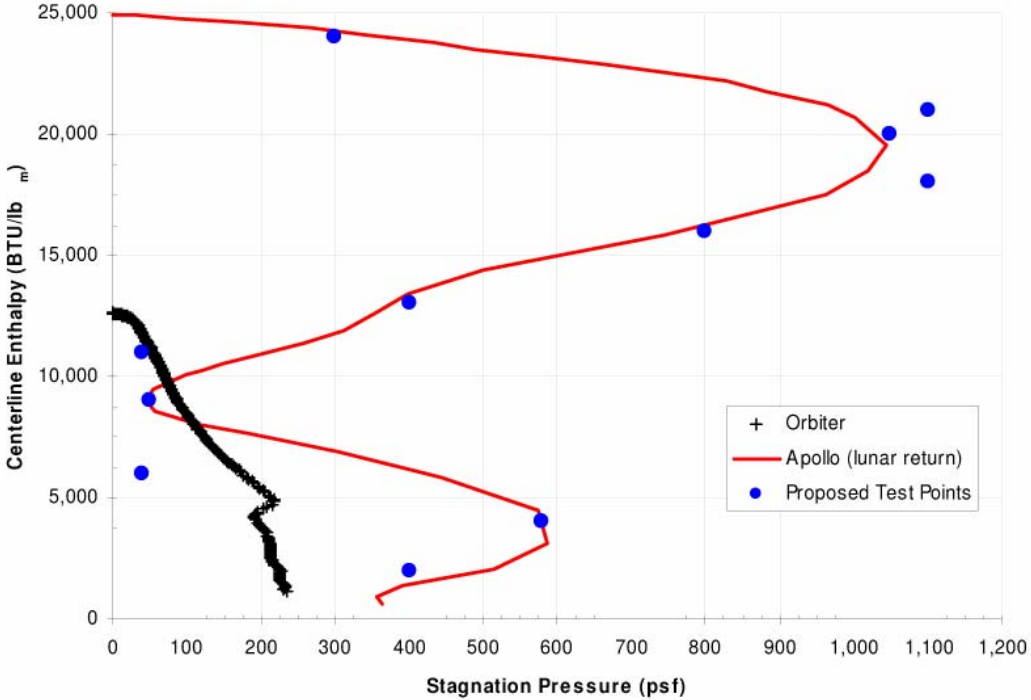
Material Development/Selection

- Analytical Analyses
  - Thermal/Structural
    - Thermal response
    - Thermal stress
    - Airloads
  - Degradation (oxidation)
  - Mission Evaluation
    - Nominal
    - Abort

Reentry Trajectory Drives TPS Material Requirements



Entry Trajectory Enthalpy/Pressure Test Points



Ablator Arc Jet Test Matrix

Damage	Lot/Batch	Facility	Qty	Pressure (psf)	Enthalpy (BTU/lbm)	Qdot (BTU/ft2-s)	Total
2	3	2	3	400	2,000		**36**
2	3	2	3	580	4,000		**36**
2	3	2	3	50	9,000		**36**
2	3	2	3	400	13,000		**36**
2	3	2	3	800	16,000		**36**
2	3	2	3	1,050	20,000		**36**
2	3	2	3	300	24,000		**36**
2	3	2	3	1,100	18,000		**36**
2	3	2	3	1,100	21,000		**36**
2	3	2	3	40	6,000		**36**
2	3	2	3	40	11,000		**36**
1	3	2	10	profile	profile	profile	**60**
							0
							456

Development Testing

- Component level testing
  - Thermal
  - Structural
  - Acoustic
- Manufacturing processes
  - Complex shapes
  - Material system
  - Repeatability
  - Improved fabrication
- Design/Installation
  - Attachments
  - Planform
  - Close-out areas
- Ground processing and repair
  - Installation technique
  - Field/factory repair
- Non-destructive evaluation techniques
  - On and off vehicle

Certification of TPS System

- Scoping out the environment
  - Temperatures – surface and structures
  - Vibroacoustic/aeroshock
  - Airloads
- How the vehicle is designed
  - Identify critical locations
    - Temperature
    - Loads
    - Margins of safety
    - Materials database
- How the vehicle is built/assembled
  - Critical processing parameters
  - Inspection points/rigor
  - Acceptance criteria
  - Repairs/maintainability

