National Aeronautics and Space Administration

NASA

Arc-jet Overview, Modeling, and Uncertainty for Hypersonic Material Environmental Test and Evaluation

Andrew J. Brune, Ph.D.

Senior Aerospace Engineer, Advanced Thermal Systems

NASA Langley Research Center

Engineering Directorate

NASA Langley Research Center

http://engineering.larc.nasa.gov/

3rd International Conference on High-Speed Hypersonic Vehicle Science and Technology

April 16th, 2024

Agenda

- **Why an Arc Jet**
  - Flight
  - Simulation Parameters
  - Facility Capabilities
- **What is an Arc Jet**
  - General Overview
  - Types of Arc Heaters
  - How an Arc Heater Works
  - Types of Tests
  - Instrumentation
- **Arc-jet Modeling and Uncertainties**
  - Modeling Approach and Examples
  - Uncertainty Quantification Process, Challenges, and Examples
- **Concluding Remarks**

Acknowledgements

Many people contributed to this presentation:

- **Langley colleagues (Walt Bruce, David Glass, Thomas West, & many others)**
- **AEDC Arc Heater Team (Mark Smith)**
- **Ames Arc Jet Team (George Raiche & John Balboni)**
- **Langley HyMETS Team (Scott Splinter & Jeff Gragg)**
- **Boeing Arc Jet Team (Matt Kardell & John Simms)**

Aerothermal Ground Testing

Arc-jet Aerothermal Ground Tests are Conducted to:

1) Support Material Development

- Screen materials
- Determine relative material thermal-ablative-structural responses

2) Support System Design

- Evaluate system performance
- Demonstrate flight system design, reduce flight risk

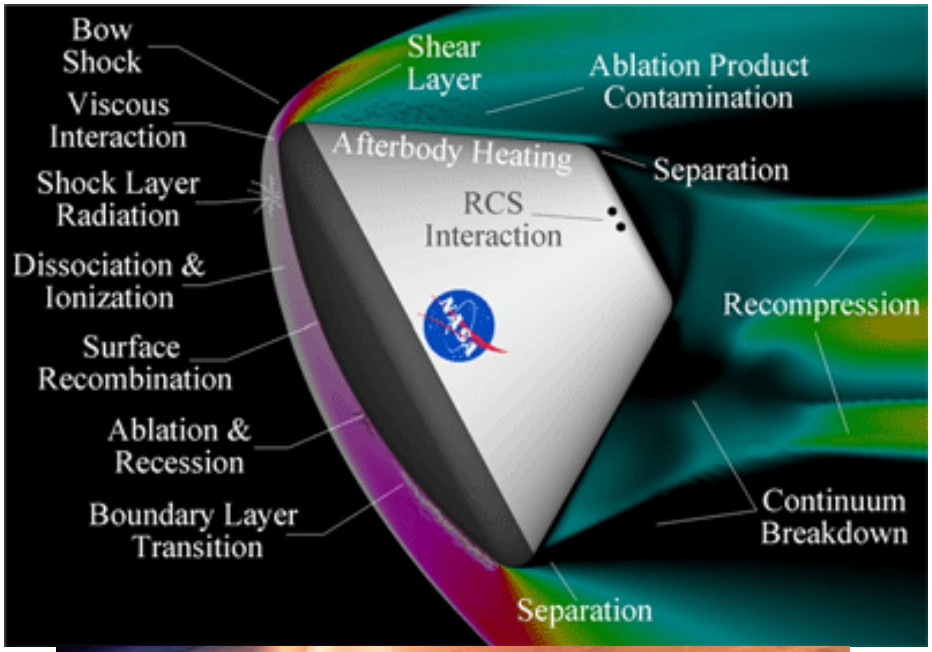
3) Support Analytical Model Development

- Support physical and analytical model development
- Generate material design response data for analytical correlation

Arc tests are designed to simulate a combination of key flight conditions so that the resulting material and/or system design performance can be accurately assessed.

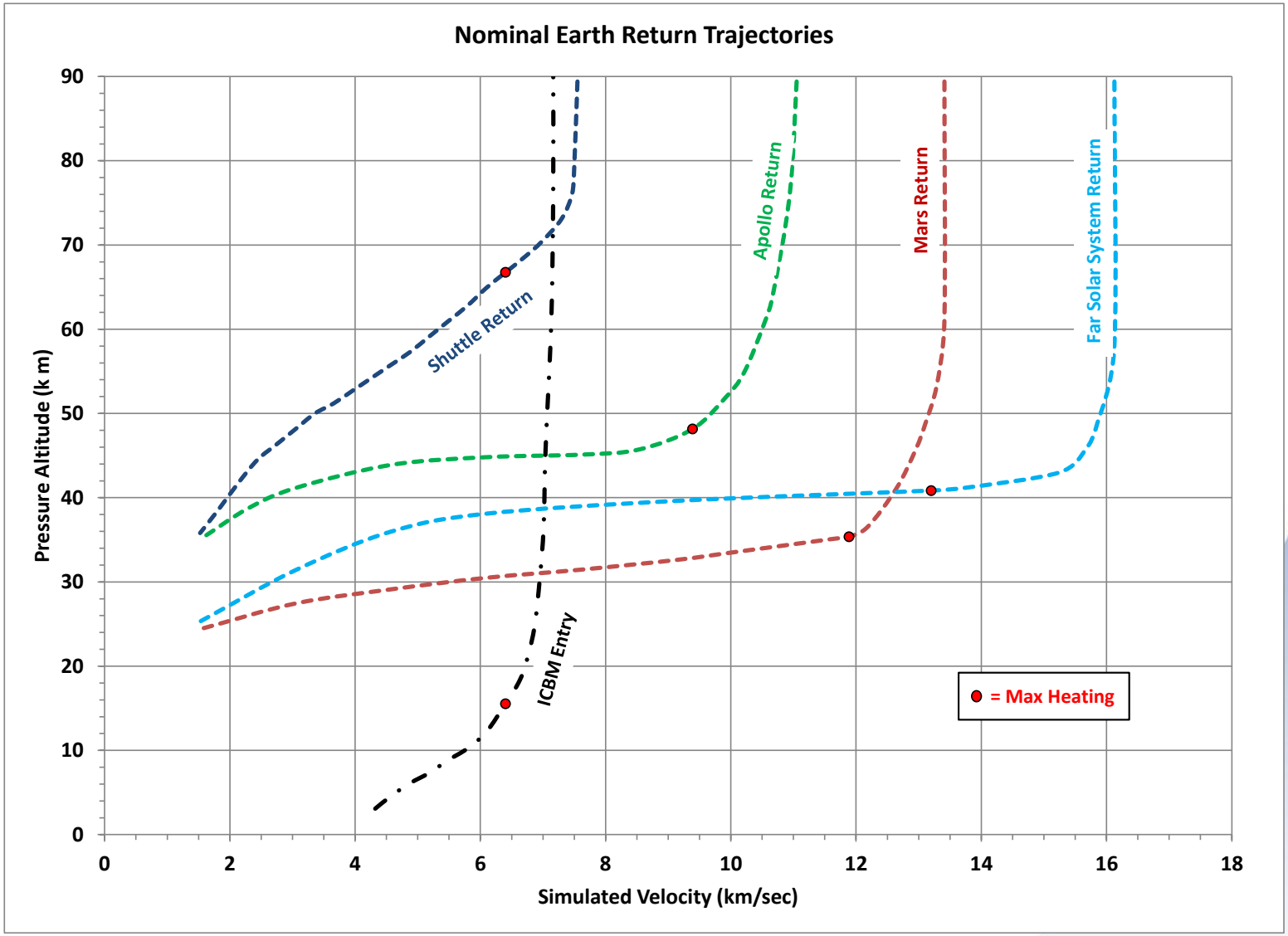
Hypersonic Entry/Flight

Blunt Bodies

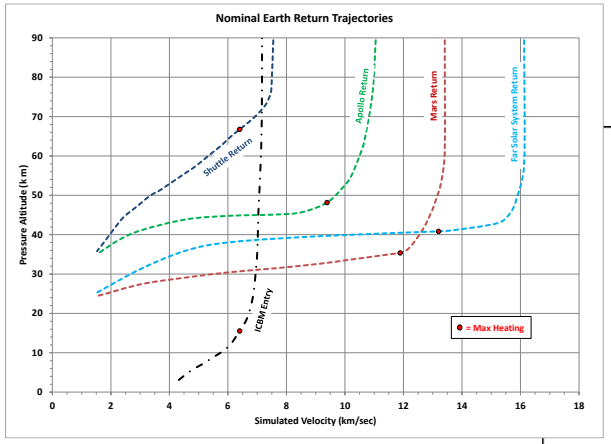


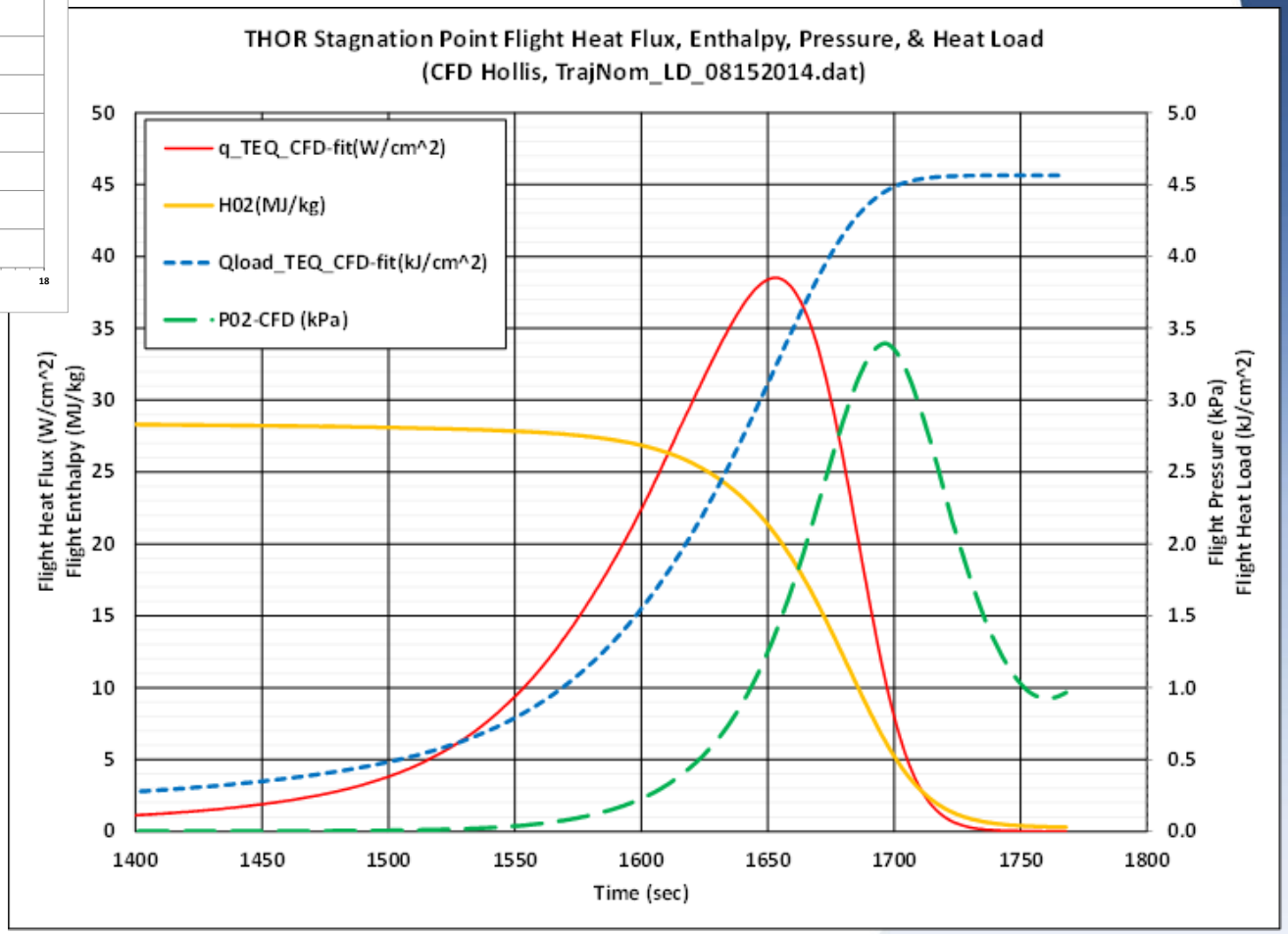
Sharp/slender Bodies

Altitude / Velocity Chart - Trajectories



Trajectory





Heat Flux: $q \sim \sqrt{\frac{\rho}{R_N}} V^3$

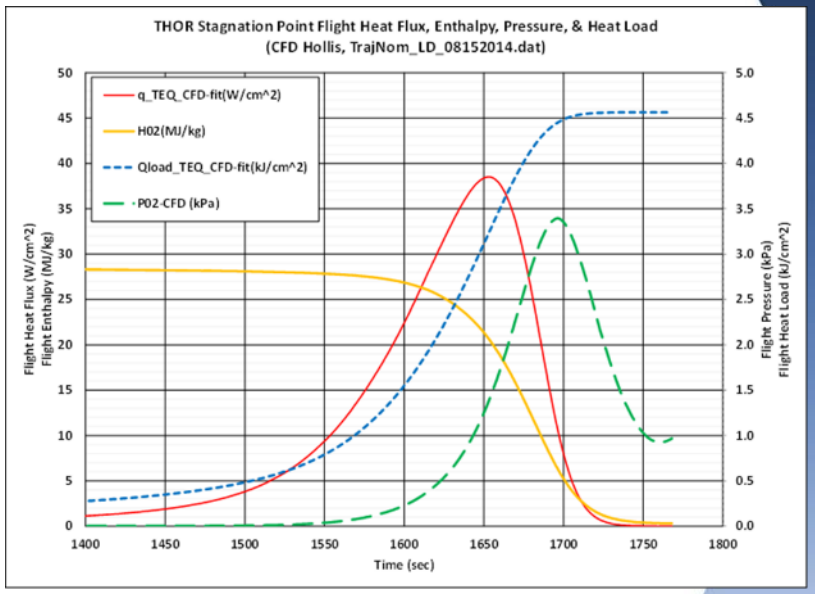
Total Enthalpy: $H_{02} \sim \frac{1}{2} V^2$

Heat Load: $Q_{load} = \int_{t_{initial}}^{t_{final}} q \, dt$

Stagnation Pressure: $P_{02} \sim \rho V^2$

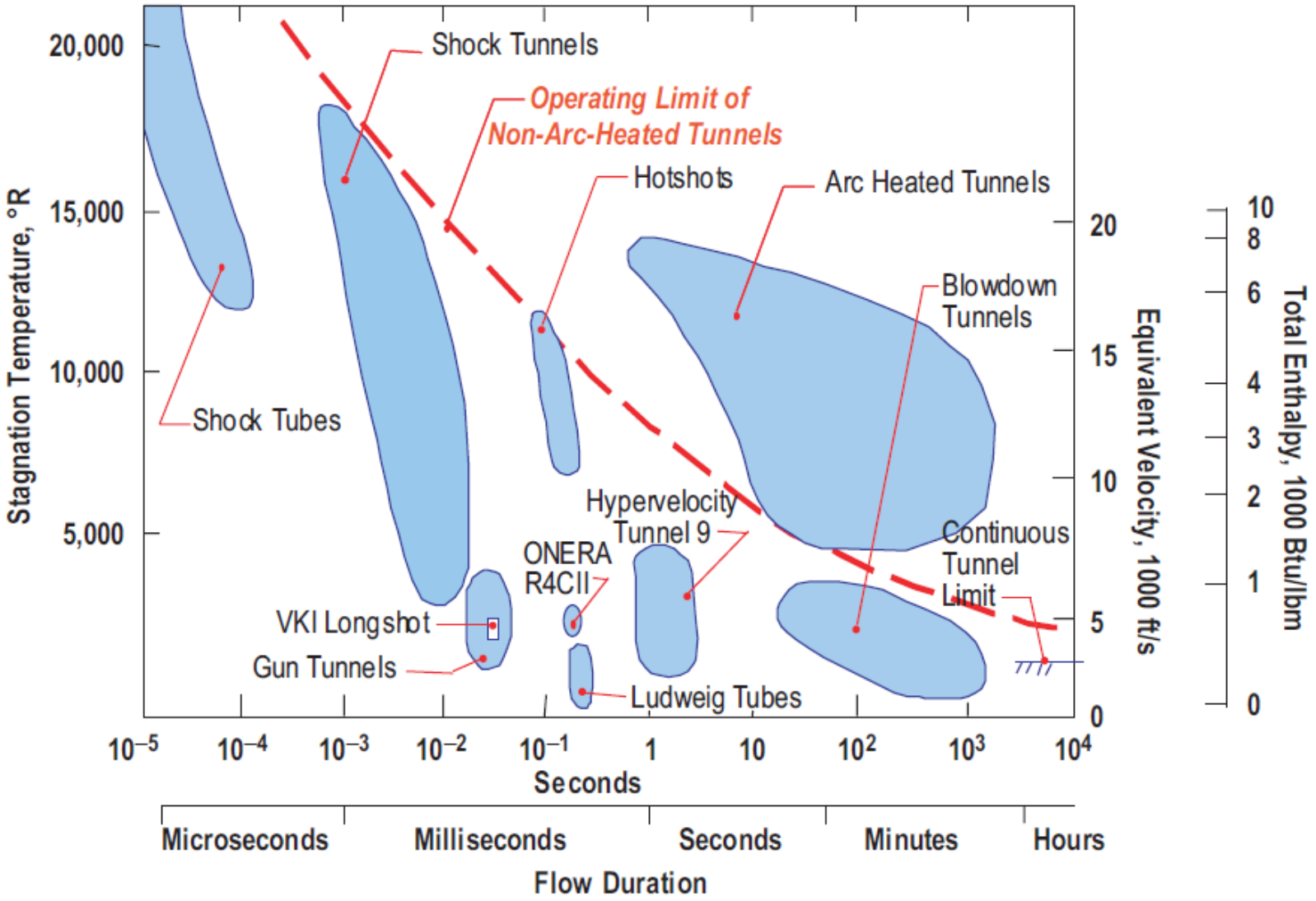
Important Parameters for TPS Evaluation

- Heat Flux
- Pressure
- Enthalpy
- Heat Load (Duration)
- Shear Force
- Flow State (Laminar / Turbulent)
- Recession
- Boundary Layer Thickness
- Protuberance

