



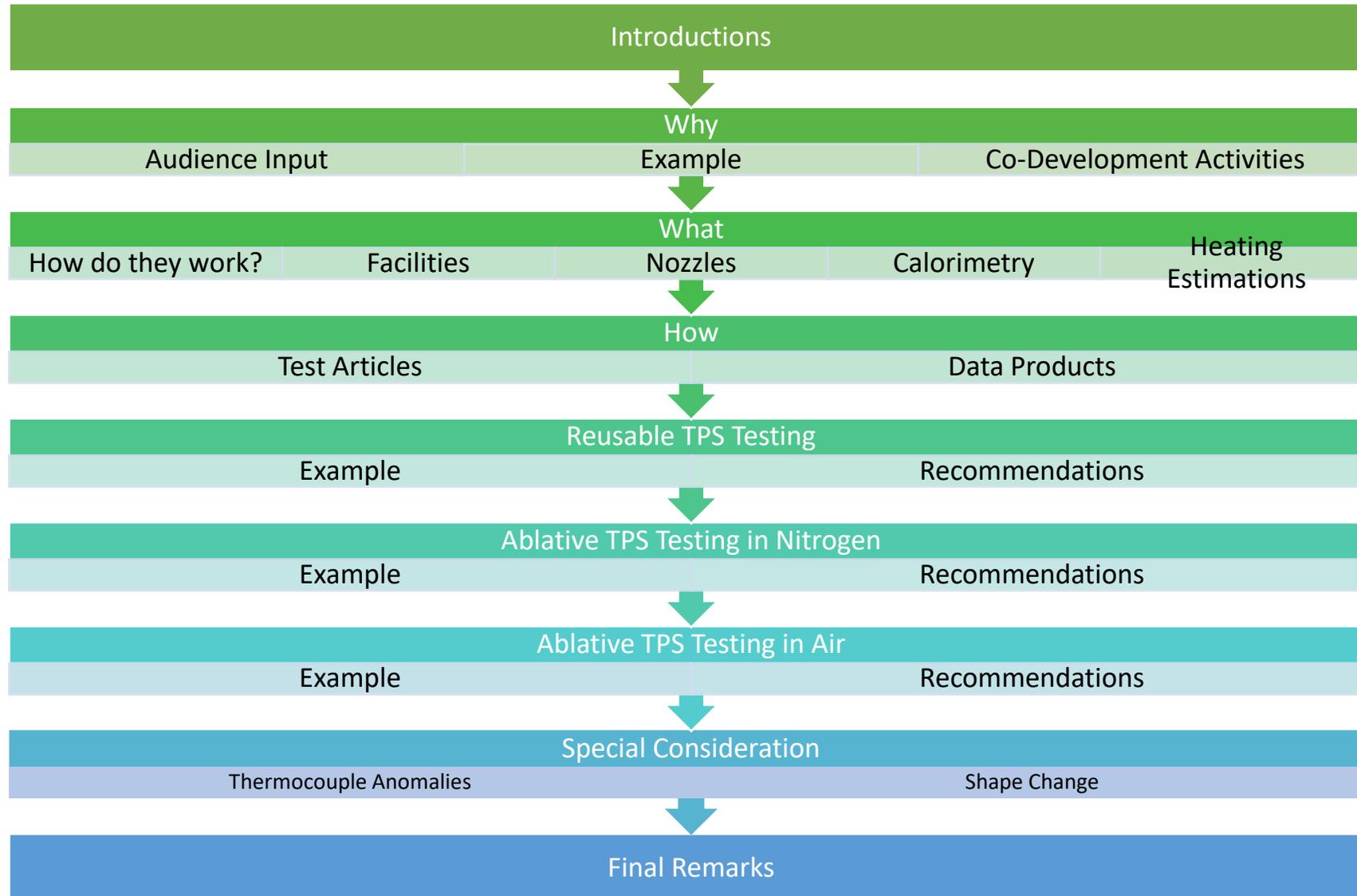
Thermal Protection System Testing and Evaluation at NASA Ames Arc-Jet Complex

a Short Course

Jonathan Morgan, NASA ARC-TSM

Kristina Skokova, Analytical Mechanics Associates

Outline



Introductions



Bio: Jonathan Morgan (jonathan.morgan@nasa.gov) has been working at NASA Ames Research Center since 2018 supporting arc-jet testing for Orion, Mars2020, Dragonfly, Mars Sample Return, and many other programs. Jonathan Morgan works in the Thermal Protection Materials Branch, part of the Entry Systems Division (ARC-TSM) as the arc-jet Liaison. That role is to aid in the development, execution, and analysis of arc-jet testing performed.

I am not the only one! With fellow PI Kristina Skokova, the Thermophysics Facilities Branch (ARC-TSF) who operate the arc-jet complex also here to help.

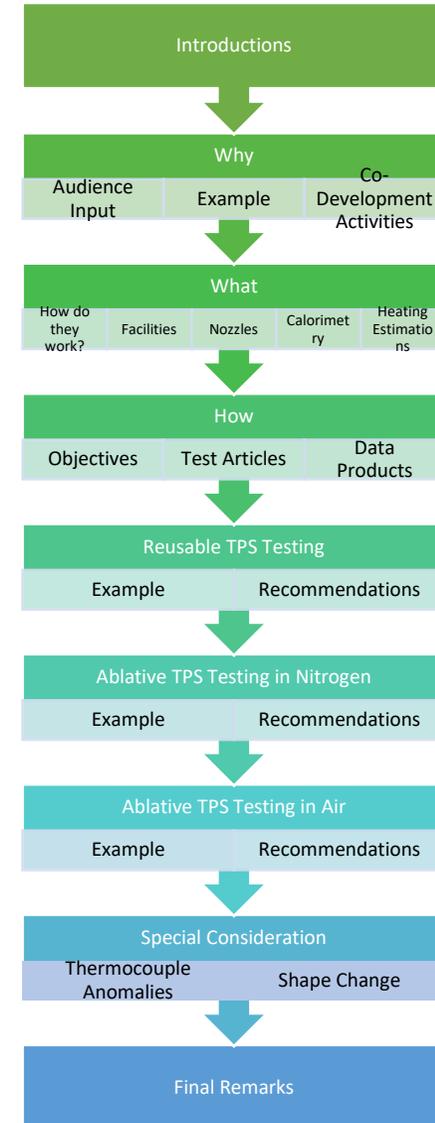
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Frank Hui, NASA, Test Engineer: frank.hui@nasa.gov

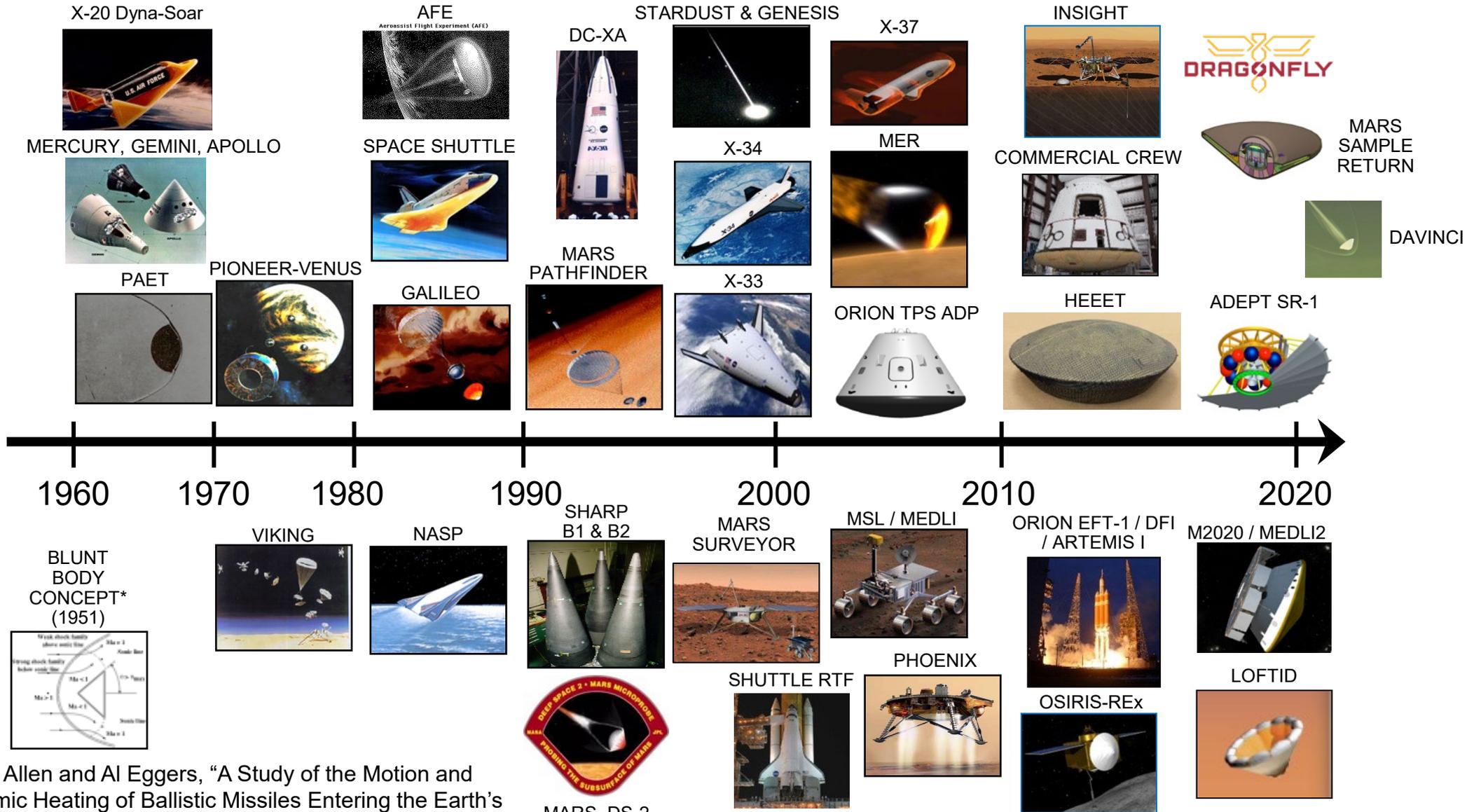
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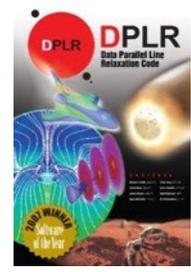
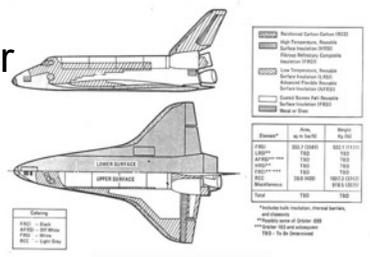
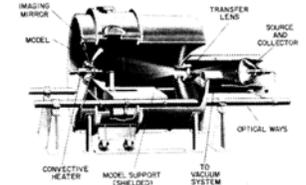
NASA Entry Projects Supported by Ames



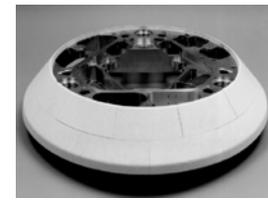
* H. Julian Allen and Al Eggers, "A Study of the Motion and Aerodynamic Heating of Ballistic Missiles Entering the Earth's Atmosphere at High Supersonic Speeds," NACA-RM-A53D28, 1953 / NACA-TR-1381, 1958.

NASA Ames Entry Systems Inventions

Advanced Entry Heating Simulator



SIRCA



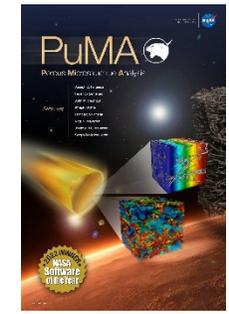
TUFROC



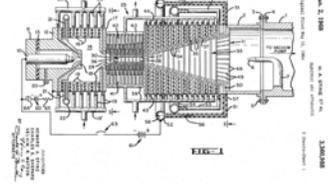
ADEPT



3DMAT



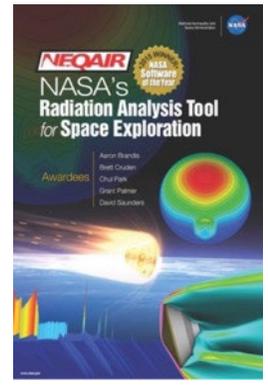
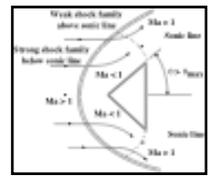
Constricted Arc Heater



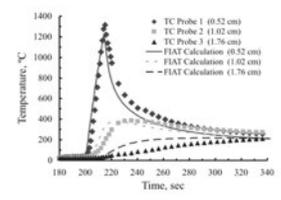
- RCG
- LI-2200
- FRCI
- AFRSI
- AETB
- TUFI



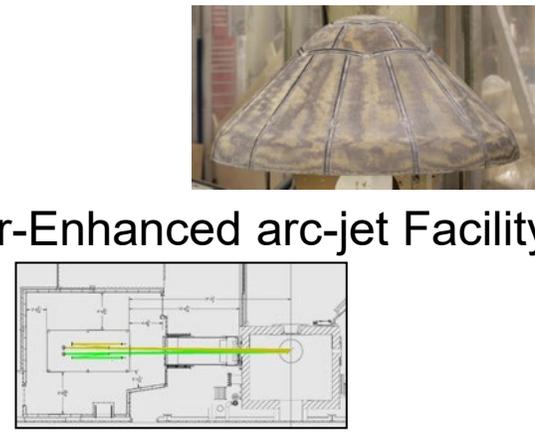
Blunt Body Concept* (1951)



