Development and Testing of Conventional and Additively Manufactured Aerospike Nozzles for Small Satellite Hybrid Propulsion

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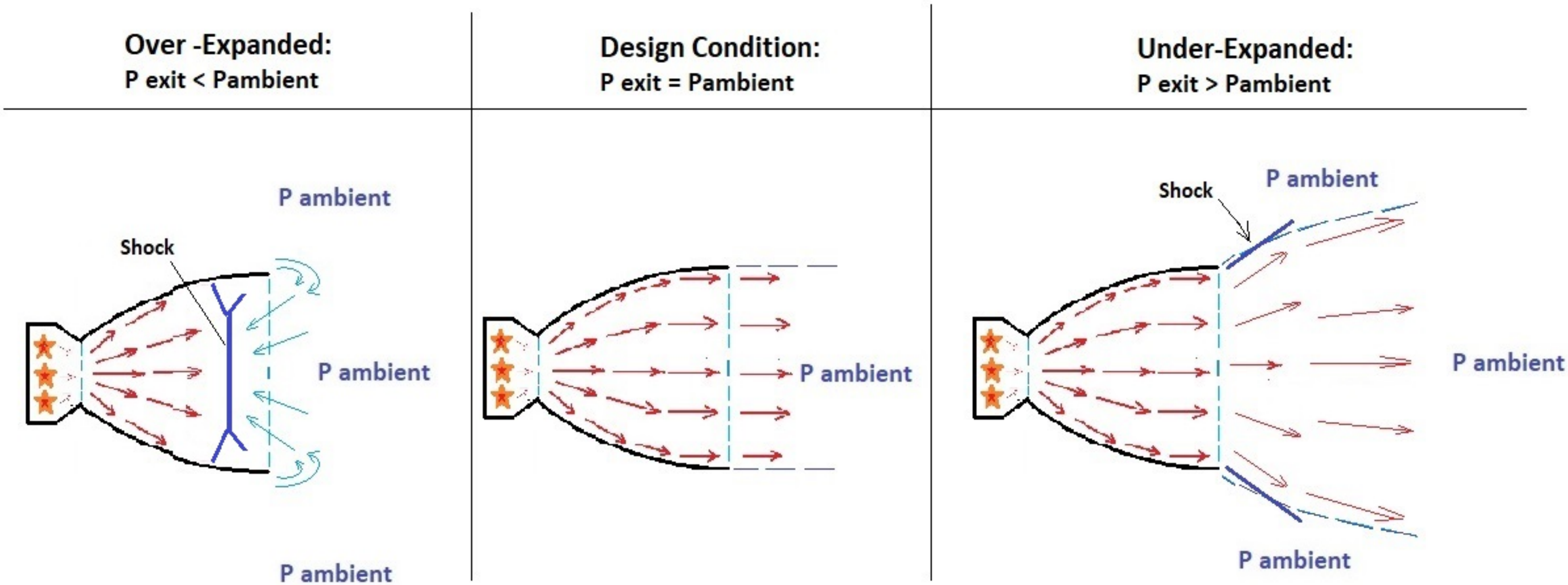
AIAA-2019-4229
Joint Propulsion Conference,
August 19-22 Indianapolis, IN

Contents:

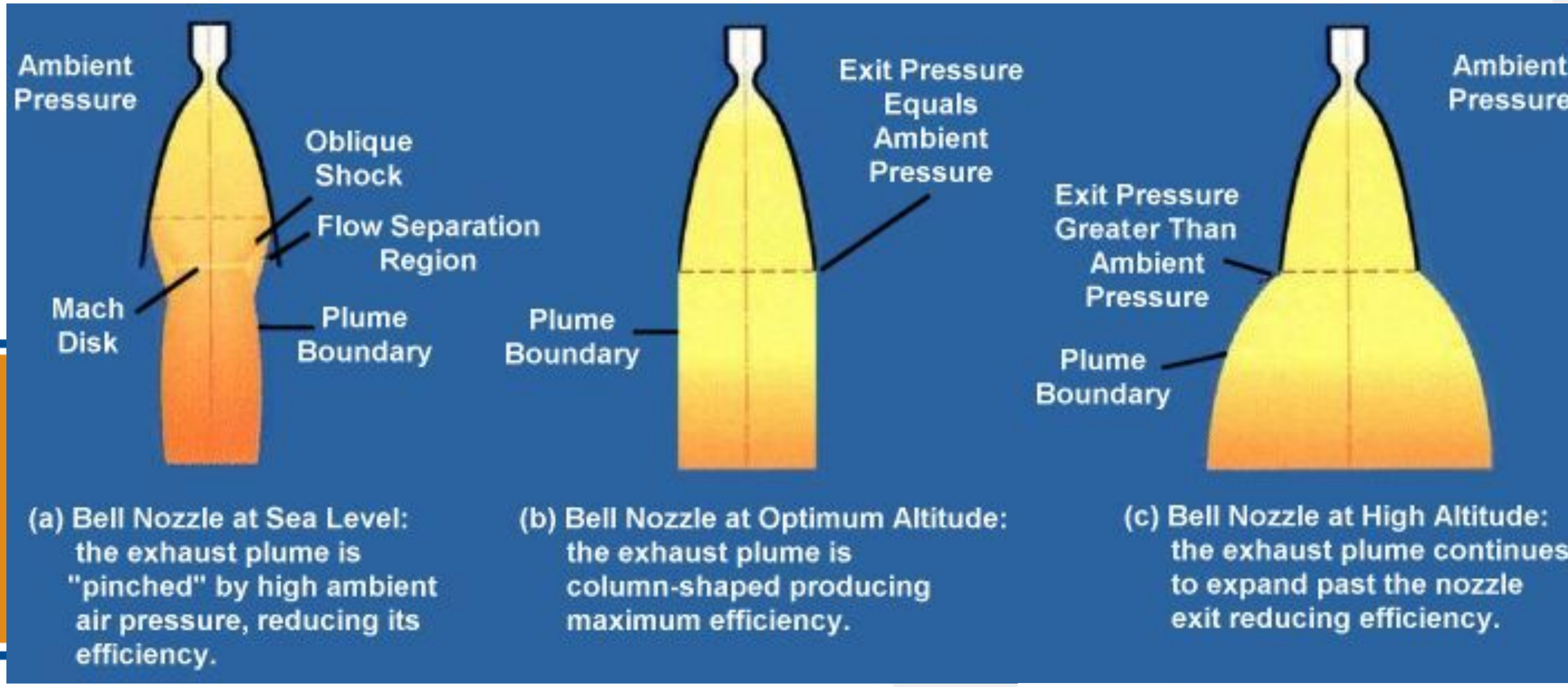
Conventional Nozzle Operating Condition

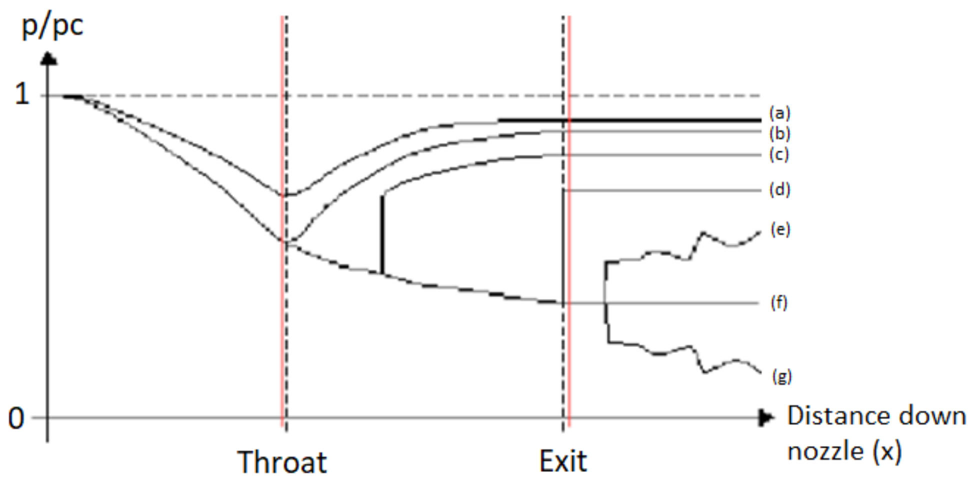


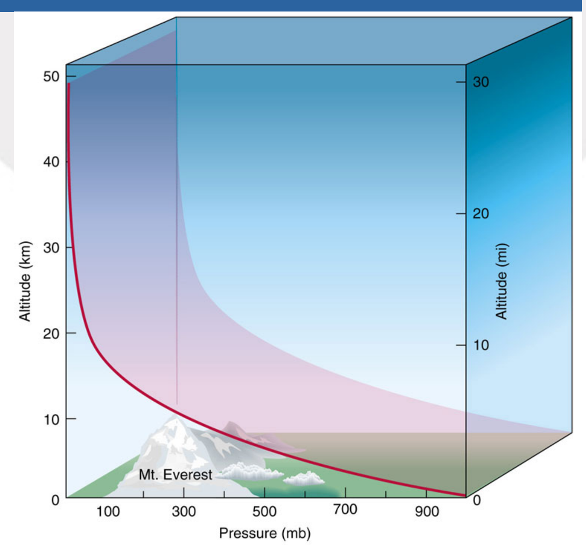
Conventional Fixed-Geometry Nozzle Trades Momentum vs. Exit Pressure Thrust as Function of Altitude, Chamber Pressure, and Expansion Ratio

