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Simulation of Hypersonic Conditions Over a Blunt Body Using a Hybrid Rocket with Nitrogen Plume Cooling

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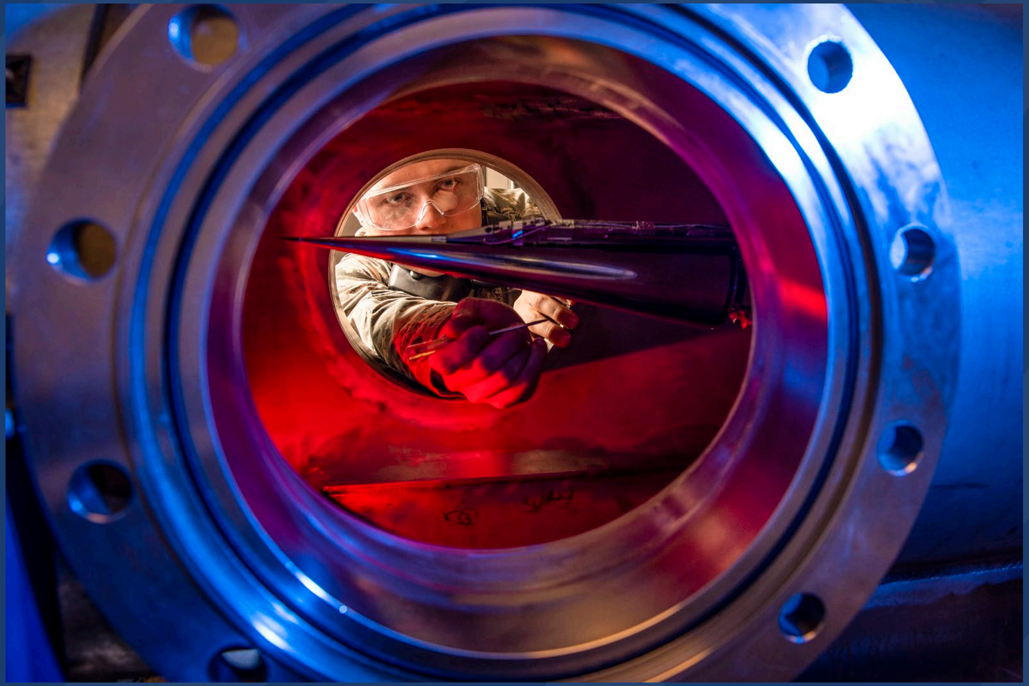
Motivation and Challenges

- Recent DoD focus on sustained stratospheric hypersonic flight
- Challenges encountered include chemical dissociation, molecular ionization, material ablation, etc.
- Reliable, ground-based simulations of high-enthalpy flows are crucial... yet current facilities are costly and access is limited

Hypersonic Test Facilities

- Expensive test costs (order of $10,000s - $100,000s a test)
- Cost and lead times make testing difficult for low TRL customers
- Unable to replicate all conditions encountered during flight
- Gu et al. [3] compared different types of hypersonic test facilities



Air Force Test Tunnel [4]

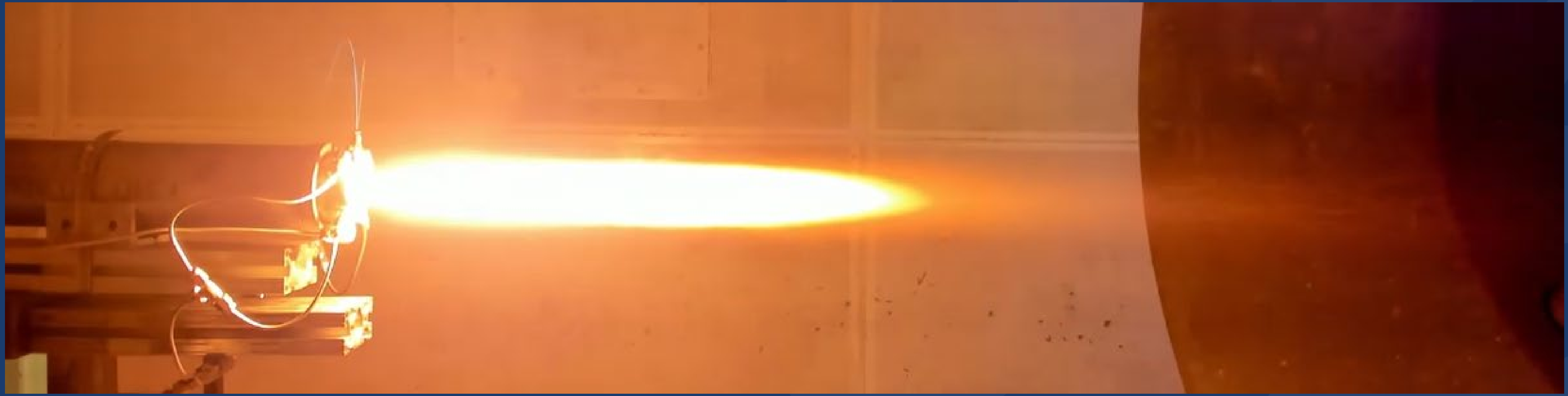
Hypersonic Test Facility Comparison

Facility Type	Test Duration	Enthalpy (Stagnation)	Flow Velocity	Temperature (Stagnation)
Continuous	Seconds to minutes (longest)	Low (< ~2–5 MJ/kg)	Low to moderate (~1 km/s max)	Low to moderate (~1000–2000 K)
Blowdown	Seconds to tens of seconds	Low (< ~2–5 MJ/kg)	Low to moderate (~1–2 km/s)	Low to moderate (~1000–2500 K)
Gun Tunnels	Tens of milliseconds (20–80 ms typical)	Low to moderate	Moderate to high (~2–5 km/s)	Moderate (~2000–4000 K)
Hotshot	Tens to hundreds of milliseconds	Moderate to high	Moderate to high (~3–7 km/s)	High (~3000–6000+ K)
Reflected Shock Tunnels	Milliseconds (typically 1–10 ms)	High (up to very high, ~5–25+ MJ/kg)	High (~4–12 km/s)	Very high (~5000–10,000+ K)
Expansion Tunnels	Microseconds to tens of microseconds (shortest)	Very high (highest achievable)	Very high (~7–15+ km/s)	Extremely high (re-entry levels)
Static Thermal Testing	Minutes	N/A	Low	Moderate (2000+)
Arc Jet Complexes	Seconds to minutes (up to 1 hour+)	High to very high (~5–40+ MJ/kg)	Low to moderate (~1–3 km/s typical)	Very high (~5000–10,000+ K)