FIAT



Laser-Enhanced arc-jet Facility



1960

1970

1980

1990

PICA

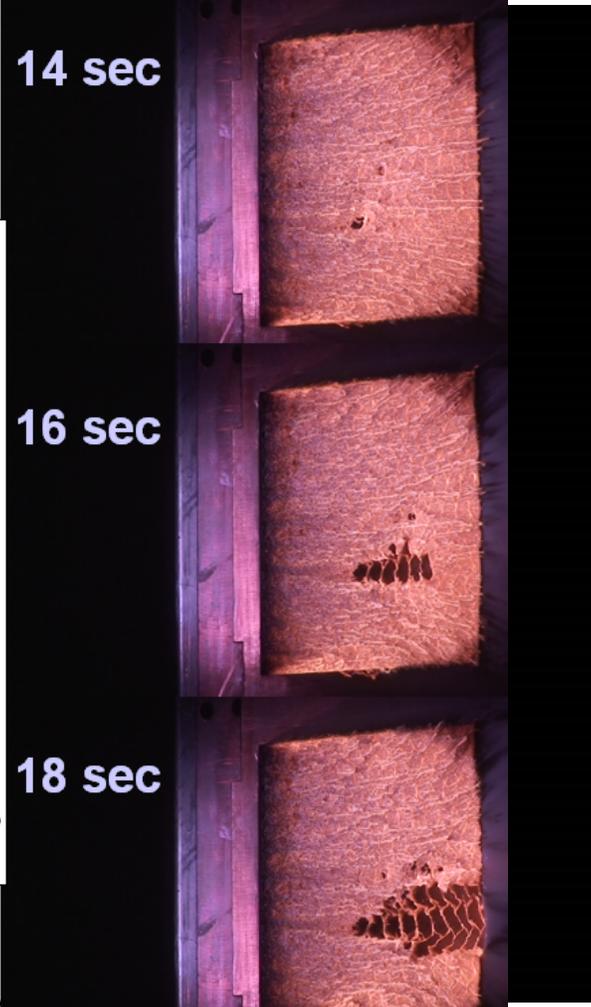
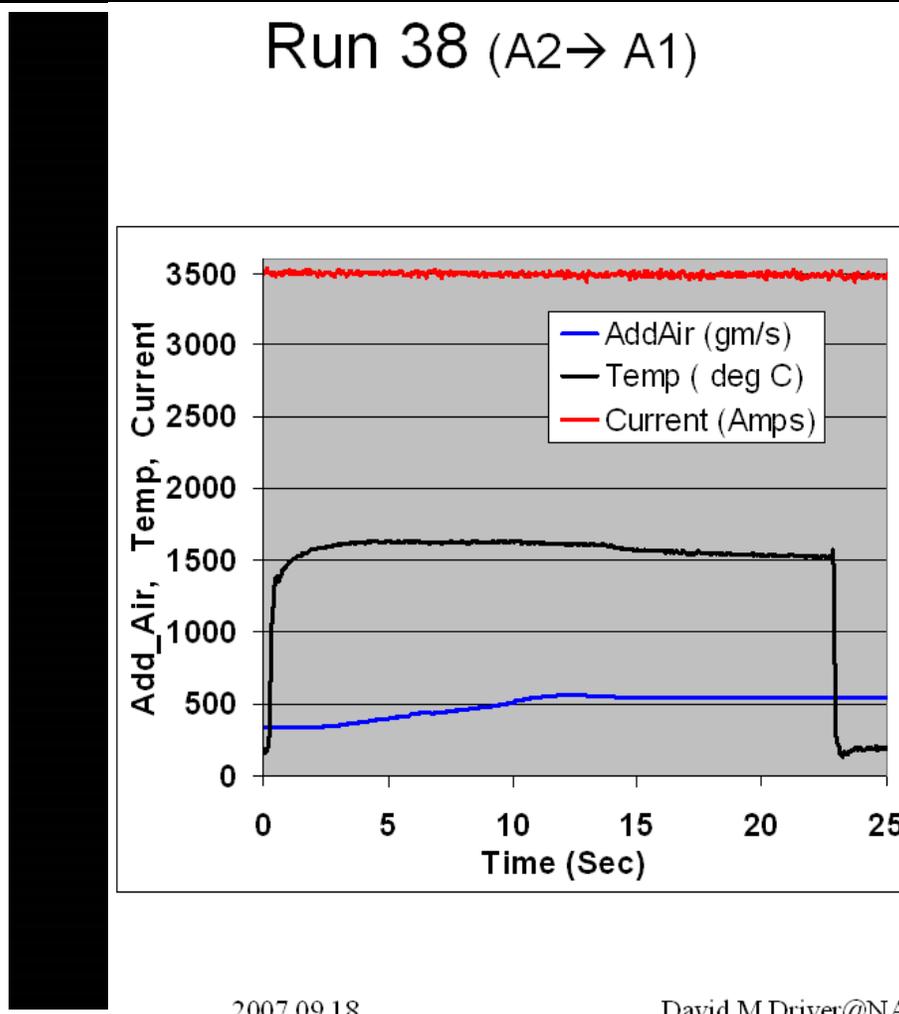
2000

2010

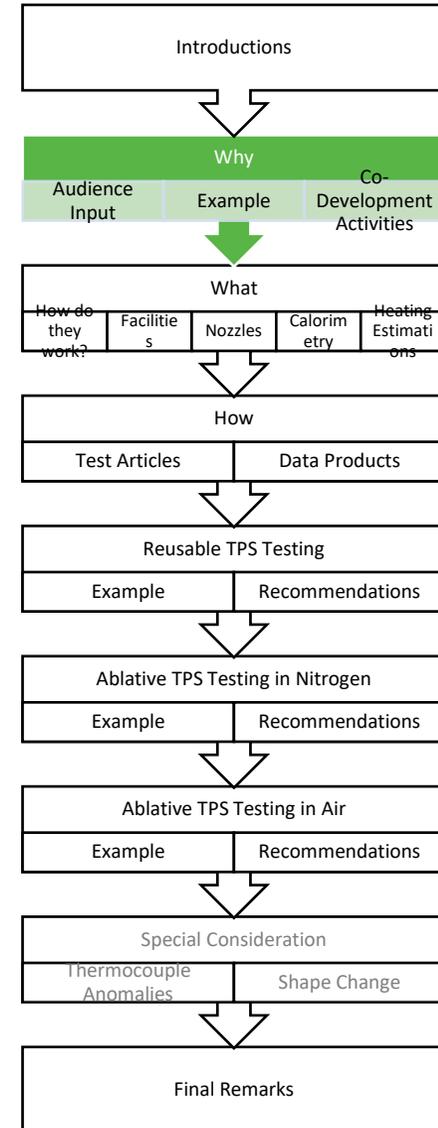
HEEET

2020

One of the Reasons we Test¹



2007 09 18 David M Driver@NA

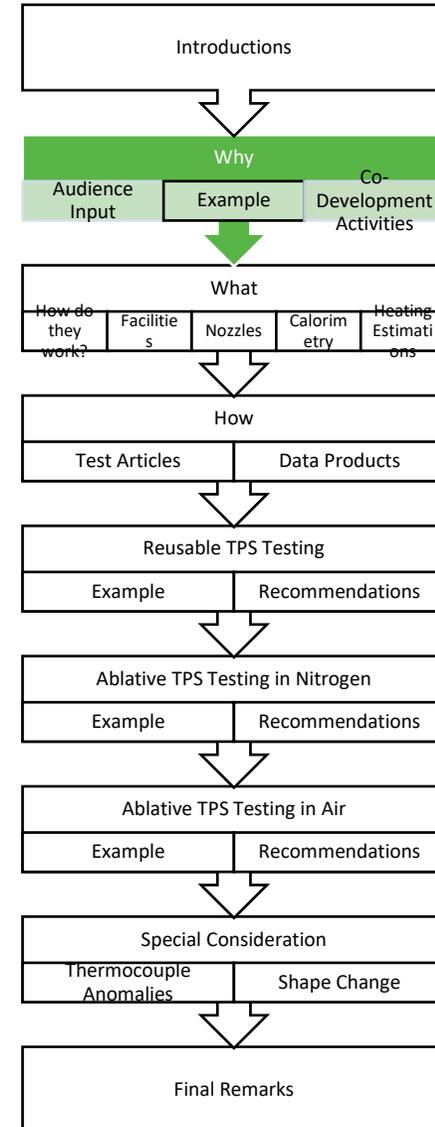


[Arc Jet Testing in a Shear Environment for Mars Science Laboratory Thermal Protection System¹](#) uncovered sensitivity in the baselined forebody TPS (SLA-561V), not accounted for by the high-fidelity response model, that led to runaway material failure. This led to the projects decision to change the forebody to PICA.

What Brings You Here?



- Arc-jet testing is a critically important piece of designing and analyzing entry systems for atmospheric entry, that can provide insight to the following areas with some caveats:
- Chemistry of super/hypersonic flow, Boundary-layer gas composition, fluid-surface interaction².
 - Caveat: high-enthalpy supersonic flow generated by arc-jets is *not* a 1:1 match to the real thing – we typically target hot-wall heat flux, temperature, and pressure but often cannot match quantities like flight enthalpy or boundary layer thickness.
 - Development and qualification of thermal protection materials, systems, and instrumentation³.
 - Caveat: test artifacts are un-avoidable and no test(s) can encompass all environments.
 - Material Response Model Development and Validation:
 - Caveat: There is no substitute for flight, and response models are only as good as the data to which they are anchored.



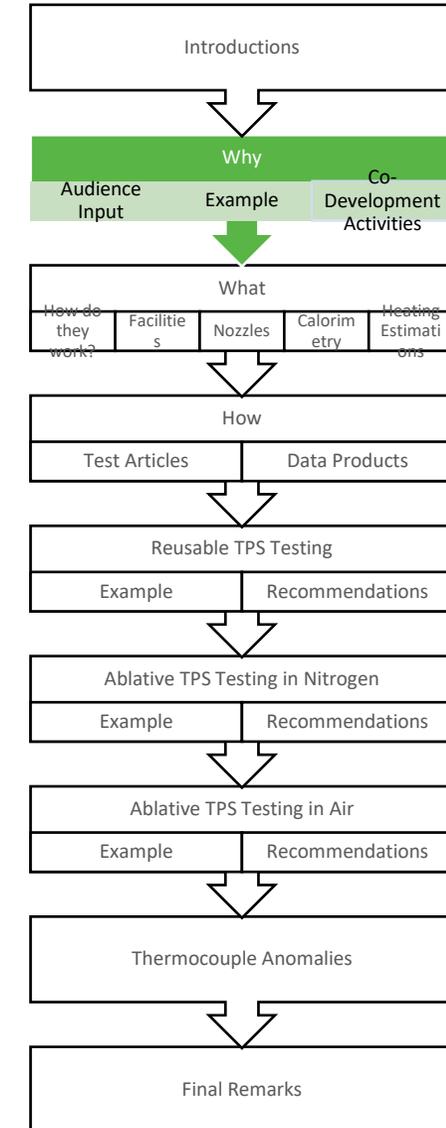
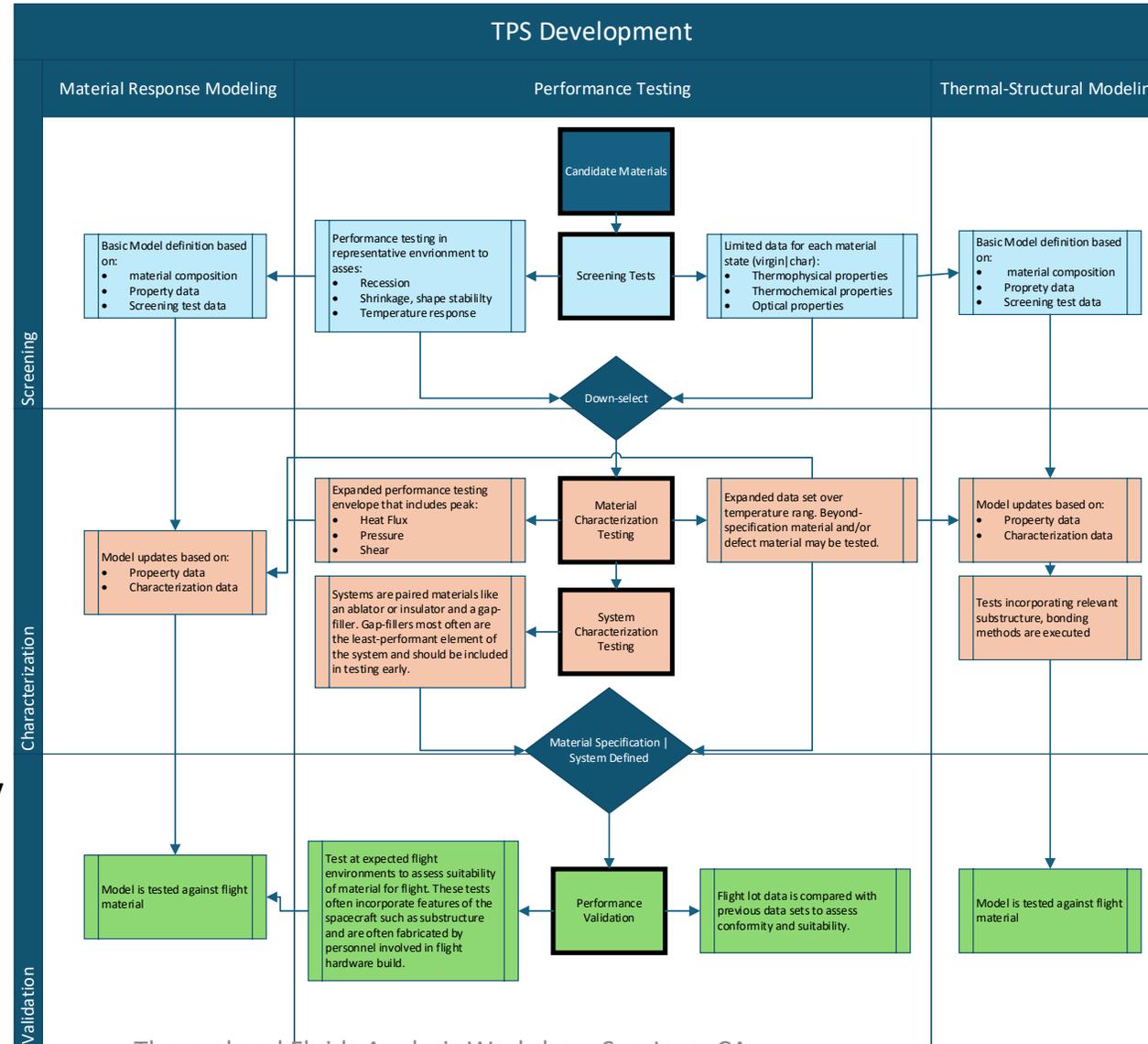
²[Ground-to-Flight Traceability Analysis of arc-jet Experimentation of the Crew Exploration Vehicle](#)

³[Development and Sizing of the Mars2020 Thermal Protection System](#)