$$F = \dot{m}_{exit} V_{exit} + (p_{exit} A_{exit} - p_{\infty} A_{exit})$$

Effect of Operating Altitude on Nozzle Performance

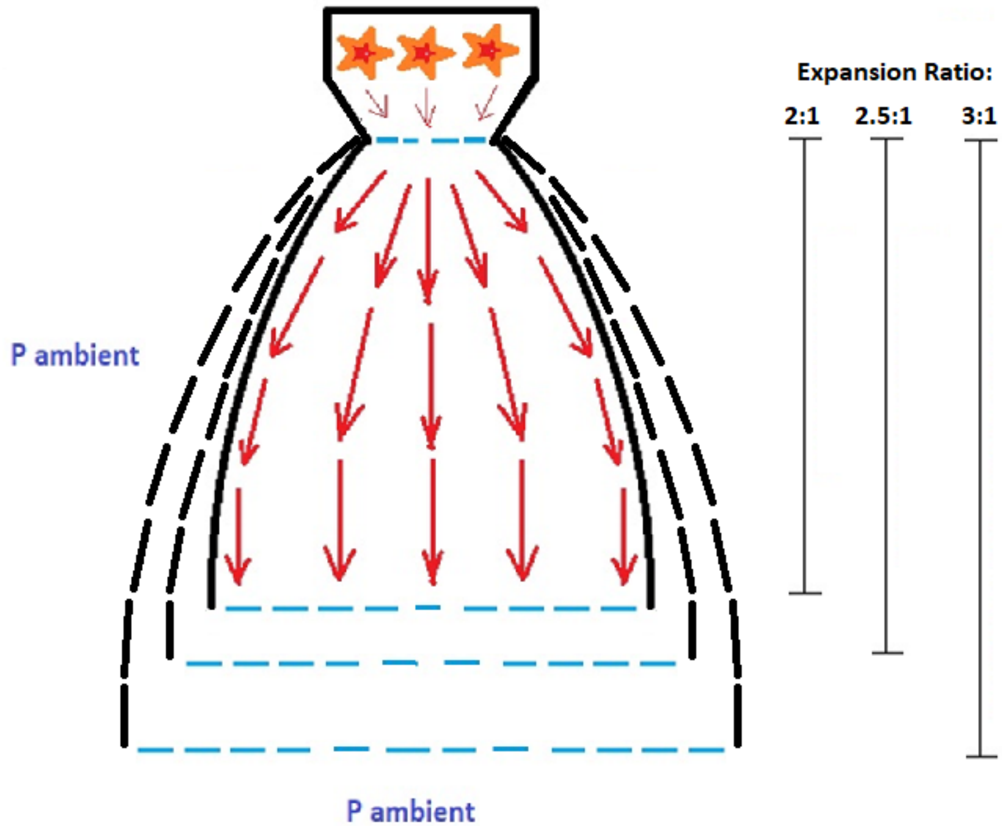






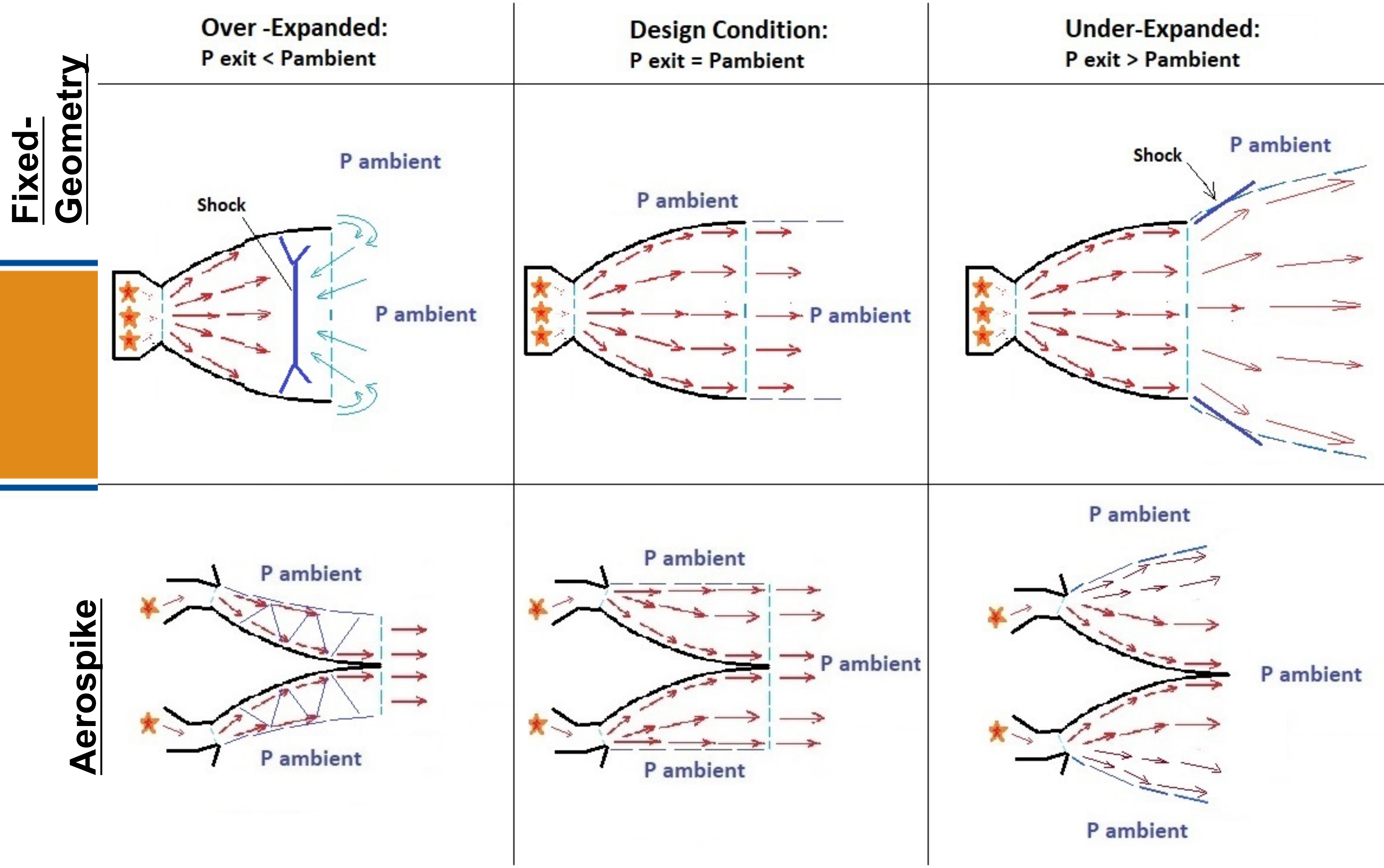
Rocket Nozzles: Altitude Compensation

TELESCOPING NOZZLE



- Traditional Academic Example of Telescoping Nozzle

Aerospike Nozzles Offer Practical Alternative for Altitude Compensation



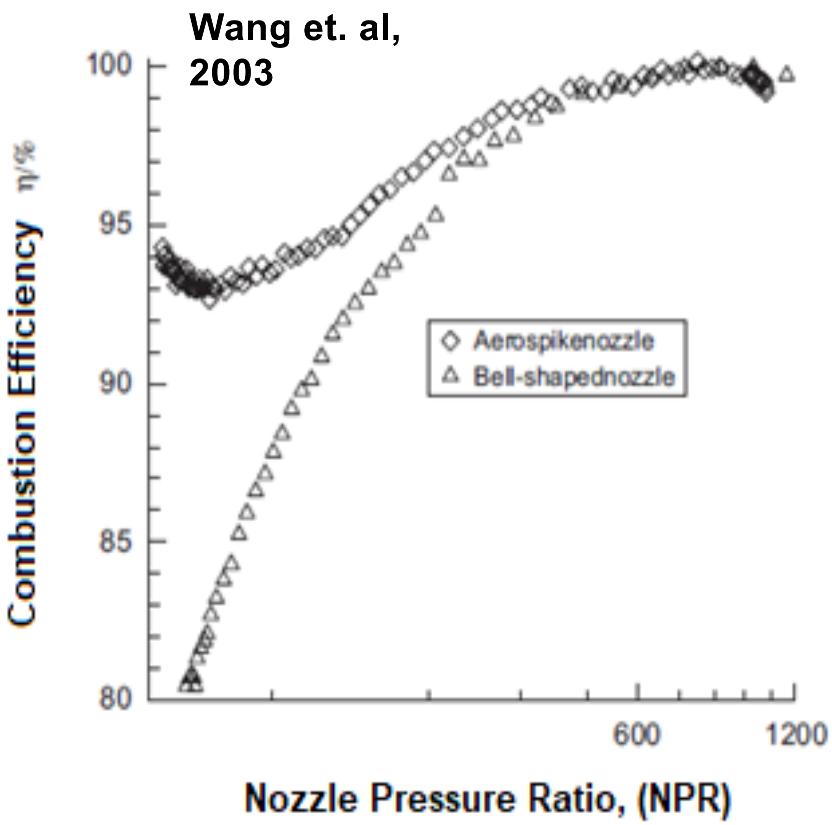
Aerospike/Fixed Nozzle Performance Comparisons