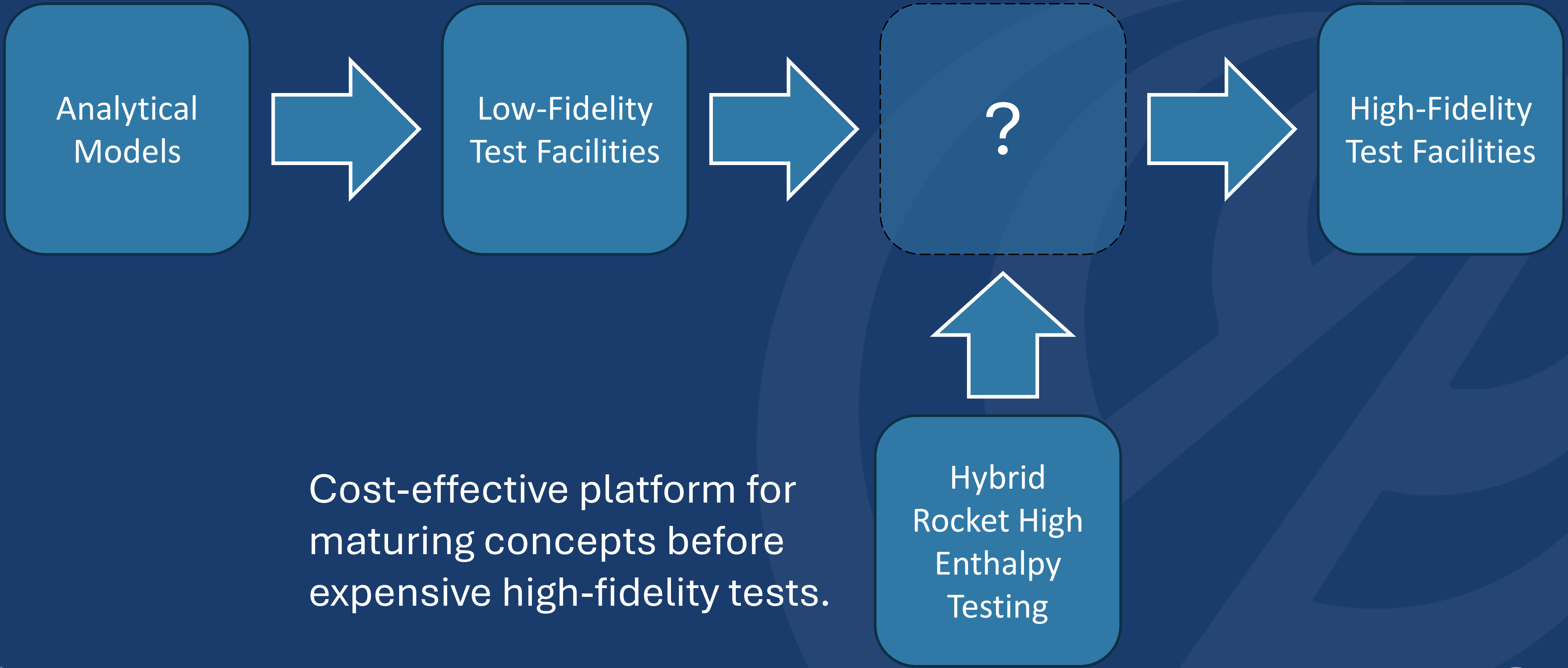
No test facility can simultaneously replicate all conditions encountered in hypersonic flight

Novel Approach: Hybrid Rocket as Gas Generator

- Laboratory-scale green-propellant hybrid rocket (GOX/ABS)
- Exhaust plume impinges on test articles representing hypersonic vehicle geometry
- Goal: simultaneously simulate enthalpy and dynamic pressure encountered in hypersonic flight



Target Application

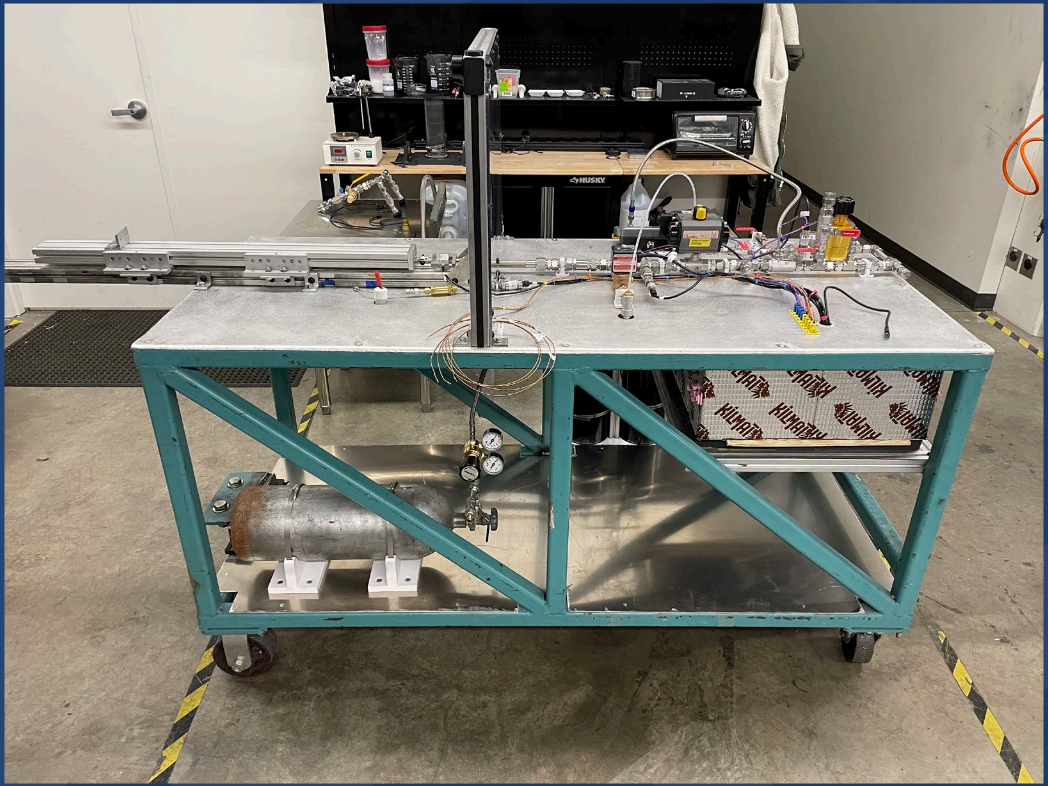


Cost-effective platform for maturing concepts before expensive high-fidelity tests.