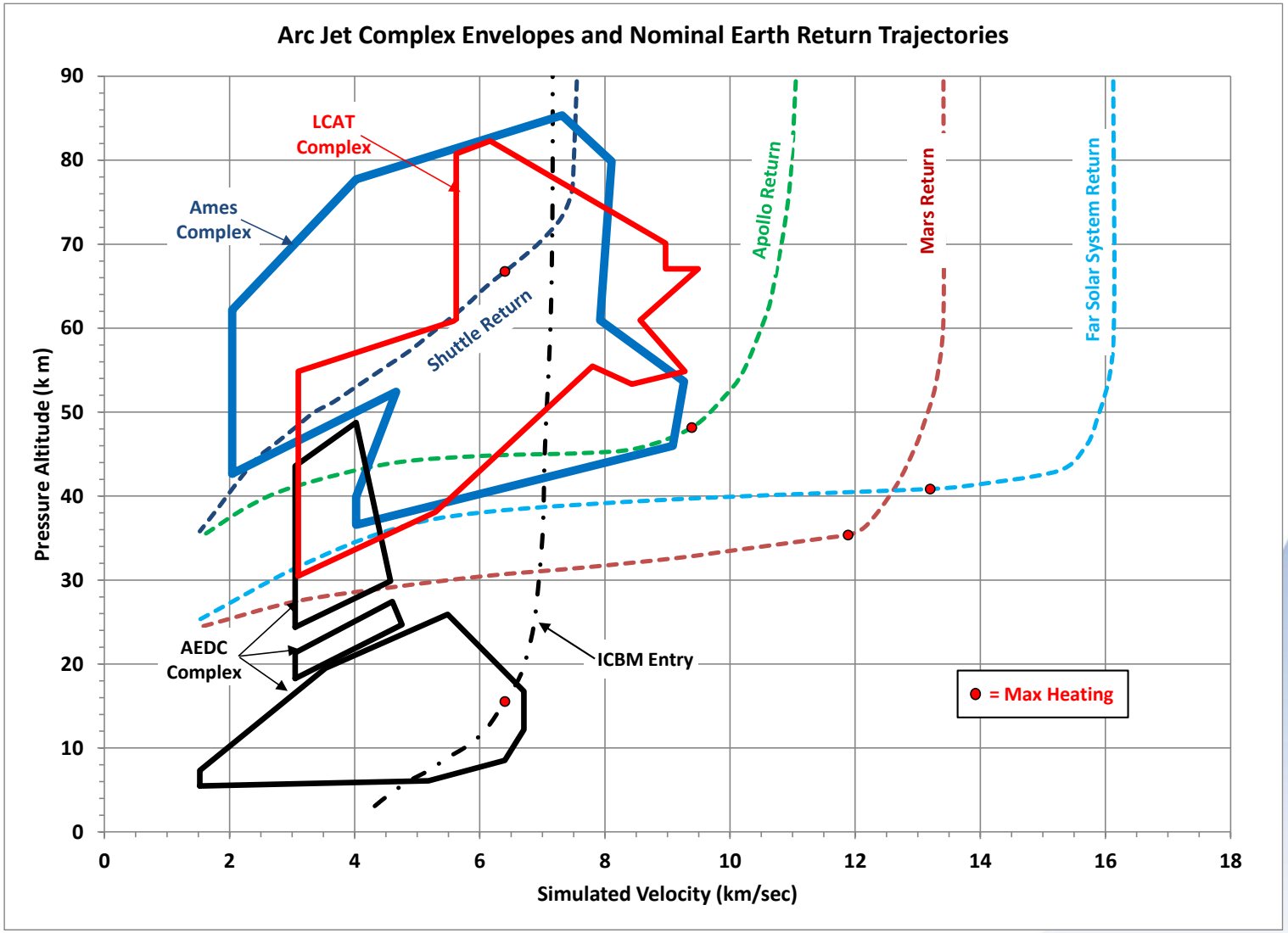


Test duration and flow energy are critical for TPS evaluation

Unique Capability of Arc Heaters



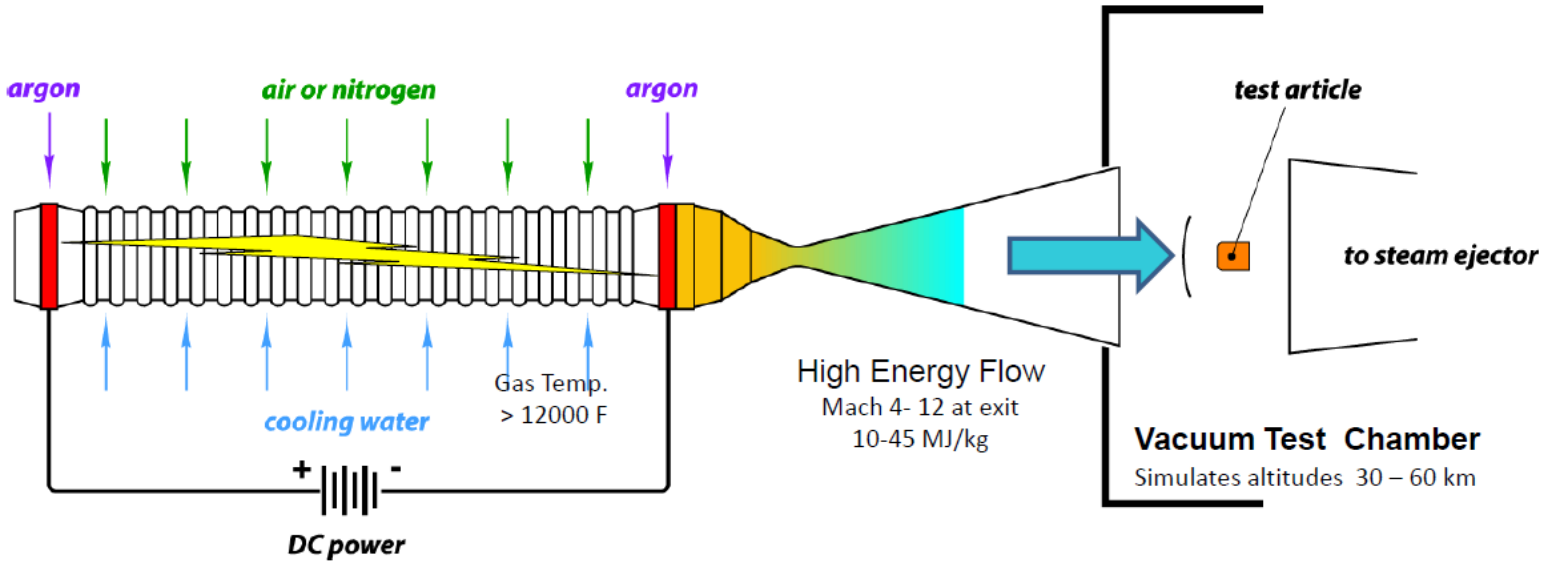
Arc Jet Facility Capabilities



Arc Jet Operating Principal

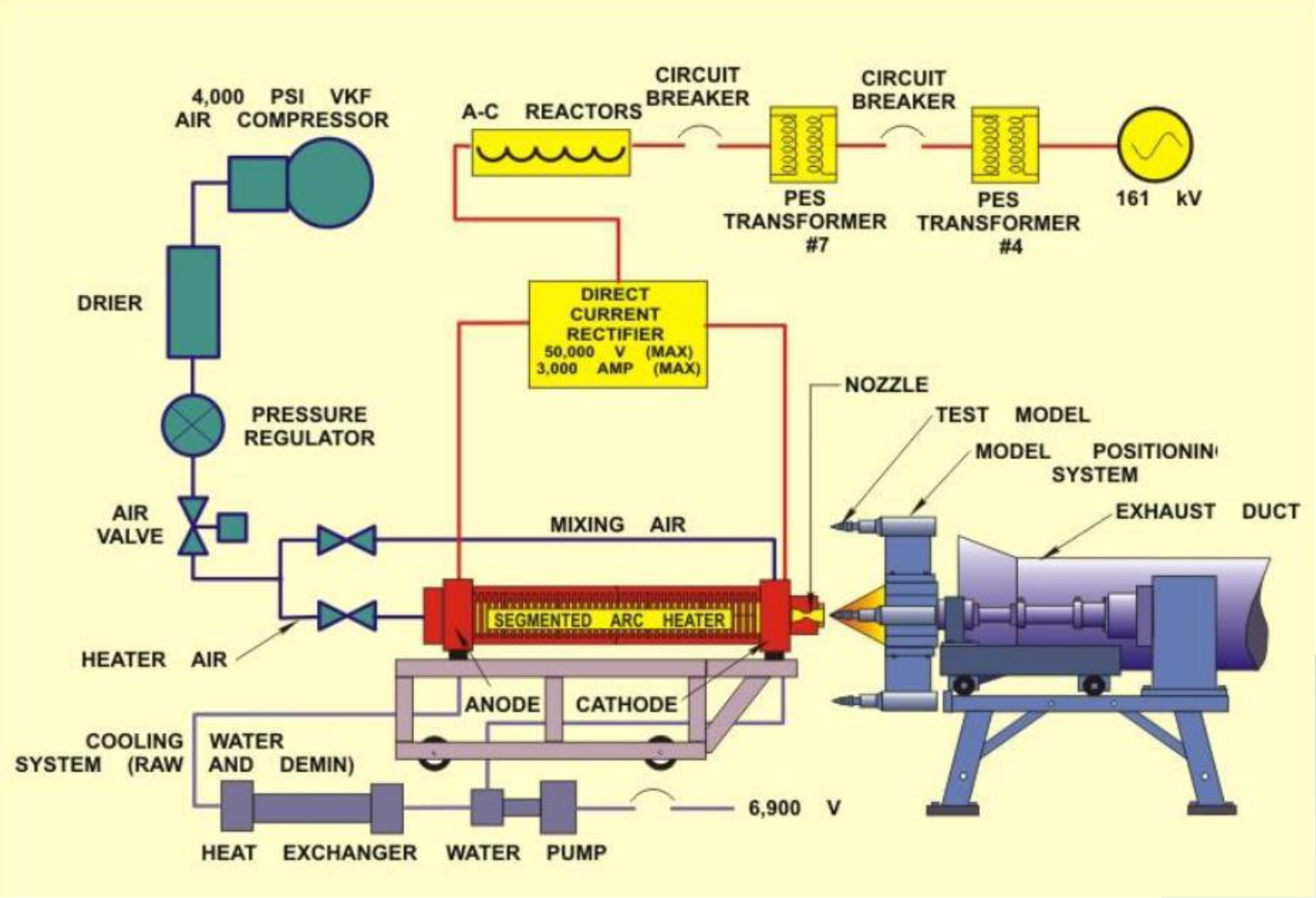
Objectives:

- **Simulate entry heating in a ground-test facility with flight-like chemical, physical, and shock flow phenomena**
- **Provide test data to verify thermal protection concepts, materials, and system designs before flight; support continuing engineering during operations**

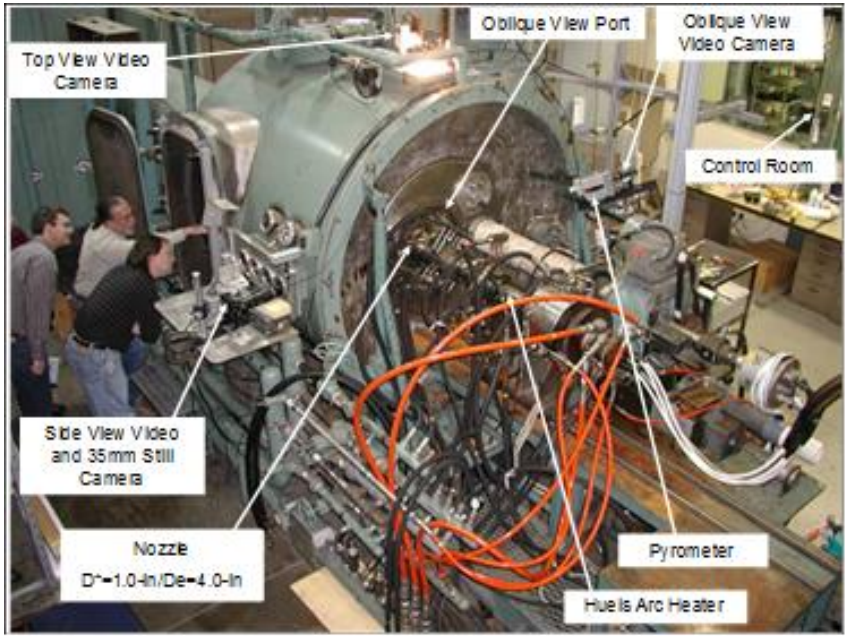


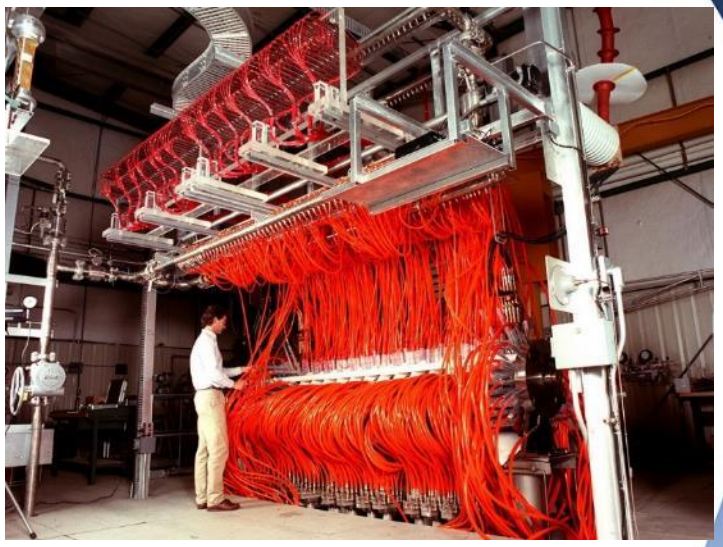
Method: Heat a test gas (air) to plasma temperatures with an electric arc, then accelerate to hypersonic velocity and direct onto a stationary test article