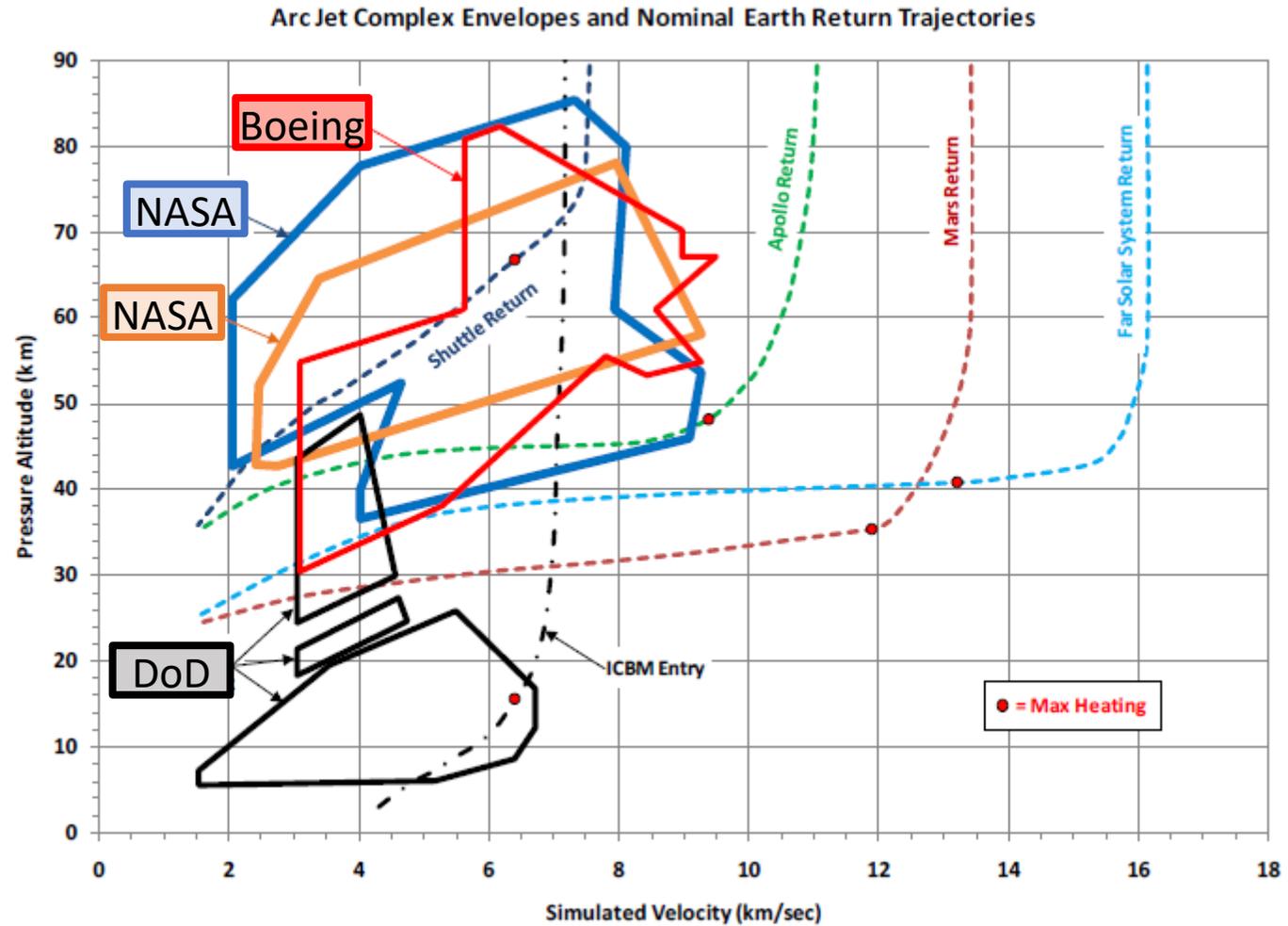


Arc-jet Testing is Seldom Done in Isolation

- Arc-jet testing may occur alongside material response modeling, thermal-structural modeling, and iterations in manufacturing – maximize the data you obtain in each test!
- Rarely is the development straightforward, as manufacturing and programmatic changes drive changes to the testing campaign – flexibility is key!
- From formulation to flight, defining an arc-jet campaign may aid in early discovery and recovery from pitfalls! Save money later by (planning to) spending the money early!



Where do we Fit?

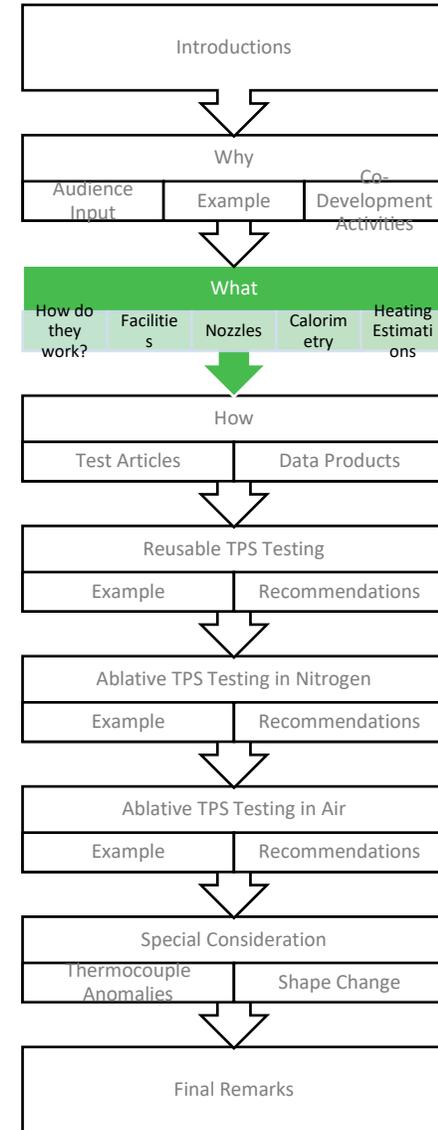
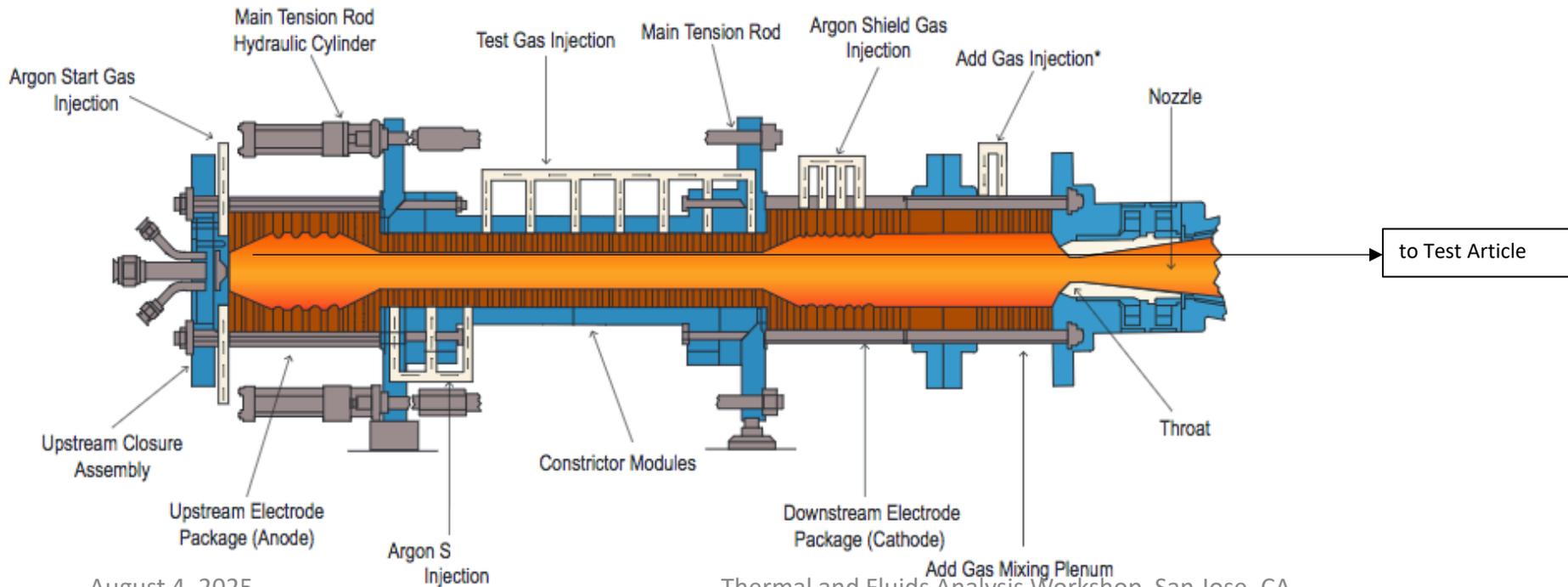


[4Evaluation of the NASA Arc Jet Capabilities to Support Mission Requirements](#)

Arc-jet Design and Operations



- An arc-jet is a device in which heated gas is accelerated down a column and expanded through a nozzle, providing high-temperature, supersonic flow.
- The high-enthalpy gas is partially dissociated as it is heated by the arc but it is considered chemically frozen upon expansion through the nozzle before encountering the test article.
- Quantities such as enthalpy and pressure are primarily functions of the power and test gas supplied to the arc-jet while the incident heat flux and surface temperatures are functions of the test article design and material.

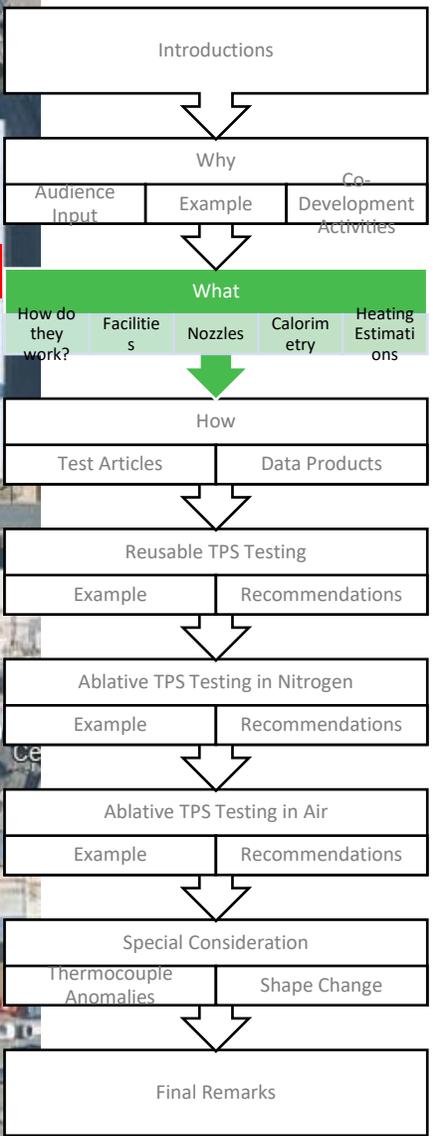
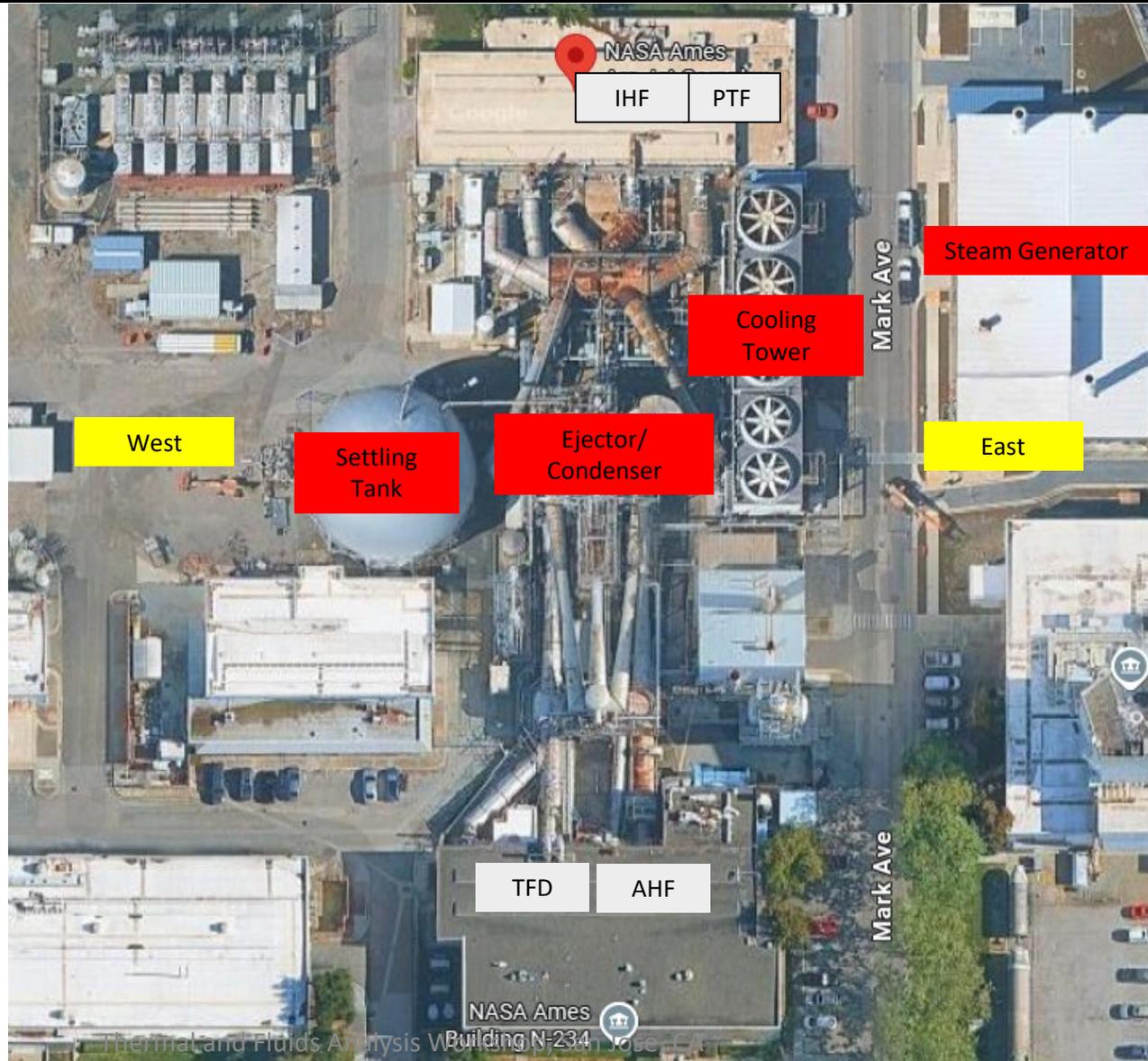




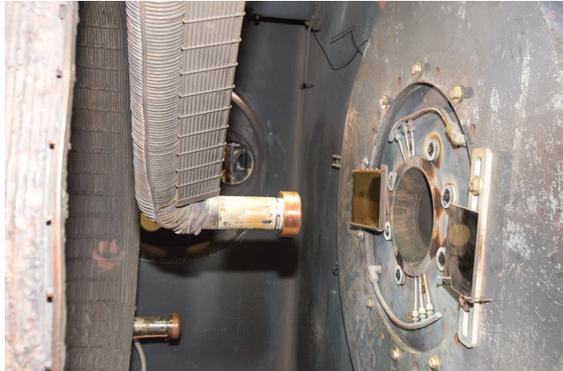
How Does it Work?

1. A steam plant produces vacuum through ejectors and condensers that serve the entire complex, bringing the test chamber down to torr-level vacuum.
2. A high potential is generated with a remote power supply to bring the facility electrodes to a potential on the order of kV. (not shown)
3. Argon is introduced to the arc-heater column. The high-potential electrodes are connected by the electrons in the gas, and we have an arc!
4. The test gas is slowly introduced while simultaneously increasing current until the target test condition is reached.

Note: The facilities personnel will orient sides of the test chamber based on cardinal orientation – they’re the only ones that can keep this straight in their heads when inside the facility ☺.



