Arc Jet Testing
A Short Course

Presented by
Robin A. S. Beck

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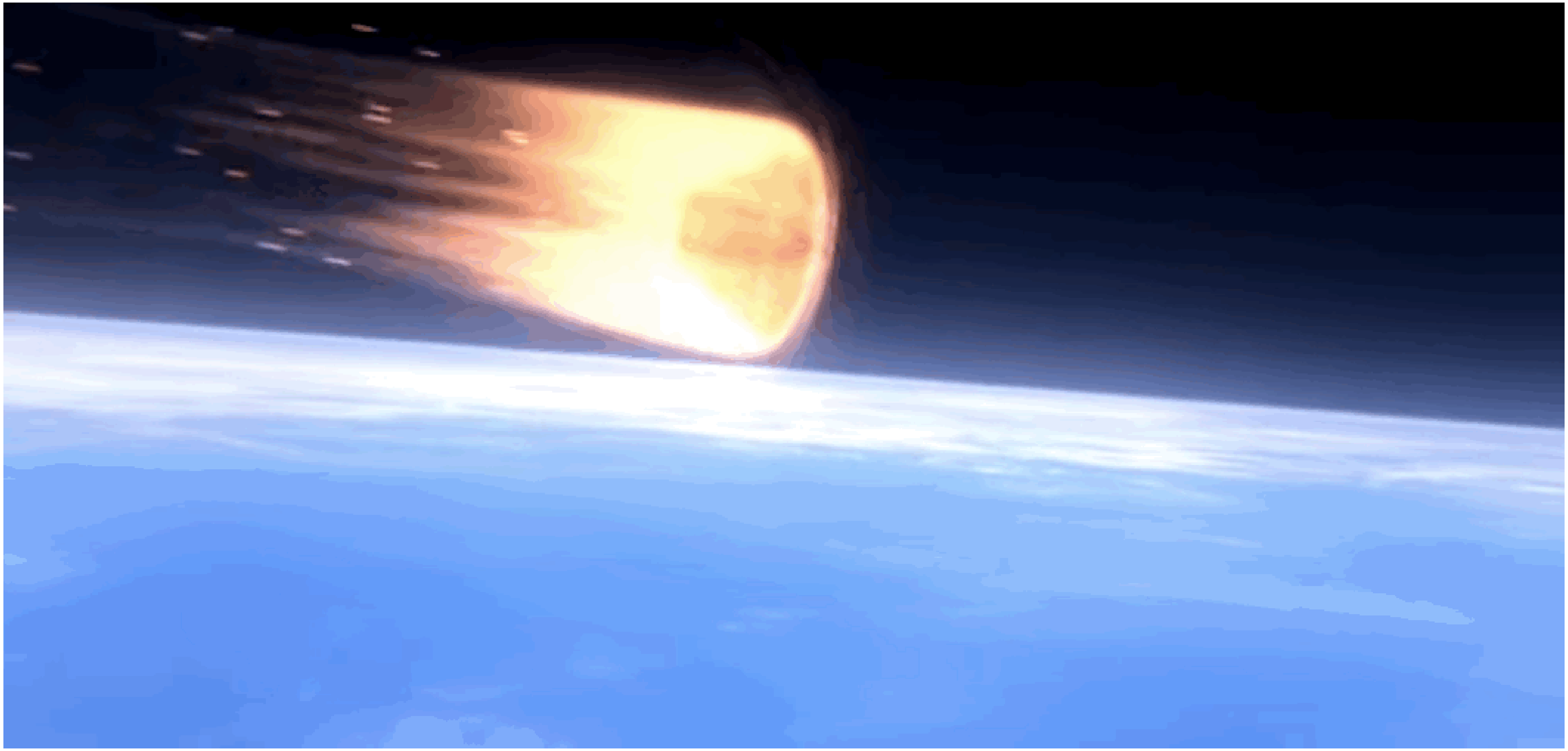
Outline

- Overview of the Entry Systems and Technology Division (TS) at NASA Ames Research Center (ARC)
- Quick look at the Earth and Planetary Entry projects supported by TS and the inventions and software developed within the division
- A description of the entry environments to which thermal protection systems (TPS) are exposed
- How we insure TPS survival will be addressed with descriptions of the various test facilities across the agency and beyond and their applicability
- The Ames Arc Jet Complex will then be described
  - how an arc heater works
  - the associated infrastructure required
  - capabilities of each of the test tunnels
- Examples of TPS arc jet test articles

Mission

Entry Systems and Technology Division (TS) at NASA Ames Research Center deals with Hypersonic entry into an atmosphere