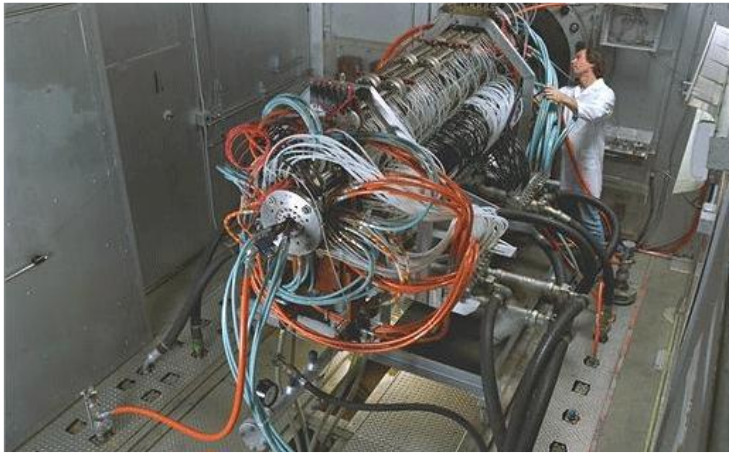
Arc Jet Facility Components

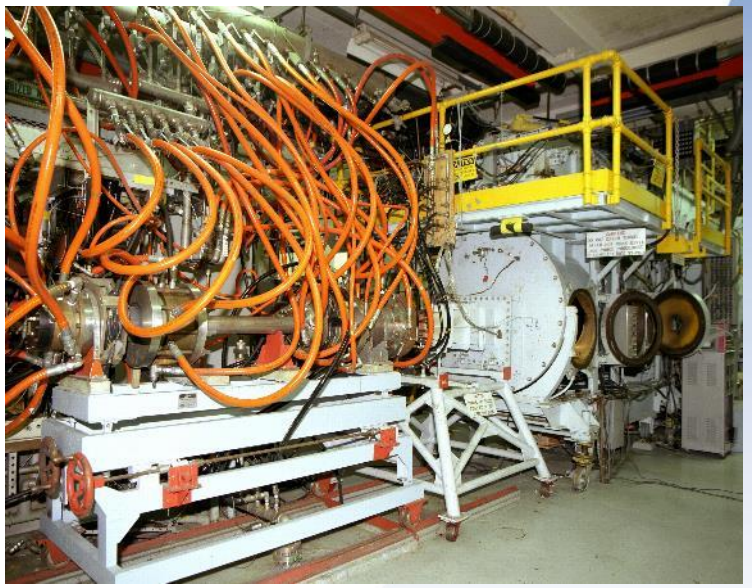


Arc Jet Facility Overview

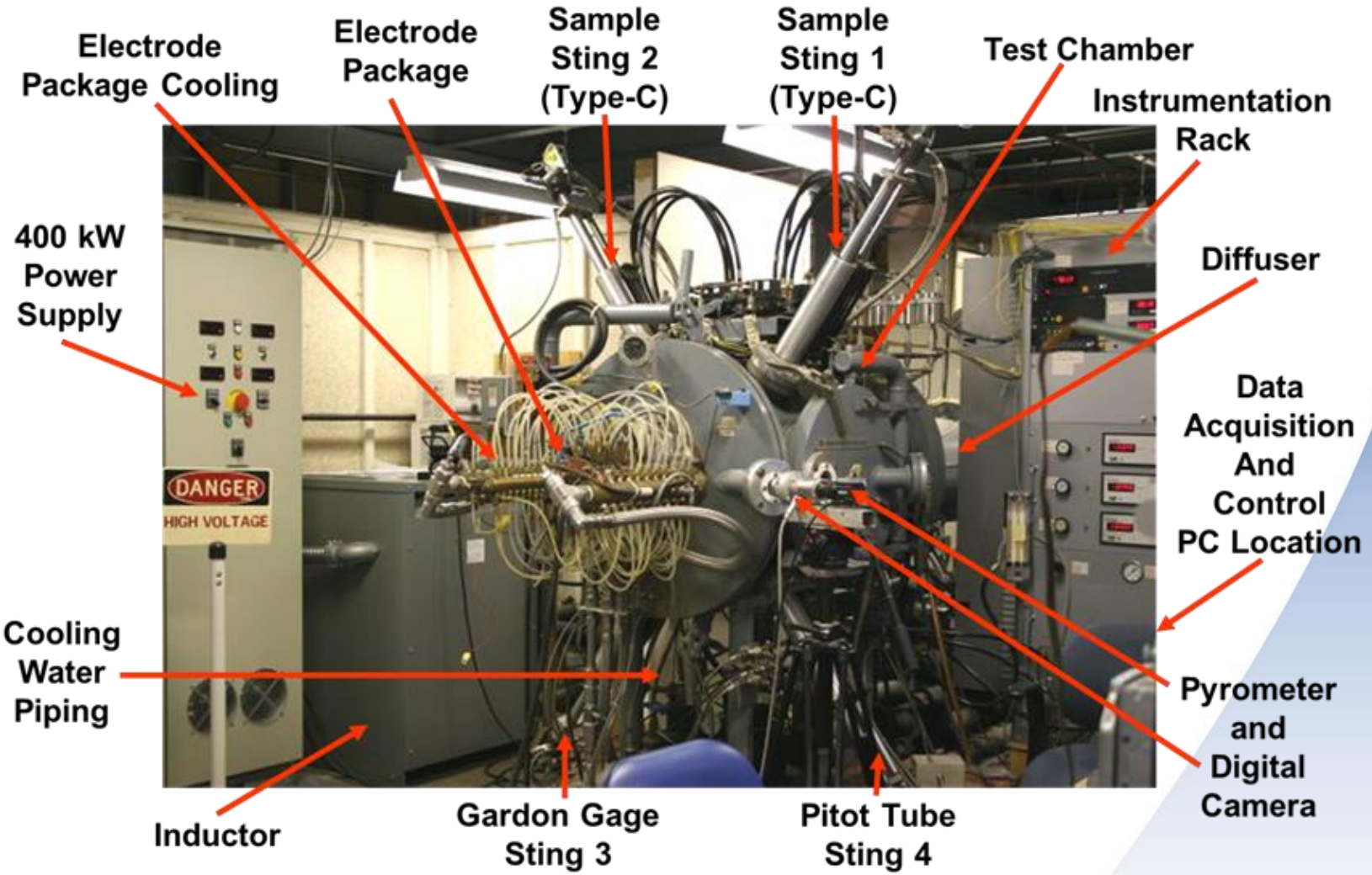




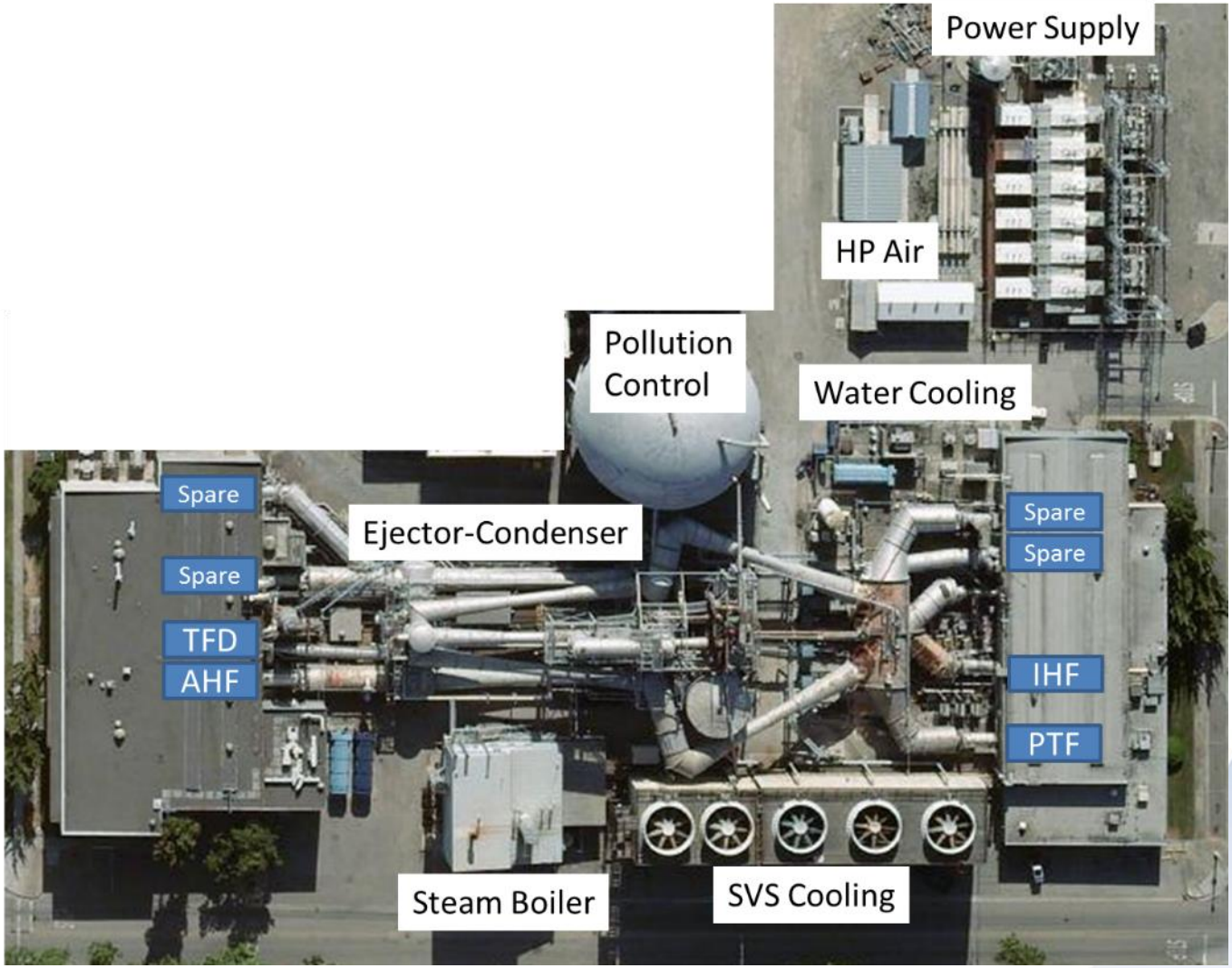




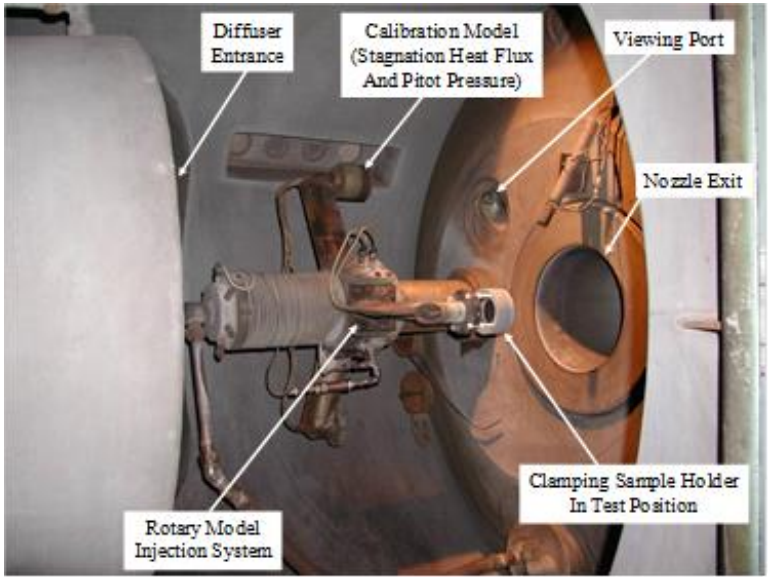
Arc Jet Facility Components

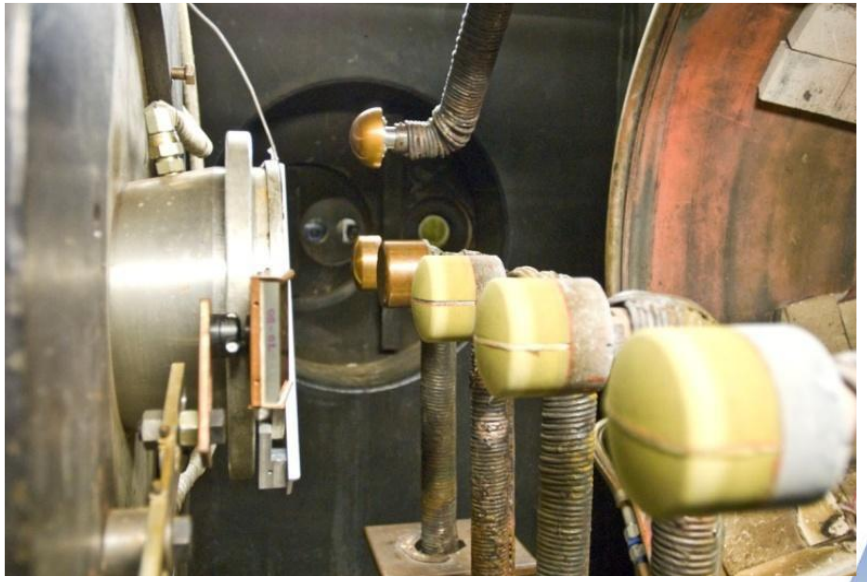


Arc Jet Facility Components

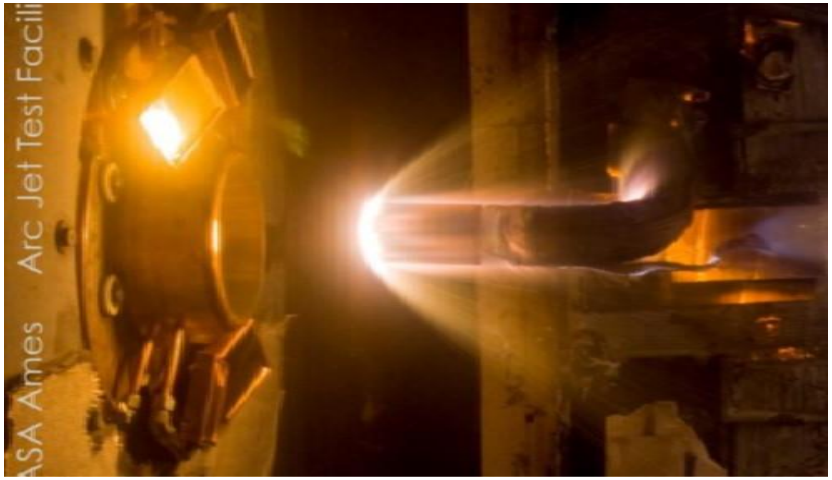


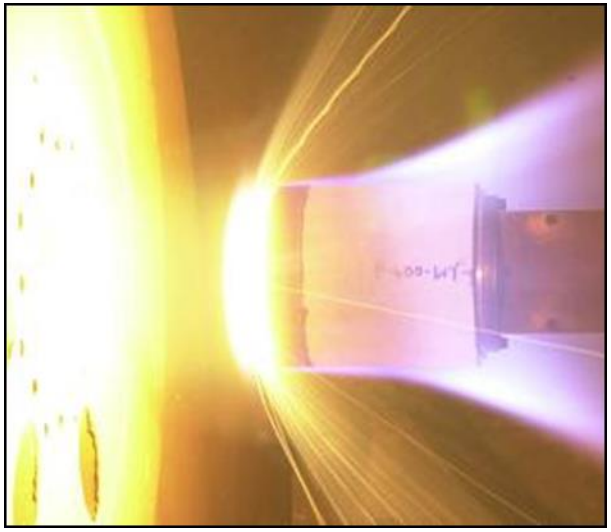
Model Injection System

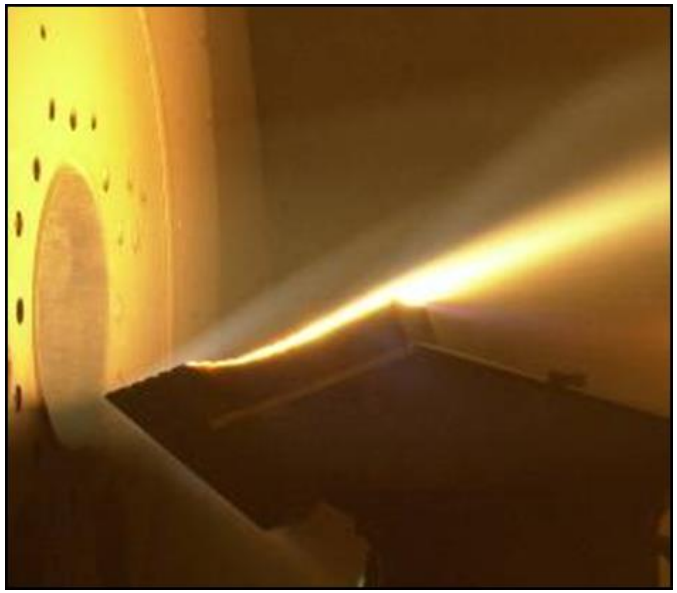


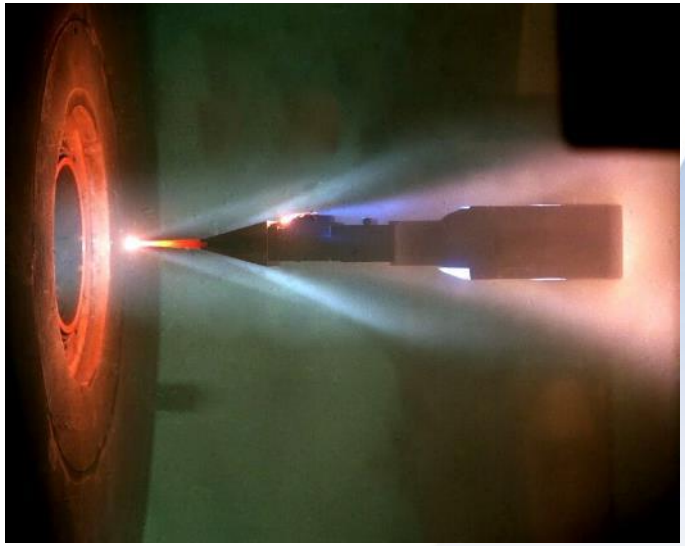


Test Models in Flow

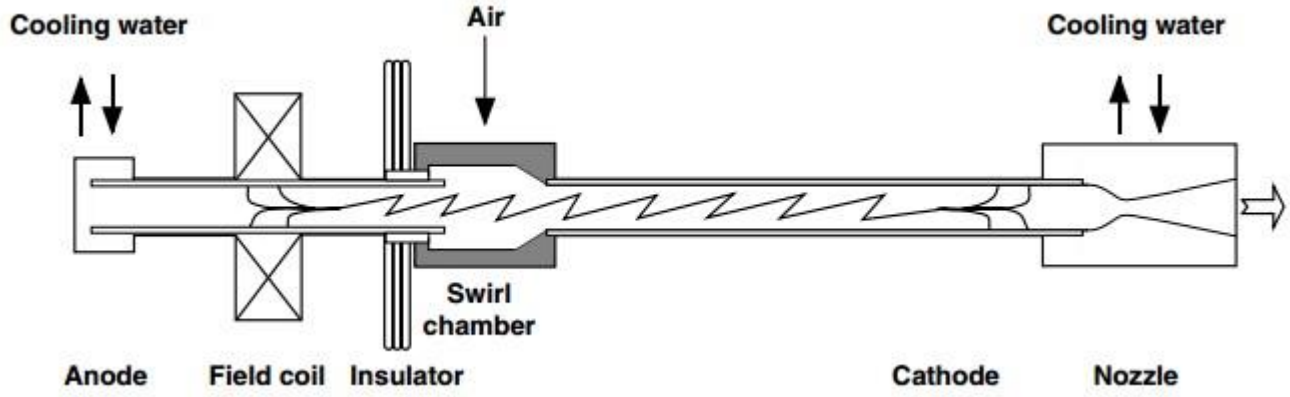


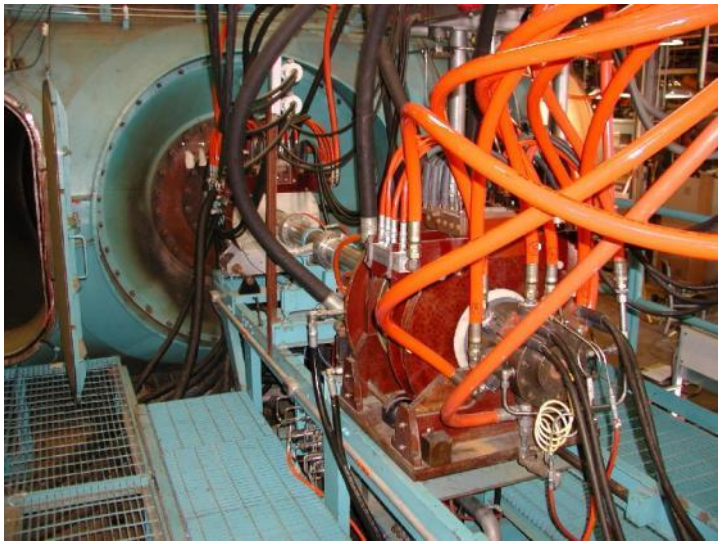






Huels (Hüls) Arc Heater

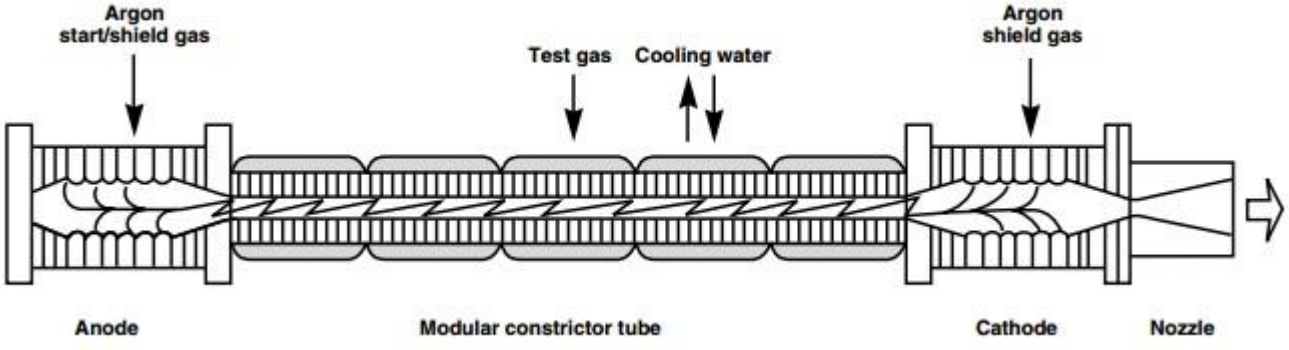


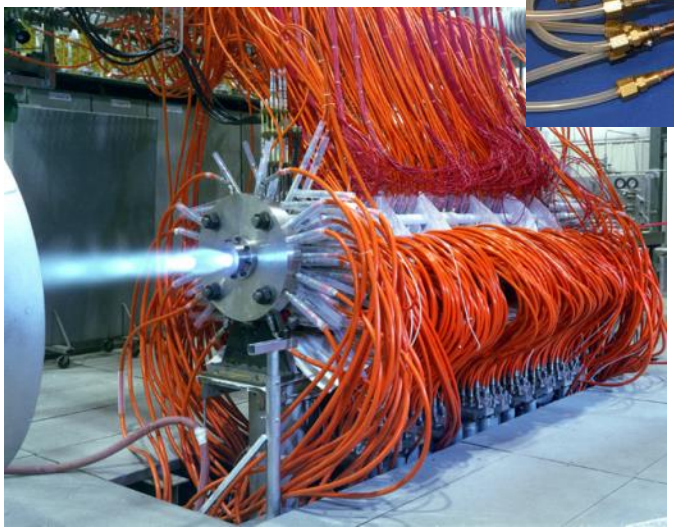


AEDC H2

Boeing LCAT

Segmented Arc Heaters

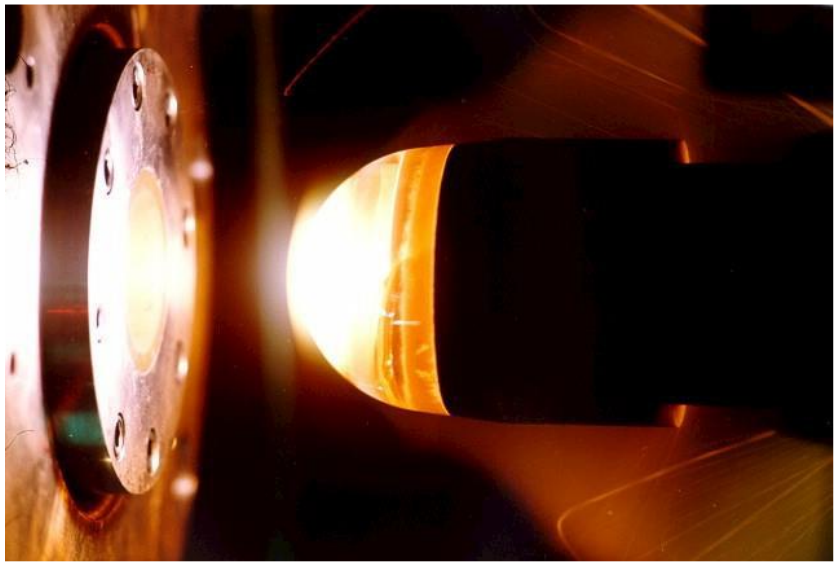


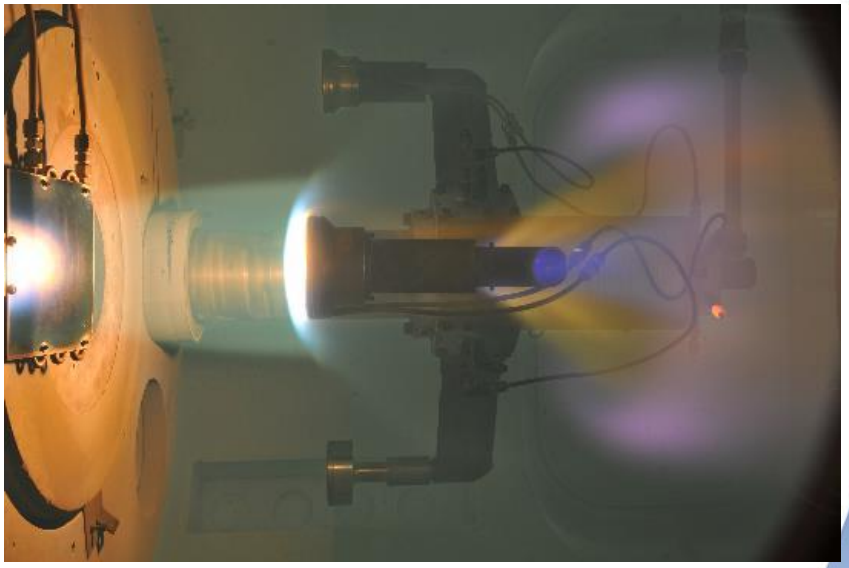


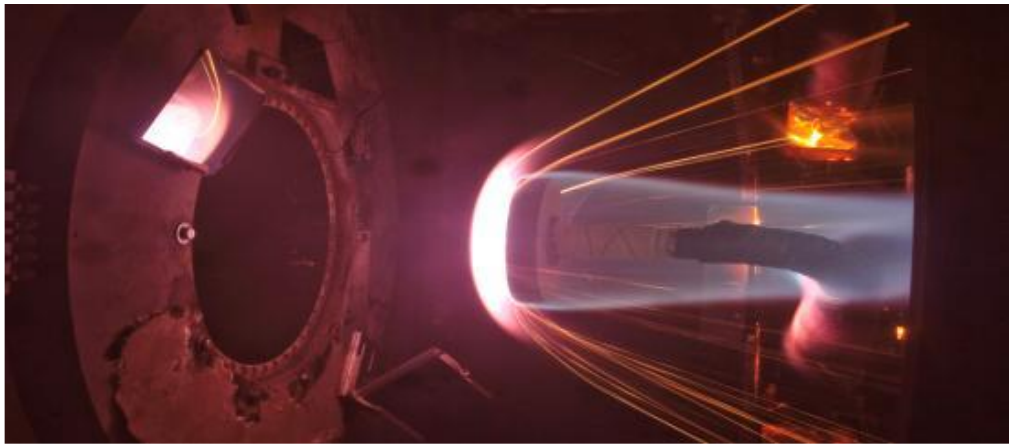
AEDC H3

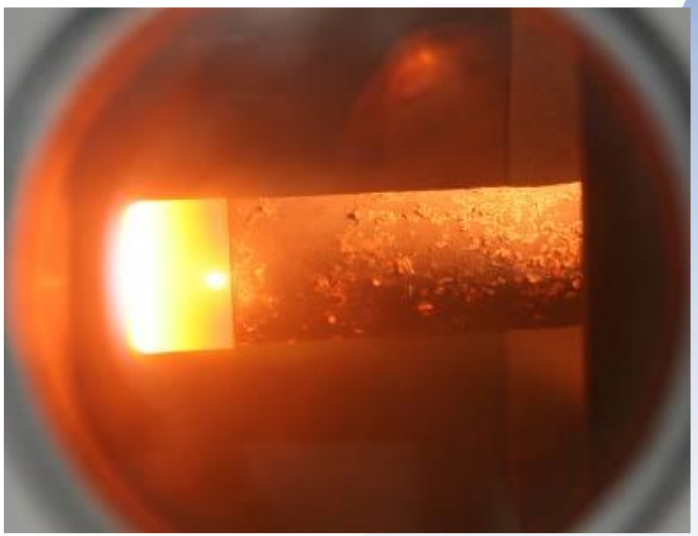
Ames IHF

Stagnation Type Testing

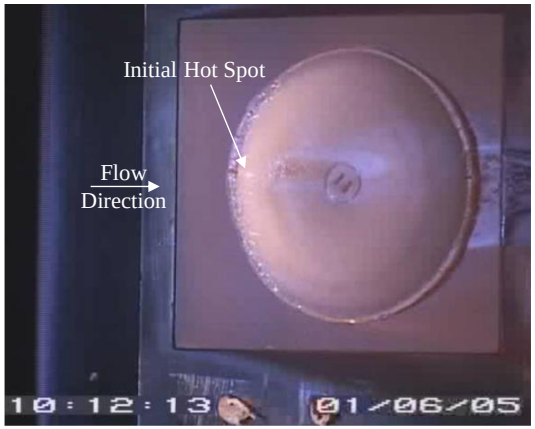


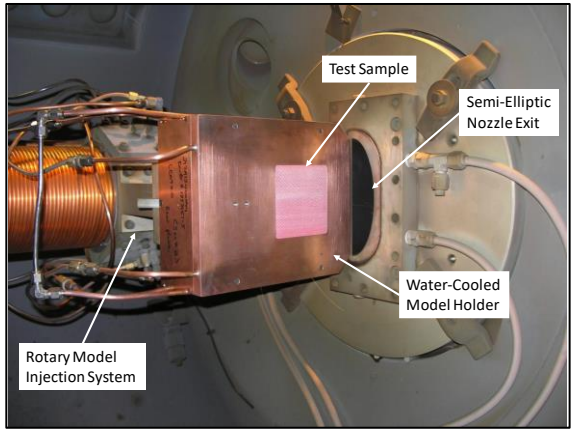


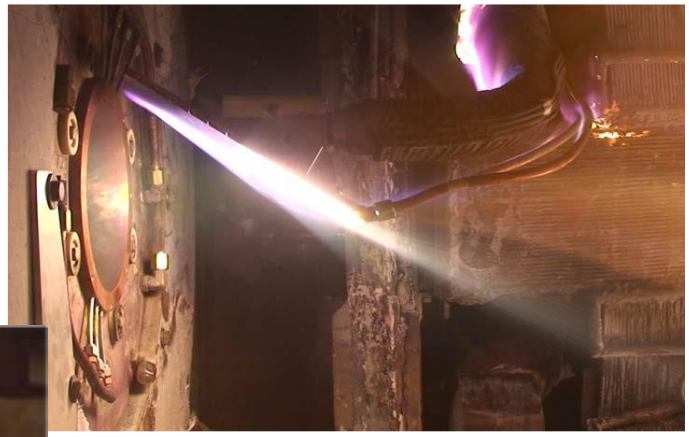


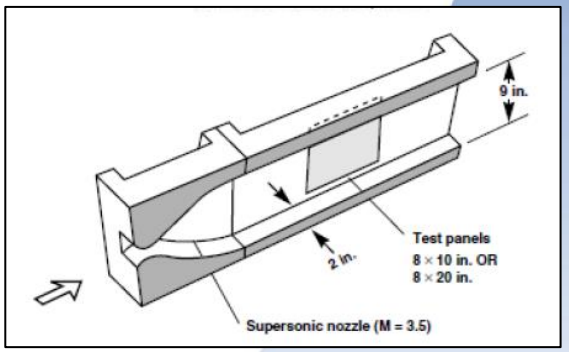


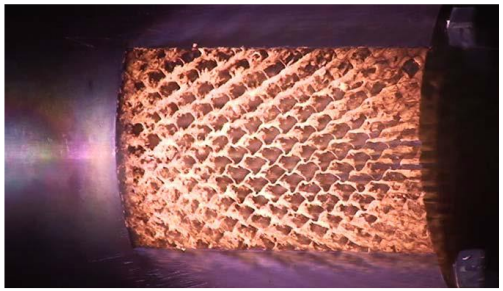
Shear Type Testing





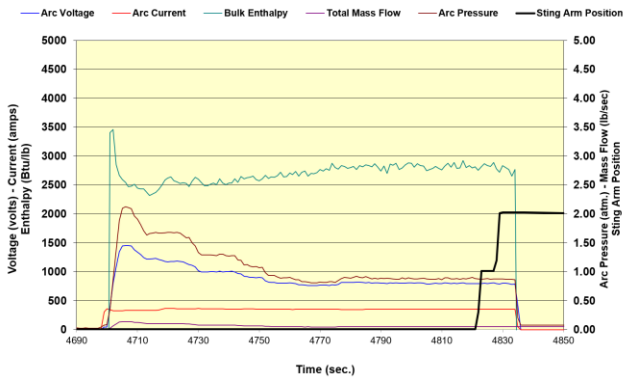






Facility Instrumentation

Facility Conditions

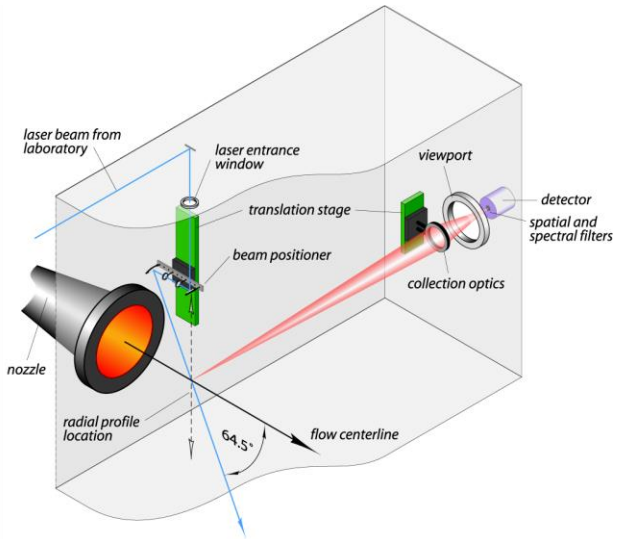


Bulk Enthalpy Calculation

$$Ho = \frac{E * I * C_1 - C_2 * CW * C_p * \rho * \Delta T}{M_{Total}}$$

Ho = Total bulk enthalpy, (MJ/kg)
E = Arc heater voltage, (Volts)