Arc-jet Facilities at NASA Ames⁵

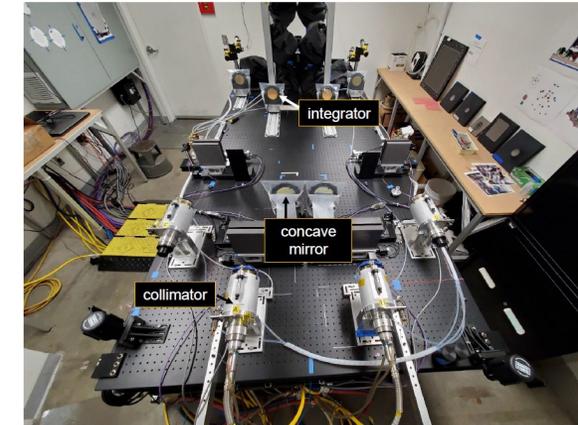


Typical test setup in IHF (and soon AHF)

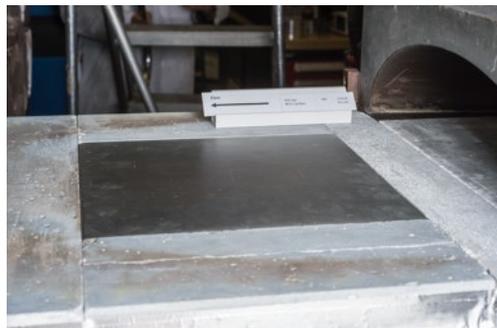
Nozzle Configuration	Aerodynamic Heating Facility		2x9 Turbulent Flow Duct	Panel Test Facility		Interaction Heating Facility		
	Conical		Multi-Dimensional	Semielliptic		Semielliptic		Conical
Test Gas	Air + Argon, Nitrogen + Argon, Argon	N ₂ + O ₂ (CO ₂ in development)	Air, Nitrogen, Argon	Air + Argon	Air + Argon	Air + Argon	Air + Argon	Air + Argon
Input Power, MW	20	10	12	20	20	60	60	60
Type of test Article	Stagnation, Wedge	Stagnation, Wedge	Flat Plate	Flat Plate	Flat Plate	Flat Plate	Flat Plate	Stagnation, Wedge
Nozzle Exit Dimension, in	7, 12, 18, 24, 30, 36 (diameter)	5, 7.5, 10, 15, 20, 25, 30, 35, 40 (diameter)	2 x 9	17 x 4.25 (2a x b)	6.7 x 1.68 (2a x b)	32 x 8 (2a x b)	22 x 5.5 (2a x b)	3, 6, 9, 13, 21, 30 (diameter)
	18, 30, 46, 61, 76, 91 (diameter)	13, 19, 25, 38, 51, 63, 76, 89, 102 (diameter)	5 x 23	43 x 10.8 (2a x b)	17 x 4.3 (2a x b)	81 x 20 (2a x b)	56 x 14 (2a x b)	8, 15, 23, 33, 53, 76 (diameter)
Throat Dimension, in	1.0, 1.5, and 2.0 (diameter)	2.25 (diameter)	1.128 x 1.6	1.141 x 0.707 (2a x b)	1.414 x 0.707 (2a x b)	4.75 x 1.1875 (2a x b)	4.75 x 1.1875 (2a x b)	2.375 (diameter)
	2.5, 3.8, and 5.1 (diameter)	5.72 (diameter)	2.865 x 4.064	0.56 x 0.28 (2a x b)	0.56 x 0.28 (2a x b)	12.07 x 3.02 (2a x b)	12.07 x 3.02 (2a x b)	6.033 (diameter)
Mach Number	4 - 9	4 - 12	3.5	4.4	2.2	5.5	3.6	4 - 9
Sample Size, in	Area blockage ratio < 0.3	Area blockage ratio < 0.3	8 x 10 8 x 20	14 x 14	4 x 4	24 x 24	18 x 18	Area blockage ratio < 0.3
	Area blockage ratio < 0.3	Area blockage ratio < 0.3	20 x 25 20 x 51	35 x 35	10 x 10	61 x 61	46 x 46	Area blockage ratio < 0.3
Bulk Enthalpy, Btu/lb _m MJ/kg	2,000 - 12,000	2,000 - 12,000	1,500 - 4,000	3,500 - 9,000	3,500 - 9,000	2,000 - 12,000	2,000 - 12,000	2,000 - 12,000
	5 - 28	5 - 28	3.5 - 9.3	8 - 21	8 - 21	5 - 28	5 - 28	5 - 28
Surface Pressure, kPa	0.5 - 50	0.5 - 75	2 - 15	0.05 - 5	2 - 25	0.01 - 2	0.1 - 5.5	1 - 600
	Convective Heating Rate*, Btu/ft ² sec W/cm ²	8 - 750	8 - 750	2 - 60	0.5 - 40	22 - 200	0.5 - 45	0.88 - 81
Radiative Heating Rate, Btu/ft ² sec W/cm ²	9 - 850	9 - 850	2 - 70	0.6 - 45	25 - 230	0.6 - 51	1.0 - 92	56 - 7500
	0	0	0	0	0	0 - 5	0 - 88	0 - 290**
	0	0	0	0	0	0 - 6	0 - 100	0 - 330**

Some notes:

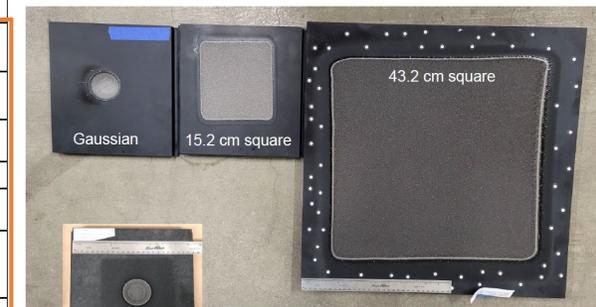
- Run times can be up to 30 minutes, with a 45-minute cool-down period.
- Area blockage ratio = $\frac{A_{article}}{A_{nozzle}} = \frac{d_{model}^2}{d_{nozzle}^2}$.



Test location is behind viewer



Typical test setup in PTF



15.2 cm square + Gaussian

NASA arc-jets have lasers!

⁵NASA Ames arc-jet Test Planning Guide Rev. J

Common Facilities and their Nozzles

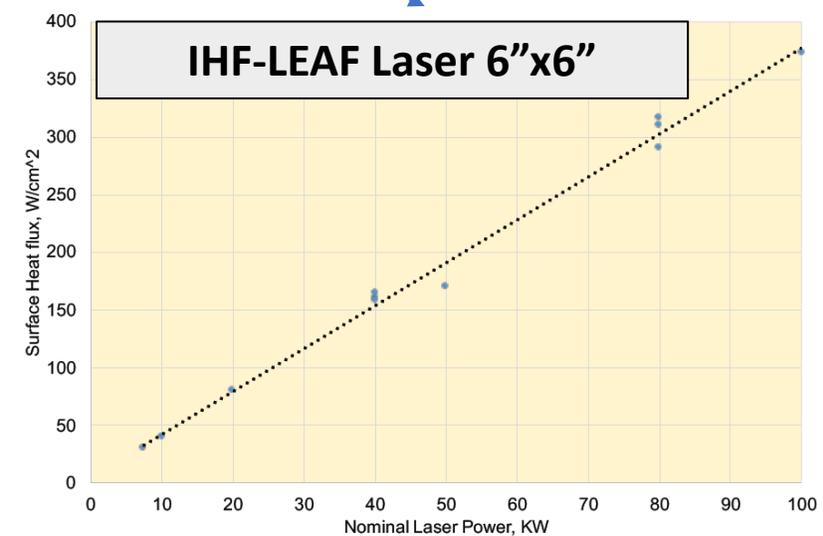
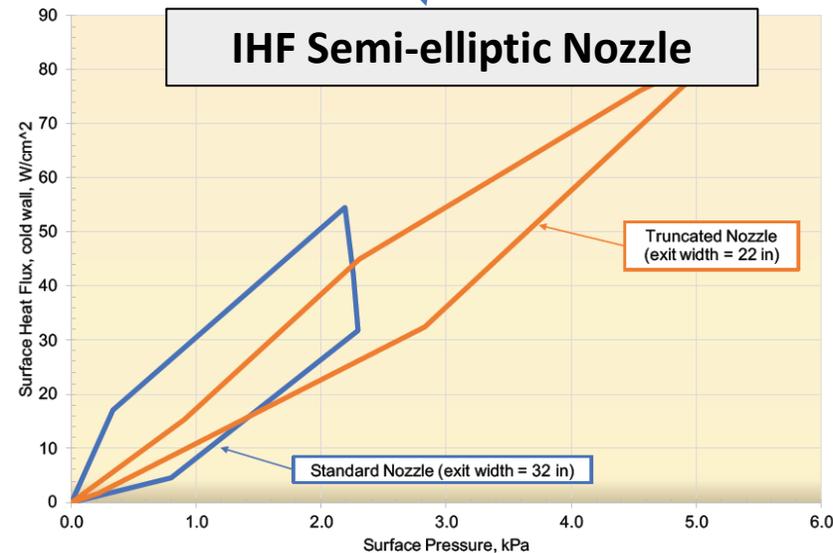
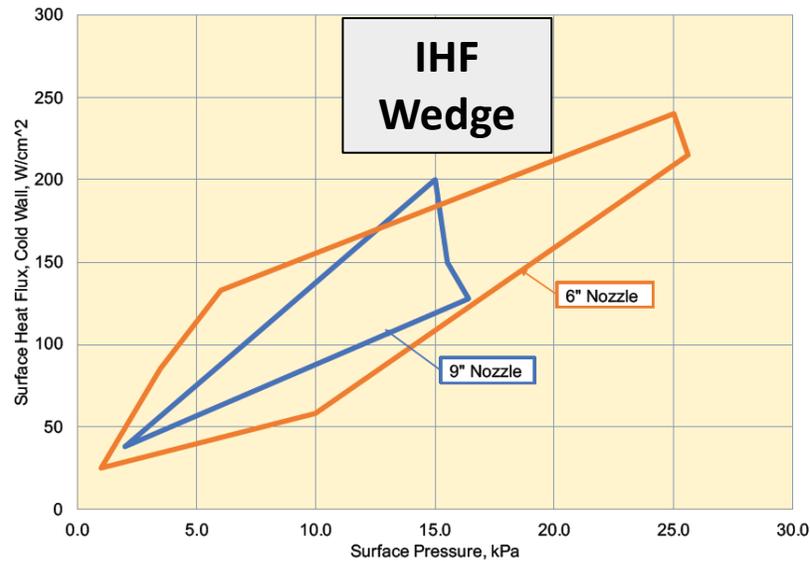
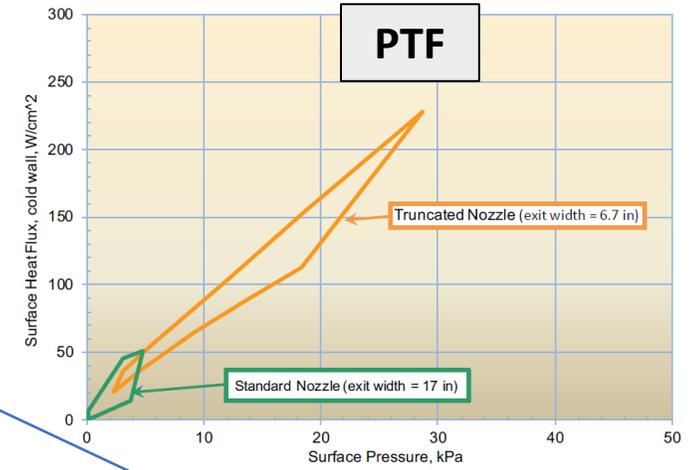
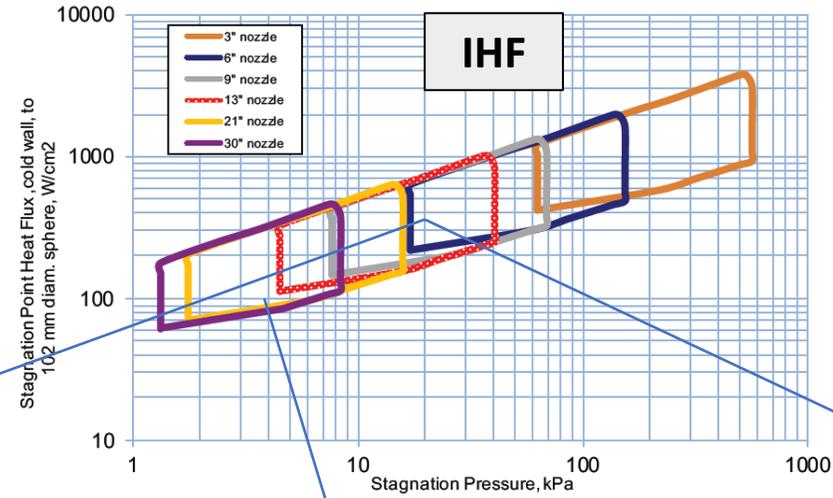
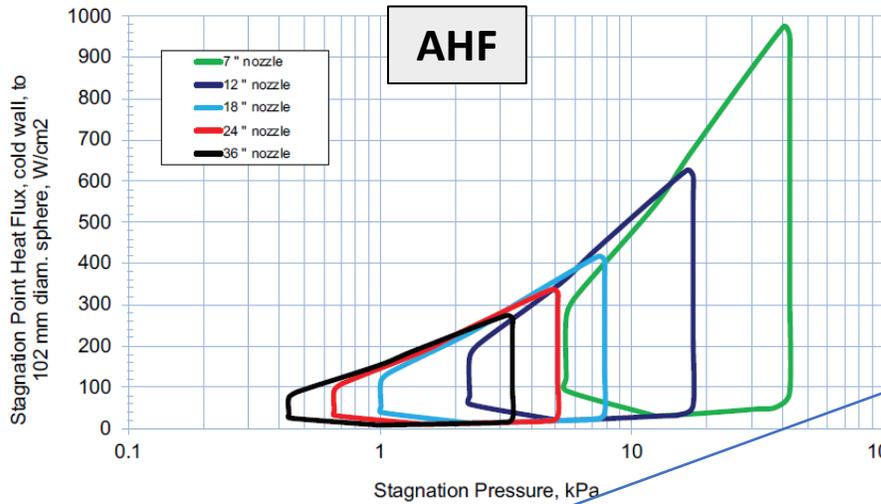


Figure 4.1.3.9. Laser Power vs. Radiant Calorimeter Readings on 6"x6" Target



Calibrations for Heat Flux⁶

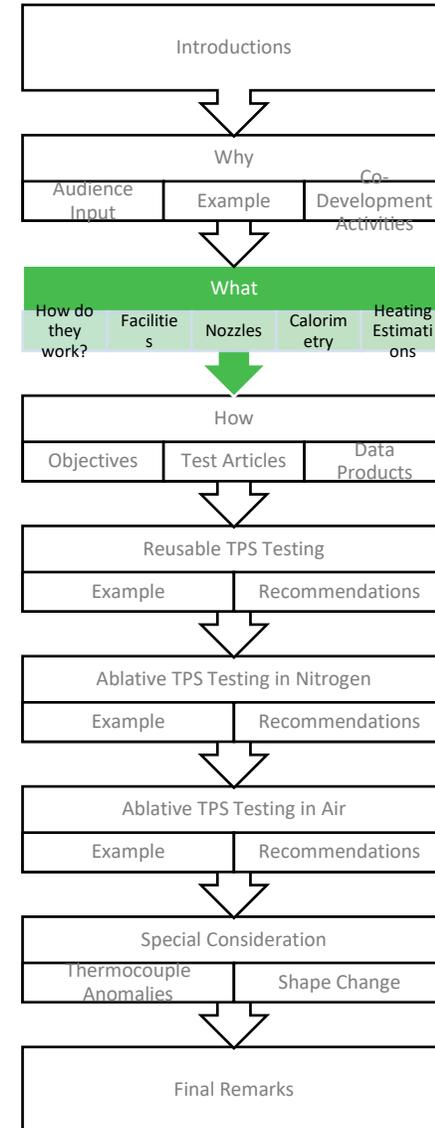
- Multiple calorimeters of different type and shapes are available for heat flux and pressure measurements for stagnation and wedge/panel tests.
 - Slug, Coaxial TC, Null Point, Thin Skin, Gardon gage...
- Ongoing discussion on validity of certain heat flux gage measurement as we don't always have CFD predictions or engineering estimates.
- If a test article with a unique shape is tested, sometimes a special calorimeter is built to the shape of the test article and special heat gages placement.
 - It is also common to obtain measurements from simple standard stagnation calorimeters and rely on CFD to deduce environments for more complex shapes.