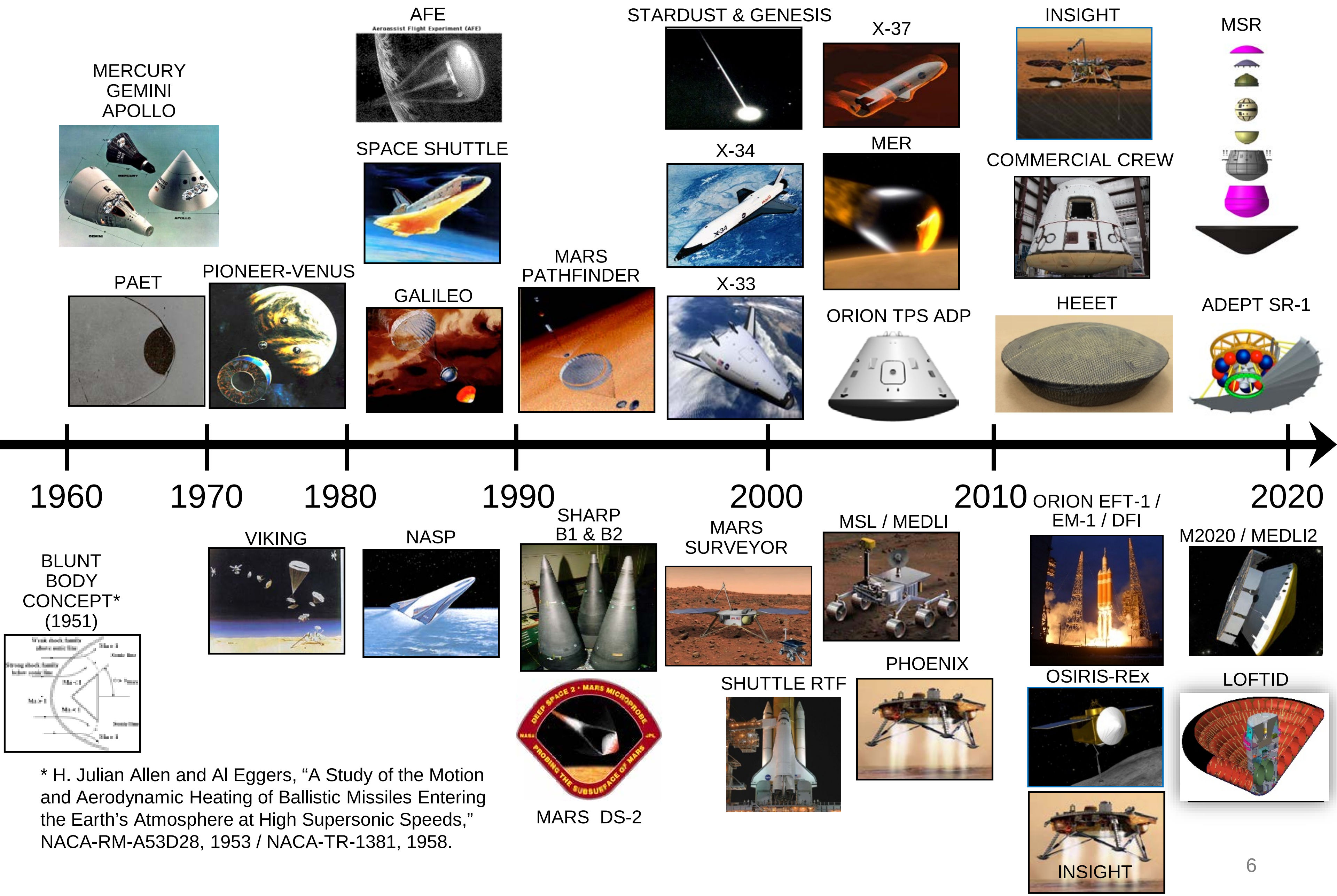
Entry Systems & Technology Division

- Four branches under Entry Systems & Technology Division (Code TS) – D. Hash
  https://www.nasa.gov/ames/exploration-tech/entry-systems
  - Aerothermodynamics (TSA) – J. Hill
    https://www.nasa.gov/archive2/content/aerothermodynamics-branch
  - Thermophysics Facilities (TSF) – S. Eddlemon
    https://www.nasa.gov/centers/ames/thermophysics-facilities-home
  - Thermal Protection Materials and Systems (TSM) – M. Stackpoole
    https://www.nasa.gov/content/thermal-protection-materials-branch
  - Entry Systems & Vehicle Development (TSS) – K. Zarchi
    https://www.nasa.gov/centers/ames/entry-systems-vehicle-development/index.html

TS Division Overview

- The TS division (Entry Systems and Technology Division) includes people who:
  - Help design spacecraft for different exploration missions
  - Analyze the environments around a spacecraft
  - Invent new materials that can protect a spacecraft
  - Figure out how those materials will behave on a spacecraft and how thick they need to be
  - Plan and perform tests on those materials and spacecraft designs to prove they will fly successfully
  - Instrument vehicles in order to get flight data on the materials
  - Build and launch demonstration vehicles

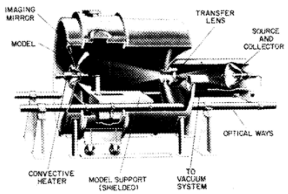
NASA Entry Projects Supported by Ames

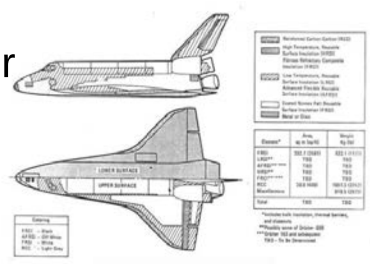


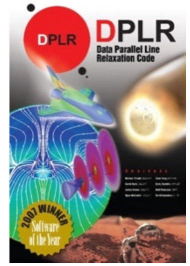
* H. Julian Allen and Al Eggers, “A Study of the Motion and Aerodynamic Heating of Ballistic Missiles Entering the Earth’s Atmosphere at High Supersonic Speeds,” NACA-RM-A53D28, 1953 / NACA-TR-1381, 1958.

NASA Ames Entry Systems Innovations

Advanced Entry Heating Simulator

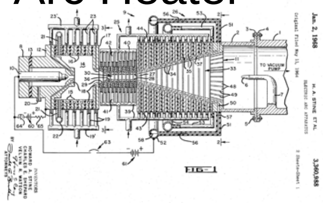






ADEPT

Constricted Arc Heater



RCG
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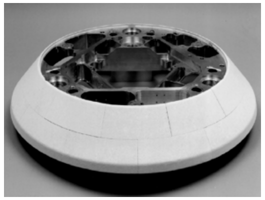
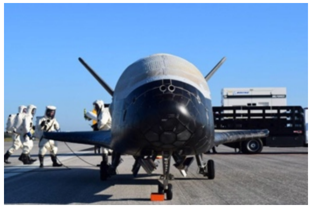
FRCI
AFRSI
AETB
TUFI

SIRCA



TUFROC



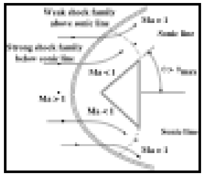
3DMAT

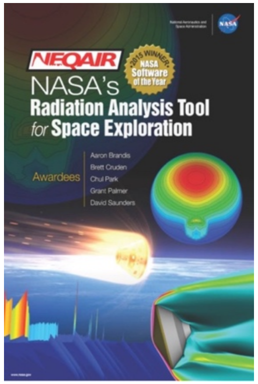
1960 1970 1980 1990 2000 2010 2020

PICA

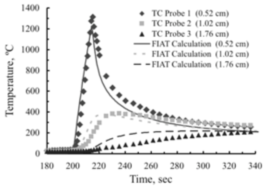
HEEET

Blunt Body Concept* (1951)