I = Arc heater current, (Amps)
C_1 = 9.48 E-4 (Btu/s.W)
C_2 = 2.23 E-3 (min.ft^3/s.gal)
CW = Cooling water flow, (LPM)
C_p = Specific heat of water, (4.2 kJ/kg K)
ρ = Water density, (1000 kg/m^3)
ΔT = Cooling water temp. difference, (K)
M_{Total} = Total gas mass flow, (kg/s)

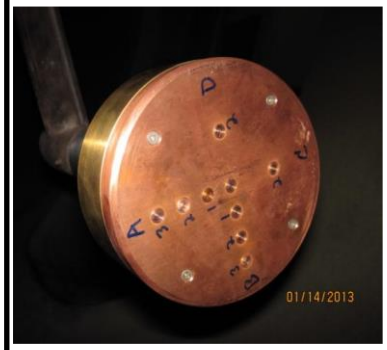
Non-Intrusive Measurements

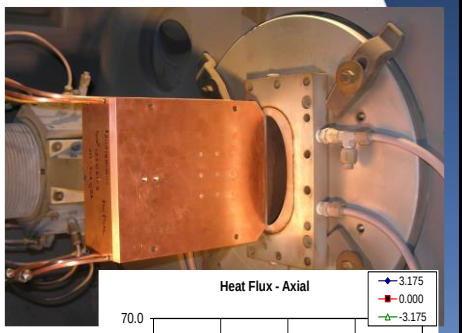


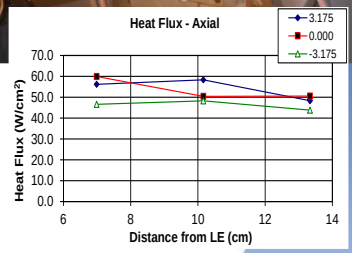
Measured properties:
- Temperature
- Velocity
- Atomic density

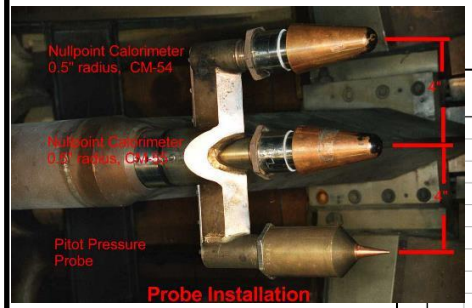
Derived by analysis:
- Total enthalpy
- Modal distribution

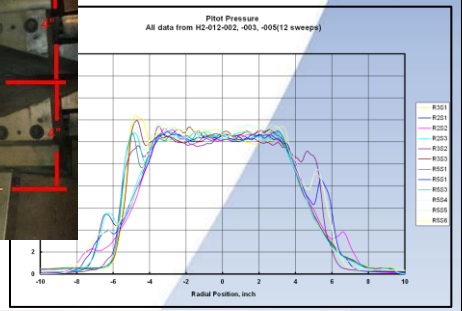
Flow-field Probe Measurements





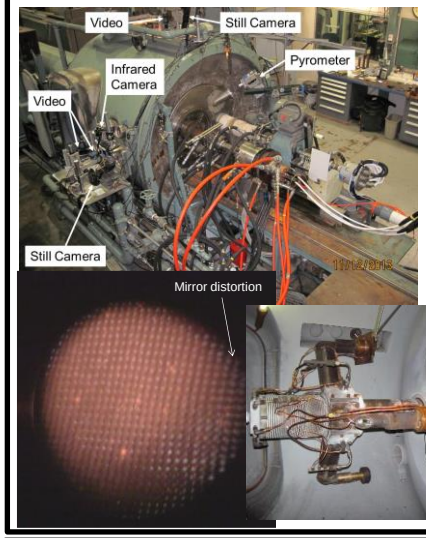


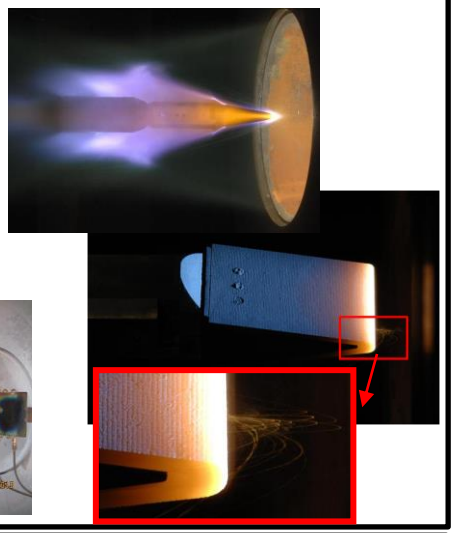




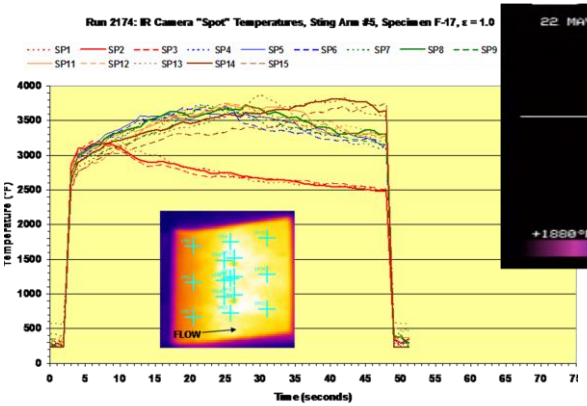
Model Instrumentation

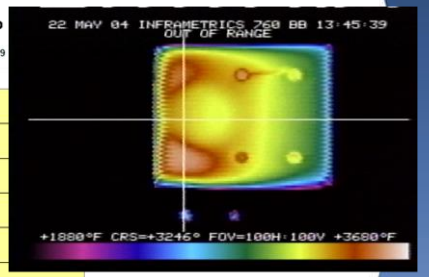
In-test Photos/Videos



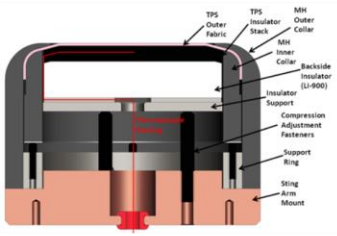


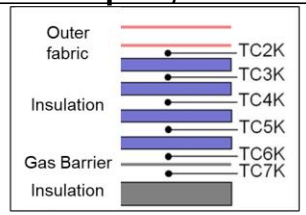
Surface Temperatures (IR camera, pyrometry)

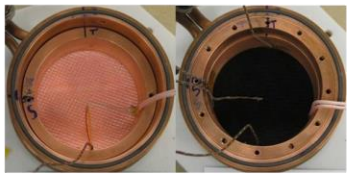


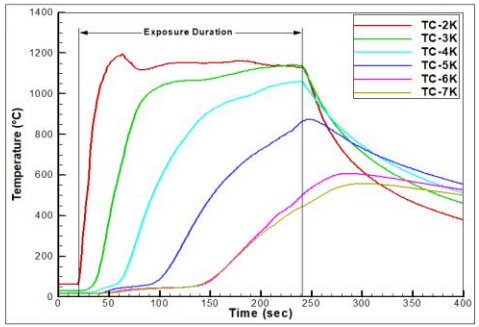


In-depth Temperatures (thermocouples, heat flux gages)

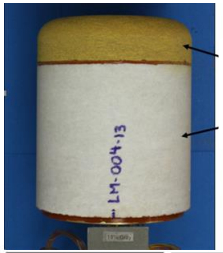


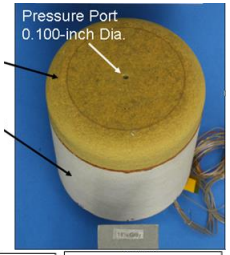


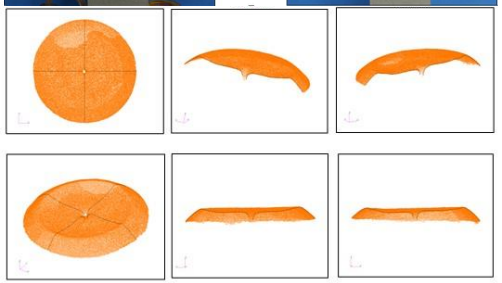


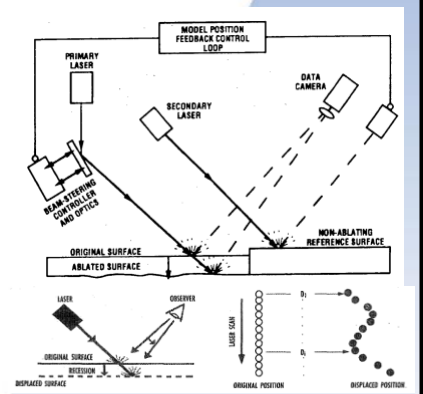


Recession/ Recession Rates

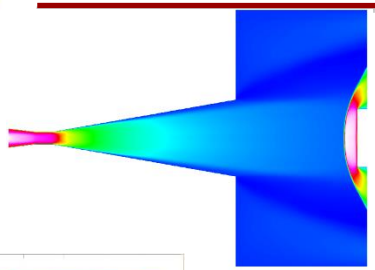


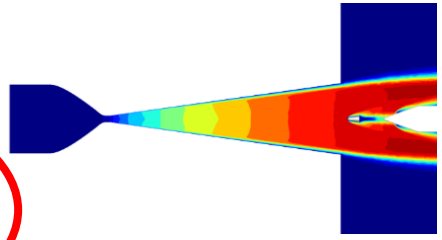




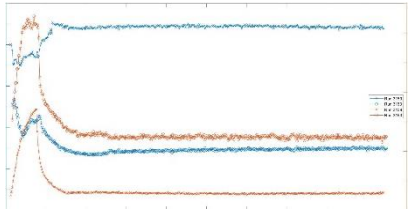


Computational Modeling





Aerothermodynamics
(i.e., CFD, correlations, etc.)