TPS Environments for Certification

- Natural Environments
  - Temperature – atmospheric
  - Thermal – vacuum
    - Solar radiation – thermal
  - Pressure
  - Fungus
  - Meteoroids
  - Humidity
  - Lightning
  - Ozone
  - Rain
  - Salt spray
  - Sand/dust
  - Solar radiation – nuclear
  - Wind
- Induced Environments
  - Temperature
    - Ascent heating
    - On-orbit and entry heating
  - Pressure
  - Acoustics
  - Shock
  - Random vibration
  - Structural loads
    - Limit and ultimate
  - Acceleration
- Miscellaneous Environments
  - Life – full and limited
  - Fluid compatibility

TPS Certification Process

- Tests
  - Thermal performance
  - Aerodynamic flow
  - Acoustic fatigue
  - Strength integrity
  - Material properties
- Analysis
  - Natural environments
  - Induced environments
  - Miscellaneous
- Similarity
- Commit-to-flight

Certification - Methods

- Utilization of existing database
  - Analytical methods
  - Ground test results
  - Flight tests
- Ground-based testing TPS system concepts
  - Ability to simulate environment
  - Lack of correlation with actual flight environment
- Analytical certification
  - Verified models using available flight and ground test data
- Flight test of entry system
  - Forces disciplined design and fabrication
  - Encourages acceptances of new (revolutionary) concepts
  - Addresses complex problem of mutual interactions within system
  - Acquires vital quantitative data not available through ground test

Certification – Some Key Issues

- Design/Assembly
  - Gap heating in joint regions between segments
  - Seal performance at interfaces
  - Prevention of hot gas/radiation leaks
  - TPS penetrations
- Materials
  - Damage Tolerance/Impact Resistance
  - Long term space exposure

Orbiter Reinforced Carbon-Carbon Certification Example

Design Allowable Tests

- MECHANICAL PROPERTY TESTS

BASELINE RCC	AS-FABRICATED	CONDITIONED
FLEXURE	181	205
TENSION	177	66
COMPRESSION	171	57
SHEAR STRENGTH	167	53
SHEAR MODULUS	30	31
INTERLAMINAR TENSION	29	30
INTERLAMINAR SHEAR	30	19
COEFFICIENT OF THERMAL EXPANSION	9	6
FLEXURE FATIGUE	20	17
TENSION FATIGUE	19	14
CORNER FLEXURE	15	10
CORNER COMPRESSION CRIPPLING	5	---
POISSON'S RATIO	2	4
IMPACT RESISTANCE	5	5
LUGS - STATIC	64	39
LUGS - FATIGUE	9	6
MISSION CYCLING		
TENSION	3	36
FLEXURE	3	24
COMPRESSION	3	27
TOTAL =	942	649

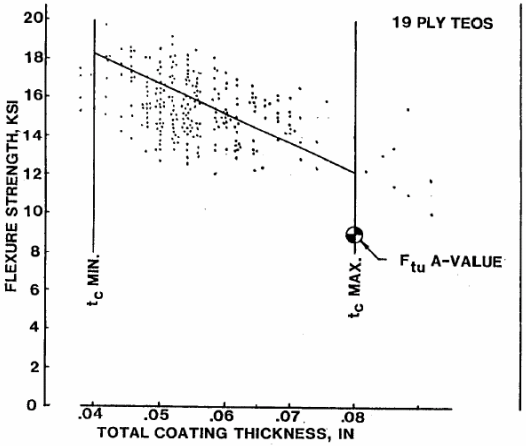
Design Allowable Tests

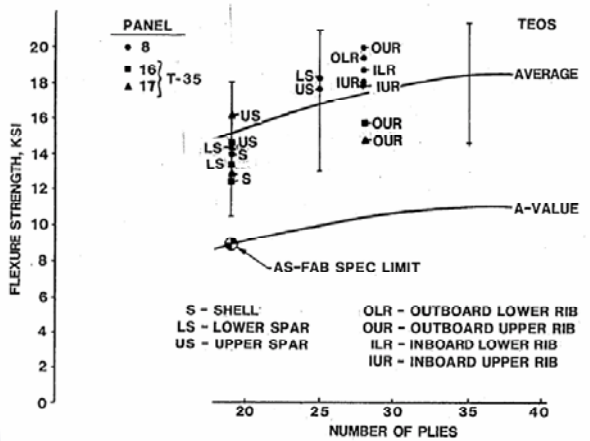
- MECHANICAL PROPERTY TESTS

TEOS RCC	AS-FABRICATED	CONDITIONED
FLEXURE	40	24
TENSION	52	34
COMPRESSION	46	28
SHEAR STRENGTH	11	10
SHEAR MODULUS	6	6
INTERLAMINAR TENSION	5	5
COEFFICIENT OF THERMAL EXPANSION	9	6
CORNER FLEXURE	3	3
SIMULTANEOUS CYCLING	3	18
LUGS		
TENSION CONTROLS	3	---
STATIC	58	35
VIBRATION - STATIC	---	15
FATIGUE	6	6
AXIAL - MOMENT INTERACTION	14	3
TOTAL =	256	193