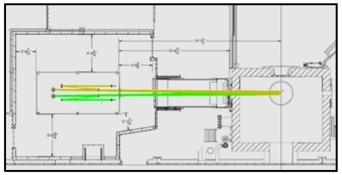




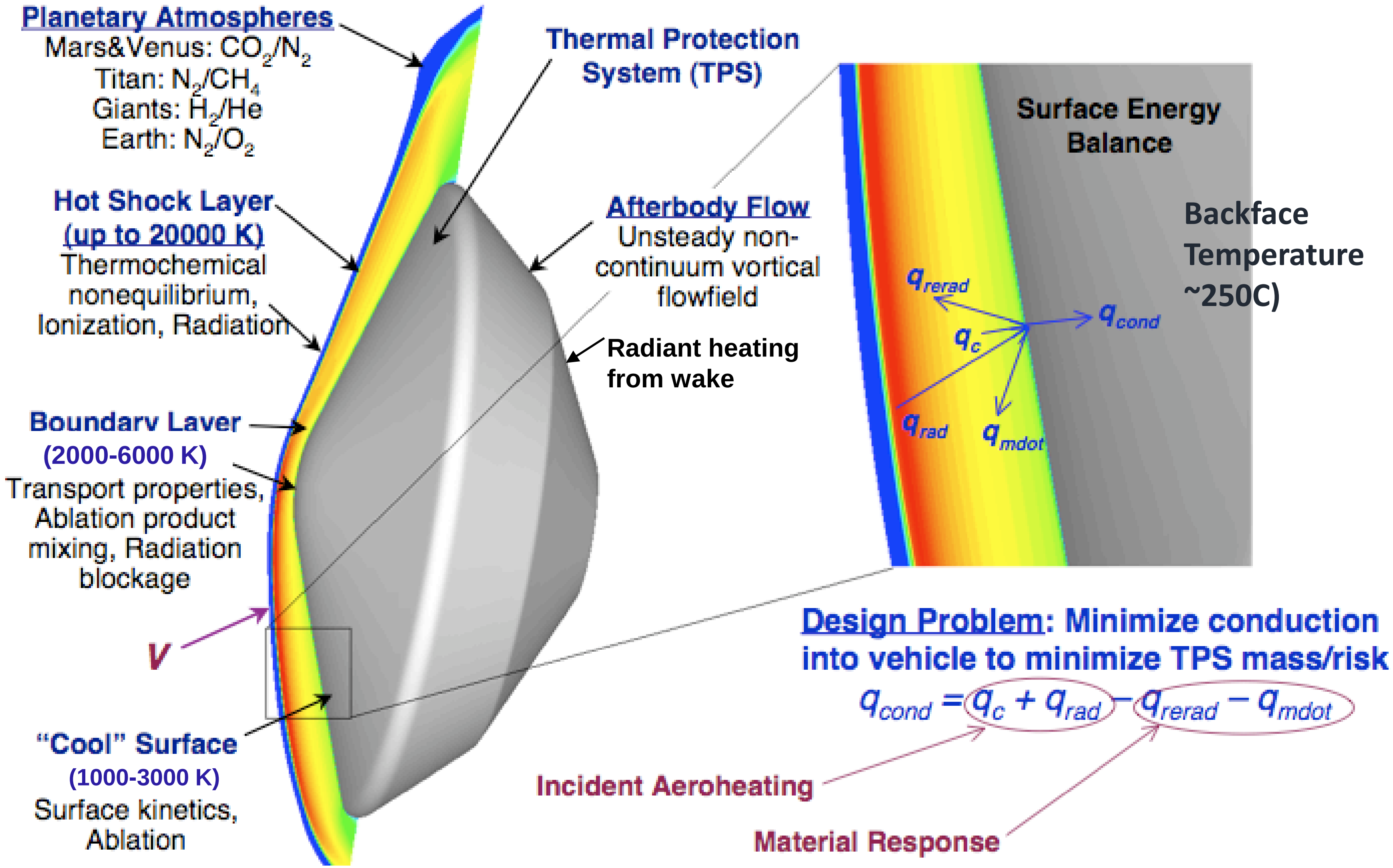
FIAT



Laser-Enhanced IHF



High Energy Heatshield Environments



Courtesy M. J. Wright

How Do We Insure TPS Survival?

- We test!
- We get as many property measurements as possible
  - Material compositions – virgin, char, pyrolysis gas
  - Density, density degradation with temperature
  - Heats of combustion – helps to derive the heats of formation
  - Specific heat vs temperature for virgin and charred material
  - Thermal conductivity vs temperature for virgin and charred material
- Evaluate entry environments and test facility environments
- Try to match relevant environment parameters (q, p, h, τ) in test facilities
  - Usually this must be done piece-wise
- Combine measured properties and thermal response during tests to develop material response model
- Predict response during entry

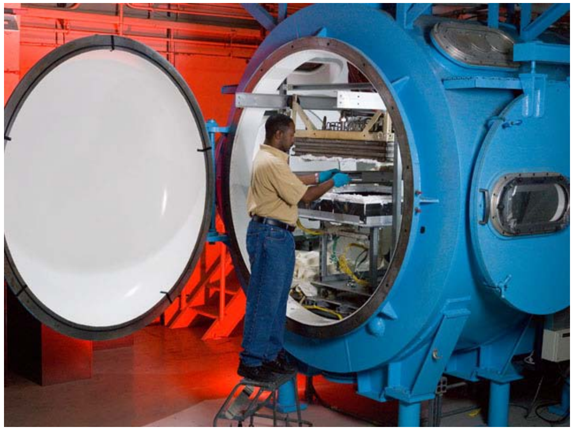
Philosophy

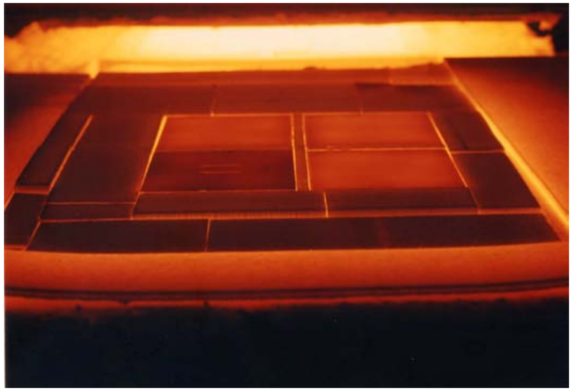
- What is the test objective?
  - Screening several candidate ablative materials for comparative performance
  - Evaluating ablation performance over broad range of conditions
  - Evaluating performance limits of a material (failure threshold)
  - Developing data base for thermal modeling
  - Developing data base for reliability assessment (design margin)
  - Validating performance of material interfaces (gaps, seals, penetrations, etc.)
- The test objective dictates the test approach, and drives the selection of:
  - Test facility
  - Test article design
  - Test conditions
  - Instrumentation
  - Post-test evaluation

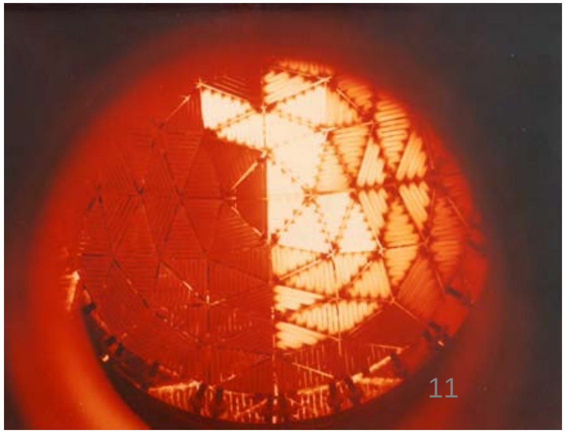
Test Facilities - 1

Radiant Heating Facilities (JSC)

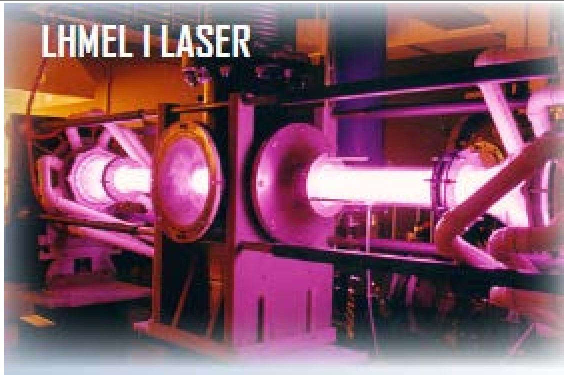
- Useful for evaluating insulation performance of complex TPS configurations
  - Relatively low heat fluxes (<100 W/cm^2)
  - Large test articles
- Only meaningful if surface-boundary layer interaction effects are *negligible,* i.e., effects of surface catalycity, surface oxidation, transpiration, atmospheric 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 known optical properties (if they won't blow off)
- For complex test article geometry, must be aware of potential for shadowing