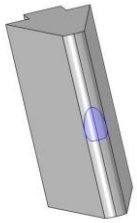
Coating
Emissivity

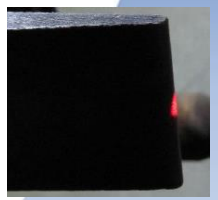
Thermocouple
Measurements

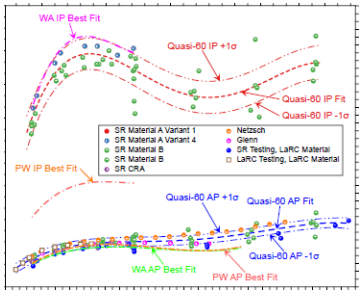
Thermal
Properties

THERMAL SIMULATION TOOL

FAR Pyrometer
Measurements

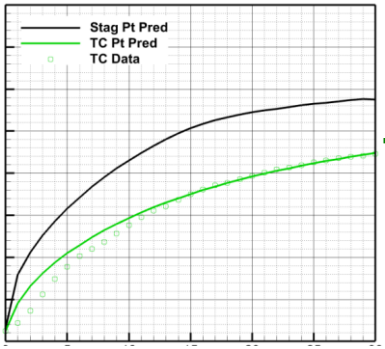






Mass
Properties

Uncertainties

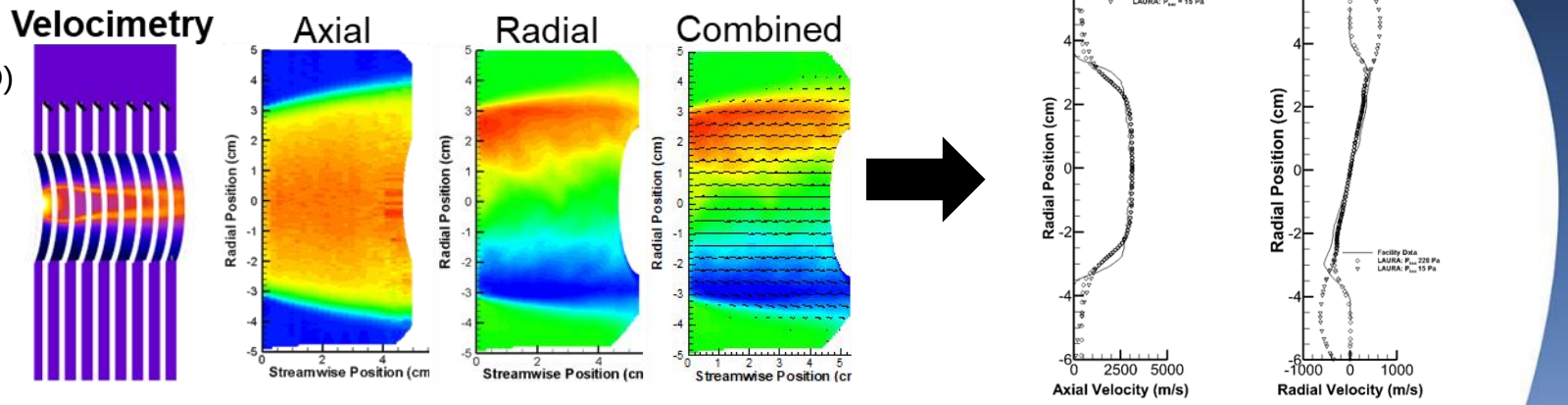


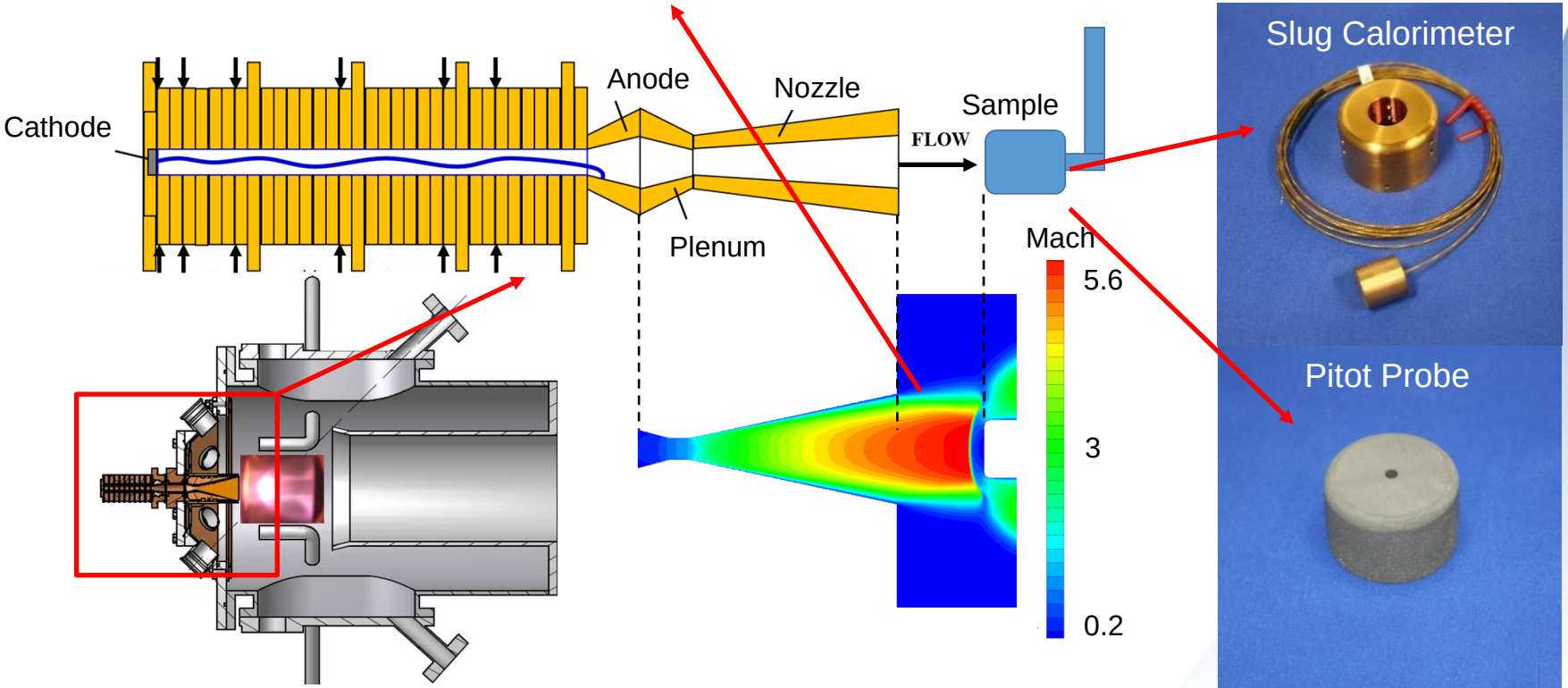
Thermal Model
Correlation

KEY
FOCUS
AREAS

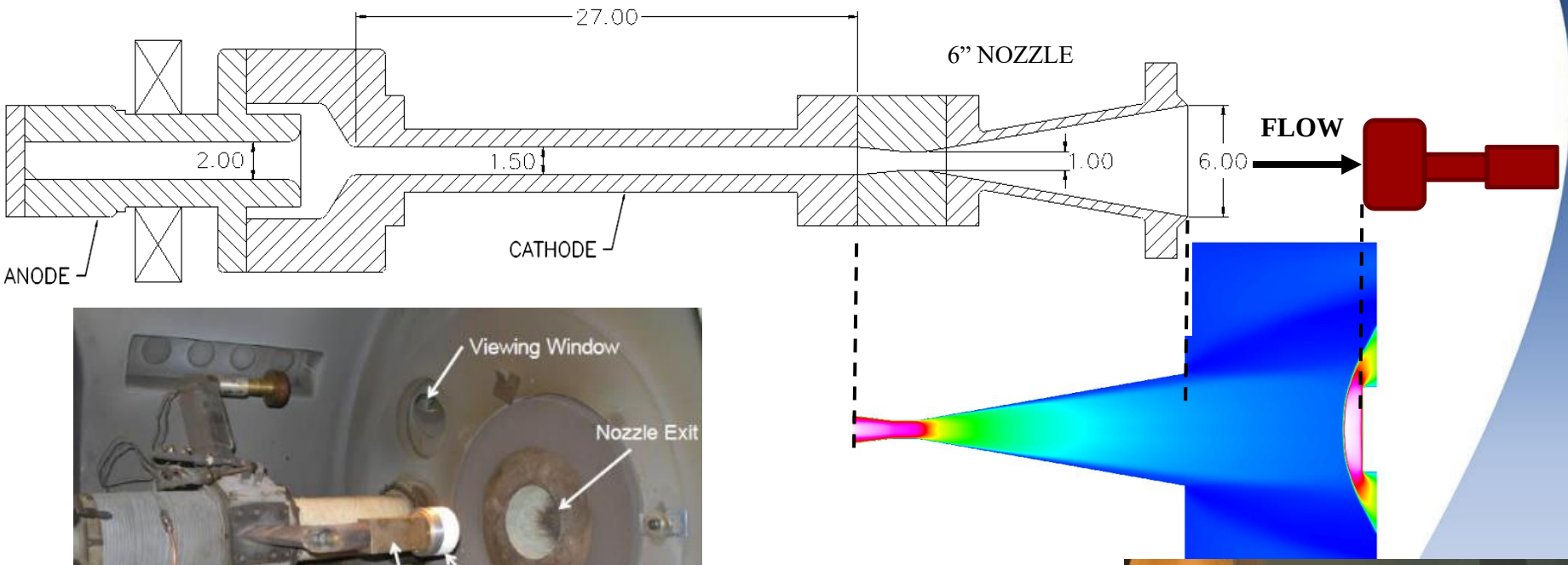
Langley Computational Example

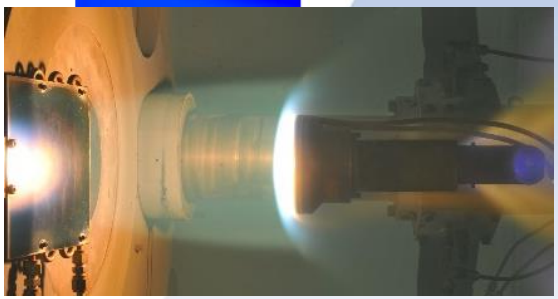
Nitric Oxide (NO) PLIF Molecular Tagging and Doppler Velocimetry



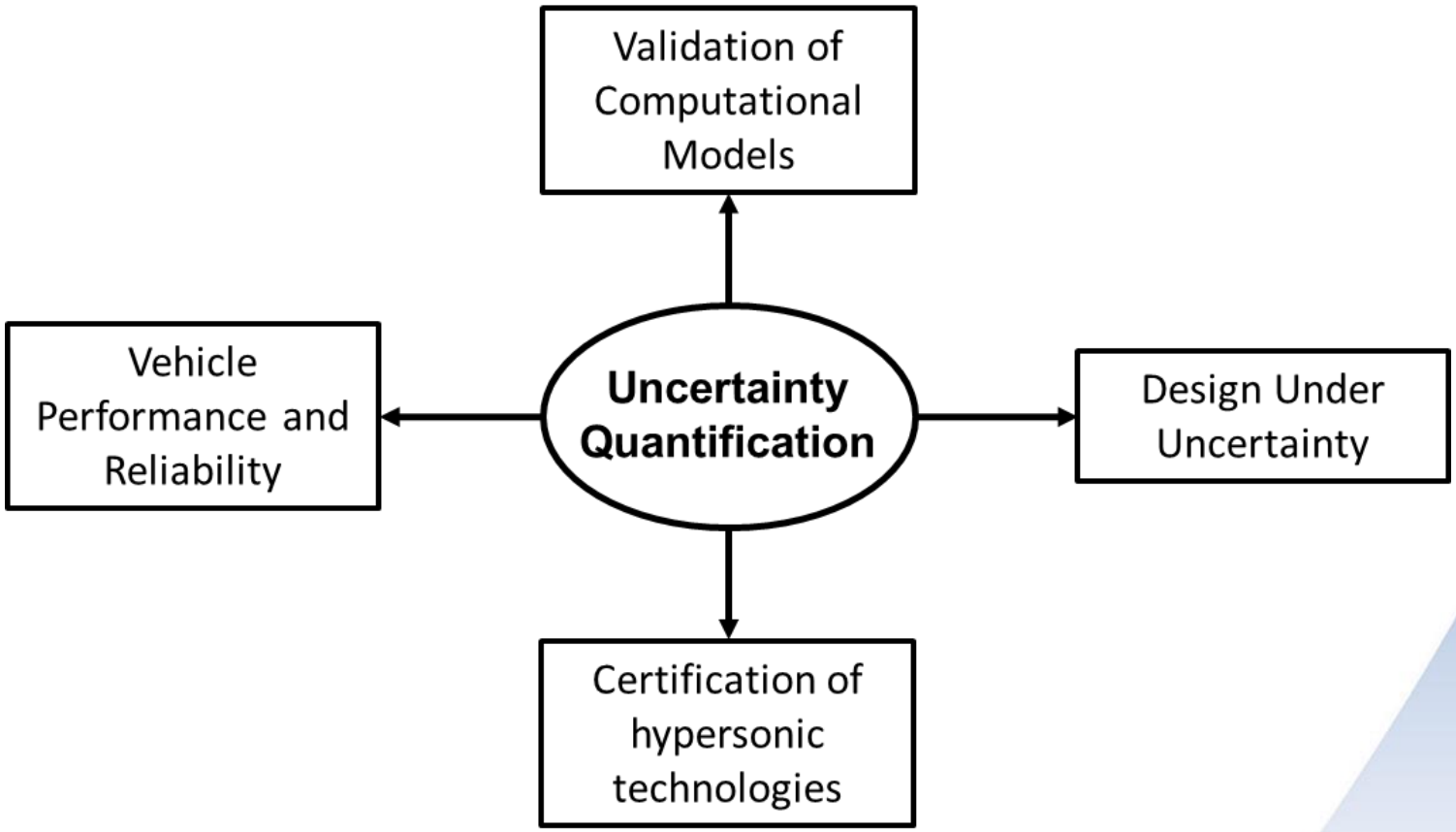


Langley Computational Example
HyMETS

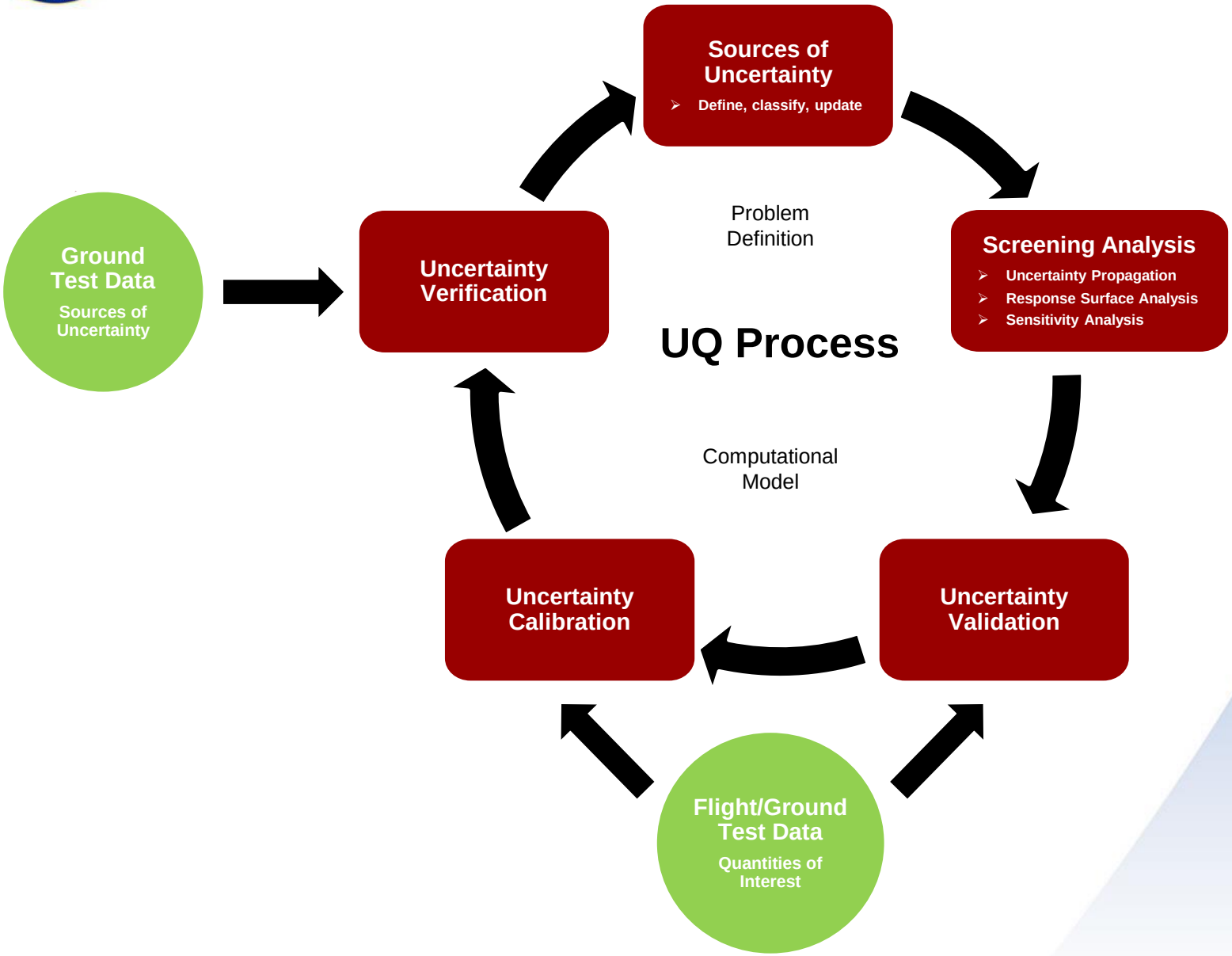




Benefits of Uncertainty Quantification (UQ)