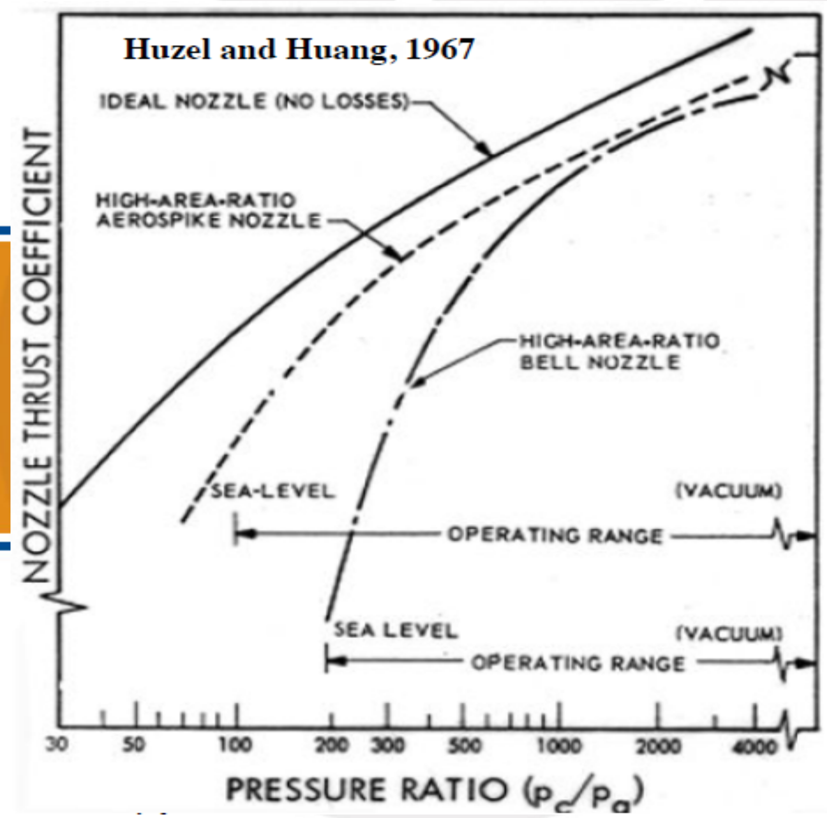
- **Aerospike Nozzle Primary Advantage 1:** Provide high performance across a wider range of altitudes than a bell nozzle

- **Aerospike Nozzle Primary Advantage 2:** High Expansion ratio nozzle can be significantly more compact than fixed geometry nozzles of equivalent expansion ratio, *higher volumetric efficiency*

  - *Important Potential Mass and Volumetric savings for In-Space Propulsion*

Nozzle Performance Comparisons (2)



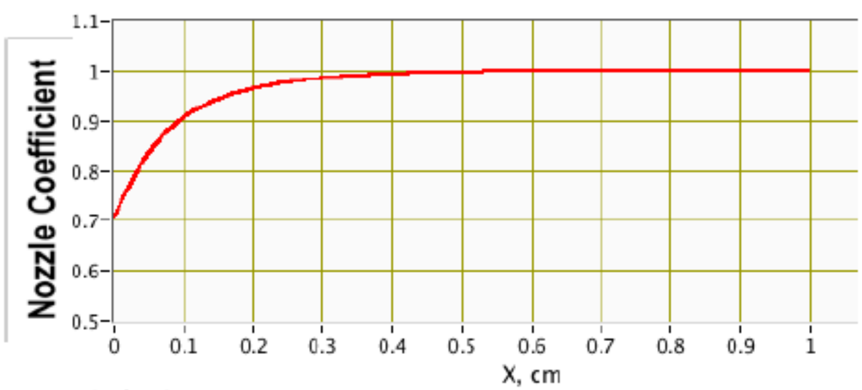


Nozzle Performance Comparisons (3)

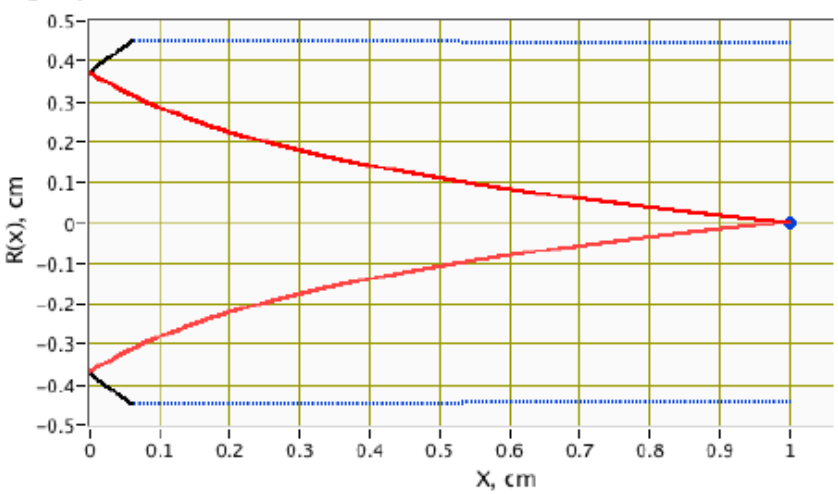
- Aerospike nozzles also offer advantages for space applications … higher expansion ratio for smaller size and volume

-- Truncated aerospike nozzles can be as short as 25% length of conventional nozzle (for equivale

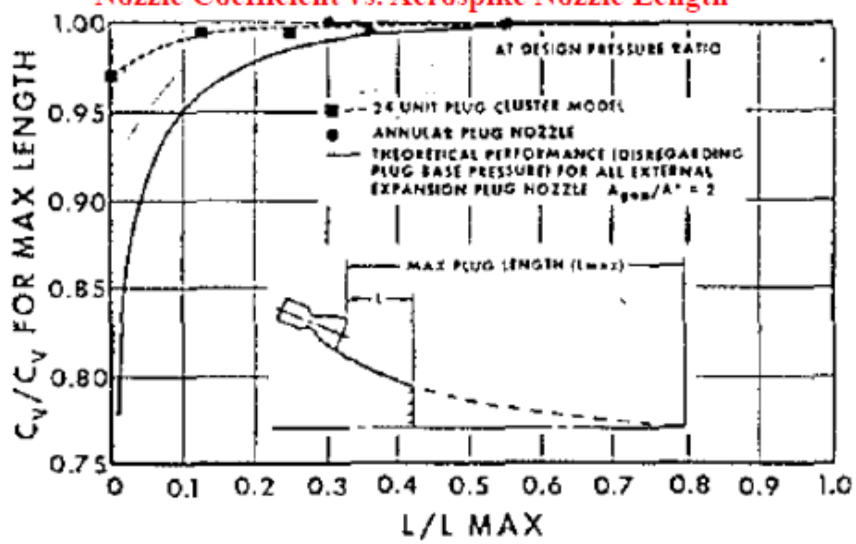
Accumulated Spike Thrust at Design Condition

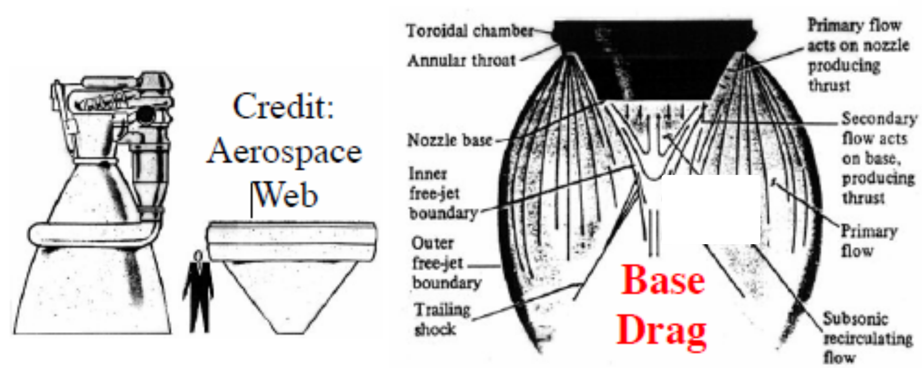


Design Spike Contour



Nozzle Coefficient vs. Aerospike Nozzle Length





Comparison of Saturn V F-1A Engine and Proposed J-2T-250K Aerospike of Same Expansion Ratio.