Experimental Setup and Methodology

Test Setup

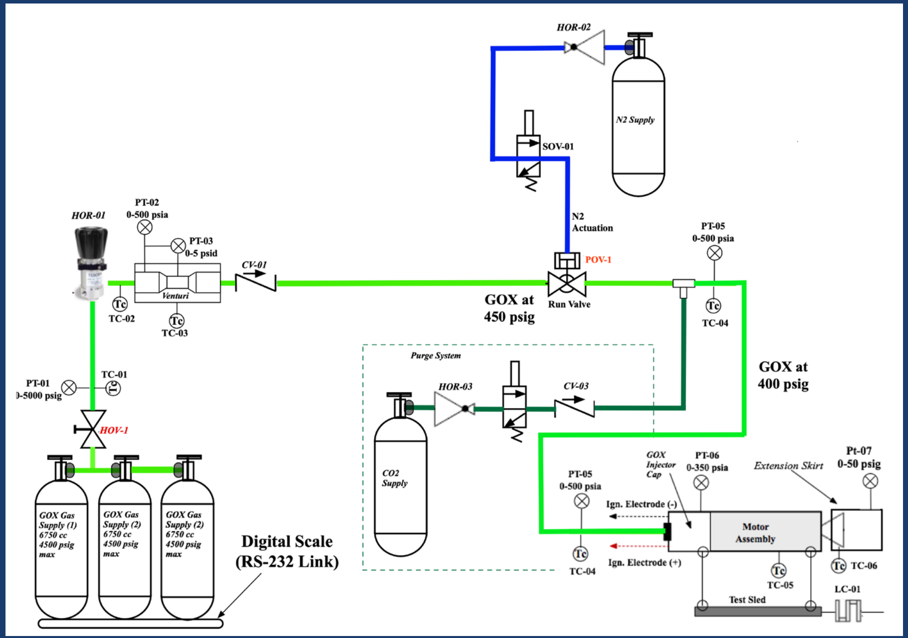
USU Battery Limits and Survivability Testing Lab



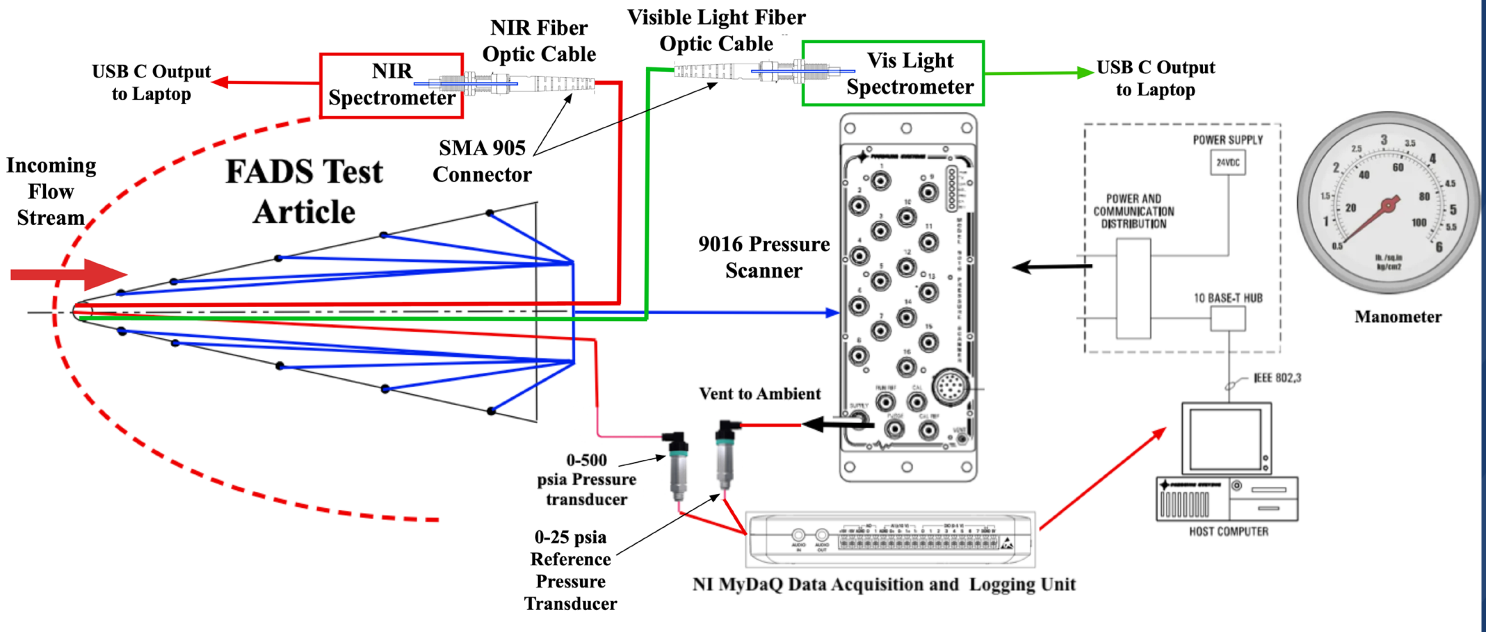
Test Cart equipped with oxidizer flow path plumbing

Hypersonic Test System P&IDs

- Temperature is calculated using fiber optic cables and spectrometers [6]
- Data is extrapolated to stratospheric flight (80,000 ft) [7]