Uncertainty Quantification Process



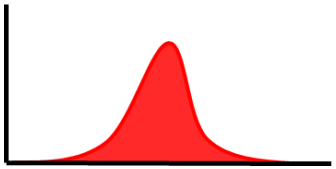
Uncertainty Classification

Aleatory Uncertainty

Definition: Inherent variation of a physical system

Key Features:
- Naturally random
- Mathematically represented by a probably distribution
- Uncontrollable and well-understood
- Sometimes referred as irreducible

Examples:
- Water cooling flow rate and ΔT
- Arc heater total pressure
- Arc heater power (current and voltage)
- Model stagnation pressure (temporal variability)
- Test gas injection flow rates
- Other quantifiable ground/flight data



PDF

Epistemic Uncertainty

Definition: Lack of knowledge of a physical system

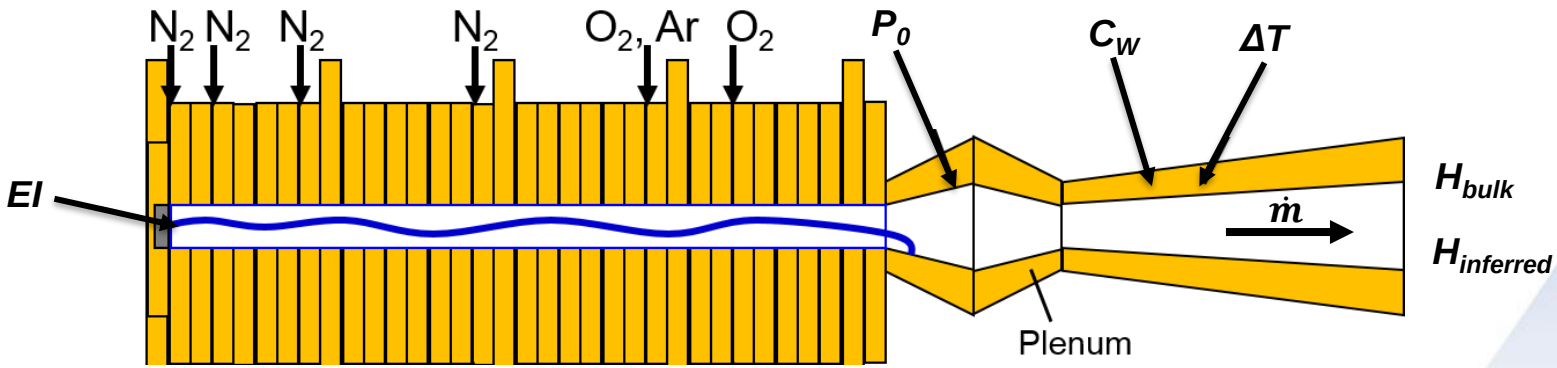
Key Features:
- Typically modeled using intervals
- Limited experimental data or expert opinion
- Deficiency, negligence, incomplete information
- Numerical error of a physical model
- Sometimes referred as reducible

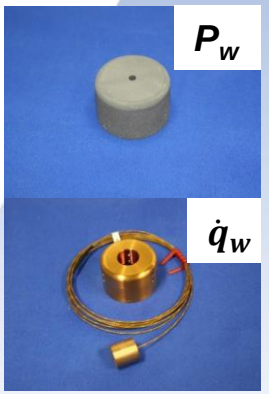
Examples:
- CFD model approach
- Discretization error in temporal/spatial domains
- Arc-jet/model instrumentation bias errors
- Test model surface properties (i.e., catalysis)
- Deficiency in the assumptions of engineering correlations

Interval

Sources of Uncertainty

- **Arc Heater/Facility**
  - Arc voltage and current
  - Plenum total pressure
  - Arc water ΔT
  - Arc water flow rate
  - Gas injection flow rates: N_2, O_2, Ar
  - Bulk (average) enthalpy
  - Inferred (peak) enthalpy
- **Flow-field Probes**
  - Slug calorimeter
  - Pitot probe
- **CFD Model**
  - Transport properties
  - Surface Catalysis
  - Thermochemistry





Surface Property: Catalytic Recombination Efficiency

- **Dissociated species in hypersonic flow**
- **Recombination**
  - Includes flow and surface
  - Can be exothermic
  - Si + O $\Longleftrightarrow$ SiO

    ΔH = -605 Btu/mol

Heat flux:

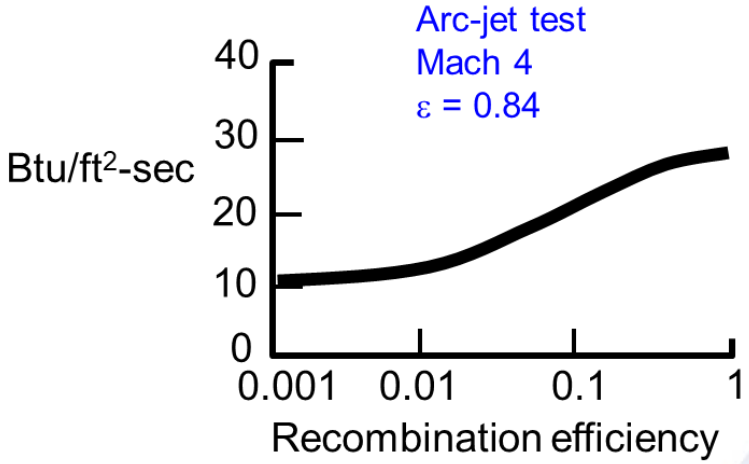
$$q_w = \underbrace{k\frac{\partial T}{\partial y}}_{\text{thermal conduction}} + \underbrace{\rho \sum_i D_{im} h_i \frac{\partial c_i}{\partial y}}_{\text{species diffusion}}$$

Non-catalytic

q = 10.1 Btu/ft²-sec

Catalytic

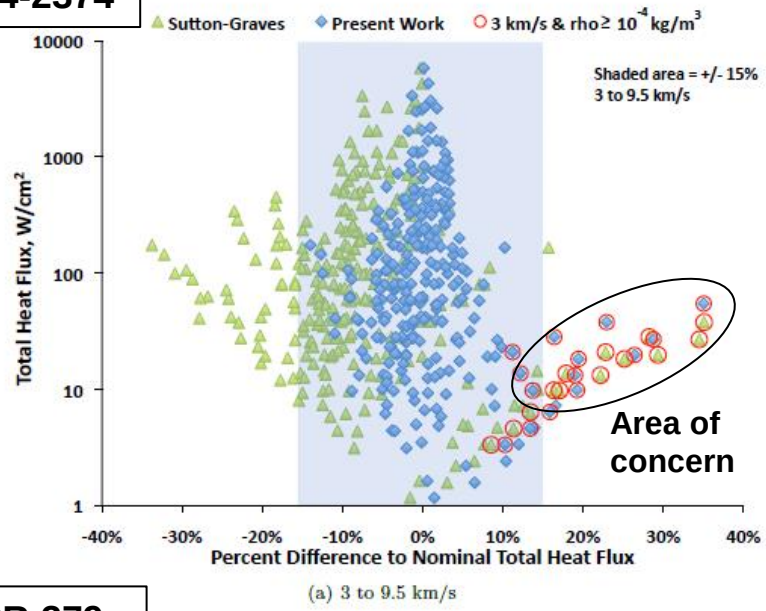
q = 28.3 Btu/ft²-sec



Ronald. K. Clark, George. R. Cunnington, Jr., and Karl. E. Wiedemann, "Determination of the Recombination Efficiency of Thermal Control Coatings for Hypersonic Vehicles", Journal of Spacecraft and Rockets, Vol. 32, No. 1, Jan.-Feb. 1995.

Flow Property: Total Freestream Enthalpy

AIAA 2014-2374



(a) 3 to 9.5 km/s

NASA-CR 379

SUMMARY OF COMMERCIAL FACILITIES

ORGANIZATION	PLASMA HEAD	P_{t_1} (ATM) min	P_{t_1} (ATM) max	$\dot{q}$ max 1.25 in. FF h = 5,000	T_{fs}	INSERTIONS	SUBJECTIVE RATING (1)	MOTION PICTURES
Giannini Scientific Corporation	Giannini	0.02	0.36	165	Yes	3	E	Yes
AVCO Corporation	AVCO	0.013	0.13	55	Yes	4	E	Yes
General Dynamics	Vidya Rotating Arc	0.5	35	170	No	4	M	--
Goodyear	Vidya Rotating Arc	0.1	1.0	170	No	8-13	M	Yes
Martin Company	Modified Giannini	0.005	0.2	85	Yes	3	M	Yes
Boeing Company	Boeing Rotating Arc	0.1	0.5	95	No	1	M	Yes
North American Aviation	Modified Thermal-Dynamics	0.3	5.5	300	No	2	M	Yes
General Electric Space Technology Center	Tandem-Gerdien	1.0	1.6	130	Yes	1	M	No
Douglas	Radial Arc Jet	0.2	14	200 (2)	Yes	1	S	Yes
University of Chicago	Air Stabilized Arc	0.1	1.0	subsonic	Yes	1	S	Yes
Space Dynamics	Space Dynamics	0.01	100	?	No	1	S	Yes
Johns Hopkins University	JH Rotating Arc	1.5	2.6	130	No	1	S	No
McDonnell	McDonnell Vortex Stabilized	0.3	2.0	240	No	1	S	No
Republic Aircraft	Thermal-Dynamics	1	5.0	subsonic	Yes	6	S	Yes

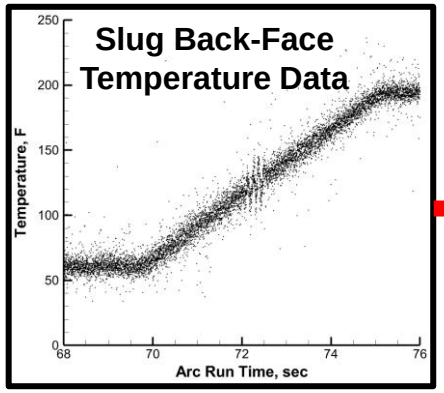
Sutton-Graves Correlation:

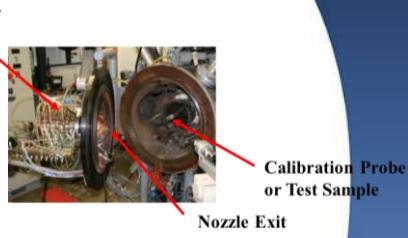
$$q_w = k\sqrt{\frac{\rho}{R_N}}V^3$$

$$H_{02} = C\sqrt{\frac{R_N}{P_{02}}}q_w$$

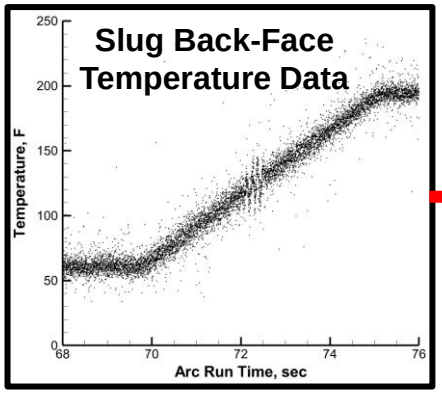
Measurement: Deduced Slug Calorimeter Stagnation Heat Flux

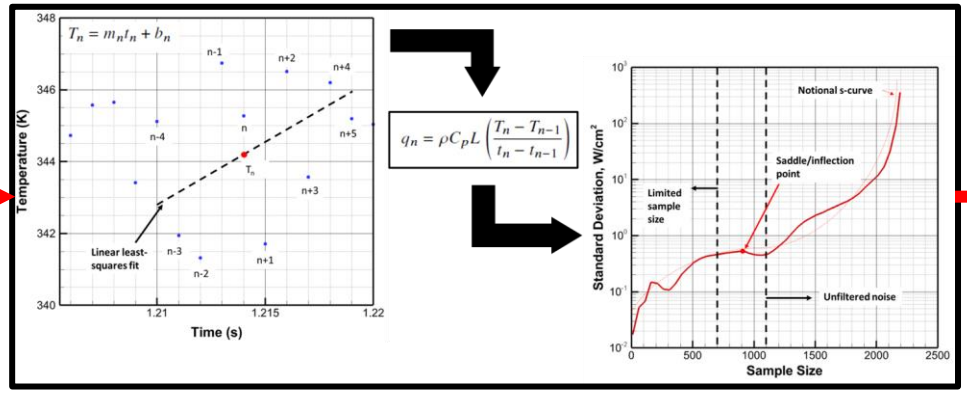
State-of-the-art approach

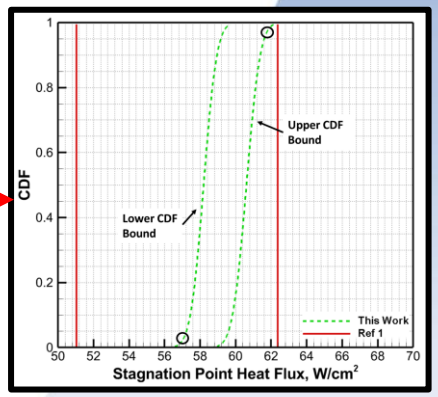




Alternative approach

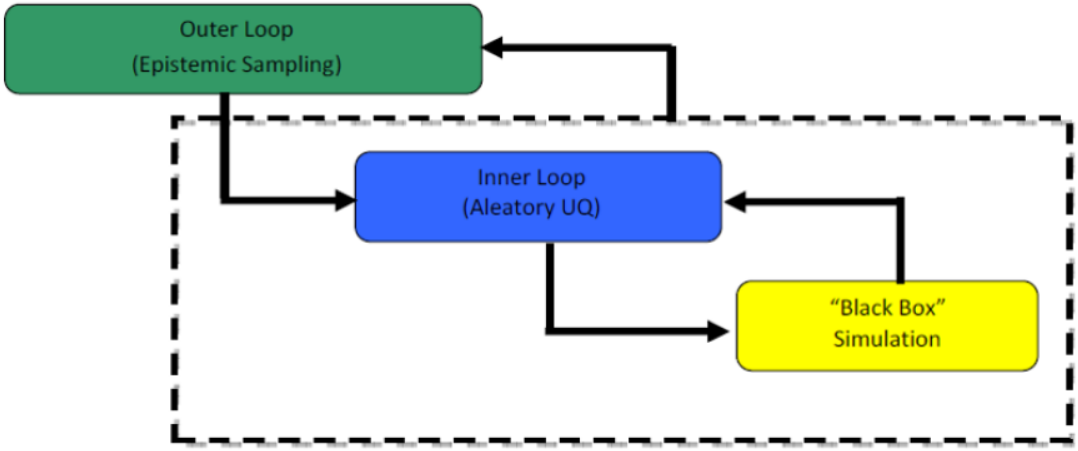


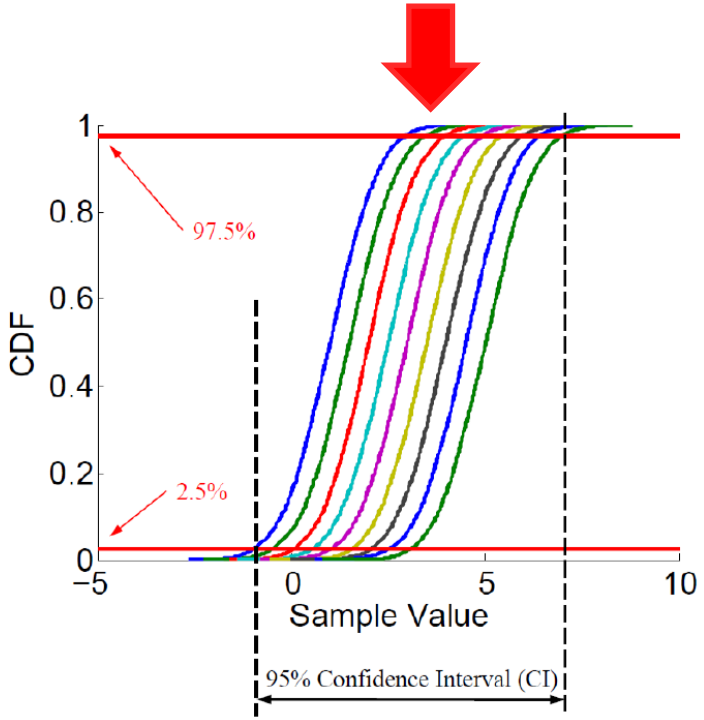




Uncertainty Propagation

- **Objective**
  - Evaluate computational model within domain spanned by uncertain parameters
- **Common Approaches**
  - Monte Carlo
  - Quasi-Monte Carlo
  - Importance Sampling
  - Response Surface
  - Polynomial Chaos
- **Outcome**
  - Quantify variation in output quantity of interest