Nozzle Performance Comparisons (3)

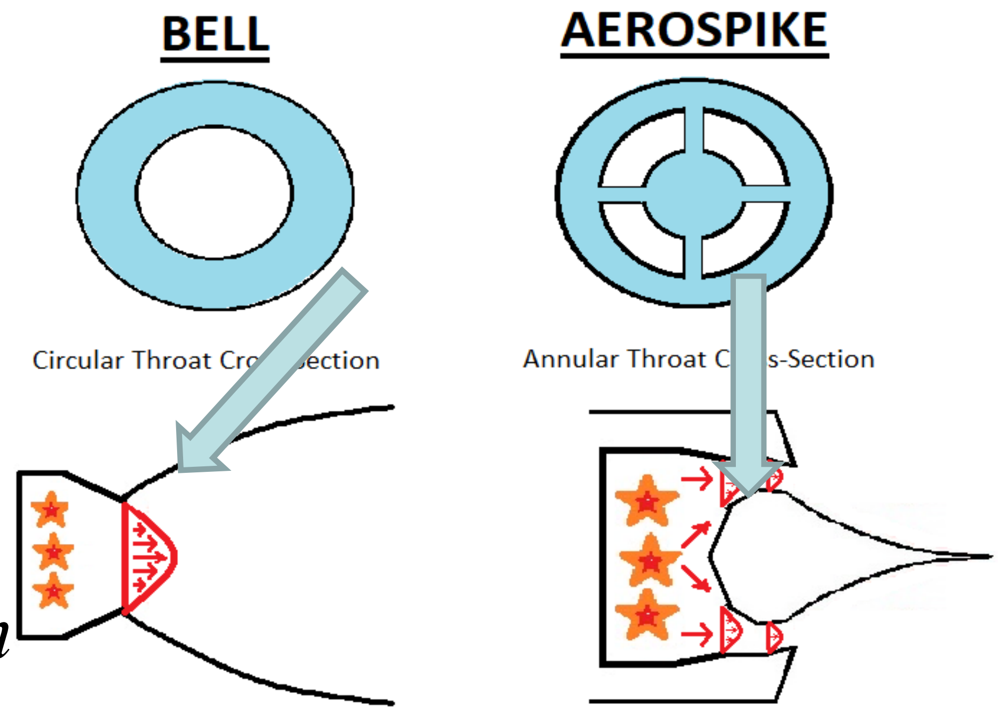
Aerospike Disadvantages:

- Significantly more complex geometry than Conventional fixe-geometry nozzles
- High Heating Levels at Nozzle Throat
- Potential for Destructive Structural harmonics due to Cantilever Design

Aerospike Nozzles: Thermal Loading Issus at Throat Annulus

Thermal Loading Issues

- Reynold's-Colburn Analogy
- Skin friction inversely proportional to Reynolds number
- *C_f significantly higher in an annular aerospike throat due to small gap distance*



$$D_{H,annulus} = \frac{4 * A_t}{Perimeter} = D_{out} - D_{in}$$

$$S_t = \frac{\Delta H_{convective}}{Heat\ Capacity\ of\ Fluid} = \frac{1}{2}\frac{C_f}{P_r^{2/3}}$$

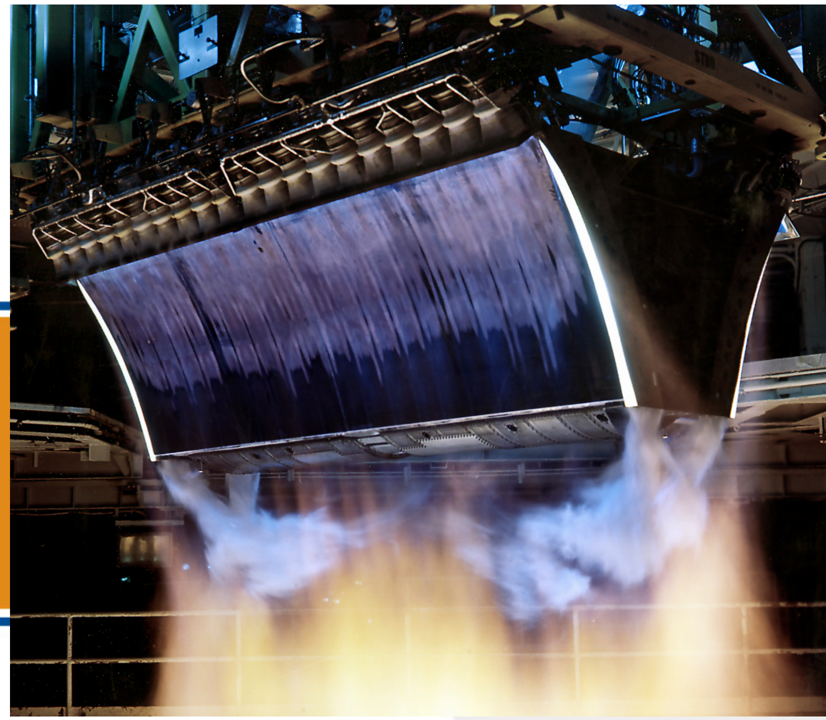
$$Re_D = \frac{\rho * V * D_H}{\mu}$$

$$C_f \approx \frac{0.074}{\left(R_{e_D}\right)^{1/5}}$$

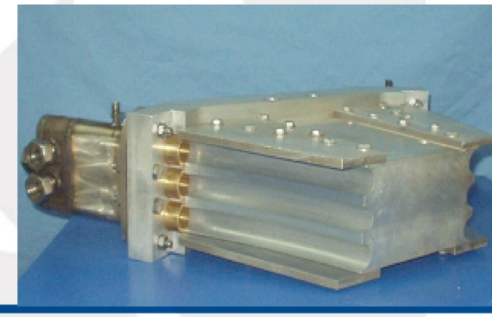
The World's Forum for Aerospace Leadership