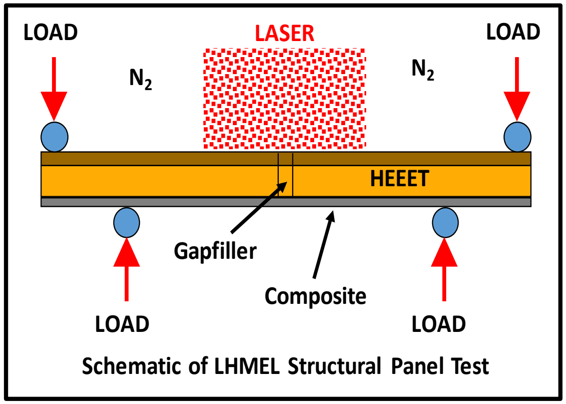


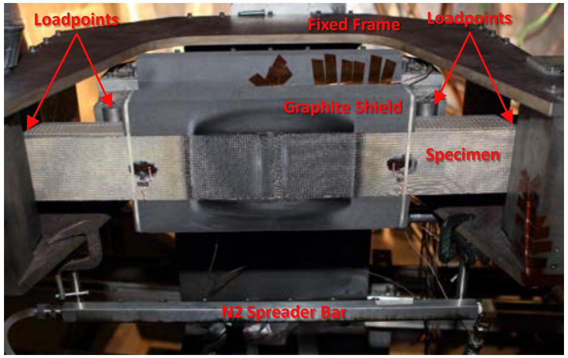
Test Facilities - 2



Radiant Heating Facilities -- CW and Fiber lasers (LHMEL)

- 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)
    - Many materials are NOT opaque at 1.7 μm (Fiber 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 phenomena at very high heat fluxes
- NASA has developed mechanisms for thermostructural testing (laser environments with specimens under load) at LHMEL

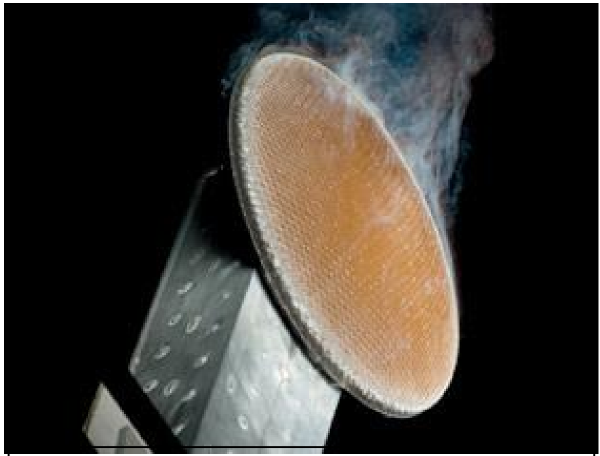




Test Facilities - 3

Radiant Heating Facilities – National Solar Thermal Test Facility

- Primary application is to obtain moderately high heat fluxes on very large specimens
  - 100-ton capacity elevating module for lifting experiments to the top of the tower
  - Water glycol cooling systems and air coolers to provide heat removal from experiments
  - Rotating platform and shutter system to protect experiments while system sets up
- Requires very accurate knowledge of:
  - Heat flux distribution across test article (diagnostics)
  - Optical properties of test material at the solar wavelengths
- Cannot simulate surface-boundary layer interaction effects
  - Can employ (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
  - All tests at 1-atm, in air

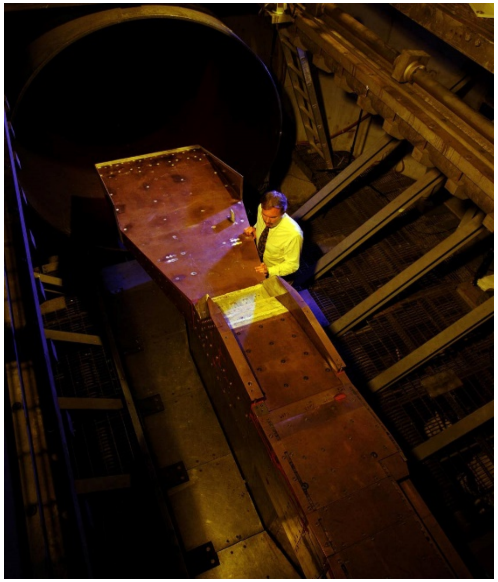


1.0-m diameter heatshield tested by ARA at 150 W/cm2 for 200s

Test Facilities - 4

Combustion Facilities (LaRC)

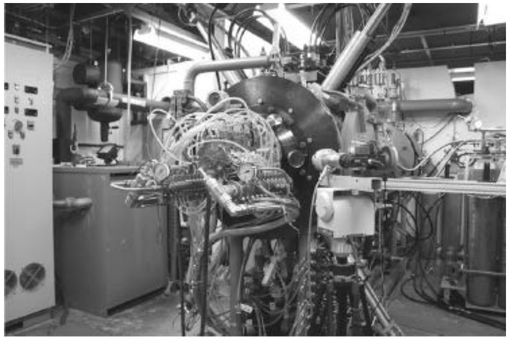
- Useful for testing TPS materials in motor applications
  - Rocket nozzles, combustor liners
  - Well-suited for full scale systems-level tests
- Very limited utility for studying TPS performance in hypersonic flight at Mach > ≈ 7
  - Cannot simulate many important environmental parameters
  - Limitations in total temperature of combustion products (little flexibility)
    - Maximum gas temperature set by theoretical combustion limits (≈ 2800 K)
  - 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 - 5

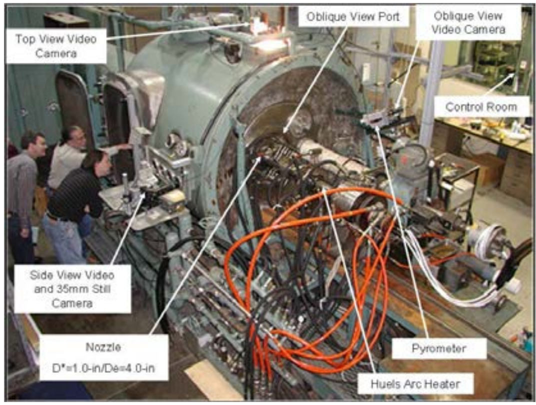
Arc Plasma Facilities (ARC, LaRC, AEDC, LCAT)

- Have been used for over 50 years to study TPS material performance
  - Two classes:
    - Lower enthalpy, high pressure, high heat flux (high β vehicles)
    - Higher enthalpy, low pressure, low-moderate heat flux (lifting entry, aeroassist, aerocapture, planetary entry, etc. – 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.
- Few can simulate time-varying conditions (trajectories)



