Thermal Protection System Needs

Don Curry
The Boeing Company

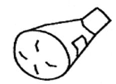
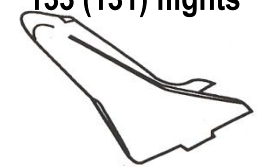
March 11, 2011

Outline

- History
- TPS Materials
- TPS Testing
- TPS Analysis

TPS History

TPS Mass Fraction – Historic Crewed Vehicles

	MERCURY	GEMINI	APOLLO	SHUTTLE
DATE No. of flight	10/7/58 - 5/16/63 6 flights	3/23/65 - 11/15/66 10 flights	10/11/69 - 12/19/72 11 flights	4/12/81 – 3/9/11 133 (131) flights
				
AREA	32 FT^2	45 FT^2	365 FT^2	11 895 FT^2
WEIGHT	315 LB	348 LB	1465 LB	18 904 LB
WT/FT^2	10.2	7.5	3.9	1.7
MATERIAL	ABLATOR (FIBERGLASS-REINFORCED LAMINATED PLASTIC)	ABLATOR (DOW CORNING DC 325)	ABLATOR (AVCO 5026-39)	Rigidized silica fibers
DENSITY	114 LB/FT^3	54 LB/FT^3	33 LB/FT^3	9-22 LB/FT^3
USAGE	1 FLIGHT	1 FLIGHT	1 FLIGHT	133 (131) FLIGHTS
Vehicle Weight	**2724 lb**	**4861 lb**	**11500 lb**	**180,000 lb**
TPS Mass Fraction	**11.6%***	**7.16%***	**12.8%**	**10.5%**