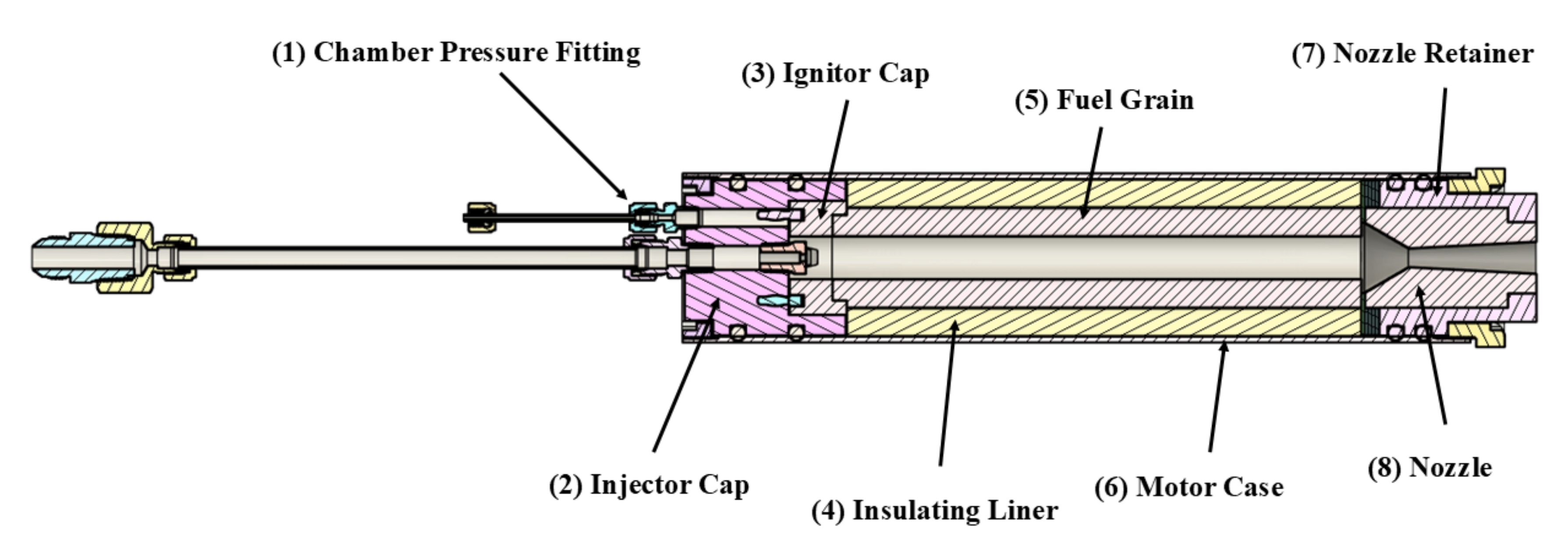
Test Cart System



Pressure and Spectrometer System

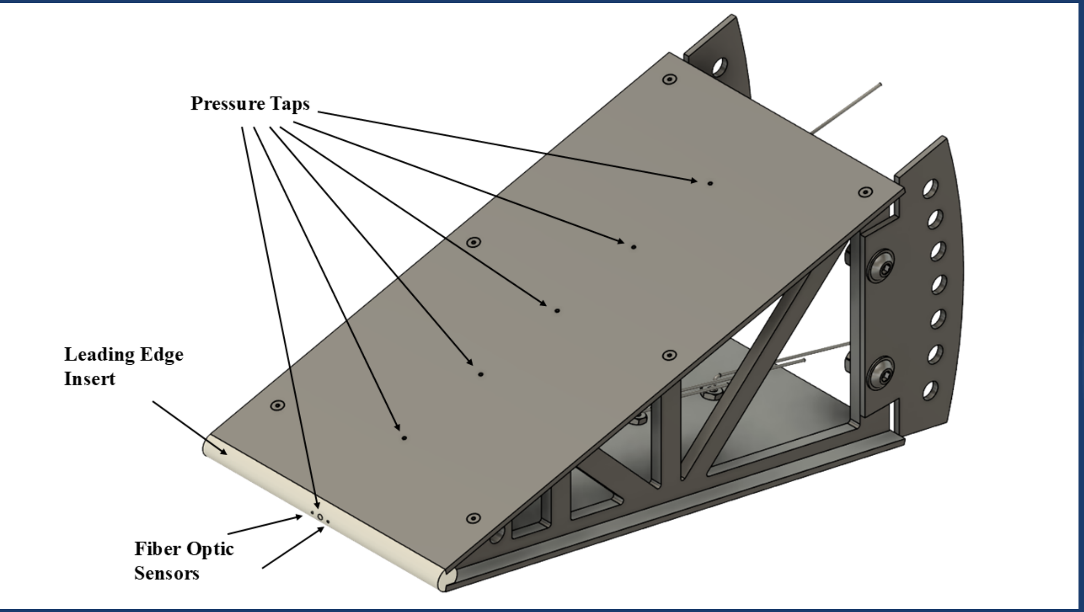
Hybrid Rocket Motor

- Hybrid Rocket: Fluid oxidizer + solid fuel
- Repurposed 75-mm thruster (GOX/ABS) developed for NASA PSI program [8]
- Chosen because highly characterized (over 100 successful hot fires)



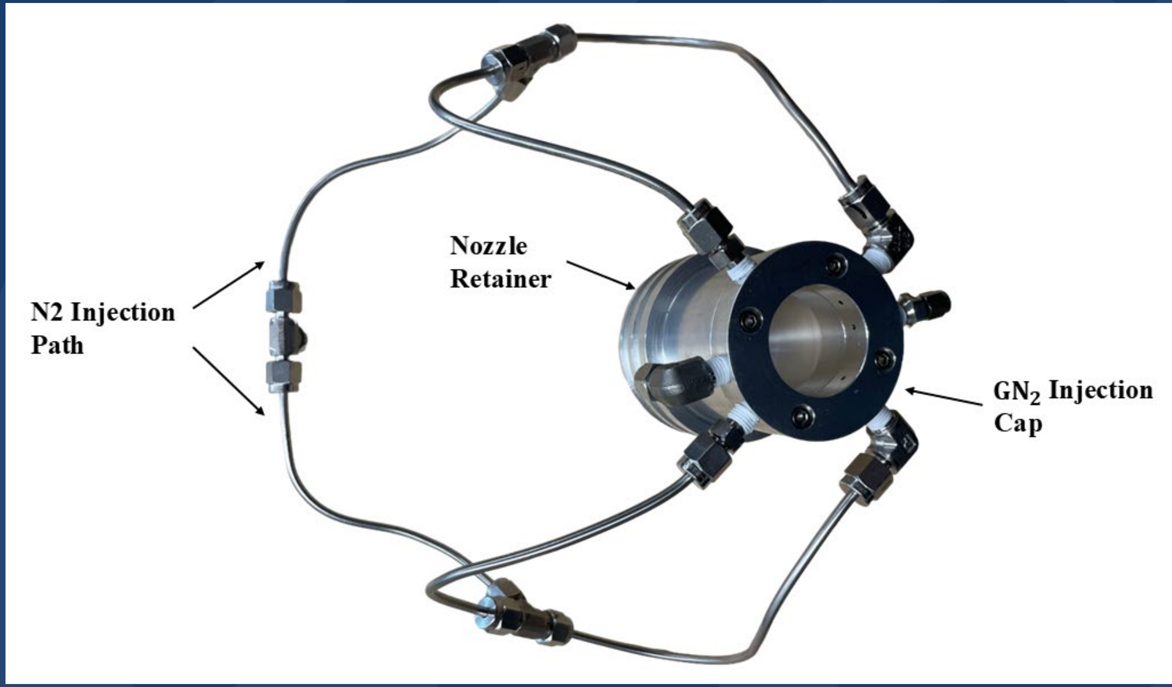
Test Article Setup Example

- Test article is positioned downstream of nozzle exit at a specified distance
- Exhaust directed at test article fitted with flush pressure taps (FADS) and fiber optic ports