HYMETS facility

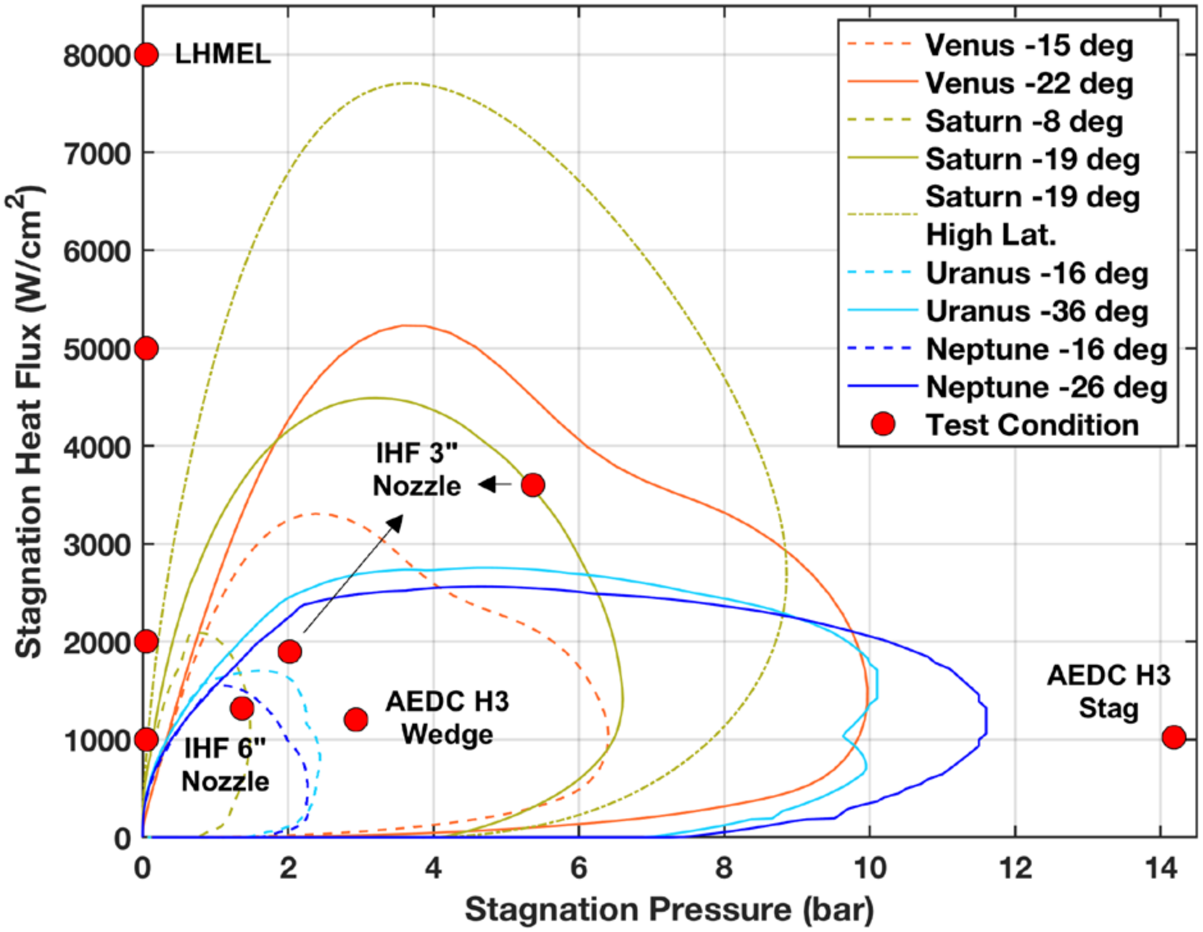
AEDC H2 Test Chamber



Boeing LCAT Facility

Testing TPS for Extreme Environments

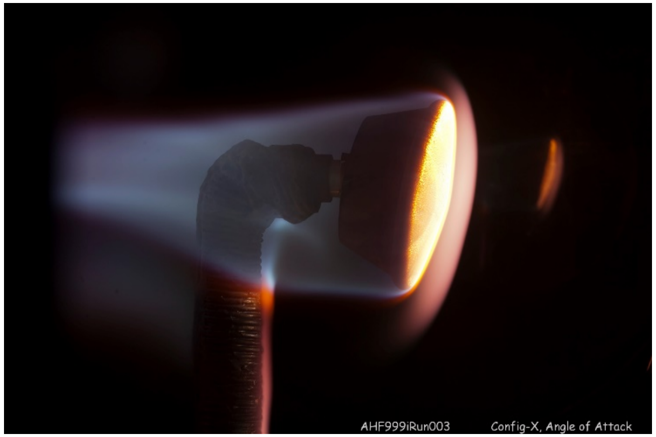
- Requires piecemeal testing at various facilities to cover the environments



NASA Ames ArcJet Complex

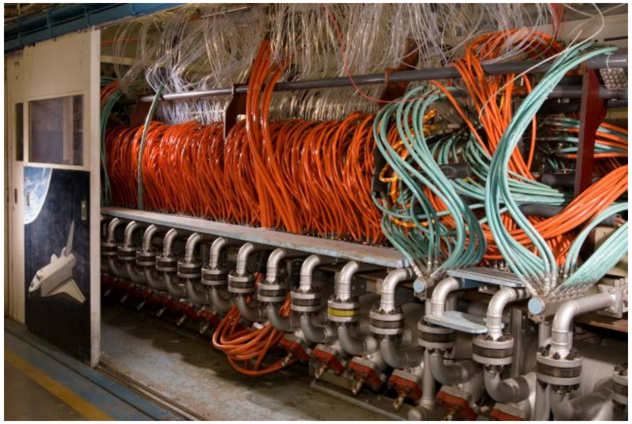
TS Testing

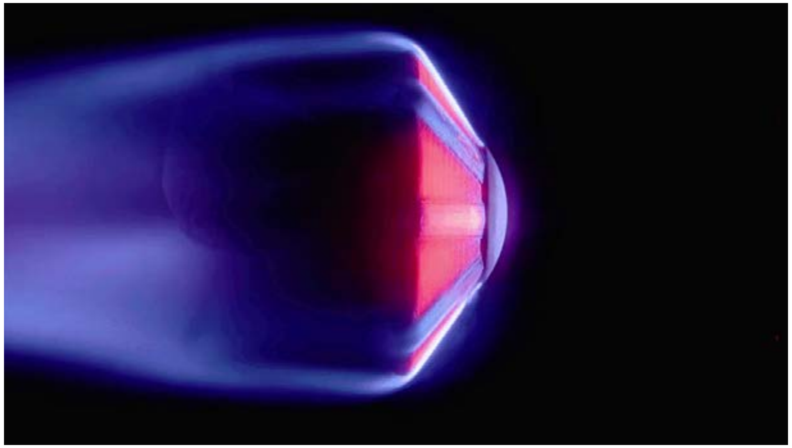
- The Ames Arc Jet Complex has a rich heritage of over 55 years in Thermal Protection System (TPS) development for every NASA Space Transportation and Planetary program
  - Apollo, Space Shuttle, Viking, Pioneer-Venus, Galileo, Mars Pathfinder, MER heatshield, Stardust, NASP, X-33, X-34, SHARP-B1 and B2, X-37 WLE TPS, Orion heatshield development and MSL TPS
- The arc jets are used for the three major areas of TPS development: selection, validation and qualification