Aerospike Nozzles: Examples of Previous Work

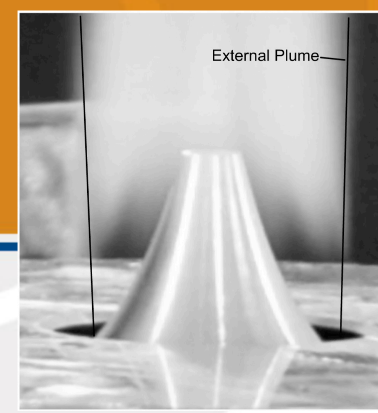
NASA X-33 VentureStar Vehicle



NASA X-33 Linear Aerospike Engine



Beijing University

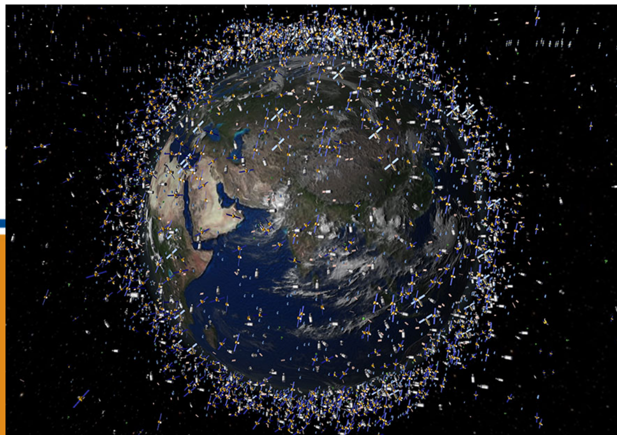


Previous USU Aerospike With Thrust Vectoring

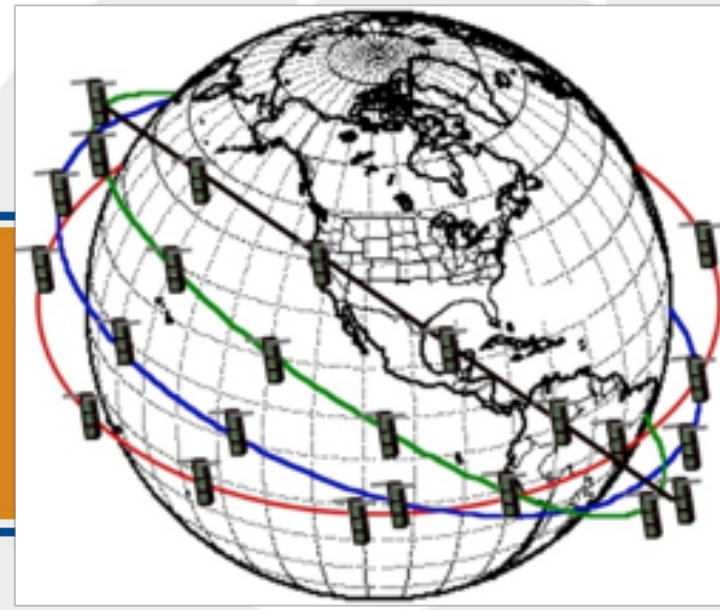
Environmental Aeroscience

NASA Armstrong

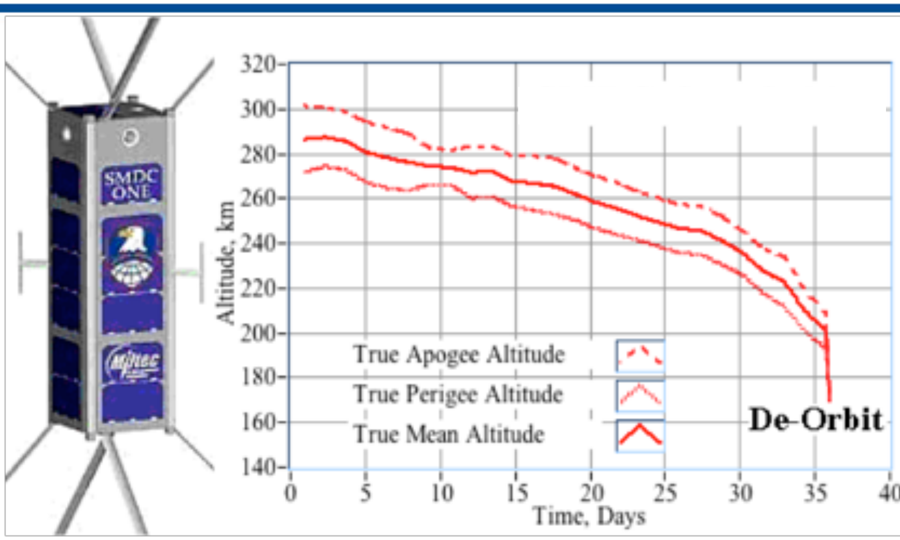
Research Motivation: CubeSat Propulsion for Potential Savings in Weight, and Volume

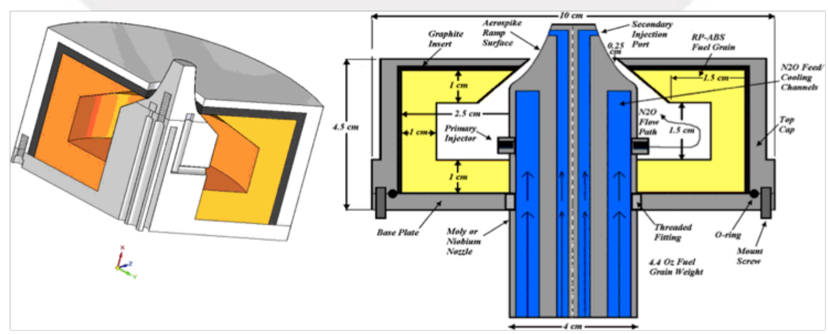


Orbital Debris Mitigation



LEO Constellations





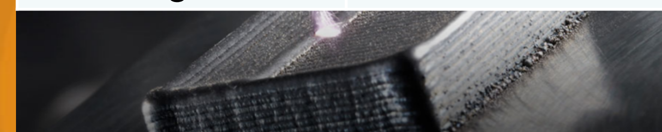
Highly Compatible with 10 cm Cubesat Form Factor

Key Innovation: 3D Printing

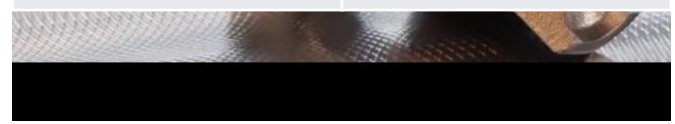
EOS M290 Printer

Materials*
EOS Aluminium AlSi10Mg, EOS CobaltChrome MP1, EOS MaragingSteel MS1, EOS NickelAlloy HX, EOS NickelAlloy IN625, EOS NickelAlloy IN718, EOS StainlessSteel CX, EOS StainlessSteel PH1, EOS StainlessSteel 17-4PH, EOS StainlessSteel 316L, EOS Titanium Ti64, EOS Titanium Ti64ELI, EOS Titanium TiCP Grade 2

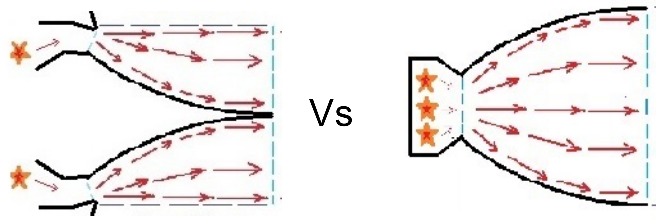
METAL	Melting Point (K)
Inconel 718	1700 K
Tungsten	3650 K



Propellants	Combustion Temp. (K)
Hydrazine	1020 K
ABS/GOX	2530 K
LOX/Hydrogen	2980 K
LOX/Kerosene	3670 K



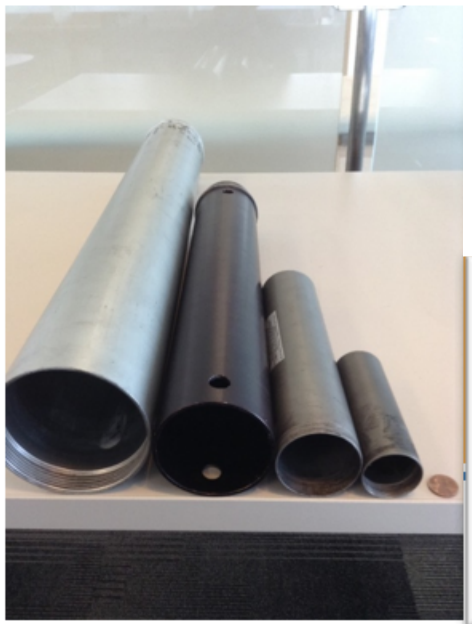
Primary Research Emphasis



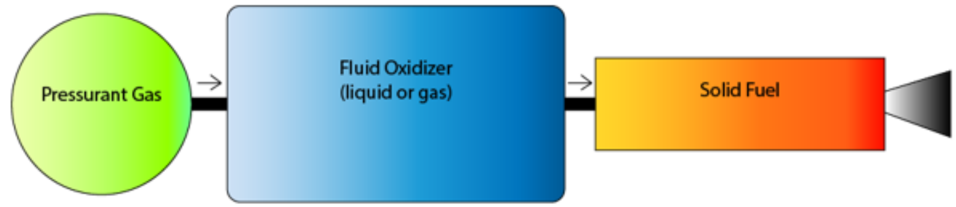
- Develop a 3D printed aerospike nozzle and test in both over-expanded and under-expanded flow regimes to contrast existing fixed-nozzle data.
- Developed aerospike *Must* integrate into existing USU hybrid rocket hardware sized for potential use on a CubeSat-sized small satellite.
- Literature search shows smallest aerospike nozzle tested previously was ~10cm in diameter, and fabricated without the aid of additive manufacturing.
- Simply put, at small scale, show that aerospike advantages still hold and operation is practical.

Existing USU ABS/GOX Hybrid Thruster

ABS Fuel



Motor Cases



Hybrid Rocket Motor (HRM) Concept

Arc-Ignition System

Stephen A. Whitmore. "Three-Dimensional Printing of “Green” Fuels for Low-Cost Small Spacecraft Propulsion Systems”, https://doi.org/10.2514/1.A33782, July 31, 2017.

COLLEGE of ENGINEERING
UtahStateUniversity

USTAR

Suborbital Flight Test of a Novel Arc-Ignition "Green" Thruster for SmallSats

Space Dynamics LABORATORY
Utah State University Research Foundation

Marc Bulcher, Zac Lewis, Rob Stoddard, and Dr. Stephen Whitmore

USIP Thruster Team (final), Engineering Department, Utah State University

Project Overview

- The NASA Undergraduate Student Instrument Project (USIP) is a program with the goal to provide hands-on flight project experience to select undergraduate programs to fly technology investigation relevant to NASA strategic goals.
- Utah State was awarded the USIP grant to test a hybrid thruster's restart capability, vacuum performance, and plume contamination to characterize potential effects on spacecraft optical sensors, external electronics, and solar panels.
- NASA provided a section of the body of a Terrier-Malemute sounding rocket for our experiment. The sounding rocket launched from Wallops Flight Facility on March 25, 2018.