Gaseous Nitrogen Plume Cooling

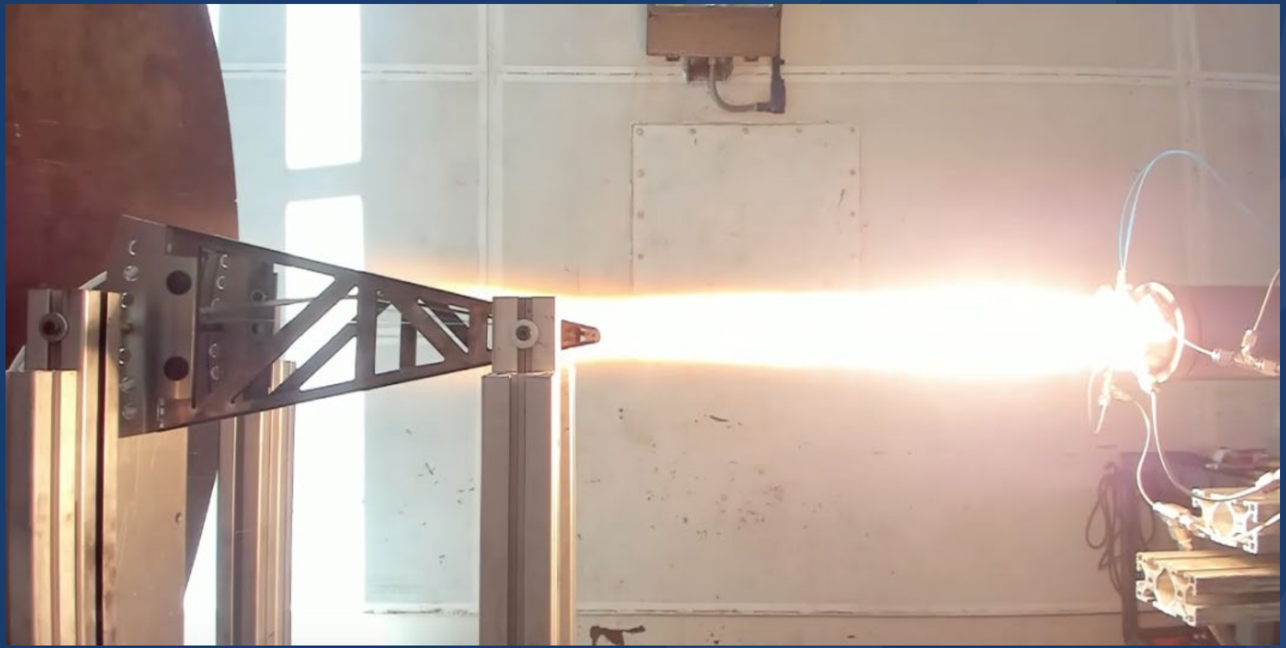
- Axial injection cap at nozzle exit to mix nitrogen
- Nitrogen will lower temperatures of plume
- Regulating injection pressure allows simulation of Mach 5 – 9 enthalpy conditions
- Improve plume composition → closer to atmospheric air



Testing and Results

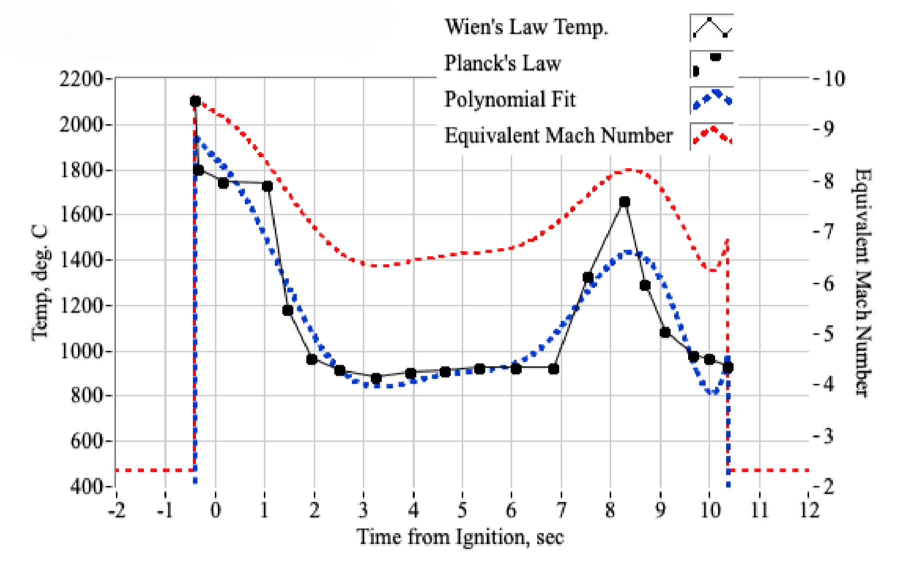
Nitrogen Injection 2D Wedge Test Article Test

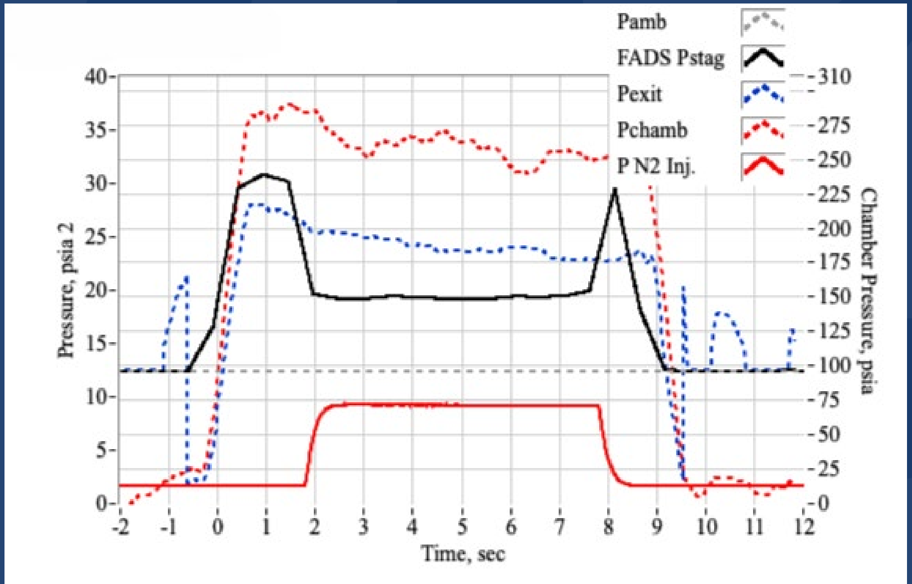
- Initial testing to tune measurement system and obtain initial data for nitrogen injection pressures
- 2 sec full enthalpy → 6 sec nitrogen injection (500 psi) → 2 sec full enthalpy