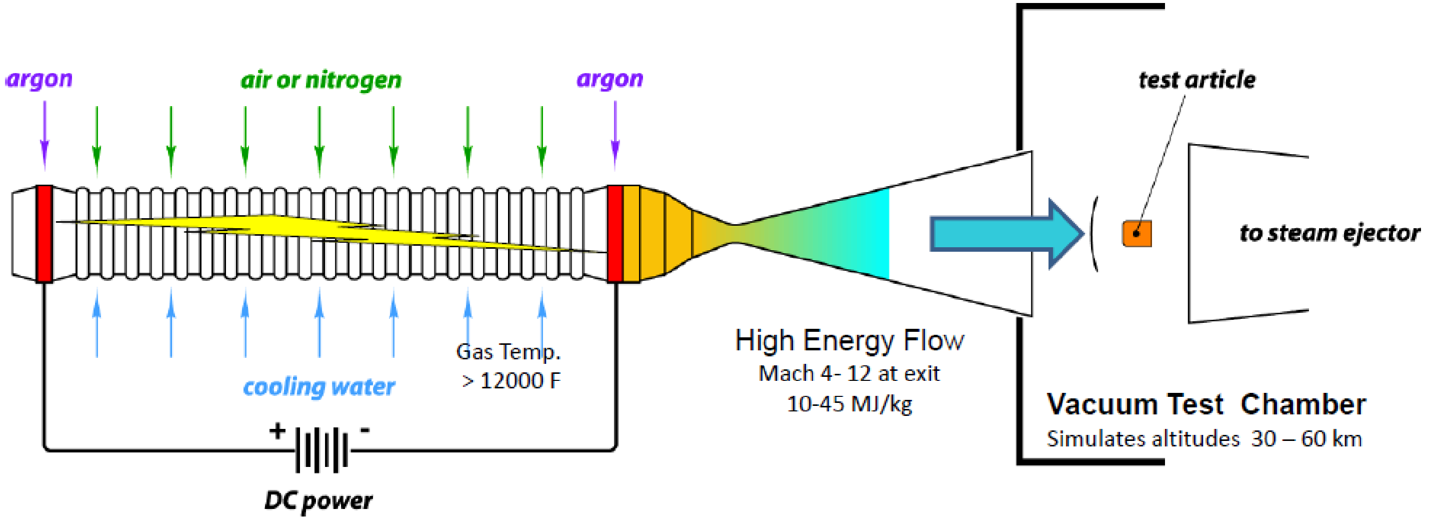
Proving the System – Arc Jet Testing

An arc jet produces an electrically heated, high speed gas flow onto a test article – matching key parameters of high speed entry from space into an atmosphere



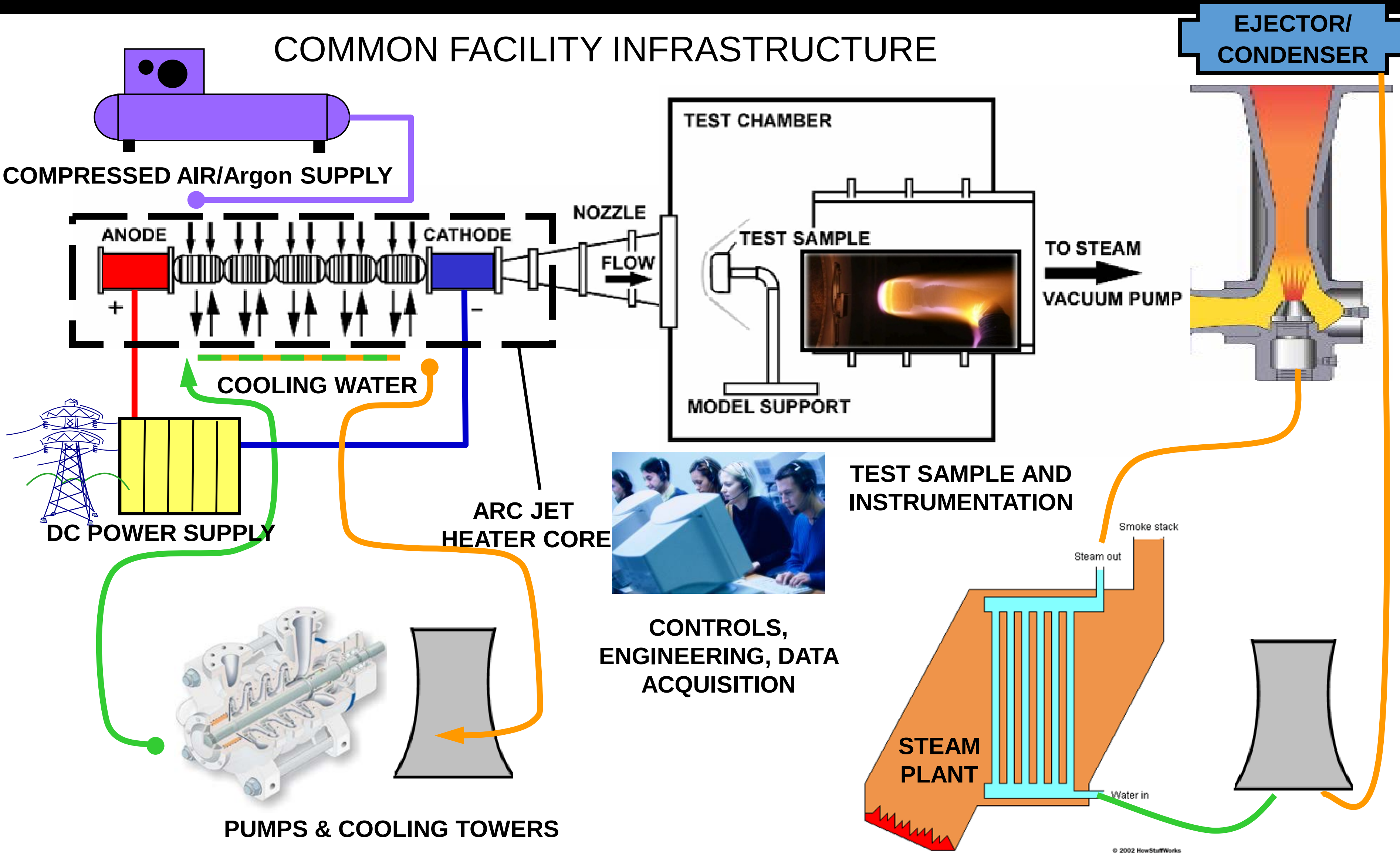


How it works



- Under vacuum, add argon gas; connect a high-voltage (10 MW- 75 MW) “car battery” across electrodes to breakdown argon; and we have a flow of electrons inside the arcjet tube.
- Air flow collides with electrons in this “lightening bolt”→ dissociated air at high temperatures (> 9000º F)
- Expand dissociated air out a nozzle to hypersonic conditions and into a chamber at altitude conditions matching peak heating
- When conditions are correct, insert test sample and see what happens!