Example of standard slug calorimeters



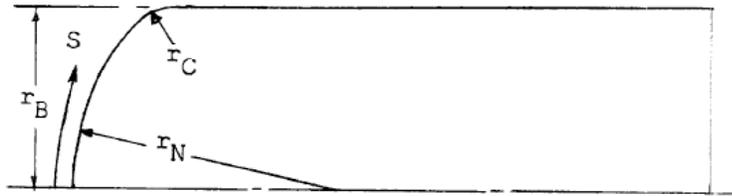
Calibration plate for wedge tests



[Challenges with Heat Flux Calorimeters in arc-jets](#)

Not All Test Articles Heat Equally

The facilities issue capability estimates through a reference hemispherical geometry, where $r_B = r_N$. You may use Zoby-Sullivan⁶ relationship to estimate the heating your own geometry.



Ames facilities use 102 mm diameter hemisphere geometry for cold-wall heating estimates.

Question: What would the multiplier for heating on a 54 mm diameter iso-q?

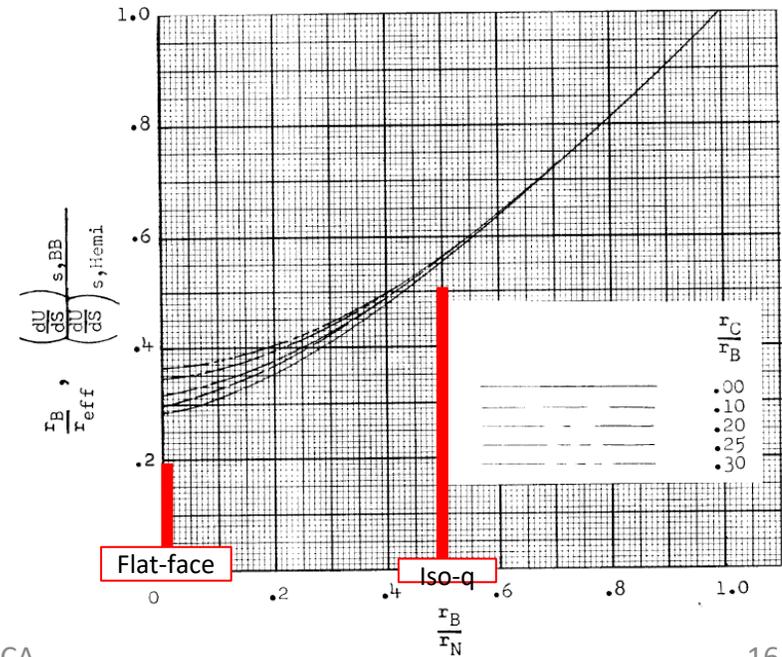
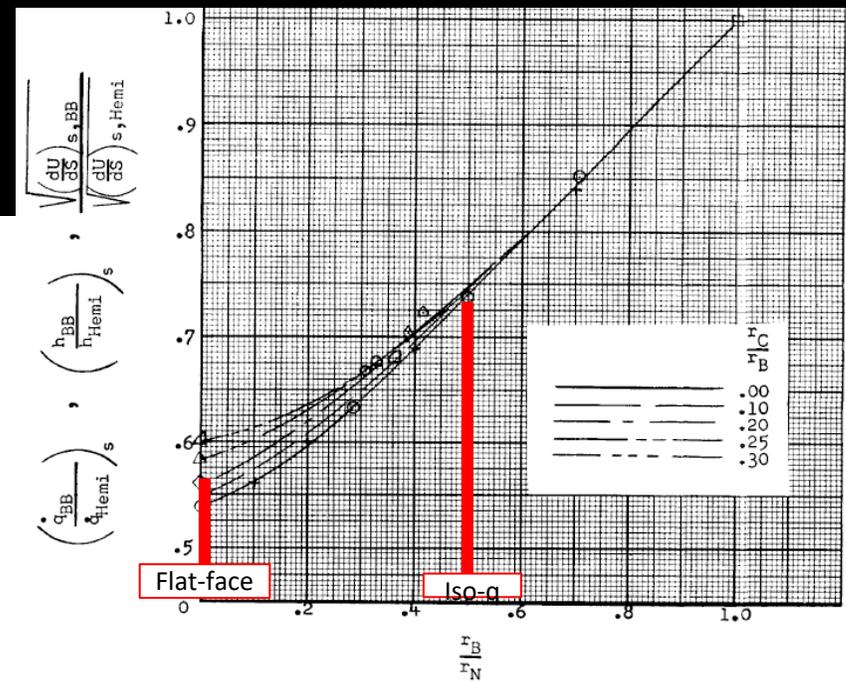
$$\left(\frac{r_B}{r_{eff}} \right)_{isoq} \approx 0.55 \rightarrow r_{eff,isoq} \approx 49 \text{ mm}$$

$$r_{b,Hemi} = r_{n,Hemi} = 54 \text{ mm}$$

$$r_{n,iso-q} = 54 \text{ mm}$$

$$r_{b,iso-q} = 27 \text{ mm}$$

$$\frac{q_{isoq}}{q_{hemi}} = \sqrt{\frac{r_{eff,hemi}}{r_{eff,isoq}}} \approx 1.44$$



[Effects of Corner Radius on Stagnation-Point Velocity Gradients for Axisymmetric Bodies](#)

Common Project/Mission Test Objectives



- Reusable TPS (Shuttle Tile and like):
 - Maximum temperature of a TPS material or number of multiple use cycles at representative flight aeroheating environments.
- Ablative TPS (Avcoat, PICA, 3MDCP, etc.):
 - Material robustness at flight conditions .
 - Thermal response model development and validation.
- System tests for reusable and ablative TPS:
 - Gaps/seams performance.
 - Instrumentation performance.
 - Simulated TPS damage.
 - Flight-like heatshield features test for performance and analysis verification.
 - Windows, protrusions, connectors, cavities, antennas, etc.
 - Full size flight like test articles.

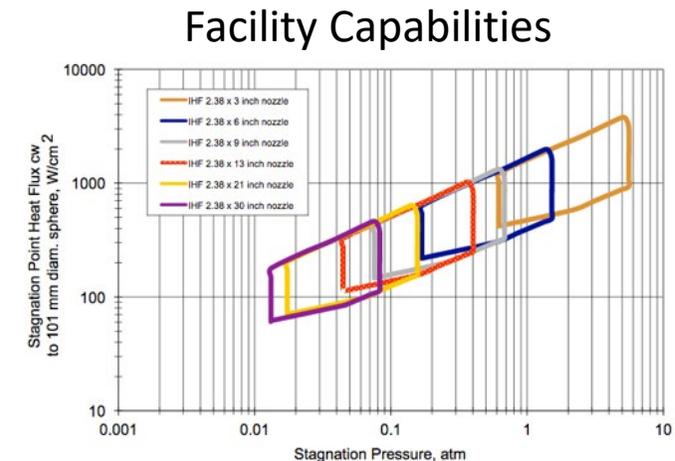
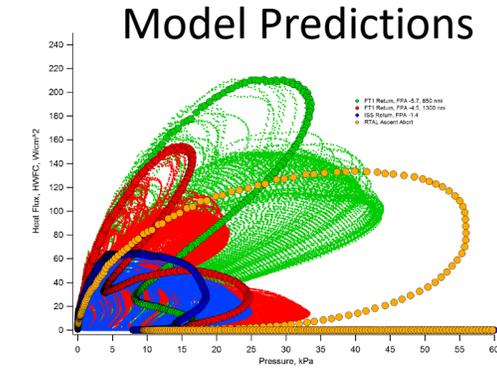
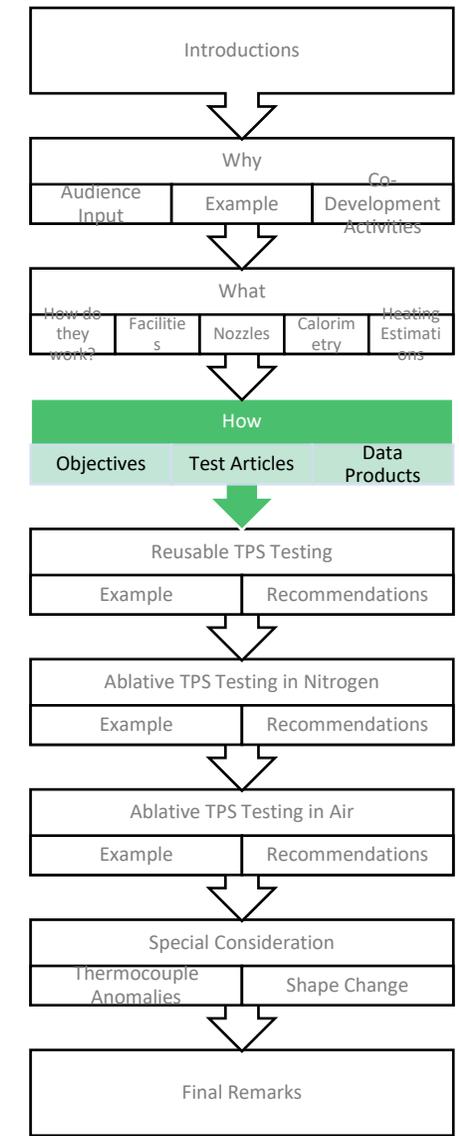


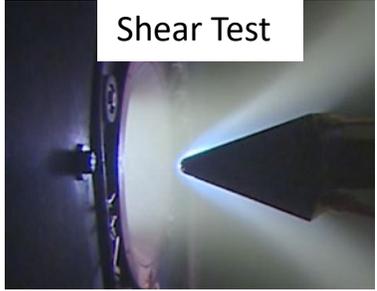
Figure 17. Operating envelope of the IHF with conical nozzles

Test Matrix

Test	q (W/cm ²)	P (kPa)
1	100	10
2	300	20
3	500	40
4	900	60

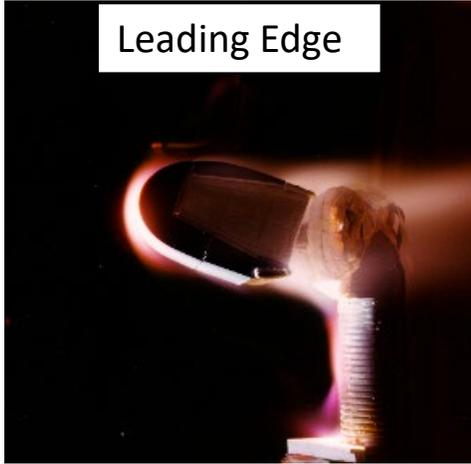


Common Test Configurations

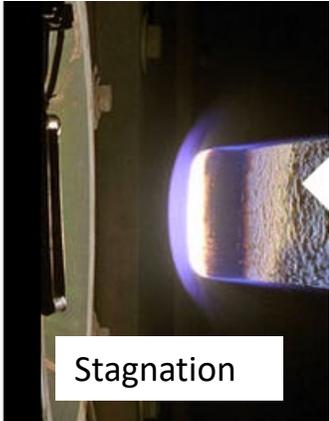


Shear Test

Typically, in Wedge Holder
~ up to 6x6" test coupons



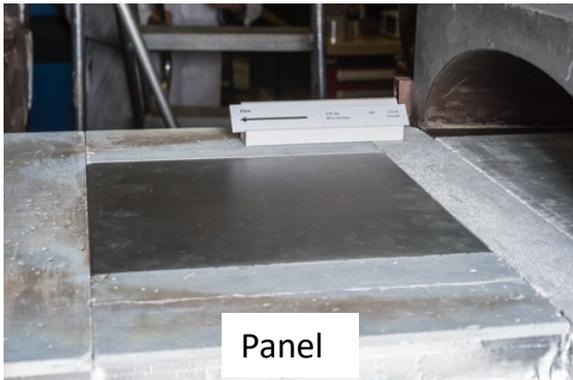
Leading Edge



Stagnation

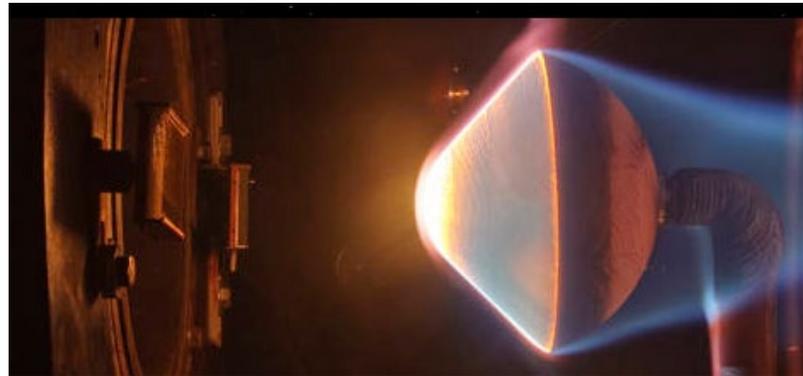
1-inch – 6-inch diameter coupons of varying effective radius are the most tested.