Wedge Test Article Results

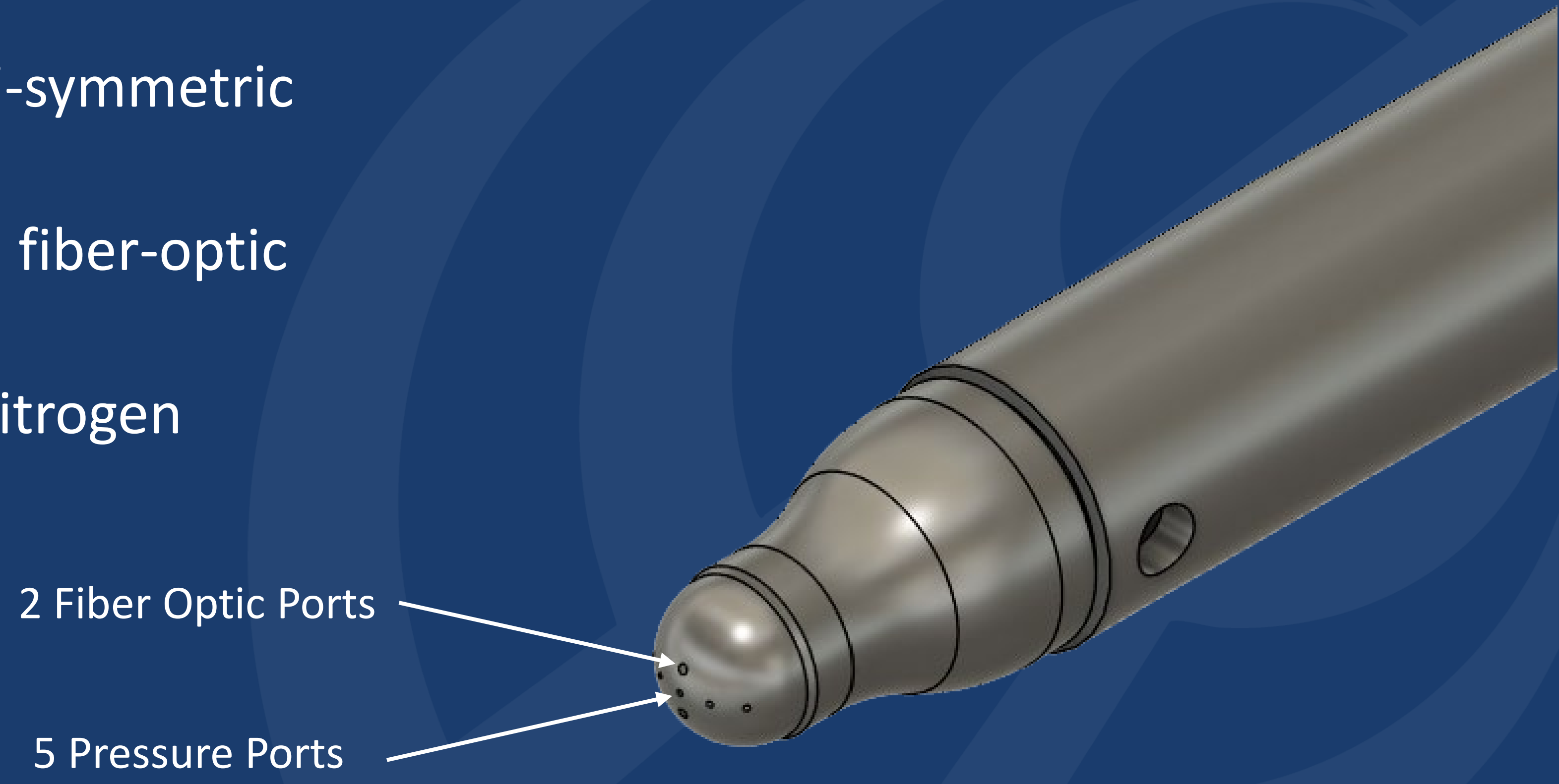
- Temperatures: 1800 C → 900 C → 1700 C
- Impingement pressures: 30 psi → 20 psi → 28 psi
- Impingement Mach number: 1.3 → 0.9 → 1.2
- Extrapolated enthalpy-equivalent Mach numbers: 9.5 → 6.5 → 8