Figure 1 – Concept of Operations

Figure 2 – Experimental Section

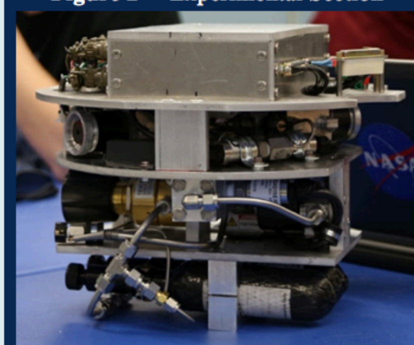
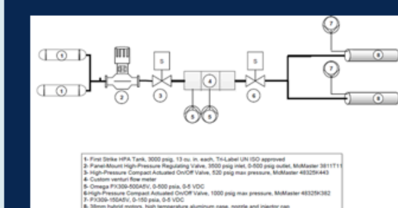


Figure 3 – Dual Thruster Diagram



Experimental Section

Thruster System

- Two thrusters are mounted in a self-nulling configuration to minimize tumbling of the rocket.
- During the 30 second test window, the thrusters were fired six times in three second pulses.

Plume Contamination Sensors

- A photometer measured the illumination degradation of a pulsing LED light source.
- The photometer is placed next to one thruster nozzle to pick up particle accumulation from the exhaust plume.

Avionics

- Control and data acquisition electronics housed in sealed box at one end of experiment
- All recorded data from flight test successfully recovered with the experiment section

Results

- Weather conditions leading to damp fuel grains caused partial burn conditions for initial thruster pulses
- After drying out, both thrusters fired successfully
- Photometer showed 15% drop in illumination from plume backflow

Figure 7 – Flight Test Results

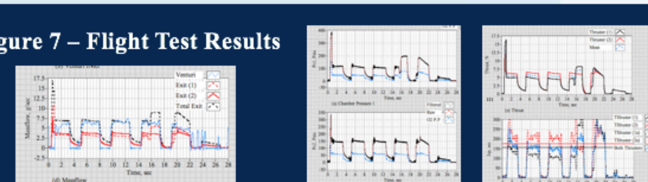
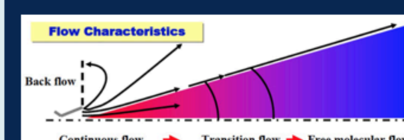
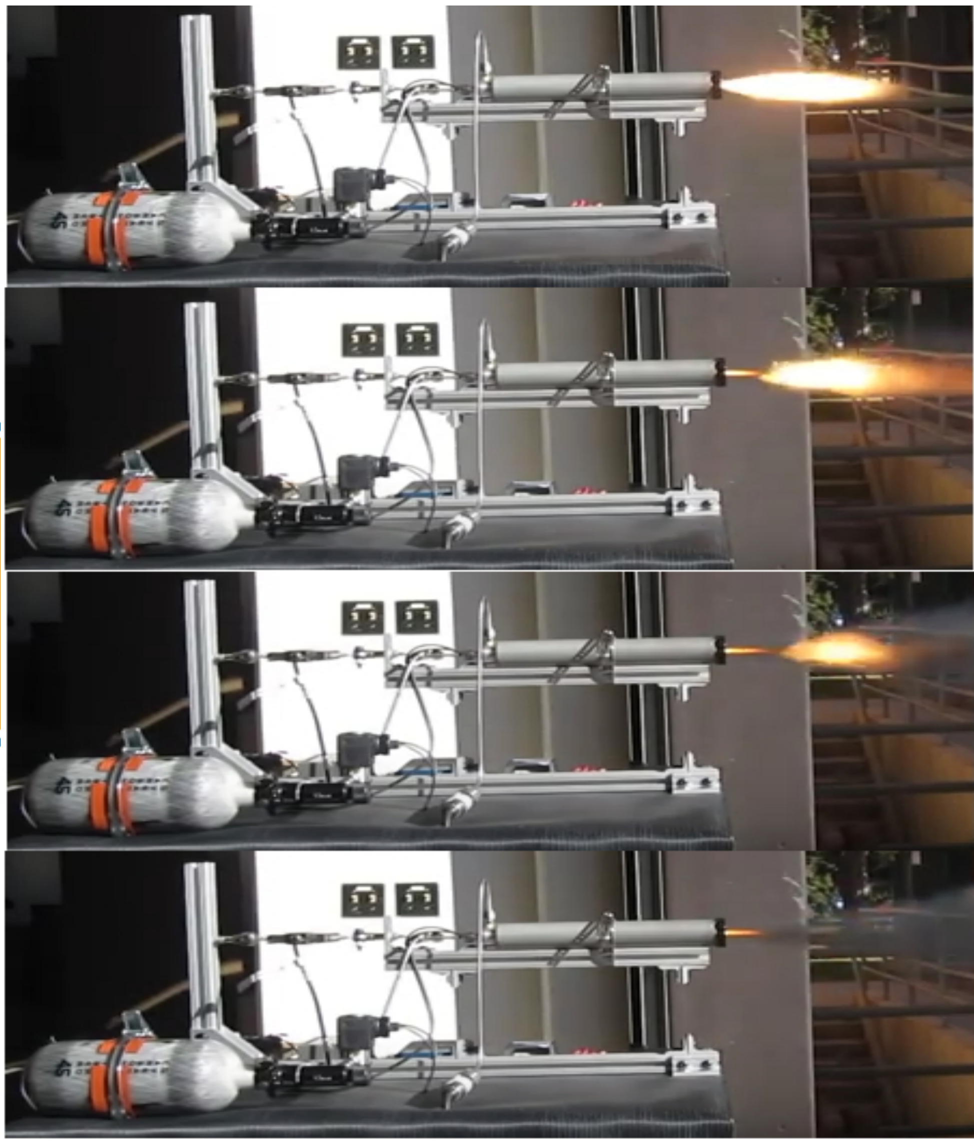


Figure 4 – Ground Test of Integrated Flight Deck

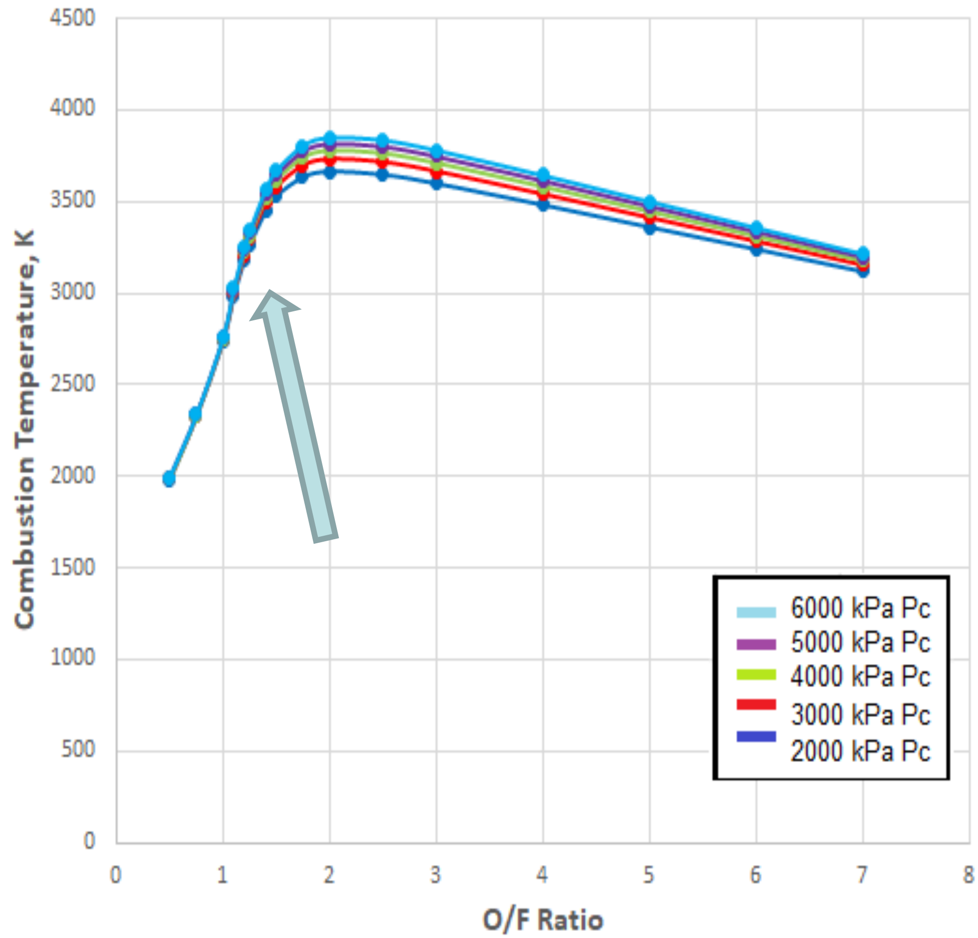
Figure 5 – Launch of the USIP Payload

Figure 6 – Exhaust Plume in a Vacuum Environment





- Extended Flight motor to 9.2 in., 29 mm thrust chamber
  - Exhibits negative O/F shift (lean-to-rich)
  - Enhanced Nozzle Survivability