August 4, 2025



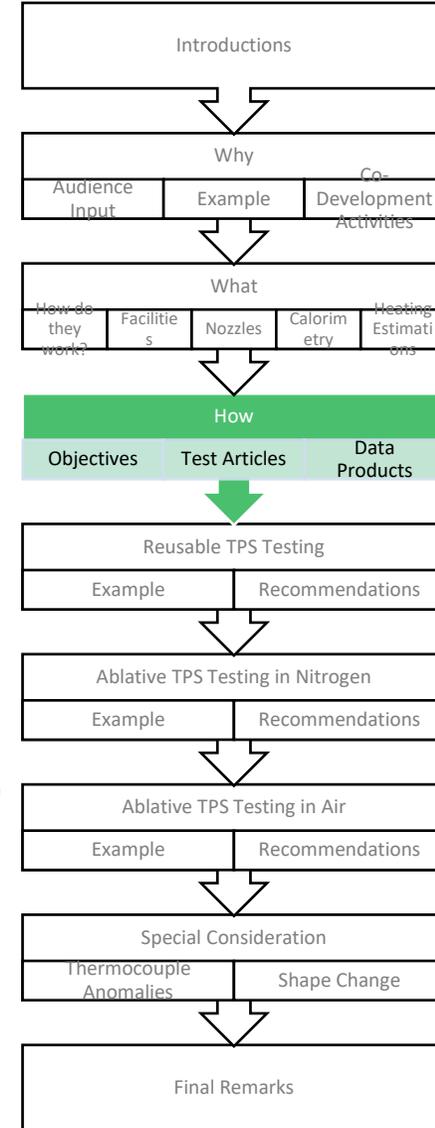
Panel

Panels up to 19"x19"



Full-size flight-like test articles (14" diameter is shown)

Thermal and Fluids Analysis Workshop, San Jose, CA



Special Features

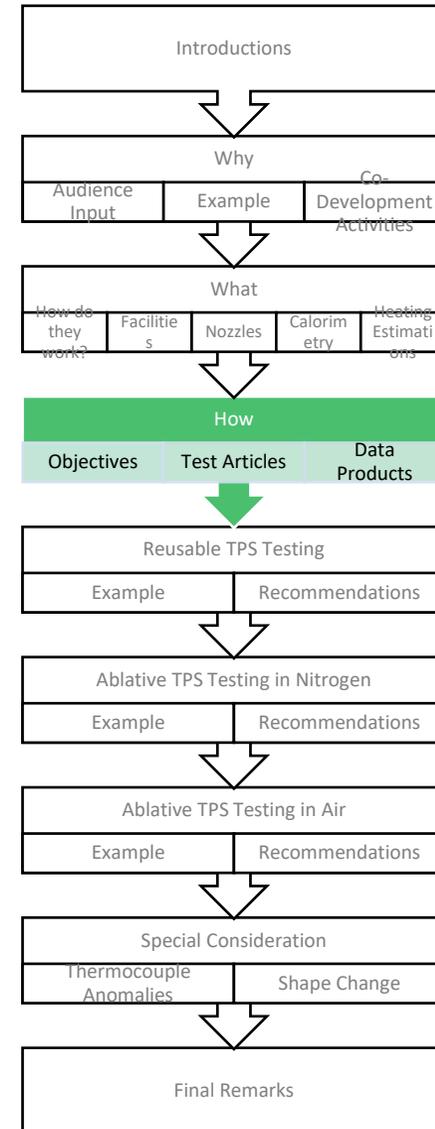


Photo of the Back Shell of Orion capsule flown during Artemis I mission

arc-jets are commonly used to qualify performance of features on the heat shield – not just to test the TPS material itself.

For example, various features present on the back shell of Orion capsule were tested at Ames arc-jet facilities, such as:

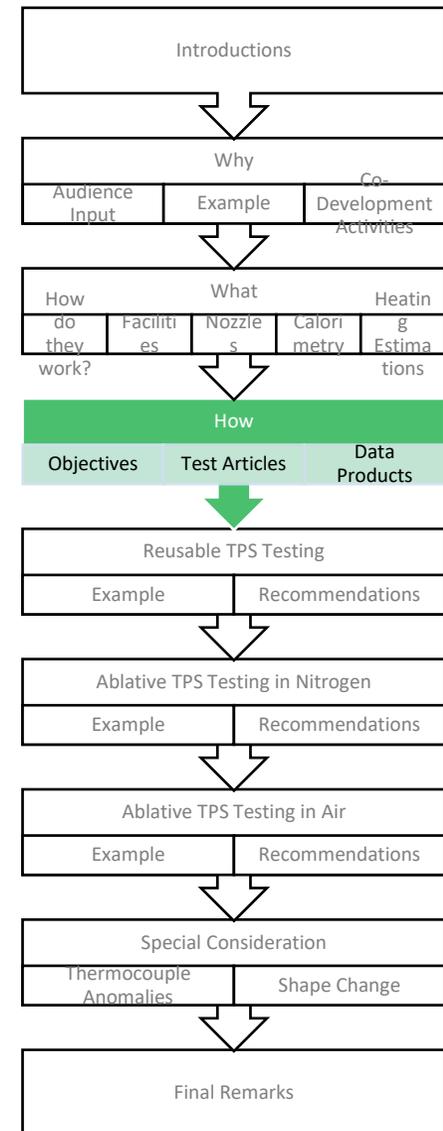
- Antennas
- Windows
- Quick-connects
- ... and more





Data Products to Obtain from an Arc-Jet Test

Modeling	Cold-wall Calorimetry	Surface Quantities	Internal Temperature	Post-test Evaluations
CFD* Hot-wall Environments Material Response Models	Heat Flux Pressure Shear**	Pyrometry Spectroscopy*** Infrared Video High-speed Video Photography Real-time Recession*** Laser Scan****	Thermocouples	CT Cross-sections SEM EDS Microscopy



*CFD is typically performed both pre-test, guiding condition selection, and post-test using as-run environments. CFD outputs hot-wall environments that may or may not be close to cold-wall environments depending on enthalpy and catalyticity of the sample.

**Shear sensors procured but has not been fully vetted and implemented.

***Spectroscopy and Real-time Recession are developmental workflows under development at NASA.

****Laser Scan data is obtained both pre-test and post-test. The ability to align test articles for the scan strongly impacts the quality of the data.

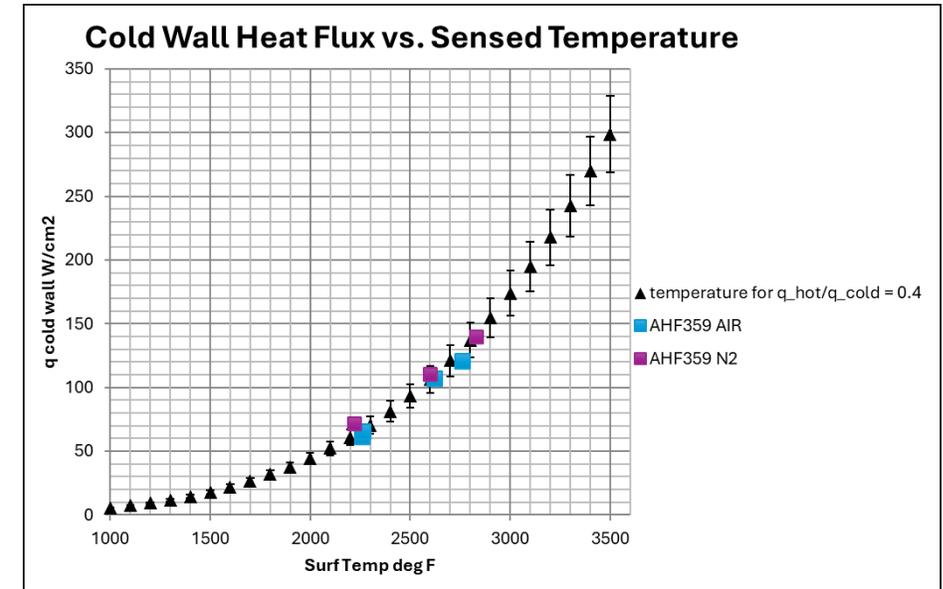


Break before Test Examples



Reusable TPS Testing – An Example Process

- Project Alpha wishes to determine the limits of their Reusable TPS to enable a new class of spacecraft operating in LEO with low pressures. They would also like to gather data on surface recombination coefficients⁸ for use in developmental codes.
- **Objectives:**
 1. Expose each model to Air and Nitrogen-only gas.
 2. Achieve target temperatures on test article surface.
 - Pressure is desired to be 10kPa but not critical. Determining surface recombination coefficients is desired.
 3. Collect thermal, optical data on test article for exposure and thermal data on coupon up to peak internal temperature.



Question: which facility and nozzle can we use to obtain our target conditions ?

Facility Settings Required

Notional Test Conditions

- Reusable target temperature: 1900±20 [K]
 - Desired impact pressure: 5±1 [kPa]
 - Dwell time: 300 [s]

Assuming reusable material has high-emissivity ($\epsilon \approx 0.9$)

1. Fully catalytic, Radiative equilibrium heat flux yields 67 [W/cm²] for the target temperature.
2. Non-catalytic material may experience as little as 1/3 the heating of a fully-catalytic system, necessitating the arc-heater to be able to produce 3x the heat flux so we can achieve target temperatures.
3. Starting at low temperatures and successively exposing test article to higher heating will help to determine the catalytic heating effect as a function of temperature.

⁸Basics of Surface Catalycity Testing in arc-jets

Reusable TPS Testing – Recommendations

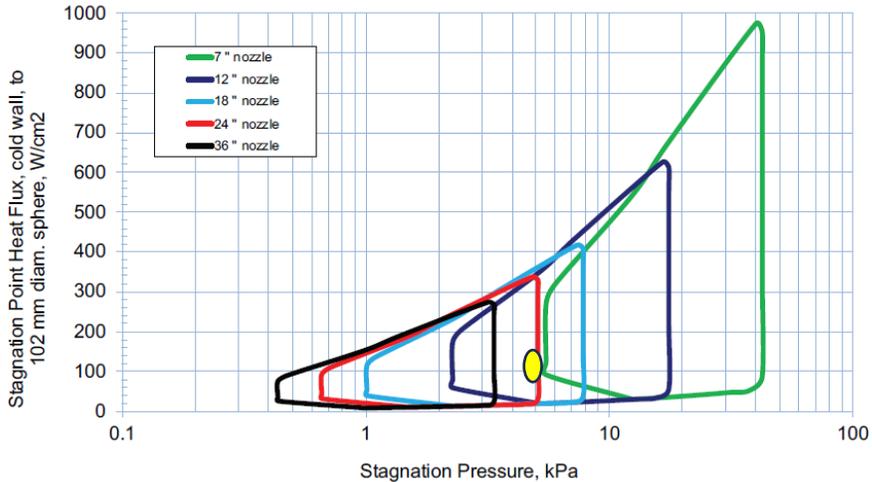
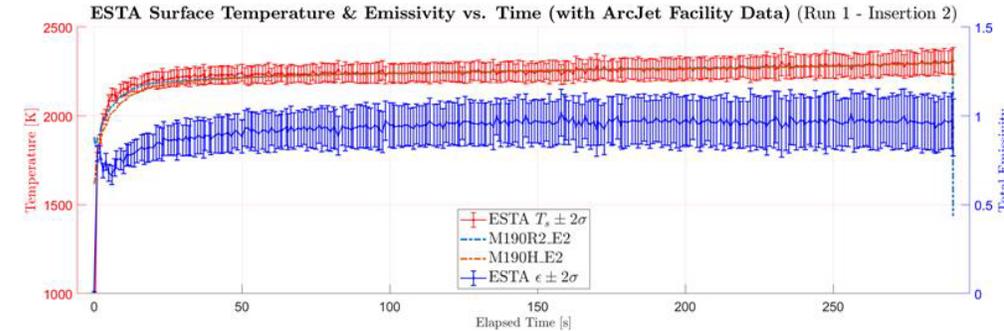


Figure 4.1.3.2. Operating envelope of the AHF with 20-MW segmented arc heater



Blunt-cones provide a flat-region that can house a near-surface TC and produce uniform heat flux and pressure with low shear.



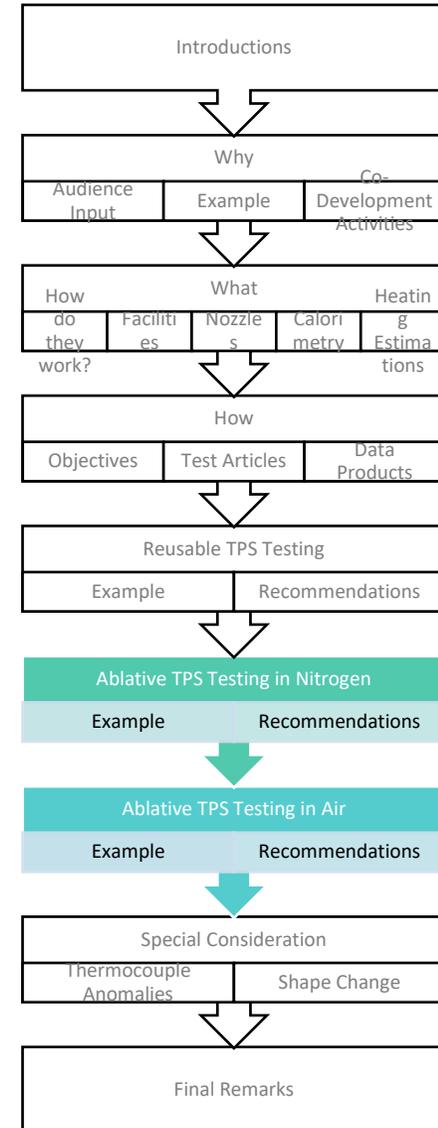
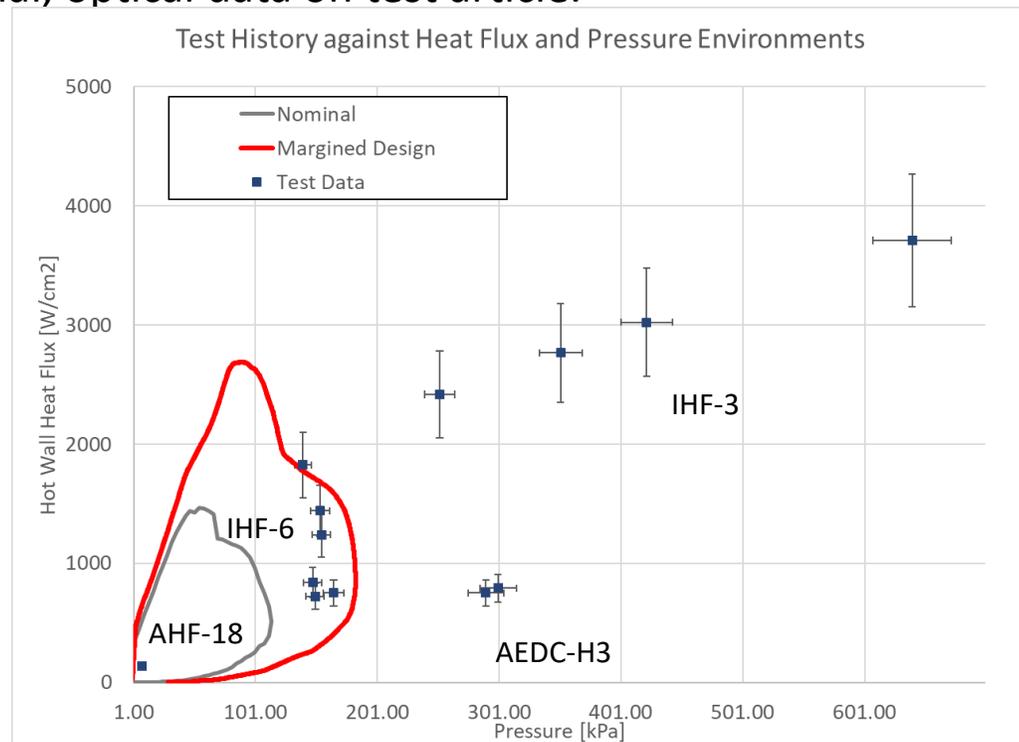
Suites of pyrometers, near-surface thermocouples can be used to estimate surface temperature, and a spectrometer can estimate emissivity.

- Recommendations and best-practices for testing reusable systems and/or coated thermal protection materials:
 - AHF-12 currently contains a joint discontinuity between the 7-inch and 12-inch section that may make calorimetry difficult. Repairs are planned but have not yet occurred.
 - Coated systems may crack if cooled down too quickly – recommend letting them cool under vacuum.
 - Optical surface quantities may be susceptible to excess light from both the shock layer radiation, as well as reflections from the plasma in the column – consult with TSF on recommendations.