* TPS Mass only includes heat shield, and not the metallic backshell

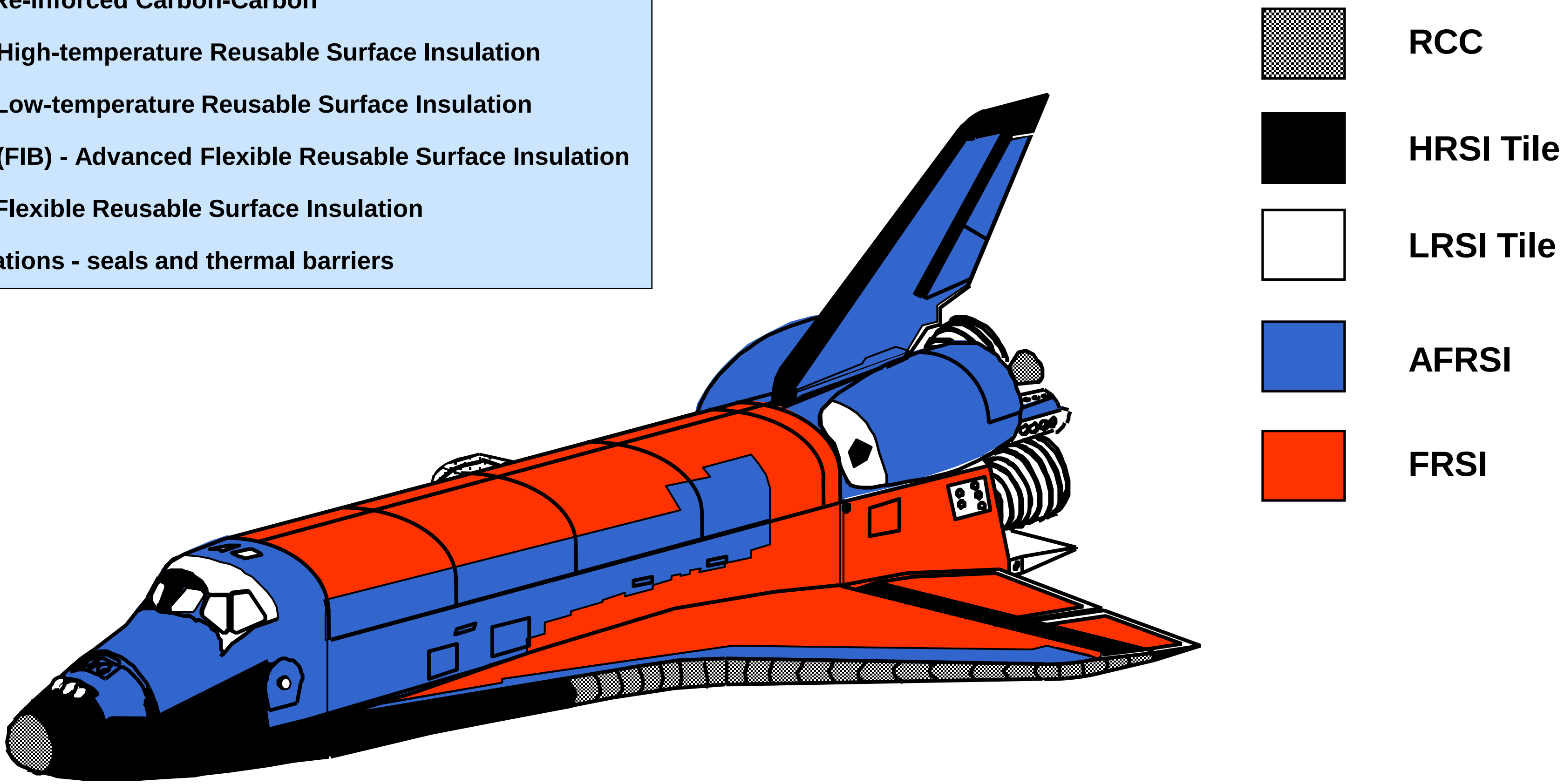
TPS Materials

Current Status

- Reusable Materials developed for Space Shuttle Orbiter
  – Maximum Operational Temperature – 2900F
- Early NASA missions (Mercury, Gemini, Apollo) used new ablative TPS
- Proposed Orion TPS
  – Apollo AVCO – Textron
  – Ames PICA

Orbiter TPS Configuration

- RCC - Re-inforced Carbon-Carbon
- HRSI - High-temperature Reusable Surface Insulation
- LRSI - Low-temperature Reusable Surface Insulation
- AFRSI (FIB) - Advanced Flexible Reusable Surface Insulation
- FRSI - Flexible Reusable Surface Insulation
- Penetrations - seals and thermal barriers



OV-103 & subs shown

Candidate ablative heat shield TPS materials for Mars and Titan

Density	TPS	Supplier	Flight Qual or TRL	Potential Limit: Heat flux, W/cm^2	Potential Limit: Pressure atm	Entry at Mars: MPF Class	Entry at Mars: MSL Class	Entry at Mars: Aero-capture	Earth Return†	Titan: Direct	Titan: Aero-capture
FOREBODY HEAT SHIELD											
Low-Mid	SLA 561V	LMA	Mars	< 120 (<300)*	< 1	●	✖	◡	✖	●	●
	PICA	FMI	Stardust	~ 1200	< 1	■	●	●	✖	●	●
	BPA	Boeing	TRL 3-4	~ 1000	~ 1	■	◡	◡	✖	◡	◡
	Avcoat	Textron	Apollo	~ 1000	~ 1	■	●	●	✖	●	●
	AQ60#	EADS	Huygens	~ 250	< 1	◡	✖	◡	✖	●	◡
	Acusil® II†	ITT	DOD MSL	100	< 1	✖	✖	◡	✖	◡	◡
	SRAM Family	ARA	TRL 5-6	~ 300*	~ 1	◡	◡	◡	✖	◡	◡
	Lower density Phen-Carb	ARA	TRL 5-6	< 2000	~1	■	◡	◡	✖	◡	◡
Mid	ACC	LMA/C-Cat	Genesis	> 2000	> 1	■	■	■	✖	■	■
	Mid-density PhenCarb	Several	TRL 4-5	~ 2,000-4000	> 1	■	■	■	✖	■	■
High	3DQP	Textron	DOD	~ 5000	> 1	■	■	■	✖	■	■
	Heritage Carbon phenolic	None today but several can	Venus, Jupiter	10,000-30,000	>> 1	■	■	■	●	■	■

● Fully capable ◡ Potentially capable, qual needed ■ Capable but heavy ✖ Not capable

† RF transparent # European Supplier * (heat flux limit is lower with high shear, higher at low shear)

Note: Reliability requirements for MSR EEV can only be met by heritage carbon phenolic TPS

Candidate ablative back shell TPS materials for Mars and Titan

Density	TPS	Supplier	Flight Qual or TRL	Potential Limit		Mars Direct		Mars	Titan	
				Heat flux, W/cm^2	Pressure atm	Size ~MPF	Size (MSL)	Aero-capture	Direct	Aero-capture
BACKSHELL TPS										
Low	SLA-561V*	LMA	Mars	< 120 (<300)*	< 1	●	●	●	●	●
Low	SRAM Family	ARA	TRL 5-6	~ 300	~ 1	◡	◡	◡	◡	◡
Low	AQ60	EADS	Huygens	~ 250	< 1	◡	◡	◡	●	●
Low	SIRCA†	Ames	Mars	~ 150	> 1	◡	◡	◡	◡	◡
Low	Acusil® II†	ITT	DOD MSL	100	< 1	●	●	●	●	●
Low	SLA-561S	LMA	Mars	< 20	< 1	●	✖	✖	◡	✖