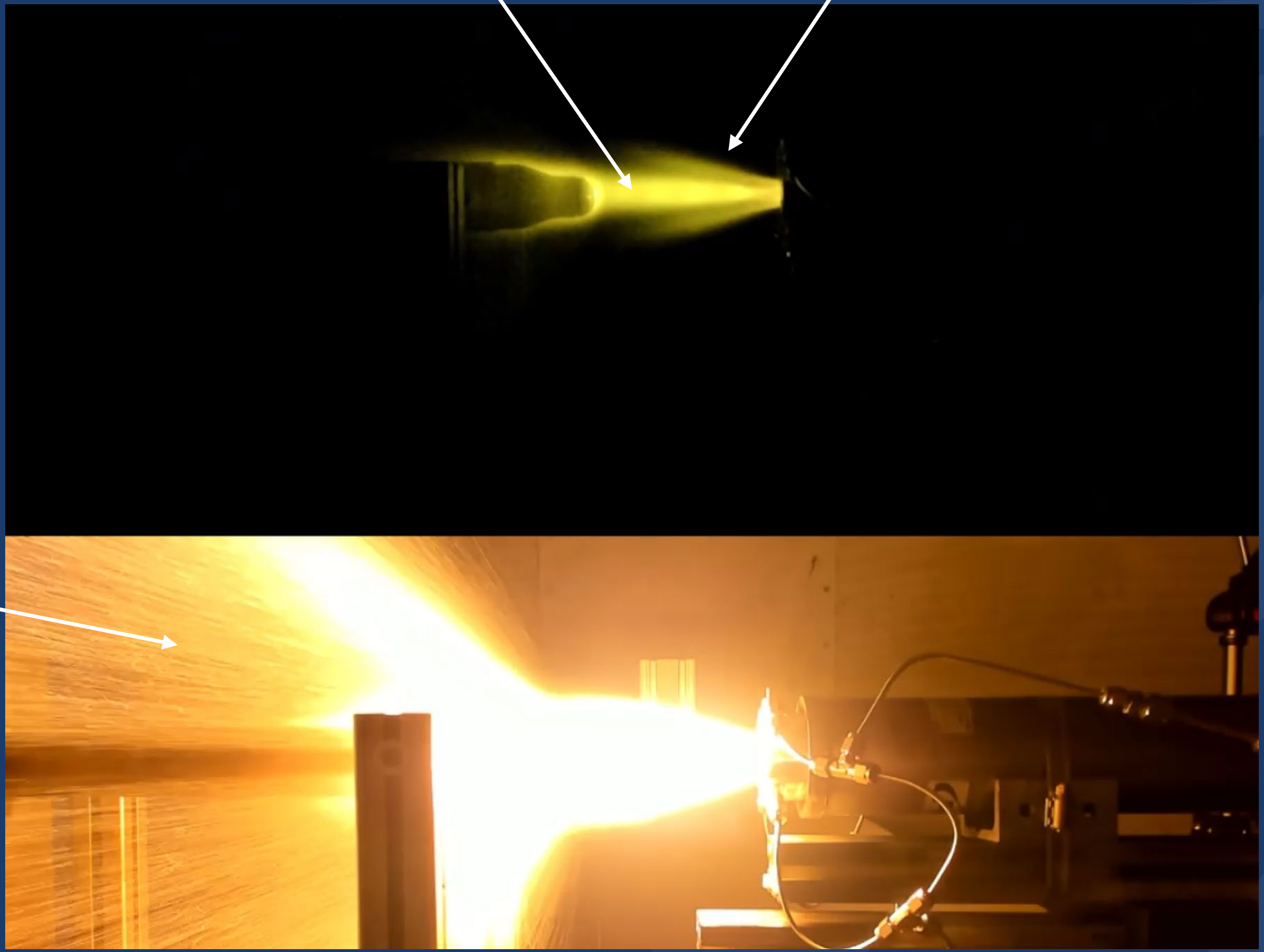
Blunt-Body Test Article

- Sphere-cone blunt body shape (replaces earlier 2D wedge)
- Plume is axi-symmetric → axi-symmetric test article
- Fitted with pressure taps and fiber-optic sensor
- 4 sec burn with continuous nitrogen injection (500 psi)