RCC Design Allowables

- "A" basis RCC allowables are statistically calculated from mechanical test data per the general guidelines of MIL-HDBK-5B
  - "A" strength allowables designate the 99% minimum strength with 95% confidence
  - Over 2,000 specimens tested to define the mechanical properties used in design
  - Testing done on baseline, TEOS and Type A RCC
  - RCC design values included for as fabricated, mass loss and temperature effects





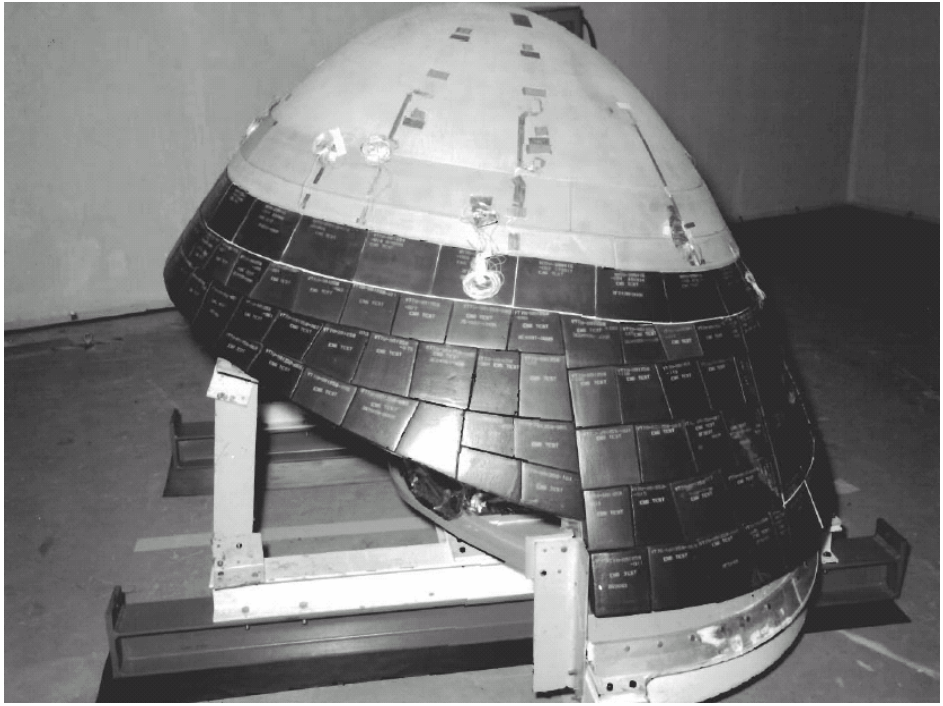
Material Thermophysical Property Tests

	BASELINE	TEOS	TYPE A
RADIANT MASS LOSS	38	90	120
CONVECTIVE MASS LOSS	31	20	27
THERMAL CONDUCTIVITY	36	12	10
SPECIFIC HEAT	5	6	2
EMISSIVITY	32	6	3
TOTAL =	142	134	16

RCC/LESS Certification

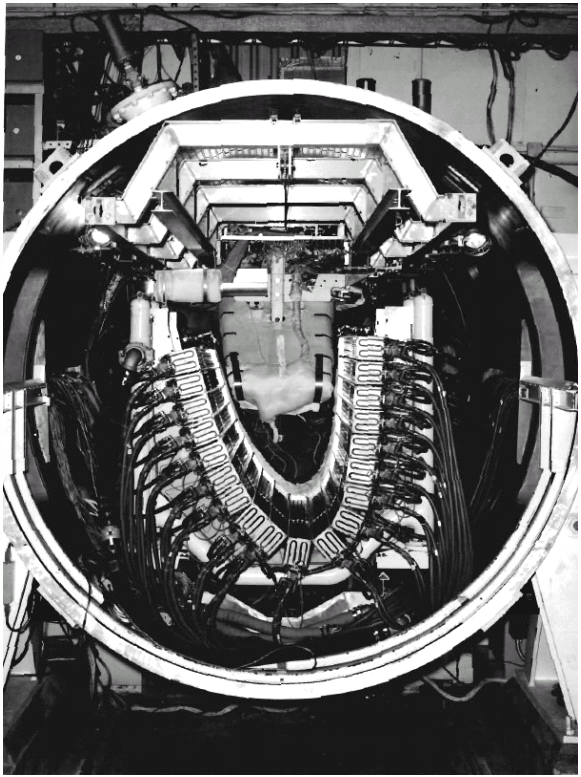
- Certification of RCC/LESS is accomplished by test verified analysis
- Extensive test program used to verify analytical techniques
  - RCC design allowables
    - Mechanical properties
    - Thermophysical properties
    - Mass loss
- Full scale hardware and integrated testing (Radiant Thermal, Airloads, Acoustics)
  - RCC Shell Development Tests
  - RCC/LESS System Qualification Tests