● Fully capable ◡ Potentially capable, qual needed ■ Capable but heavy ✖ Not capable

†RF transparent #European Supplier * (heat flux limit is lower with high shear, higher at low shear)

TPS Testing

Apollo Heat Shield Evolution (Materials – Arc Jet Utilization)

1960 - 61

- Screening Evaluations (Materials)
  - Phenolic Nylon
  - GE Epoxy Ablator
  - AVCO 5026-22 (66 lb/ft^3)

1962 — **DDTE** — **1969**

Primary Contractor AVCO

(Materials)
5026-22 (66 lb/ft^3)
(Tiles)

↓

5026-39 HCG
(33 lb/ft^3)

↓

AVCO Model 500
AVCO 10MW
AVCO ROVERS

North American / Rockwell Monitoring & Backup

(Materials)
5026-39
DC325 (Gemini)
GE ESM1000
Thermolag (T500-13)
Purple Blend (LARC)

↓

Chicago Midway
Plasmadyne
Rocketdyne (Rockets)
GE MALTA (Rockets)

Independent NASA Monitoring & Backup

(Materials)
Chance Vought
(Burnt Toast)
Melamine Phenolics
Thermolag
Honeycomb Fill Thermolag

↓

NASA MSC
NASA Ames
NASA LARC
Plasmadyne
General Electric
Aerotherm
Boeing

Arc Jet Facilities Utilized →

Estimated Number Of Tests

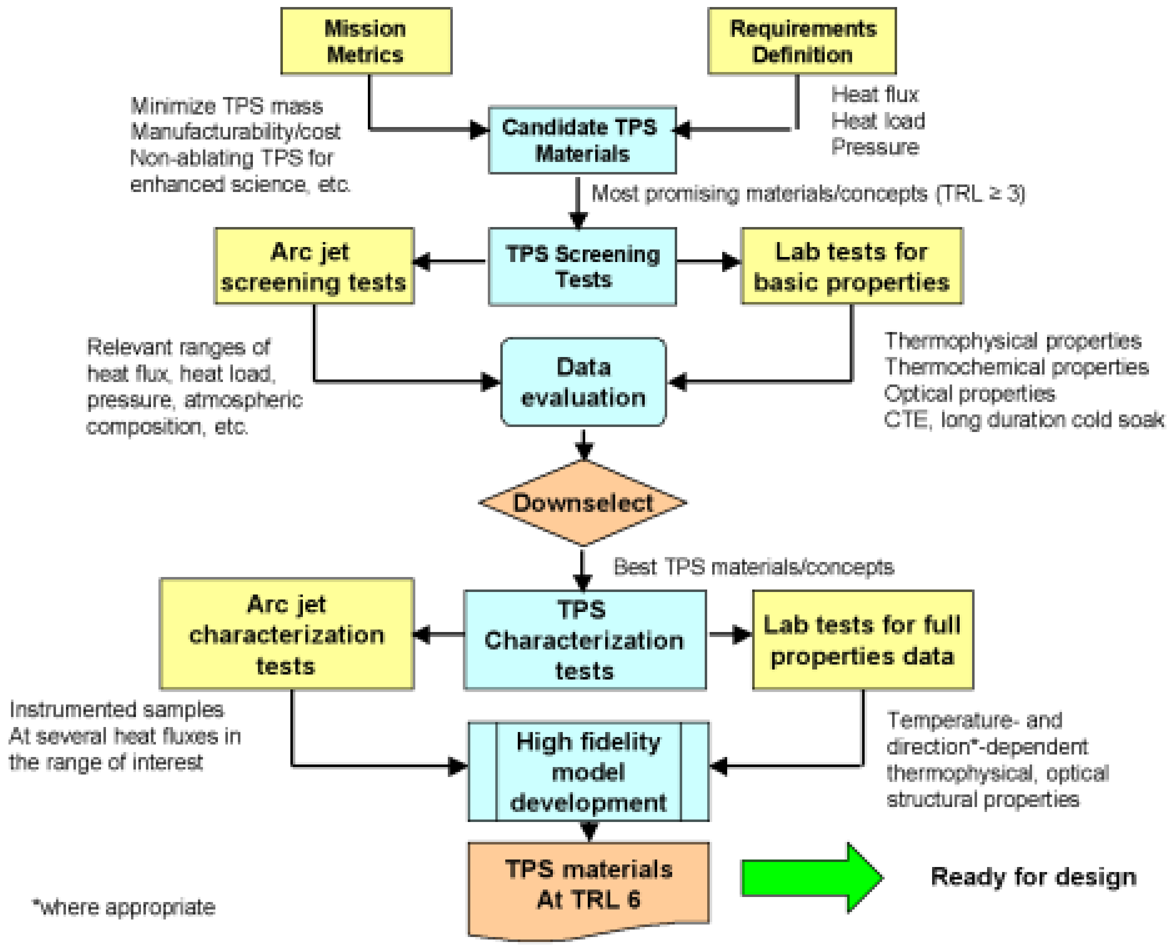
AVCO	North American Monitoring	Independent NASA Testing
~5000	>1000	>2000