Oh Yes, And All That Other Stuff



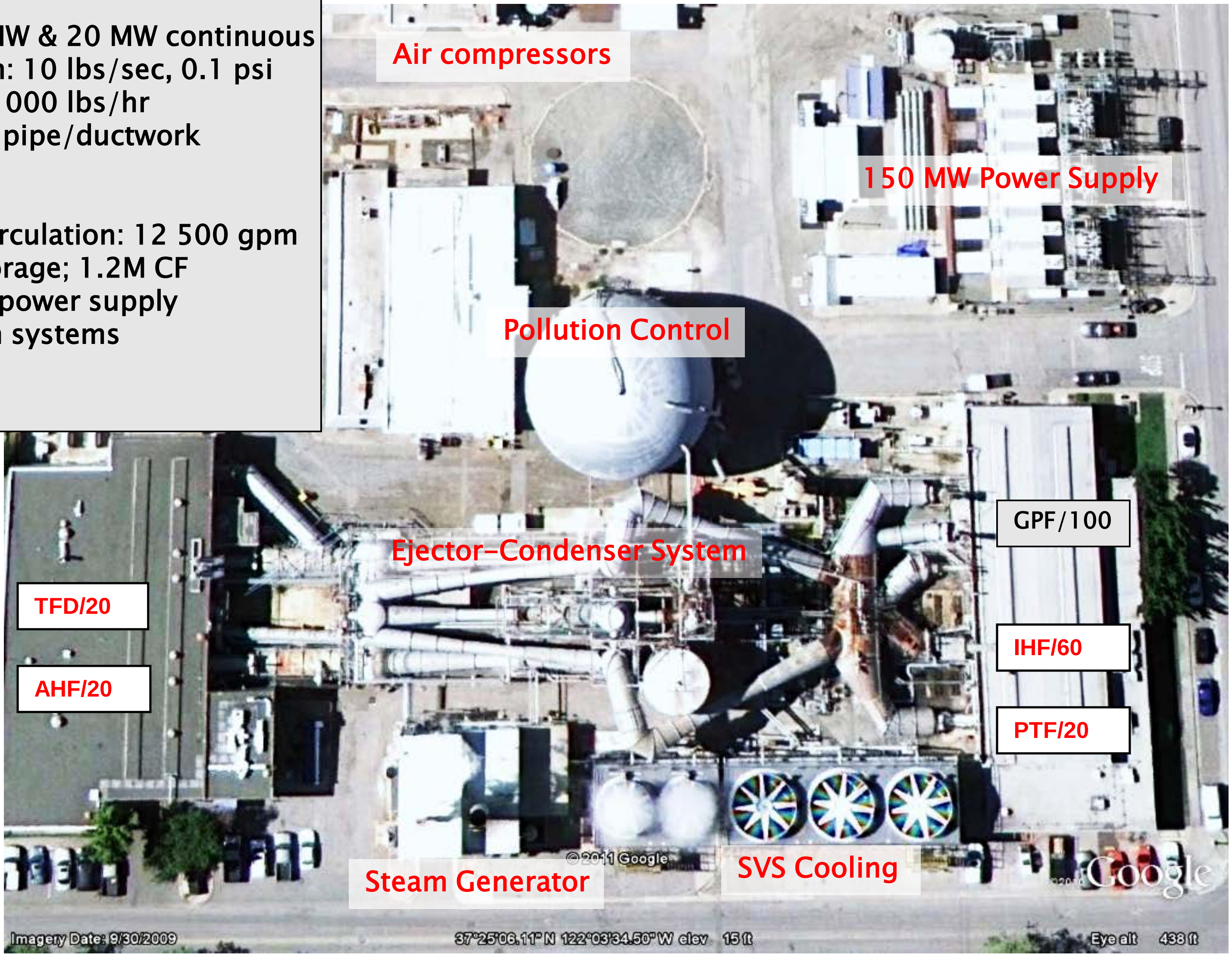
NASA Ames ArcJet Complex Overview

Power supplies: 150 MW & 20 MW continuous
Steam Vacuum System: 10 lbs/sec, 0.1 psi
Steam Generator: 250 000 lbs/hr
Approximately 1.5 mi pipe/ductwork

Not picked:

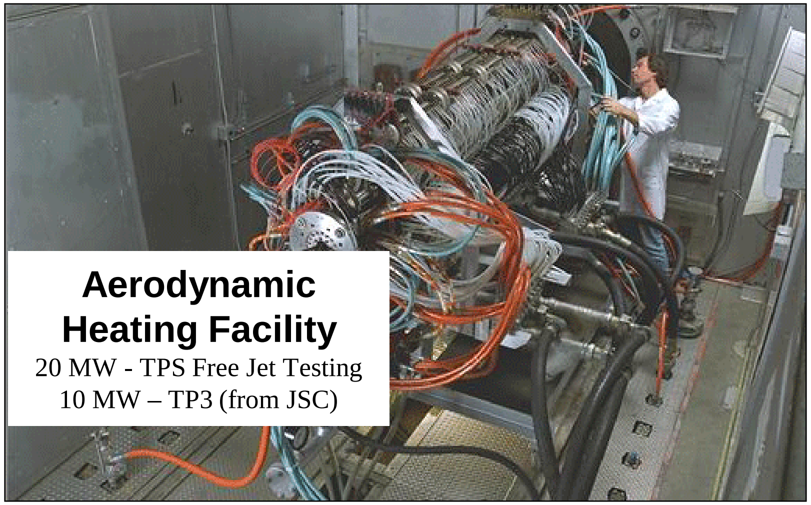
- Arc heater coolant circulation: 12 500 gpm
- High pressure air storage; 1.2M CF
- Independent 20 MW power supply
- Control and isolation systems

1 MW = 750 homes

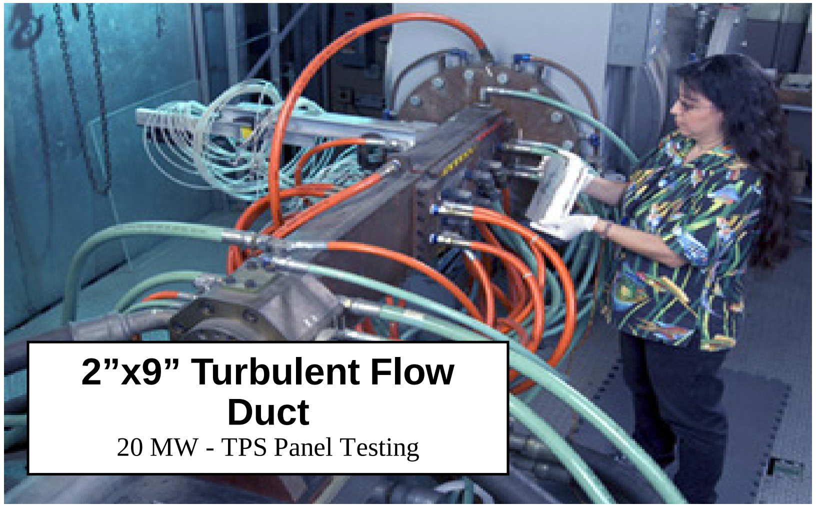


Four Active Test Legs, One set of shared Utilities

NASA AMES ARCJET COMPLEX



Aerodynamic Heating Facility
20 MW - TPS Free Jet Testing
10 MW – TP3 (from JSC)