RCC Full Scale Nose Cap Test



RCC Wing Leading Edge Full Scale Test

Full Scale Wing Leading Edge Heater Configuration



Orbiter RCC Certification Requirements

CERTIFICATION REQUIREMENTS INDEX
ENVIRONMENTS FOR CERTIFICATION

LOCATION CODE
1 = EXTERNAL COMPONENTS
2 = INTERNAL COMPONENTS (UNPRESSURIZED COMPARTMENTS)

OPERATIONAL CODE
G = GROUND
F = FLIGHT
} USED ONLY FOR NATURAL ENVIRONMENTS, TEMPERATURE AND PRESSURE

CERTIFICATION CODE
T = TEST
S = SIMILARITY
A = ANALYSIS
X = METHOD TO BE DETERMINED

							NATURAL ENVIRONMENTS														INDUCED ENVIRONMENTS																			MISC. ENVIRONMENTS					
							TEMPERATURE														TEMP			PRESS		SHOCK						VIBRATION			STRUCT							LIFE					
CR NUMBER	PART NUMBER	PART NAME	LOCATION	TSA	OSA	NUMBER OF TEST SPECIMENS	HIGH	LOW	CYCLE	THERMAL-VAC	PRESSURE	FUNGUS	METEOROIDS	HUMIDITY	LIGHTNING	OZONE	RAIN	SALT SPRAY	SAND/DUST	SOLAR RAD.	WIND	HIGH	LOW	CYCLE	LAUNCH	ENTRY	CYCLIC	TRANS-PACKAGE	HANDLING	CRASH	PYRO/SEP	LANDING	MISSION	TRANSPORTATION	SINE	RANDOM	ACOUSTIC	LIMIT	ULTIMATE	FATIGUE	ACCELERATION	EXPLOSIVE	CORROSIVE	CABIN ATMOS	FULL	LIMITED	CYCLE	EMC	FLUID-COMP	OAVT	OATT
08-399200	V070-399200	NOSE CAP RCC INSTL	1 2			1	A/F	A/F	A/F	A	A/F	A	A	A	A	A	A	A	A	A		A T_5	A T_5	A T_5	A T_5	A T_5										T_5 A	T_5 A	T_5 A	T_5 A					T_5 A	T_5 A			A		
08-199200	V070-199200	WING L.E. RCC PANELS	1/ 2			1	A/F	A/F	A/F	A	A/F	A	A	A	A	A	A	A	A	A	A	T_{35} A	T_{35} A	T_{35} A	A	T_{35} A										T_{35} A	T_{35} A	T_{35} A	T_{35} A					T_{35} A	T_{35} A			A		
08-199200	V070-199750	WING L.E. ACCESS PANELS	1/ 2			1	A/F	A/F	A/F	A	A/F	A	A	A	A	A	A	A	A	A	A	T_{35} A	T_{35} A	T_{35} A												T_{35} A	T_{35} A	T_{35} A	T_{35} A					T_{35} A	T_{35} A			A		
08-199200	V070-199900	WING SPAR FITTINGS	2			1	A/F	A/F	A/F	A	A/F	A		A	A	A	A	A	A	A		T_{35} A	T_{35} A	T_{35} A												T_{35} A	T_{35} A	T_{35} A	T_{35} A					T_{35} A	T_{35} A			A		

Summary

- Significant advances have been made in the design, fabrication, certification and flight tests of entry systems (Mercury through Shuttle Orbiter)
- Shuttle experience has identified some key design and operational issues
- Attention to vehicle design, fabrication, and assembly