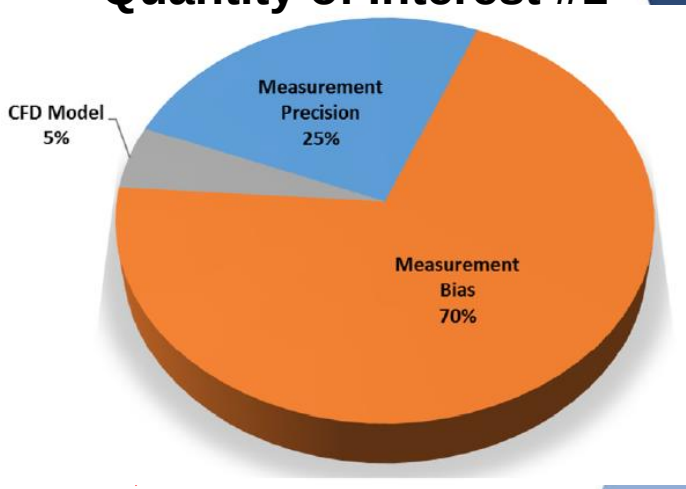


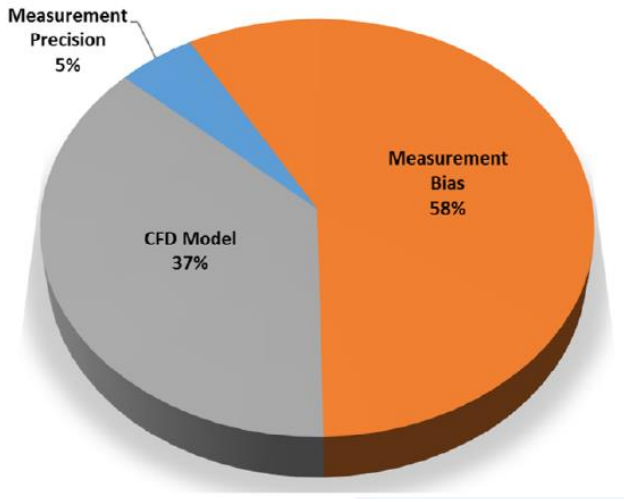


Sensitivity Analysis

- **Objective**
  - Evaluate sensitivity information across uncertainty domain
- **Common Approaches**
  - Entropy-based sensitivity
  - Sampling-based global linear regression
  - Global, nonlinear variance decomposition
- **Outcome**
  - Identify which investments to better quantify epistemic uncertainty

Quantity of Interest #1

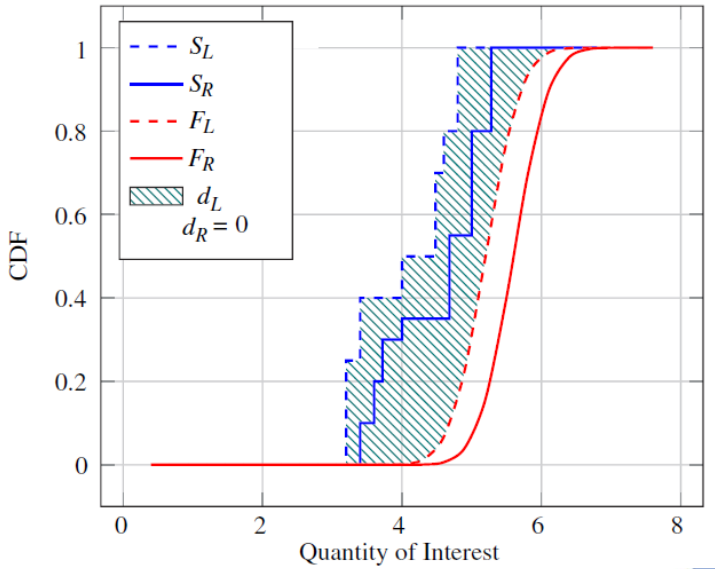


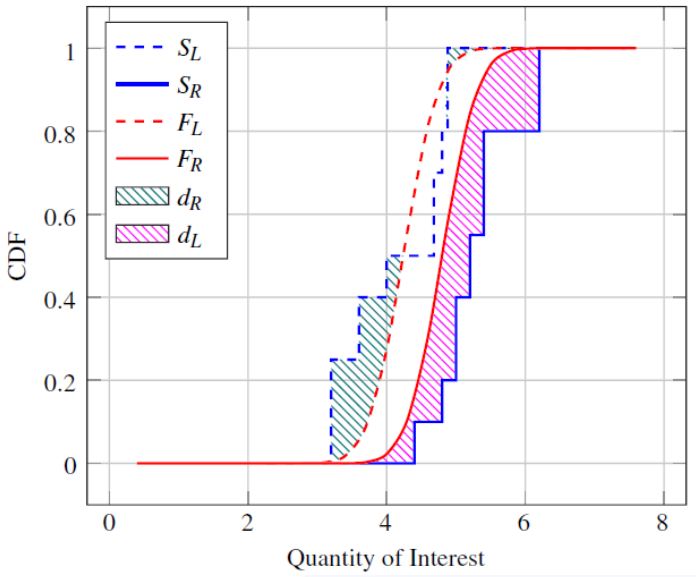


Quantity of Interest #2

Uncertainty Validation

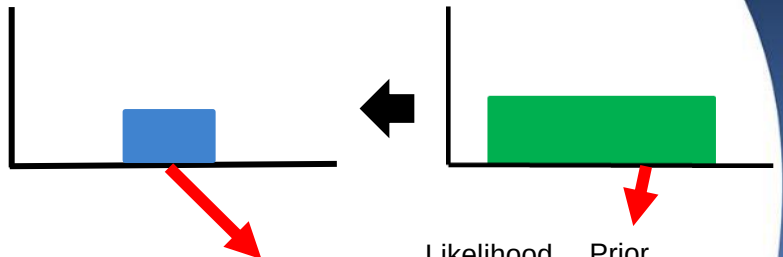
- **Objective**
  - Characterize the disagreement between the quantitative model predictions and relevant experimental data
- **Common Approaches**
  - Mean-based comparisons
  - Area-based comparisons
  - Hypothesis testing
- **Outcome**
  - Identify whether investments should be made to better quantify epistemic uncertainty





Uncertainty Calibration

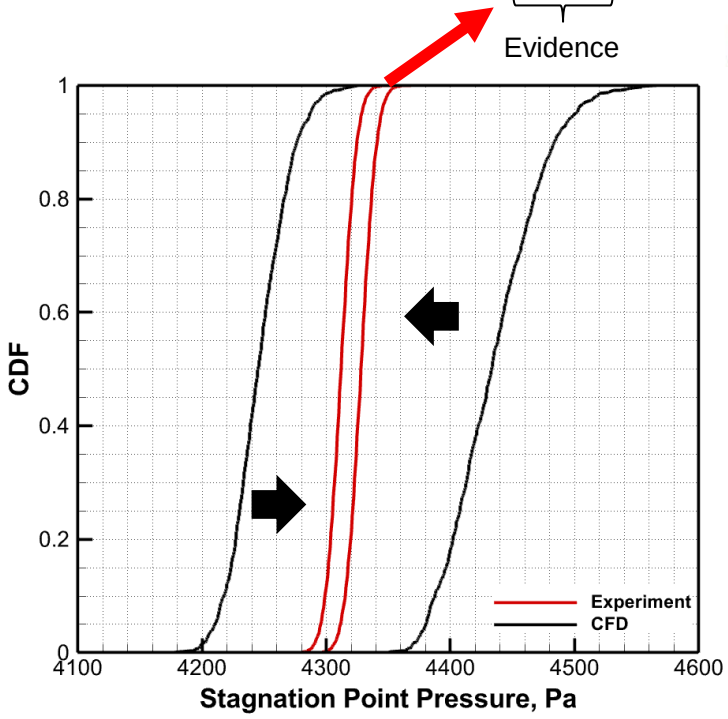
- **Objective**
  - Minimize the disagreement between the quantitative model predictions and relevant experimental data
- **Common Approaches**
  - Markov Chain Monte Carlo
  - Neural Networks
  - Variational Inference
  - Polynomial Chaos
  - Support Vector Regression
  - Kriging
- **Outcome**
  - Estimate uncertain parameter input distributions or intervals



Bayes' Theorem:

$$P(\boldsymbol{c}|E) = \frac{P(E|\boldsymbol{c})P(\boldsymbol{c})}{P(E)}$$

Posterior | Likelihood | Prior | Evidence



Concluding Remarks

- Arc tests are designed to simulate a combination of key flight conditions so that the resulting material and/or system design performance can be accurately assessed
- Arc jets have a unique test duration capability to achieve relevant thermal soak conditions in support of computational model development
- Uncertainty quantification of arc jets and other ground test facilities provide valuable benefits for computational model development to aid hypersonic vehicle design under uncertainty and certification

BACK UP SLIDES

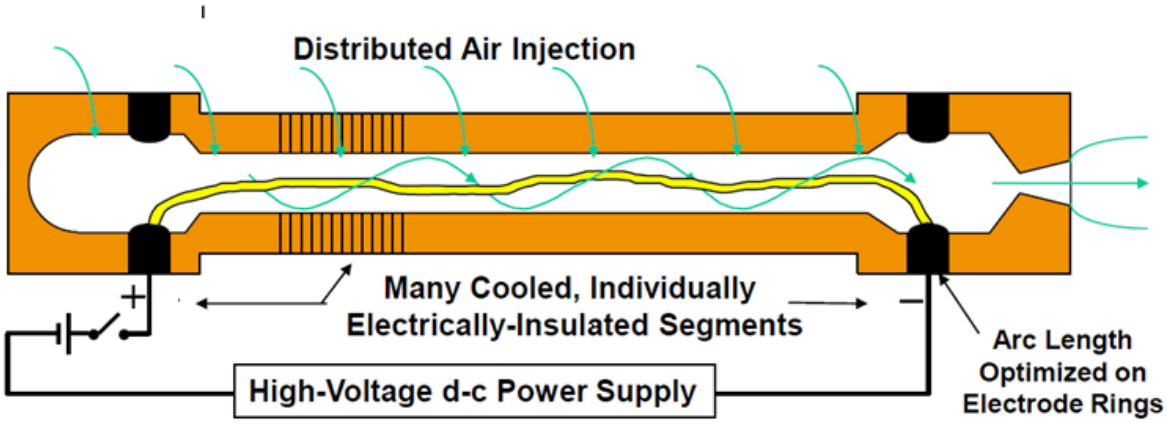
Facility Summary

Facilities in U.S.

- NASA-Ames
  - Interaction Heating Facility (IHF)
  - Aerodynamic Heating Facility (AHF)
  - Test Position 3 (TP3) (CO_2 capability)
  - Panel Test Facility (PTF)
  - Turbulent Flow Duct (TFD)
- NASA-Langley
  - Hypersonic Materials Environmental Test System (HyMETS) (CO_2 capability)
  - Arc Heated Scramjet Test Facility (AHSTF)
- Arnold Engineering Development Center (AEDC)
  - High-Enthalpy Aerothermal Test - H1 (HEAT-H1)
  - High-Enthalpy Aerothermal Test - H2 (HEAT-H2)
  - High-Enthalpy Aerothermal Test - H3 (HEAT-H3)
- Boeing
  - Large Core Arc Tunnel (LCAT)
- Several University Facilities (smaller size capability)

Former Arc Jet Facilities at JSC

Arc Heater Operation Principle



Long Arc Column → High Voltage and Performance
Column Insulation Requires Plenum Segmentation

Inductively Coupled Plasma (ICP) or Plasmatron

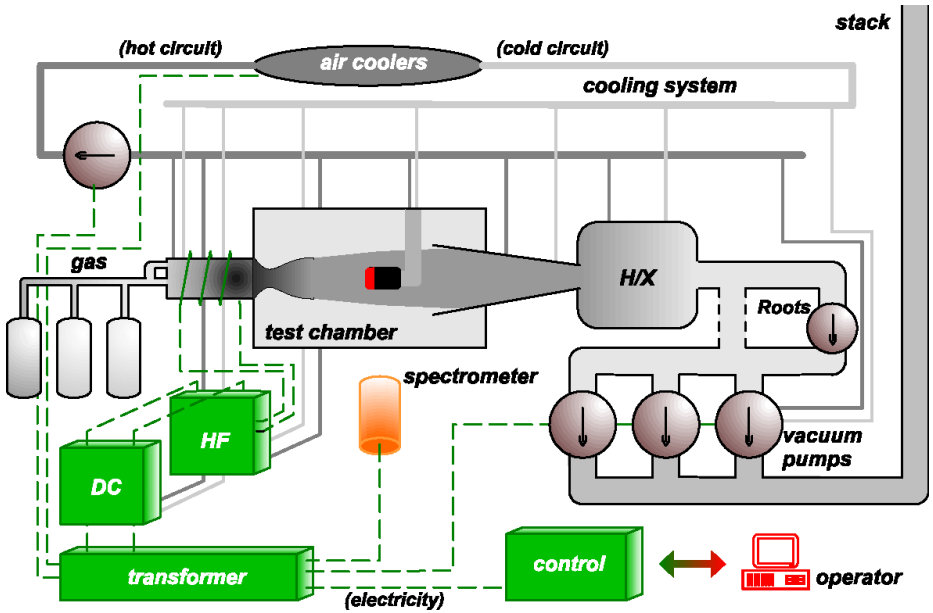
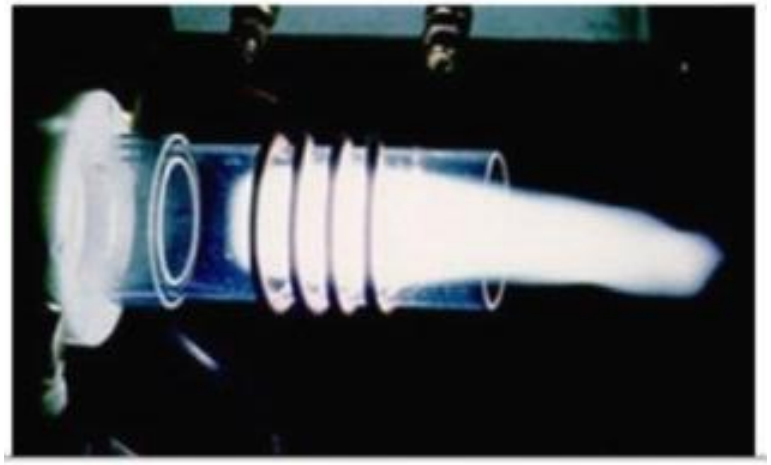
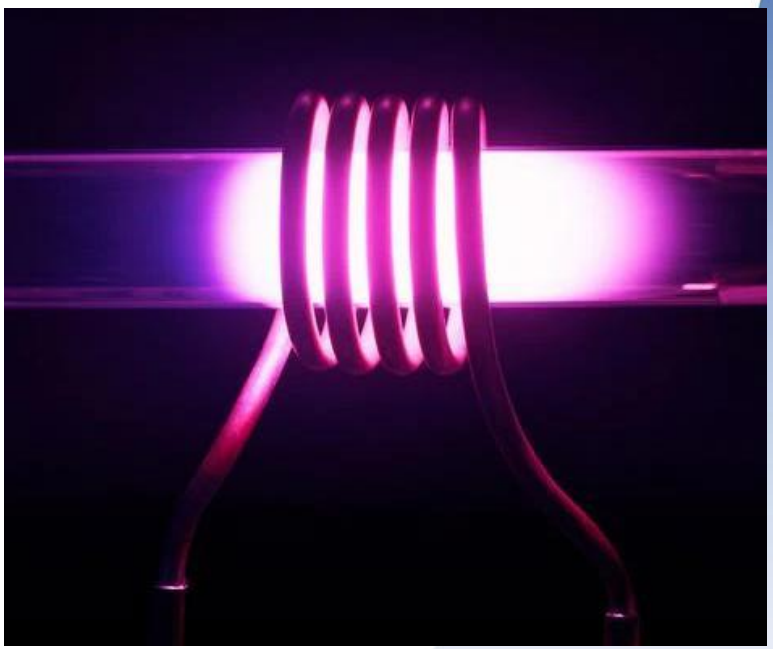
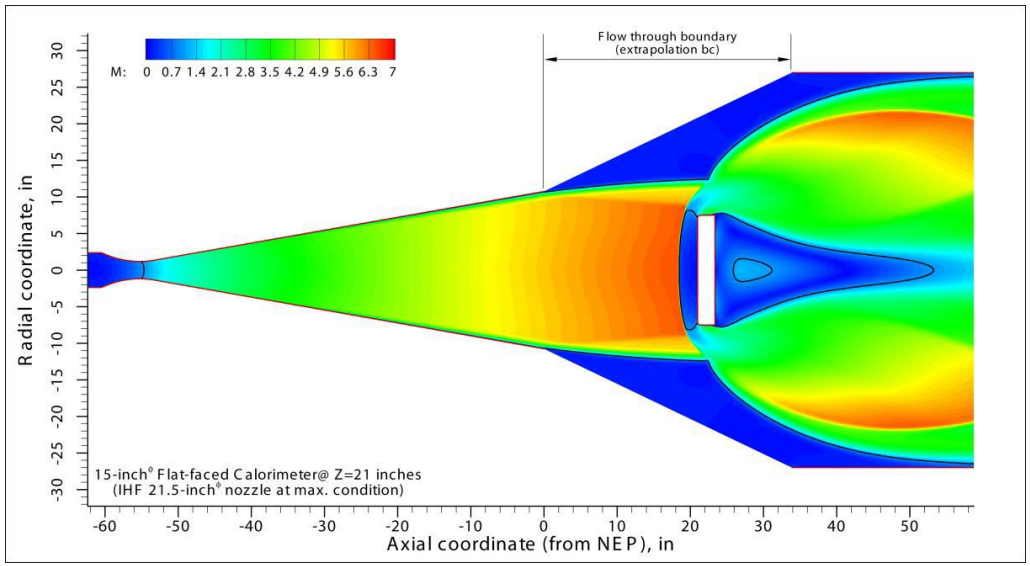


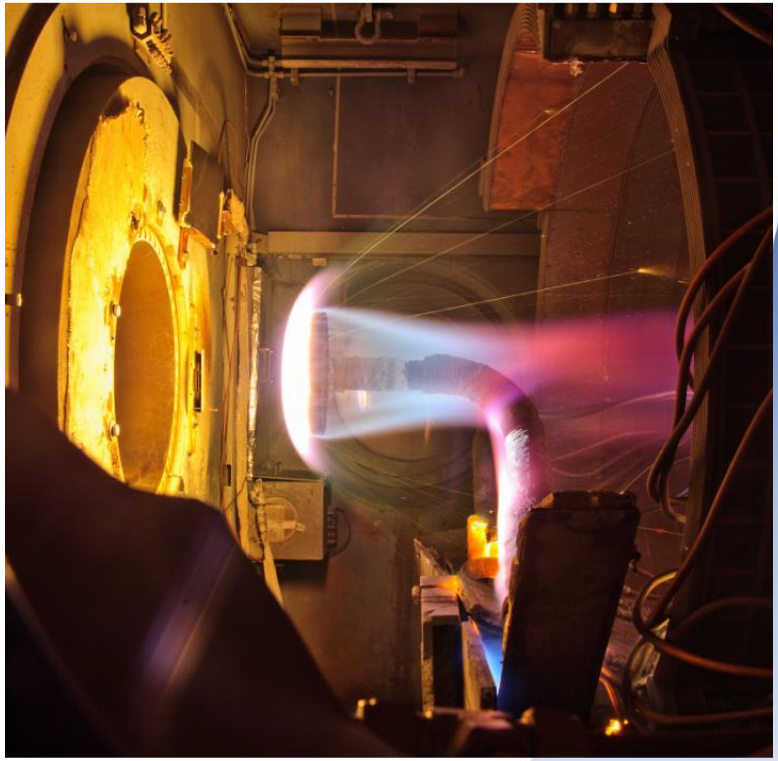
Figure 3: Plasmatron facility schematics