Ablative TPS Testing – Campaign Example



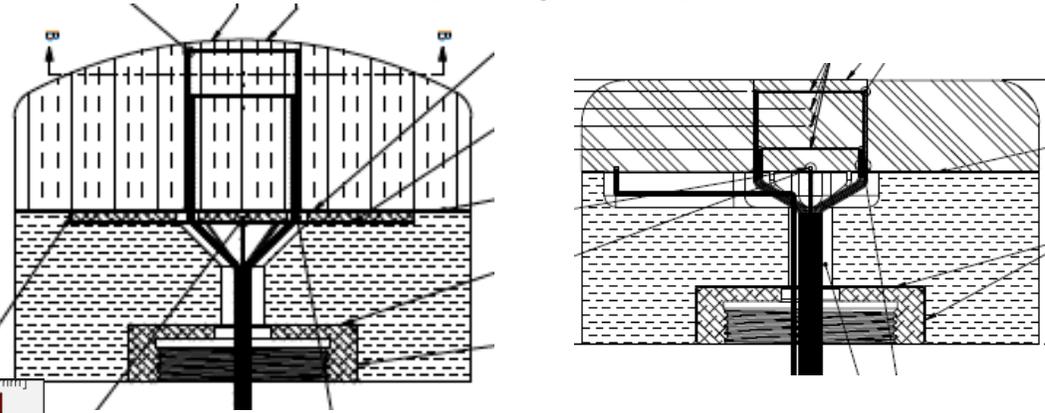
- Project Bravo is developing their ablative TPS that is a carbonaceous ablator designed to be resilient to extreme heating predicted for a fast Earth entry.
- **Objectives to inform model development and validate material performance:**
 1. Achieve flight-relevant and bounding conditions, measured through calorimetry.
 2. Expose test articles to flight-relevant heat load.
 3. Collect thermal, optical data on test article.



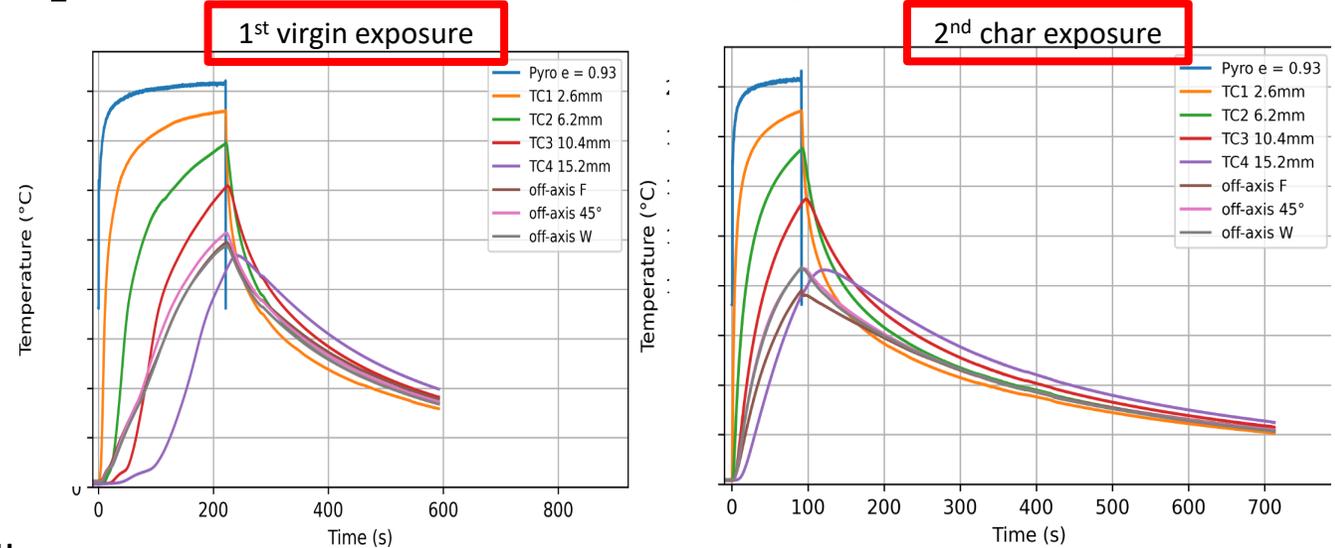
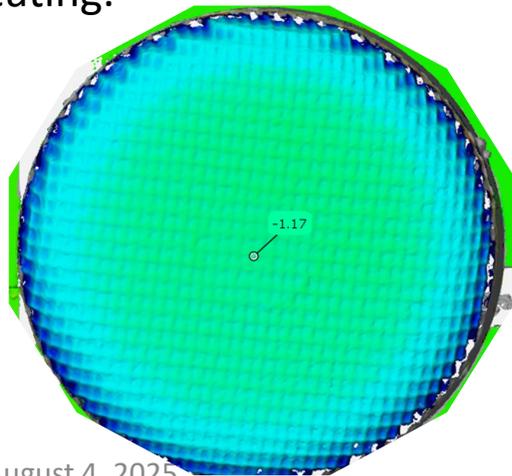
Ablative TPS Testing in Nitrogen



- The test develops high-temperatures internally in N_2 atmosphere to isolate thermal response from recession.



Consideration: Iso-q (left) experience 'uniform' heat flux across their surface, recessing evenly while Flat-face (right) experience reduce influence from side-wall heating.



- 4-inch diameter flat-face models were instrumented with a centerline plug of Type-C thermocouples to measure temperatures up to 2000°C.
- Models were exposed for several minutes to obtain virgin material response and form a complete char, then re-exposed for a char material response.

Finding for Consideration: Even though recession is not predicted due to the lack of oxidation, collecting laser scan data revealed 10 – 15% thickness change due to shrinkage in the charred material – an important update for the model and consideration for recession estimates!

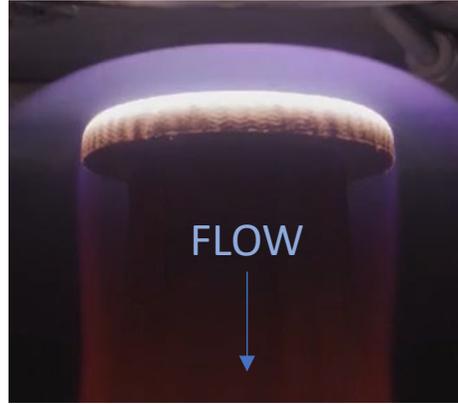
Ablative TPS Testing in Air

- Testing was performed using the same facility settings, only varying model geometry to obtain differing heating rates and, yes, pressure is affected too.

1-inch iso-q

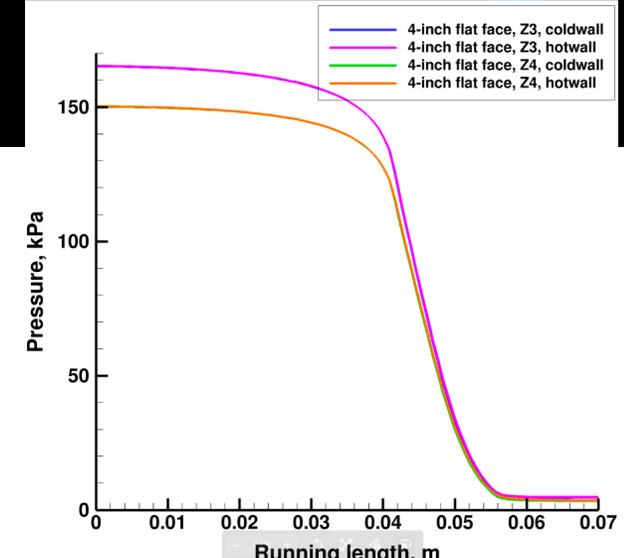
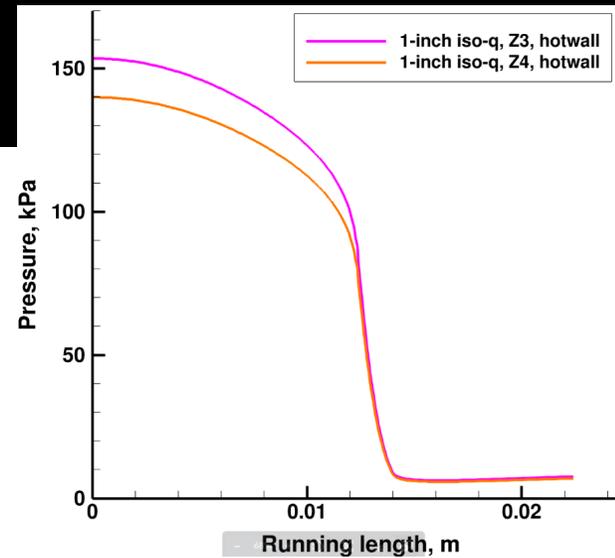


3-inch flat-face

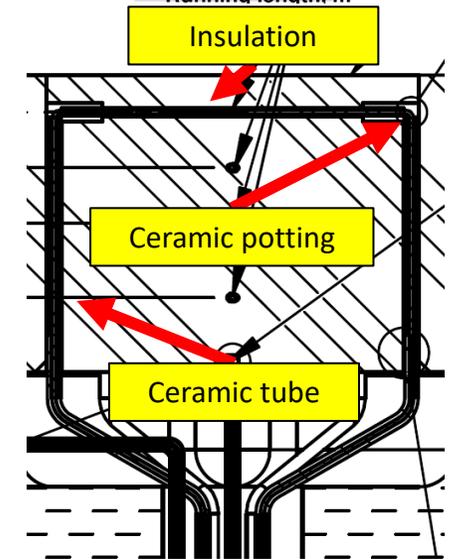
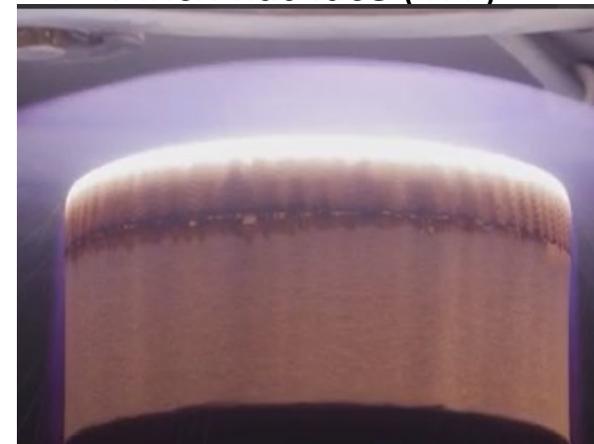


Consideration: Side wall heating for stagnation models:

- The smaller the model diameter, the greater the effect of side wall heating on thermal response, and perhaps material response.
- Test article holders should be designed deliberately with great care where flow is likely to impinge:
 - Graphite is susceptible to cracking with thermal gradients and stress concentrations.
 - Silica/carbon phenolic should be designed manufactured with care to ensure complete curing – especially if using chop-molded method.



4-inch flat-face (4FF)



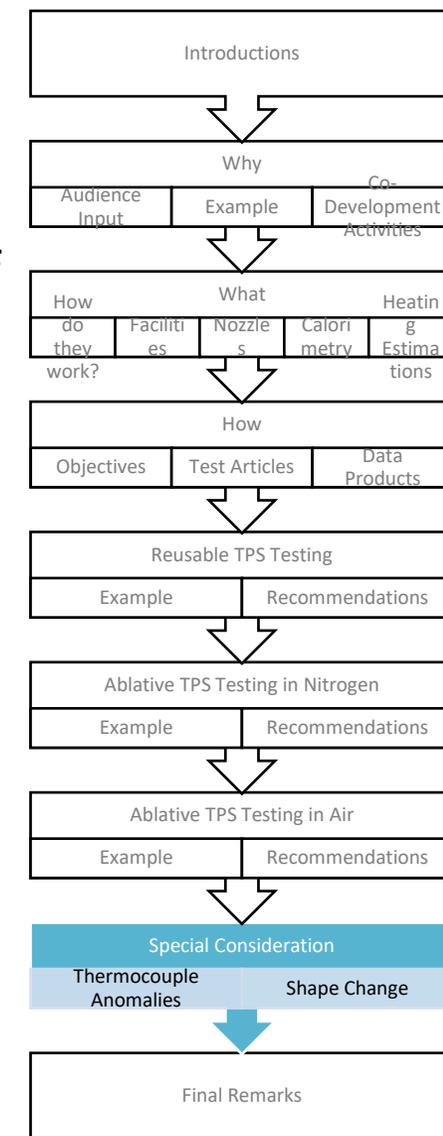
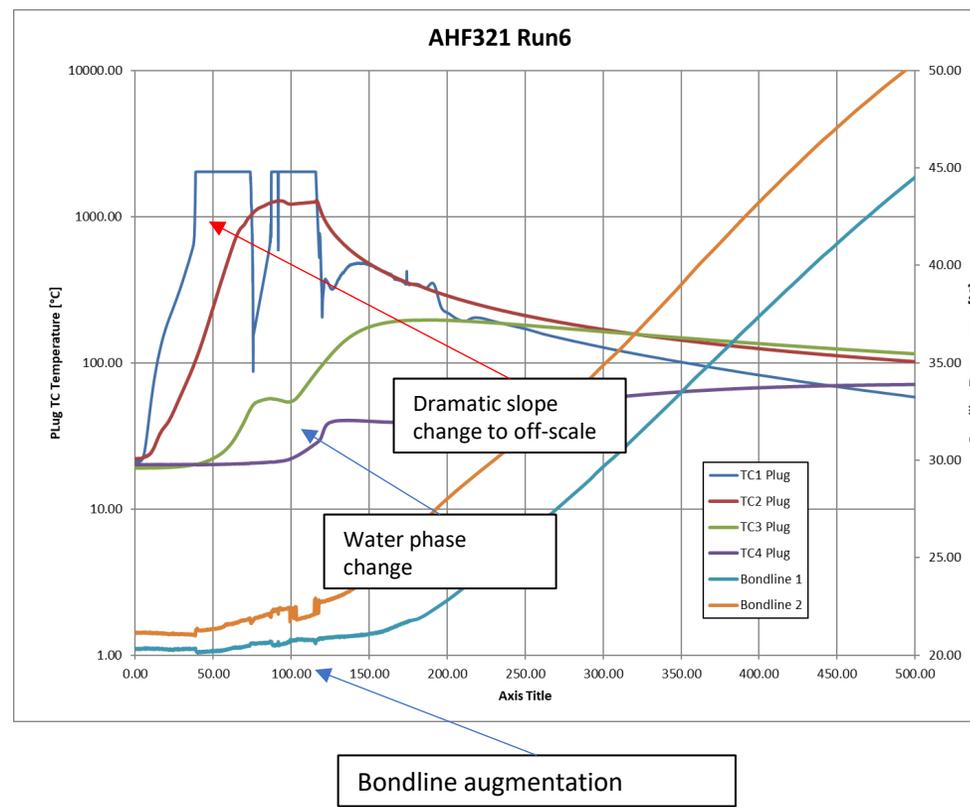
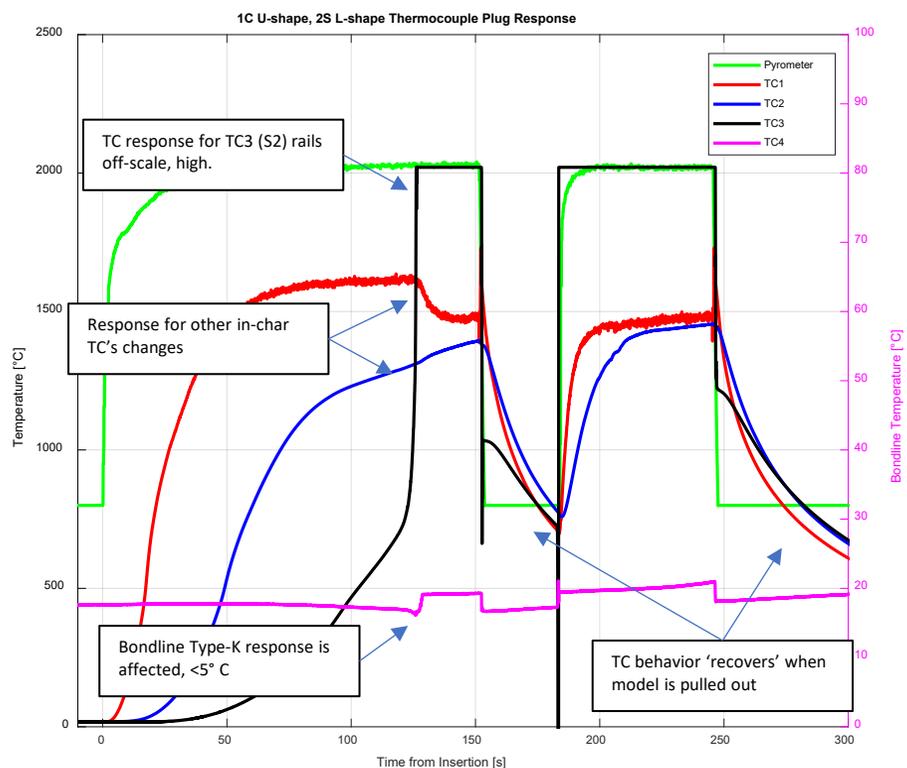
Consideration: Models where TC's may be exposed to plasma:

- While not part of ASTM 377, it is recommended to insulate land-length portions of TC's to mitigate negative effects of EMI.