2”x9” Turbulent Flow Duct
20 MW - TPS Panel Testing

Panel Test Facility
20 MW - TPS Panel Testing

Interaction Heating Facility
60 MW - TPS Free Jet and Panel Testing

Laser Enhanced Arcjet Facility
Adds up to 4 50-kW IR lasers to provide radiant flux to panels

IHF

- 60-MW Ames-designed constrictor arc heater
- Nozzle exit sizes from 76.2 mm (3”) to 1 m (36”)
- 3-arm fully programmable model insertion system, fully water-cooled
- Stagnation, free jet wedge, small sphere cones or flat panel test configurations
- Stagnation pressure from 1 to 600 kPa (0.01 to 6 atm)
- Heat fluxes from 0.5 to > 6000 W/cm^2 (0.4 to >5200 Btu/ft^2-s)
  - As nozzle size and/or model size increases, heat fluxes decrease
  - As model size decreases, 2- and 3-D effects make evaluation difficult
- Enthalpies 7 to 47 MJ/kg (3000 – 20,000 Btu/lb)
- Power supply capable of delivering 75 MW continuously and up to 150 MW for a 15 second duration
- Test times up to one hour demonstrated at lower conditions

LEAF

- Radiative laser heating facility added to the IHF
- 1 to 4 50-kW CW IR lasers can be used
  - Provides up to 390 W/cm^2 (~350 Btu/ft^2-s) radiative heating on 152 mm x152 mm (6” x 6”) wedge model or 100 W/cm^2 (88 Btu/ft^2-s) on a 432 mm x 432 mm model (17” x17”)
- Nearly uniform across illuminated surface (variation < 6%)
- Wavelength 1.07μm

AHF

- Air, Nitrogen and Oxygen gases
- 3 heaters available
  - 20-MW Ames-designed constrictor arc heater
  - 20 MW Huels arc heater
  - 10 MW constrictor arc heater (relocated from JSC)
- Nozzle exit sizes from 127 mm (5”) to 1016 mm (40”)
- Samples sizes up to 356 mm (14”) diameter or 660 by 660 mm (26” by 26”) wedge
- Surface or stagnation pressures from 0.5 to 30 kPa (0.005 to 0.3 atm) dependent on the arc heater and nozzle
- Heat fluxes from less than 0.1 W/cm^2 (0.08 Btu/ft^2-s) on a flat plate, to over 300 W/cm^2 (288 Btu/ft^2-s) on a 102mm (4”) diameter hemisphere
- 5-arm fully programmable model insertion system (limited by test model design)

PTF/TPTF

- PTF
  - 20-MW Ames-designed constrictor arc heater
  - Semi-elliptic Mach 3.5 nozzle
  - Test samples up to 355 mm by 355 mm (14-in by 14-in)
  - -4 to +8 degree inclinations of the surface of test sample to the flow
  - Run durations up to 30 minutes possible
  - Cold wall, full catalytic heat flux from 0.6 to 40 W/cm^2 (0.5 to 30 Btu/ft^2-s)
  - Surface pressures from 66 to 4700 Pa (0.0006 to ~0.05 atm)
- Truncated PTF (TPTF)
  - Shortens the PTF nozzle for higher surface conditions on smaller test articles
  - 20-MW Ames-designed constrictor arc heater
  - Semi-elliptic nozzle
  - Test samples up to 100 mm by 100 mm (4-in by 4-in)
  - -5 to +4 degree inclinations of the surface of test sample to the flow
  - Cold wall, fully catalytic heat flux from 20 to 200 W/cm^2 (18 to 180 Btu/ft^2-s)
  - Surface pressures to ~28 kPa (0.28 atm)

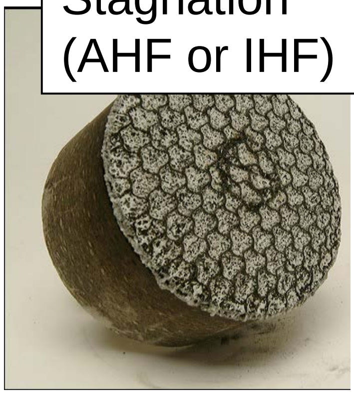
TFD

- Air or nitrogen gases
- Linde (Huels) free-length arc heater (12-MW)
- Test samples of 203 mm wide by 508 mm long (8” by 20”)
- Surface pressure from 2 to 15 kPa (0.02 to 0.15 atm)
- Cold wall heat fluxes from 2 to 70 W/cm^2 (1.8 to 63 Btu/ft^2-s)
- Surface pressures to 28 kPa (0.28 atm)

Examples of Ground Test Articles

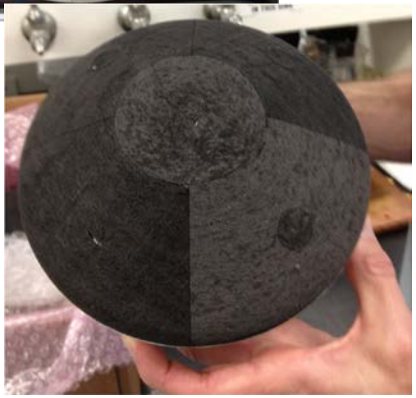
- Arc jet test model samples

Stagnation
(AHF or IHF)

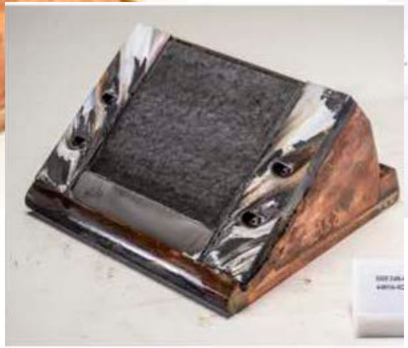


Panel (PTF)

Small probe w/ multiple heating regimes (IHF or AHF)



Wedge
(AHF or IHF)



Summary

- There are many test facilities that are necessary for evaluating the different aspects of the behavior of a thermal protection system during a mission
- But, to best understand materials in hypersonic flowfields, the arc jet test facilities provide the closest match to the environmental conditions (chemistry and physics) that TPS materials will face
- The capabilities vary from tunnel to tunnel, however, by combining their use, we can understand the material response over the extent of the mission parameters.

WITHOUT US, YOUR HEATSHIELD IS TOAST

National Aeronautics and Space Administration

Ames Research Center – Silicon Valley
Entry Systems and Technology Division