Supersonic flow

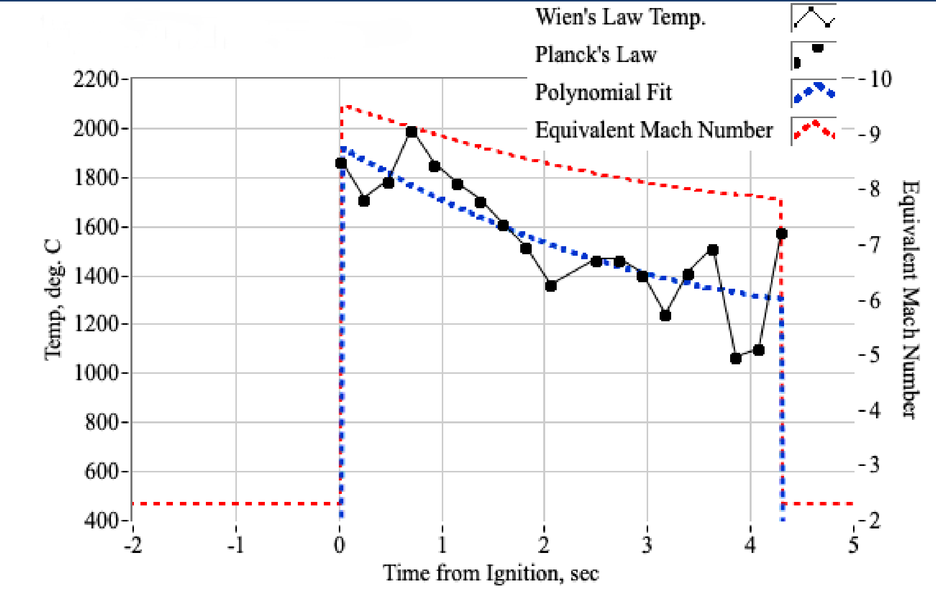
Plume splay from injection

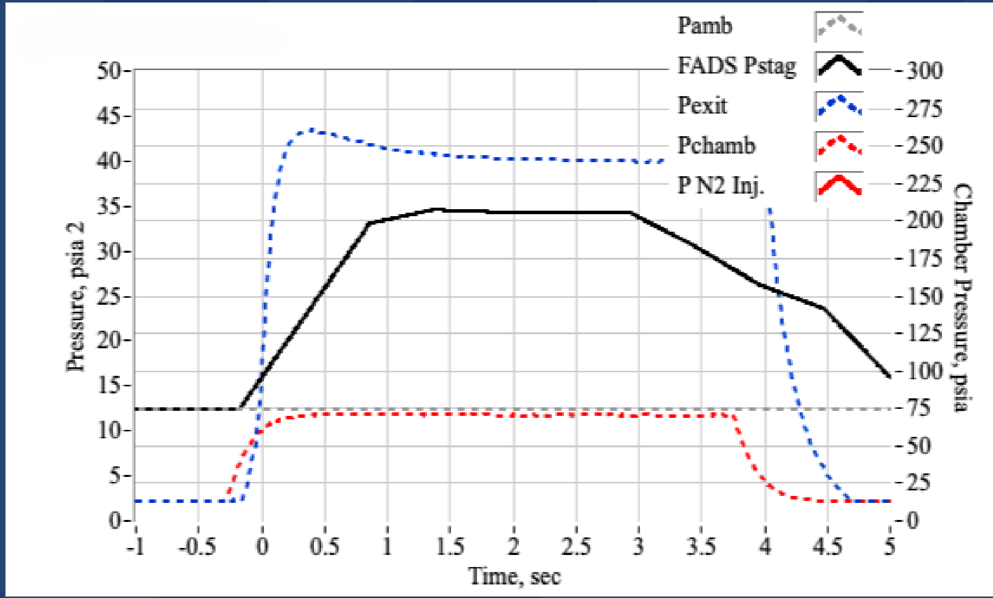


Material Ablation

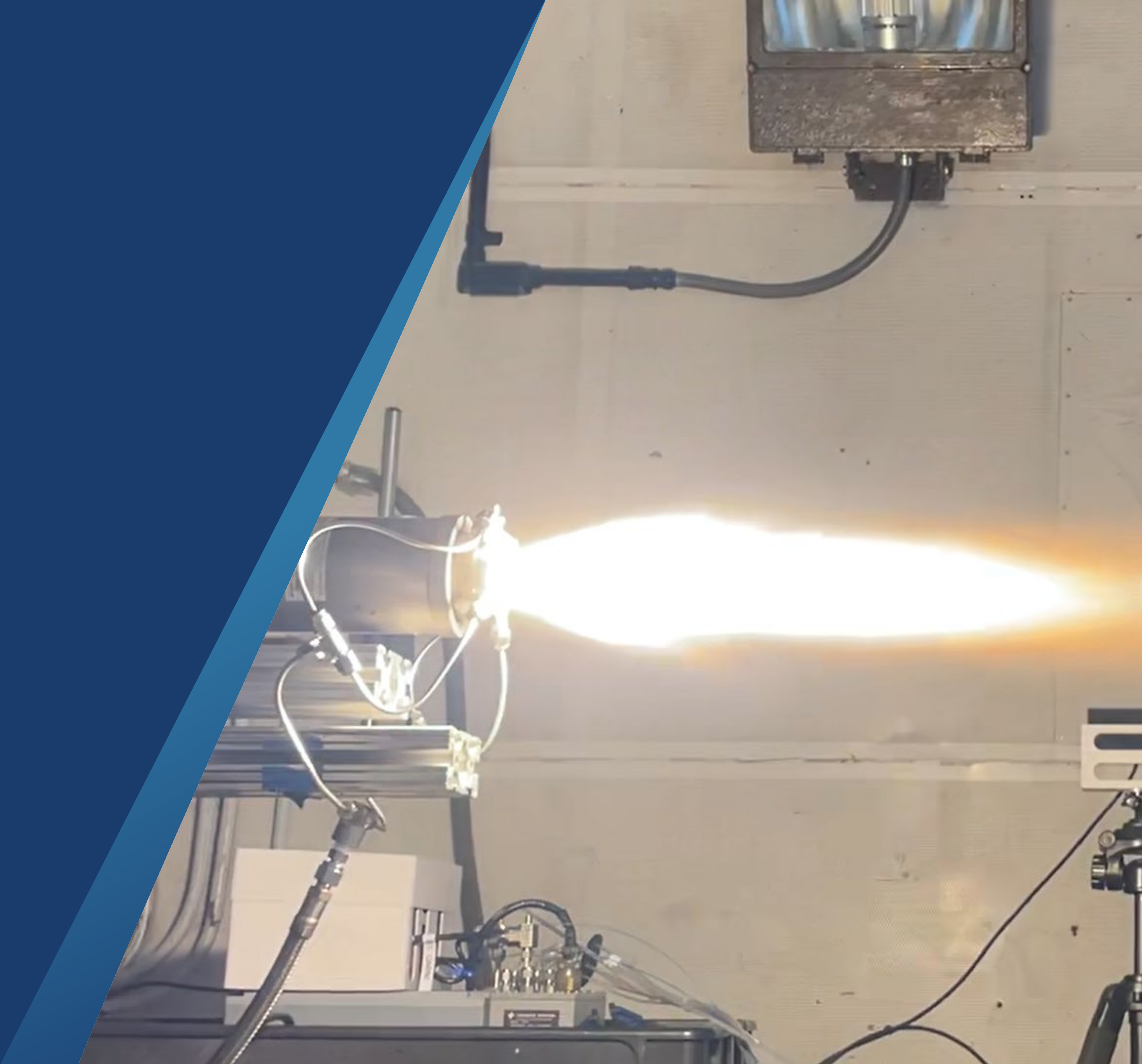
Blunt-Body Test Results

- Recorded temperatures of 1300 C – 1900 C
- Impingement pressure of 35
- Impingement Mach numbers: 1.2 – 1.4
- Extrapolated enthalpy-equivalent Mach numbers of 7.5 – 9.5





Conclusions and Future Work



Summary

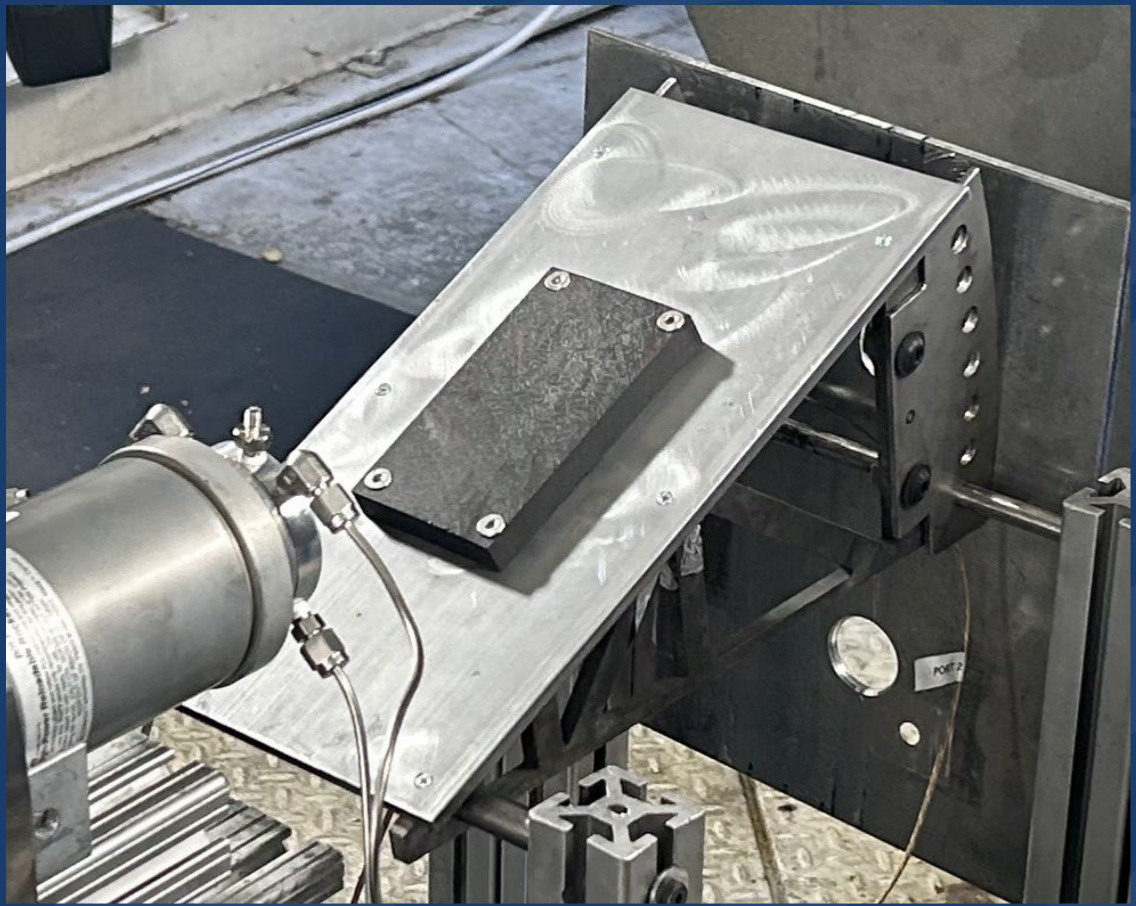
1. Successful implementation of nitrogen injection ring on legacy 75 mm motor

2. Initial validation of system using wedge test article

3. Introduction and successful test for blunt body test article

Future Work

- Correlation of pressure data with analytical models
- Different test article geometries
- Adjust oxidizer and fuel to bring thermodynamic properties closer to air
- Material Testing (sneak peak)



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Thank You

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