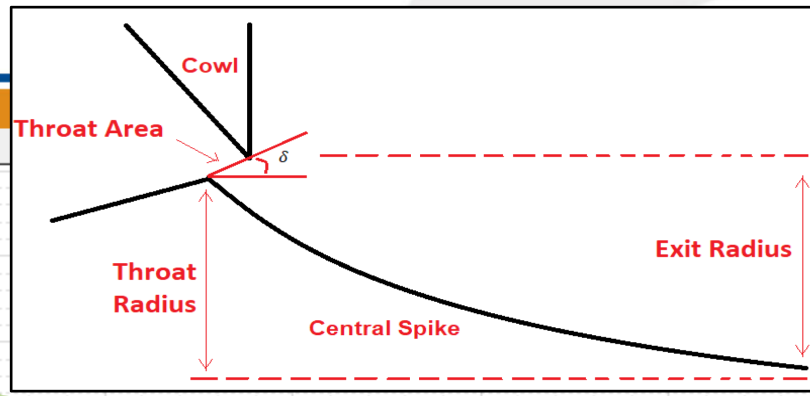


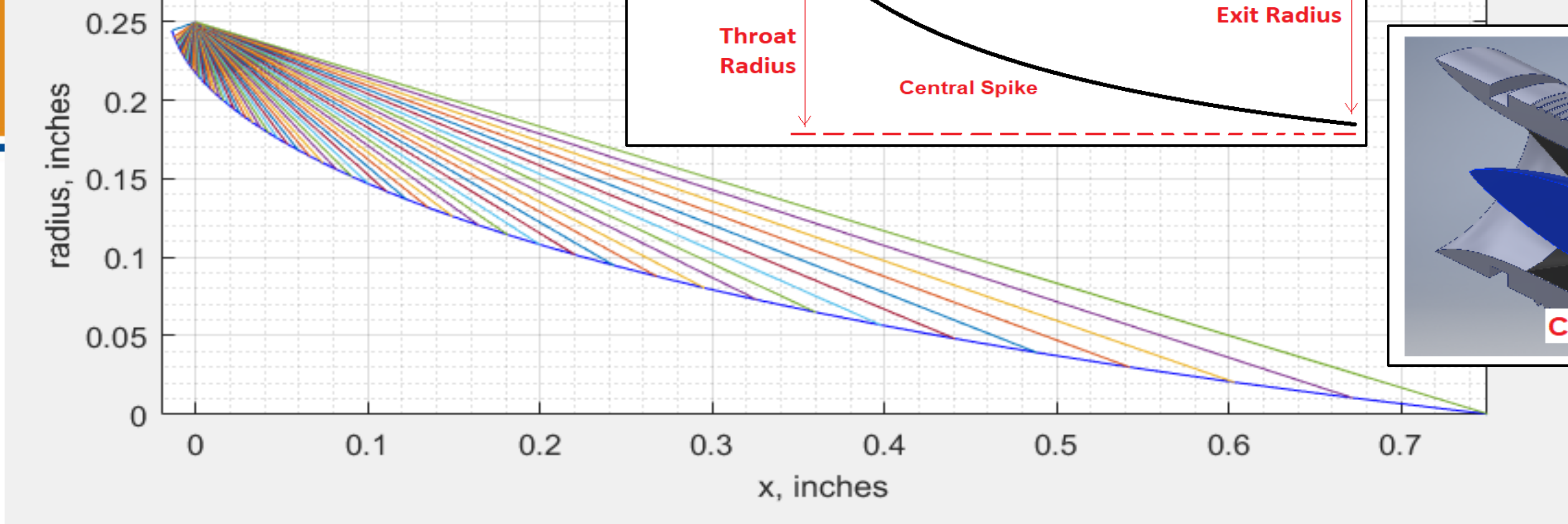
Aerospike Design: Supersonic Contour Design via Method of Characteristics

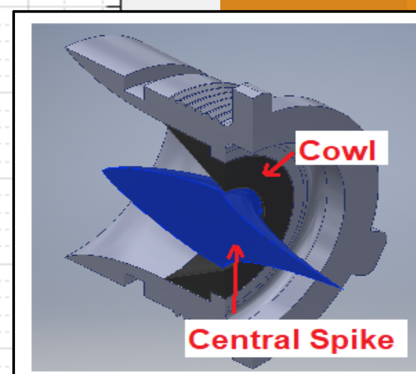
$$x_{n+1} = \frac{R_{exit} - R_{n+1}}{\tan(\upsilon_{exit} - \upsilon_{n+1} + \mu_{n+1})}$$

$$R_{n+1} = R_{exit}\sqrt{1 - \frac{\sin(\upsilon_{exit} - \upsilon_{n+1} + \mu_{n+1})}{\varepsilon} * \left[\left(\frac{2}{\gamma+1}\right) * \left(1 + \frac{\gamma-1}{2} * {M_{n+1}}^{2}\right)\right]^{\frac{\gamma+1}{2*(\gamma-1)}}}$$

8.5:1 Aerospike	
Throat Diameter, in	11/64
Exit Diameter, in	1/2
Aerospike Length, in	0.7600
Aerospike Gap height, in	0.0055
Delta, degrees	21.8





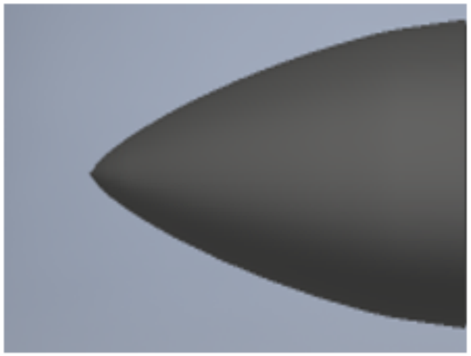


Lee, C. C., and D. D. Thompson, D. D., "FORTRAN Program for Plug Nozzle Design," NASA TM X-53019, Huntsville, Alabama, 1964. https://archive.org/details/nasa_techdoc_19630012259/page/n1

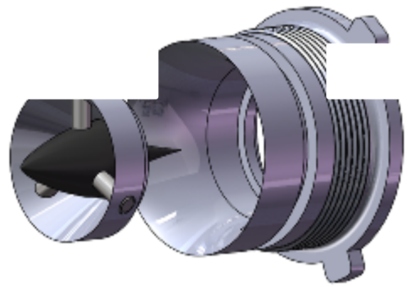
Aerospike Design: Convergent (Subsonic) Side

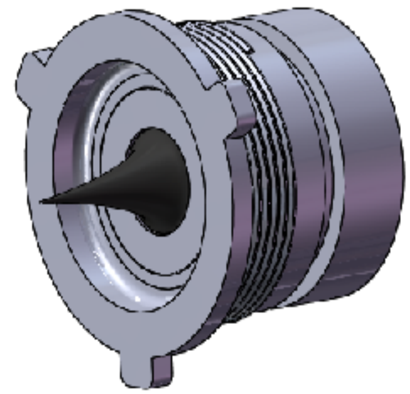
- Convergent section of spike (leading up to throat) designed as an aerodynamic Von Karman ogive (Haack series):

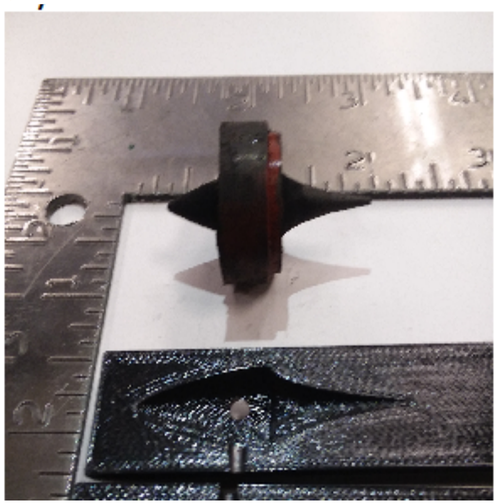
$$R_{Haack} = \frac{R_{exit}}{\sqrt{\pi}} \sqrt{\theta_{Haack} - \frac{\sin(2 * \theta_{Haack})}{2}}$$