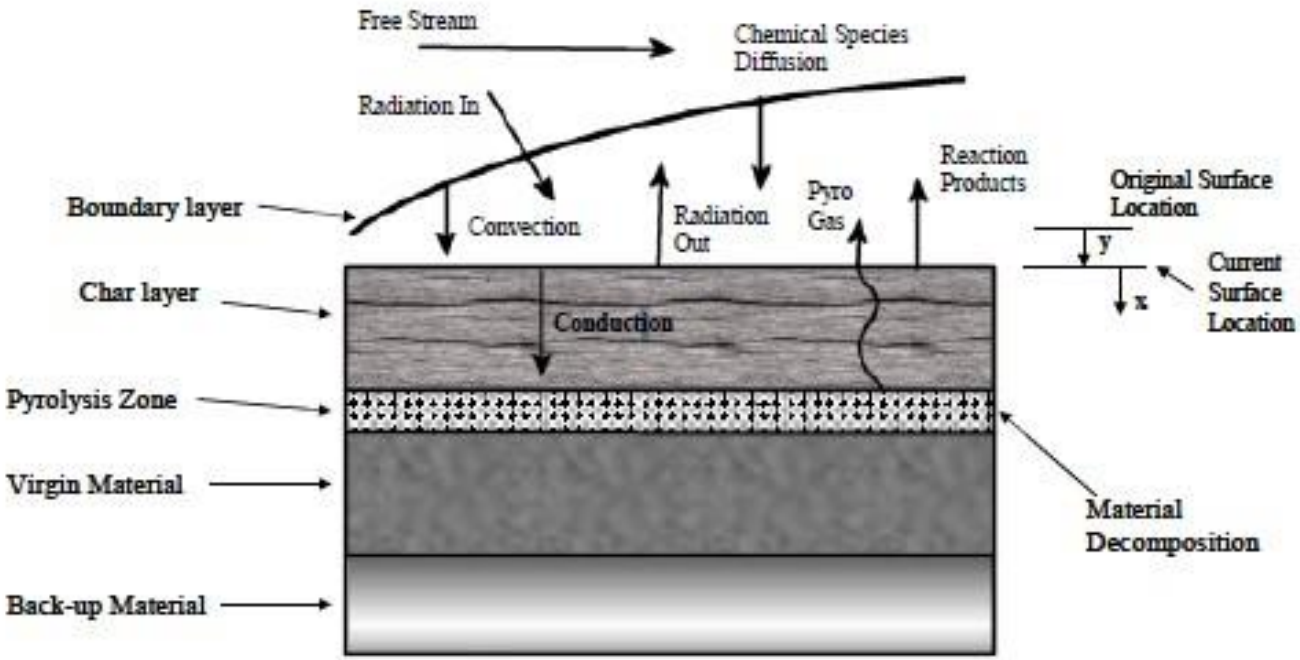


Ames Computational Example

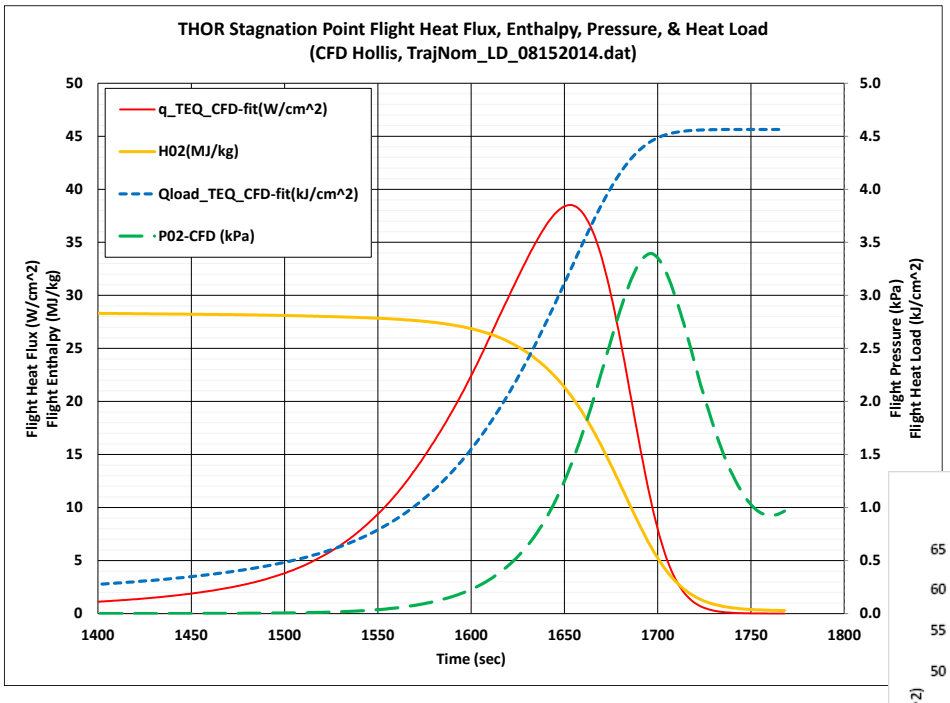


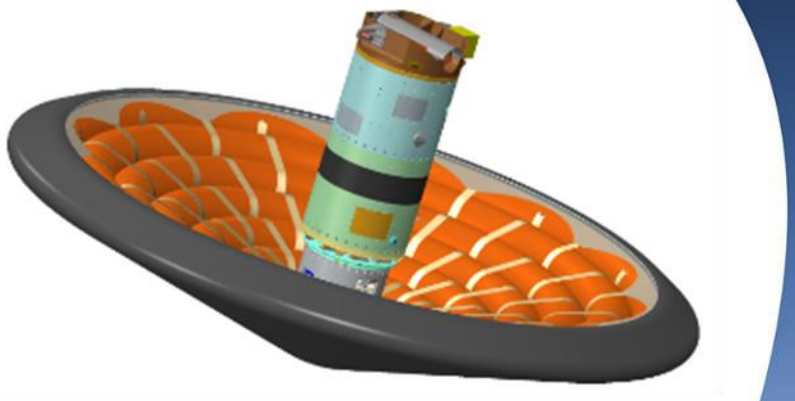


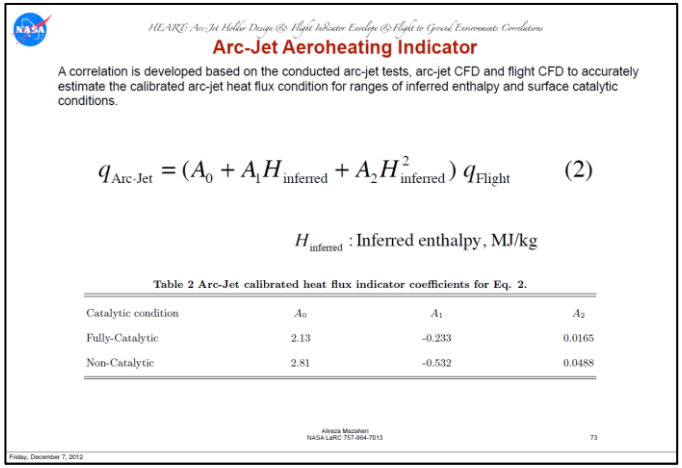
Ablation Modeling



Example: Flight to Ground Test Conditions






HEART: Arc-Jet Heller Design & Flight Indicator Envelope & Flight to Ground Environments Correlations

Arc-Jet Aeroheating Indicator

A correlation is developed based on the conducted arc-jet tests, arc-jet CFD and flight CFD to accurately estimate the calibrated arc-jet heat flux condition for ranges of inferred enthalpy and surface catalytic conditions.

$$q_{\text{Arc-Jet}} = (A_0 + A_1 H_{\text{inferred}} + A_2 H_{\text{inferred}}^2)\, q_{\text{Flight}} \qquad (2)$$

H_{inferred} : Inferred enthalpy, MJ/kg

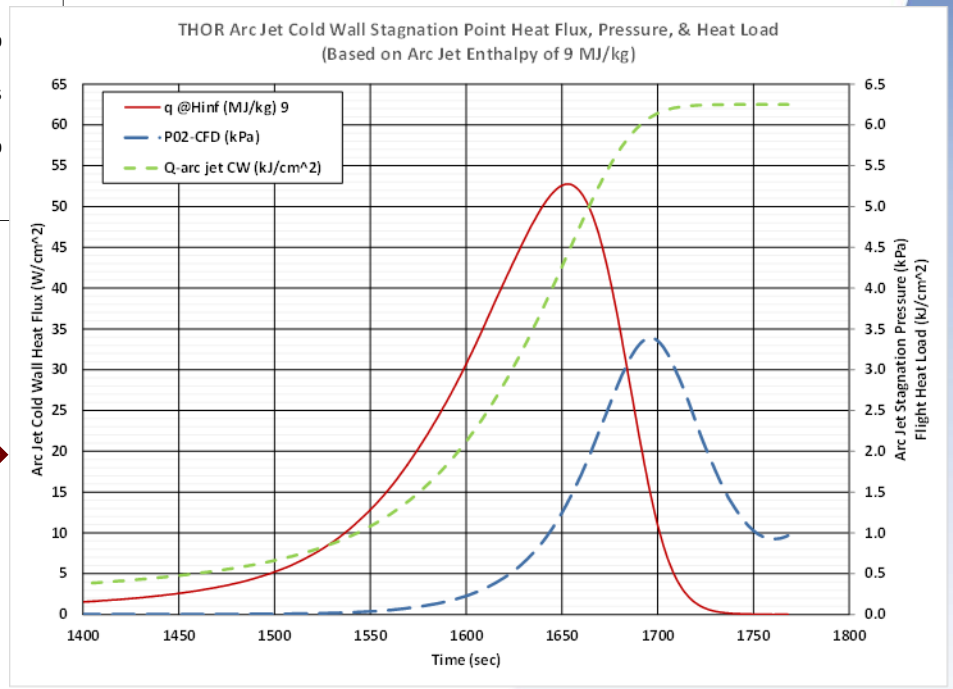
Table 2 Arc-Jet calibrated heat flux indicator coefficients for Eq. 2.

Catalytic condition	A_0	A_1	A_2
Fully-Catalytic	2.13	-0.233	0.0165
Non-Catalytic	2.81	-0.532	0.0488

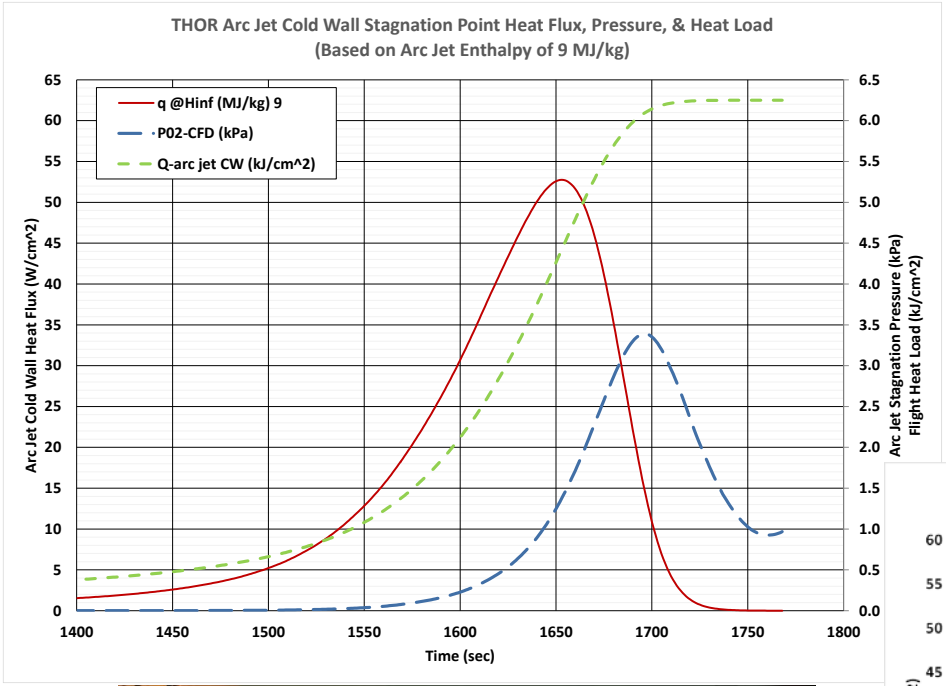
Alireza Mazaheri
NASA LaRC 757-864-7013

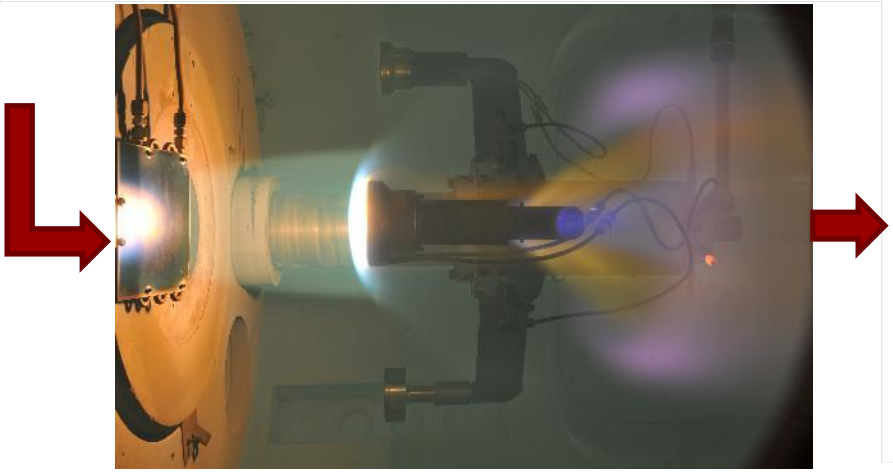
Friday, December 7, 2012

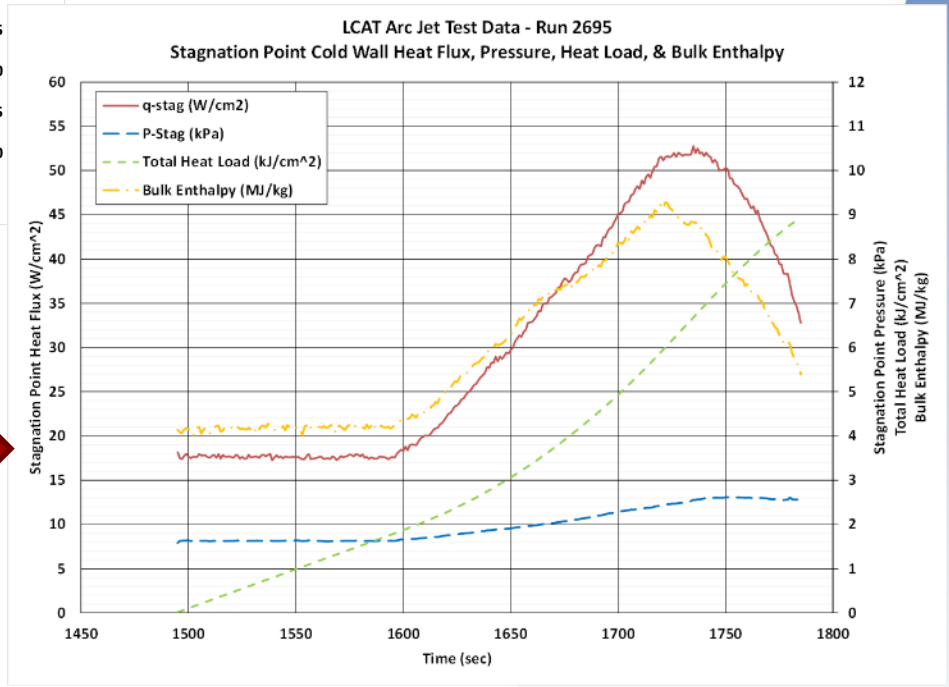
73



Example: Arc Jet Test Values

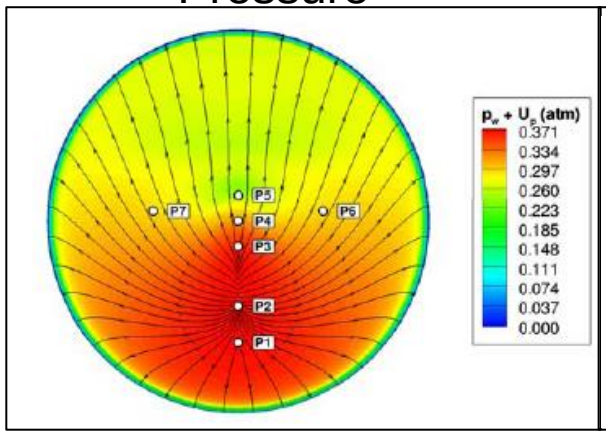




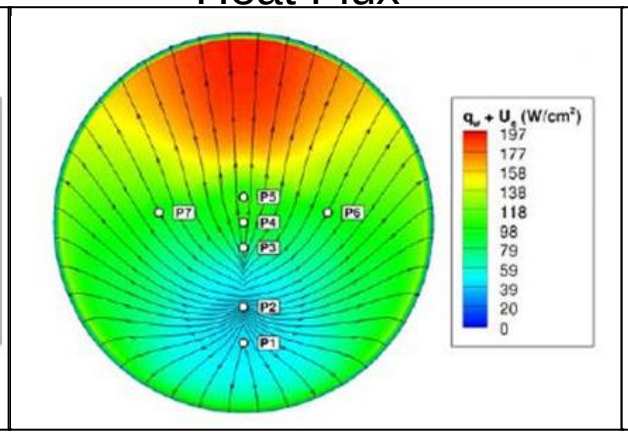


Predicted Flight vs Test Value Comparison

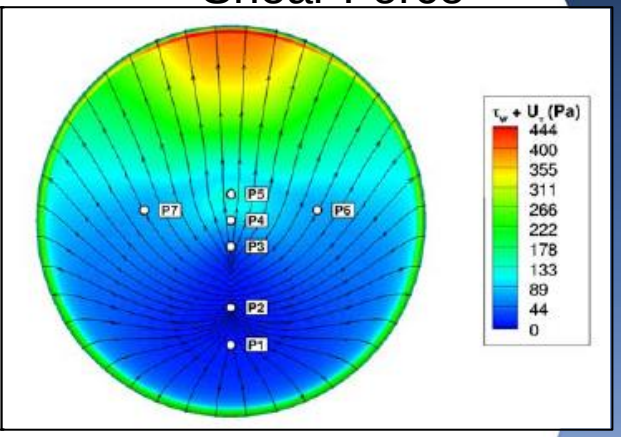
Pressure



Heat Flux



Shear Force



Parameter	Flight P5 (Shear)	LCAT - Shear	Flight P1/P2 (Stag)	LCAT - Stagnation
BL Type	Turbulent	Laminar	Laminar	Laminar
Hot Wall q_w (W/cm^2)	107	113	52	55
p_w (atm)	0.25	0.25	0.37	0.38
τ_w (Pa)	131	~400	6	0 to 30
Q_w (J/cm^2)	3591	3900 to 6600	2170	2170 to 2240
d_{hole} / δ	0.26	1.5 to 3	NA	NA
Recession (in)	0.5	0.35 to 0.7	0.22	0.12 to 0.27