NASA MSC

- Apollo Ablator
- Backup Ablators
- CM/SM Umbilical
- Antennas
- Tension Tie Bolts
- Radiometers
- T/C Plugs
- Ablator Sensors
- Apollo 6 Sideburns Experiment
- EASEP Canister

Courtesy of Don Tillian

Time-proven Approach to Materials Screening, Characterization and Modeling



Courtesy: Bernie Laub

Thermophysical Properties: Thermal Response Modeling

1. Specific Heat of Virgin Material
   - Function of temperature.
2. Thermal Conductivity of Virgin Material
   - Functions of temperature, pressure and orientation, if appropriate
     - Open porosity so thermal conductivity has dependence on pressure
     - Preferential orientation of fibers in the in-plane direction resulting in ~2x great thermal conductivity in-plane versus through the thickness
3. Specific Heat of Char
   - Measure on arcjet char
   - Derive from known (or derived) composition using rule of mixtures
4. Optical Properties of Virgin Material (Emittance)
5. Optical properties of Char
   - Measure on arcjet char
   - Estimate from known composition and properties of similar materials
6. Thermal conductivity of char as function of temperature
   - Initial values using laboratory measurements
   - Final (design) values determined from in-depth thermocouple temperatures of arc jet tested samples
7. Transition zone properties estimated using local density relationship

Courtesy: Bernie Laub

Thermochemical Properties: Thermal Response Modeling

1. Thermo Gravimetric Analysis (TGA) Experiments:
   - Inert gas, low temperature rise rates
   - Residual mass fraction defines *char yield*.
   - Data fits provide decomposition kinetic constants.
2. Differential Scanning Calorimetry (DSC) Experiments:
   - Inert gas, low temperature rise rates
   - Data provides heat of reaction for pyrolysis reactions as function of temperature.
3. Elemental composition of virgin material.
4. Heat of combustion of virgin material
   - Derive from heat of formation measurements
5. Elemental composition of char:
   - Derive from known constituents and char yield data.
   - Measure from arcjet char
   - For multi-constituent ablative materials char composition may be dependent on environment experienced during reentry
     - Example carbon to silica ratio in char may vary with conditions
6. Heat of formation of char
   - Derive from known constituents and existing data

Courtesy: Bernie Laub

Properties Required for Thermo/Structural Design

- Mechanical/Physical Properties
  - Tension (Strength and Modulus)
  - Compression (Strength and Modulus)
  - Flexure (Strength and Modulus)
  - Shear (Strength and Modulus)
  - Coefficient of thermal expansion
  - As functions of temperature
  - As functions of orientation
    - Materials such that have significantly different mechanical properties IP vs TTT.
    - Honeycomb materials also have strong and weak directions (ribbon direction vs perpendicular to ribbon direction) as well as differences IP vs TTT
  - Glass transition point (Tg)
- System Level Testing
  - Strength of bond between ablator and carrier structure
  - CTE mis-match of ablator to structure

Courtesy: Don Ellerby

TPS Analysis

Ablation Analysis

- Ablation analyses – 1960 - 1970
  - – Heat of Ablation
  - – Thermochemical (Charring Ablators)
- Ablation analyses – Today
  - – 4 Ablator Workshops Held
    - In-depth physic and Chemistry
    - Gas surface Interaction and Catalysis
    - Roughness modeling with Gas Blowing
    - Ablation Model Code Intercalibration Test Cases

Factors That Influence TPS Design

- Aerothermal Environment
  - Peak conditions (heat flux, shear, pressure) maybe used to screen suitability of a given material
  - Total heat load will be used to size the thickness and therefore total mass of the heat shield
- Strength/Stiffness (Airloads/Vibroacoustic)
  - Limits of ablator material will drive things such as carrier structure design(stiffness) and block layout for segmented approaches
- Thermal Gradients
- Venting Characteristics
- Outgassing
- Space Environment
  - LEO: Atomic Oxygen
  - UV
  - Long Term Space Exposure
- Damage Tolerance/Impact Resistance
- Repairability
- Refurbishment

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