Thermocouple Anomalies to be Watched.



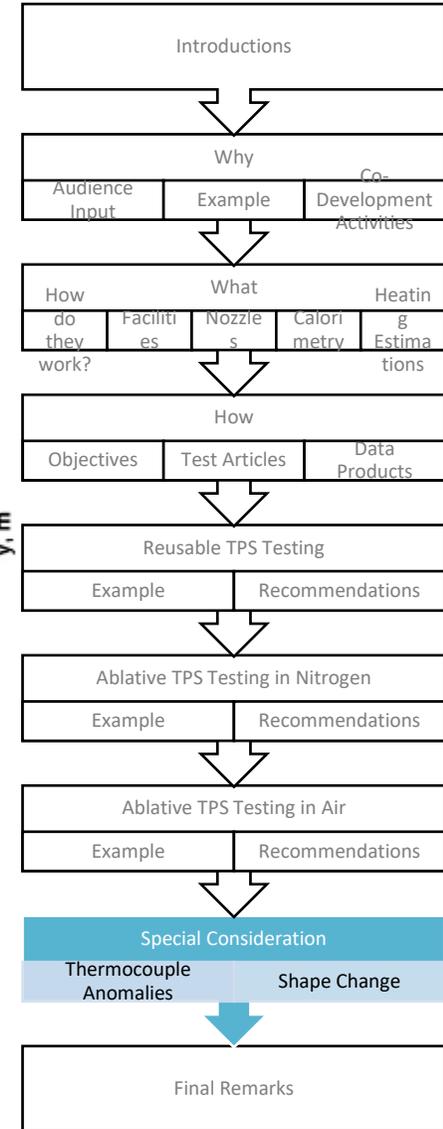
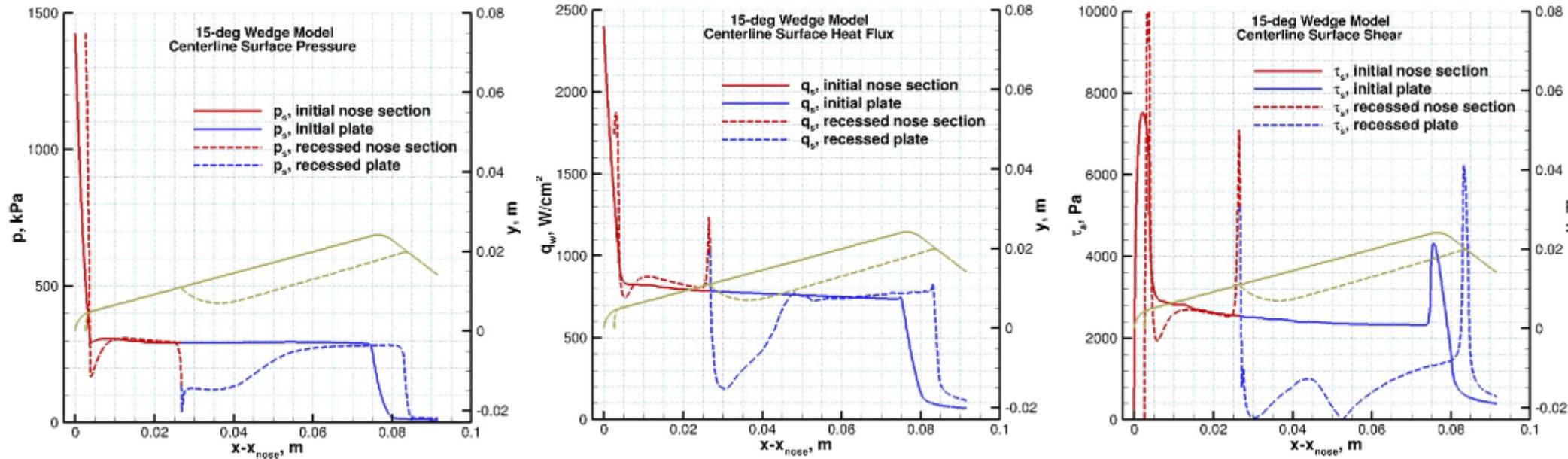
- Because there are complex interactions at play during ablative material response, it can be difficult to pinpoint exactly what is physical.
- To-date, the clearest indication of cross-talk and a possible grounding issue is when TC's *not* connected through charred TPS e.g., relatively insulated from one another exhibit simultaneous large changes in signal and then recover completely once out of the flow.





Notes on Shape Change

- Shape change will lead to environment change – particularly where wedge testing is concerned⁹.
- Best Practices for CFD Arc-Jet Experiments was recently published by our very own Grant Palmer¹⁰!



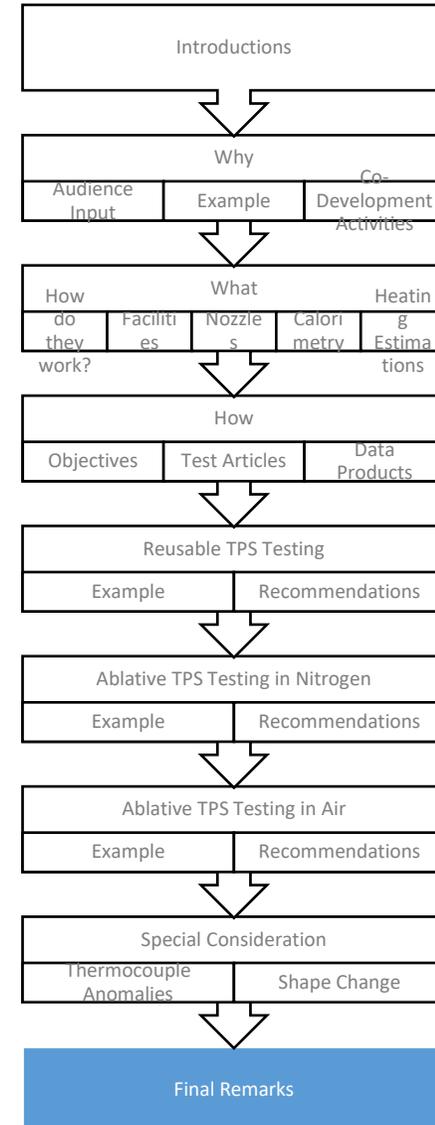
⁹CFD Simulations of the AEDC H3 Arc-Jet Flow: Mach 3.3 Nozzle, Flow Surveys, Wedge Models

¹⁰CFD Simulations of arc-jet Experiments – A Survey of Recommended Practices and Lessons Learned

Final Remarks



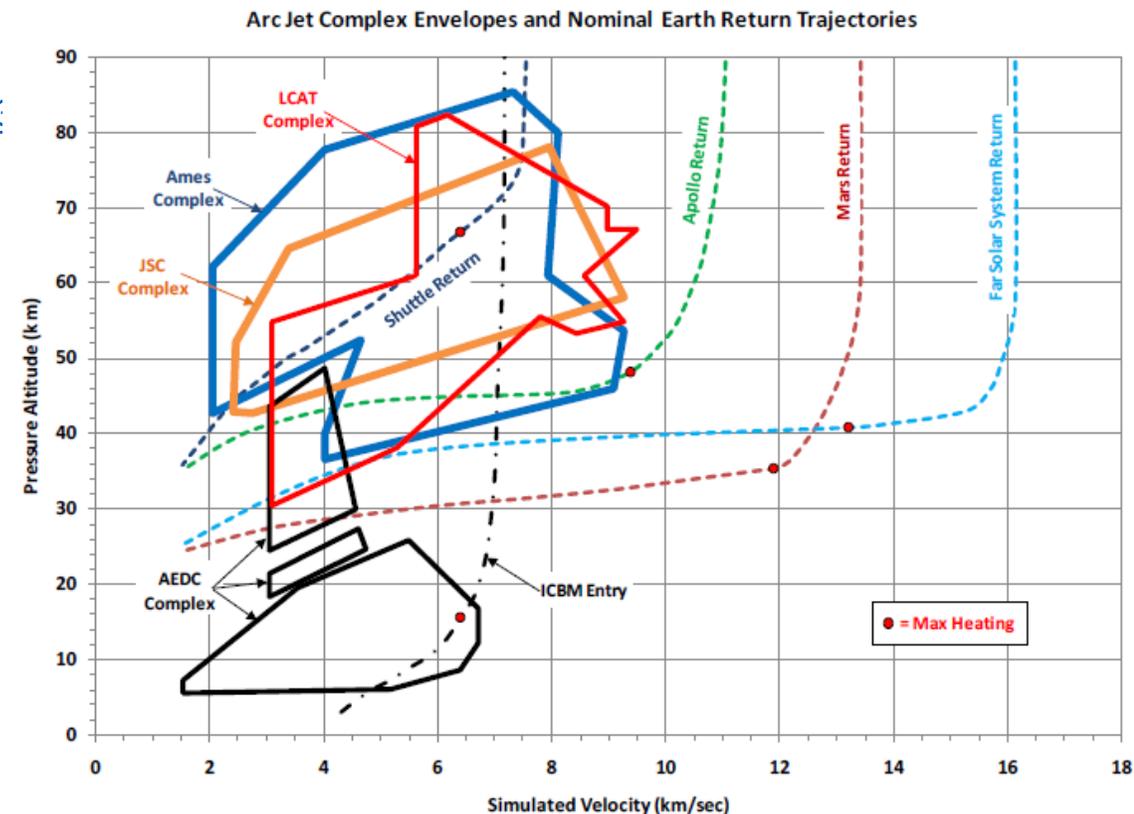
- Arc-jet testing may occur at any (and should occur at all) phases of thermal protection system or flight project development.
- Using the arc-jets at NASA Ames it is possible to simulate heat flux and pressure, and sometime shear, conditions for many destinations in our solar system, but no single test will do it, and not all the testing in the world is going to replace flying.
- The Thermophysics Facilities Branch has assembled a comprehensive test planning document that serves to educate all potential customers of its capabilities.
- The Entry Systems Division at NASA Ames wishes to be a resource to those who wish to perform arc-jet testing, be it through CFD, Material Response Modeling, Test Execution and Analysis, or Model Fabrication.
- There are a myriad of considerations when performing an arc-jet test, but the data contained within can yield incredible insight to the article under test.



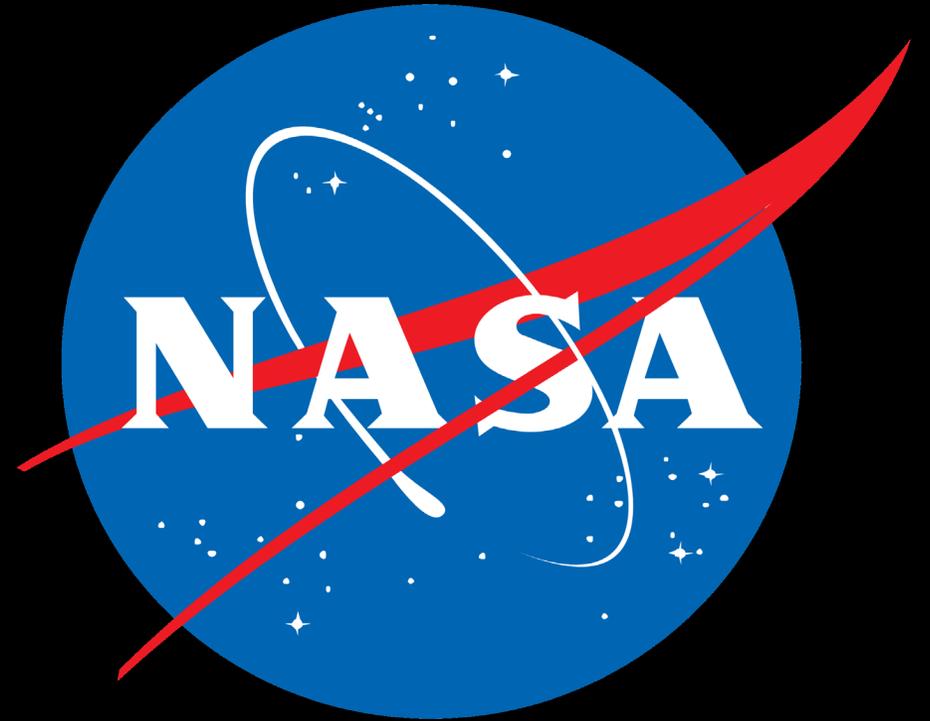
Additional References:



- Other Facilities to Consider:
<https://ntrs.nasa.gov/api/citations/20190030274/downloads/20190030274.pdf>
- Real-time Recession with arcjetCV: <https://arc.aiaa.org/doi/10.2514/1.A361>:
- Previous arc-jet Short Course with Additional Facilities:
<https://ntrs.nasa.gov/api/citations/20190030274>
- Entry Systems Division Website: <https://www.nasa.gov/entry-systems-and-technology-division/>
- Material Response Modeling:
https://tfaws.nasa.gov/TFAWS06/Proceedings/Aerothermal-Propulsion/Papers/TFAWS06-1008_Paper_Squire.pdf



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