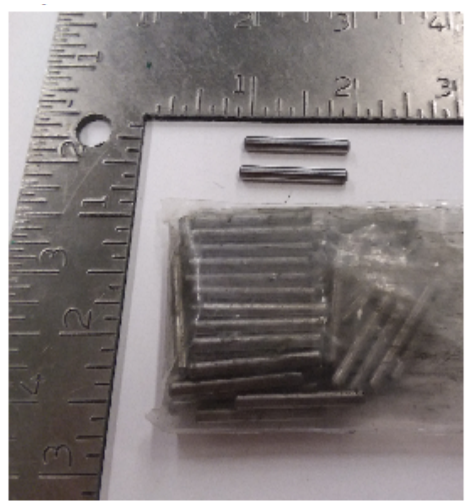


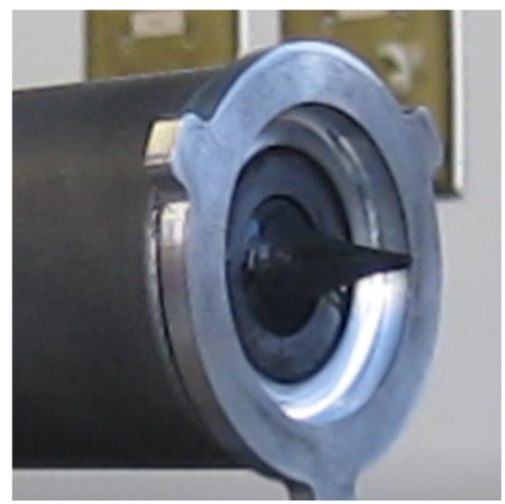
Aerospike Design I: CNC-Machined Graphite









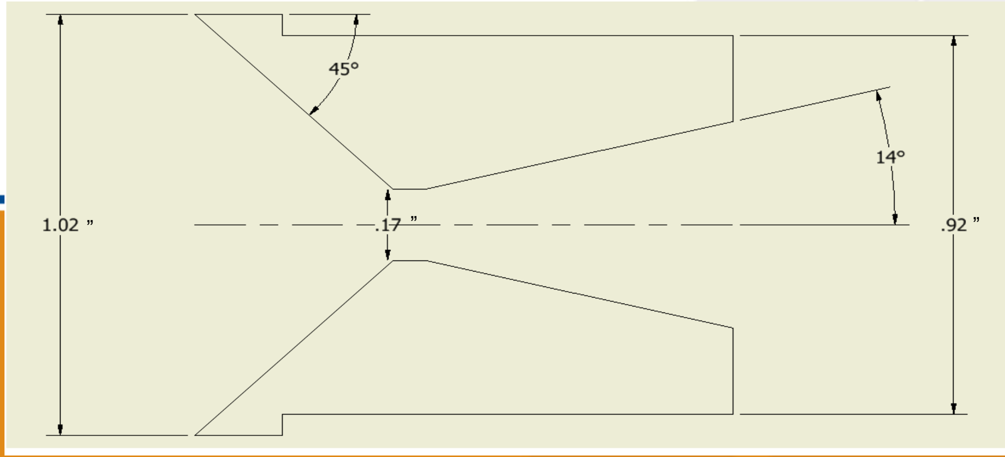


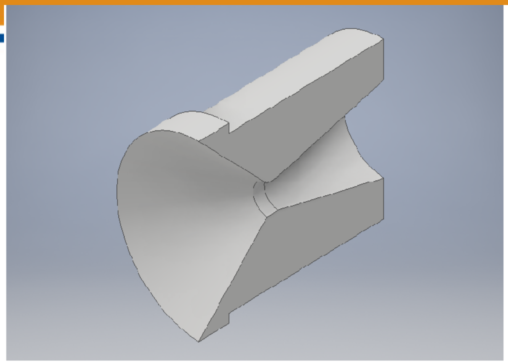
Aerospike Design II: 3D-printed Inconel

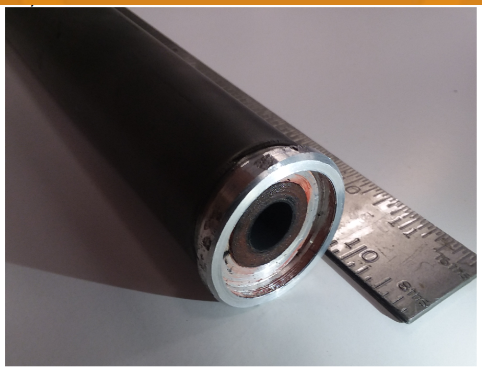
METAL	Melting Point (K)
Inconel 718	1700 K

Printed through Cooperative Agreement with EM-30 NASA MSFC

“Reference” Fixed-Cone Nozzle Design







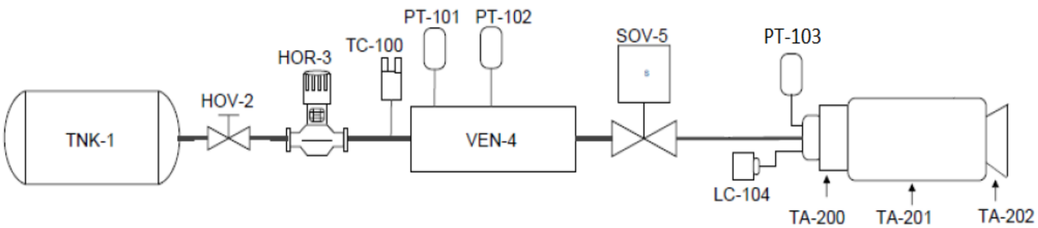
Experimental Campaign

- Test Matrix:

Nozzle Type	Location	Nozzle Expansion Ratio	Chamber Pressure	Ambient Pressure	Flow Regime
Cone	USU Main Campus	2:1	146 psia	12.28 psia	Near Design
Cone	NASA MSFC	8.5:1	180 psia	0.28 psia	Under-Expanded
Cone	NASA MSFC	2:1	180 psia	0.28 psia	Grossly Under-Expanded

Nozzle Type	Location	Nozzle Expansion Ratio	Chamber Pressure	Ambient Pressure	Flow Regime
Cone	USU Main Campus	8.5:1	100 psia	12.28 psia	Over-Expanded
Cone	USU Main Campus	8.5:1	130 psia	12.28 psia	Over-Expanded
Aerospike	USU Main Campus	8.5:1	100 psia	12.28 psia	Over-Expanded
Aerospike	USU Main Campus	8.5:1	130 psia	12.28 psia	Over-Expanded
Aerospike	NASA MSFC	8.5:1	180 psia	0.28 psia	Under-Expanded

USU Test Facility



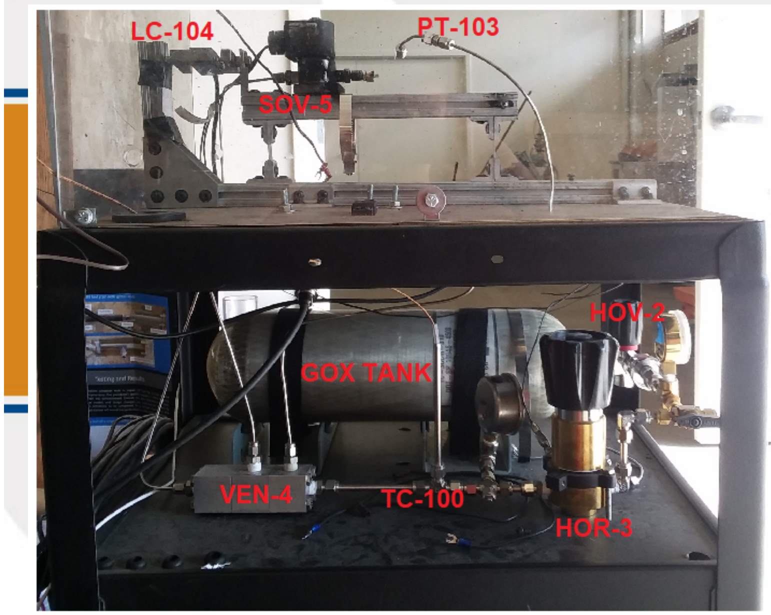
GOX Components	Functional Description
TNK-1	GOX supply tank (2000psi)
HOV-2	GOX supply on/off hand-operated valve
HOR-3	GOX hand-operated pressure reducing regulator
VEN-4	GOX Venturi flow meter
SOV-5	GOX solenoid run valve

Sensors	Functional Description
TC-100	Venturi inlet temperature
PT-101	Venturi inlet pressure
PT-102	Venturi differential pressure
PT-103	Combustion chamber pressure
LC-104	Thrust stand load cell

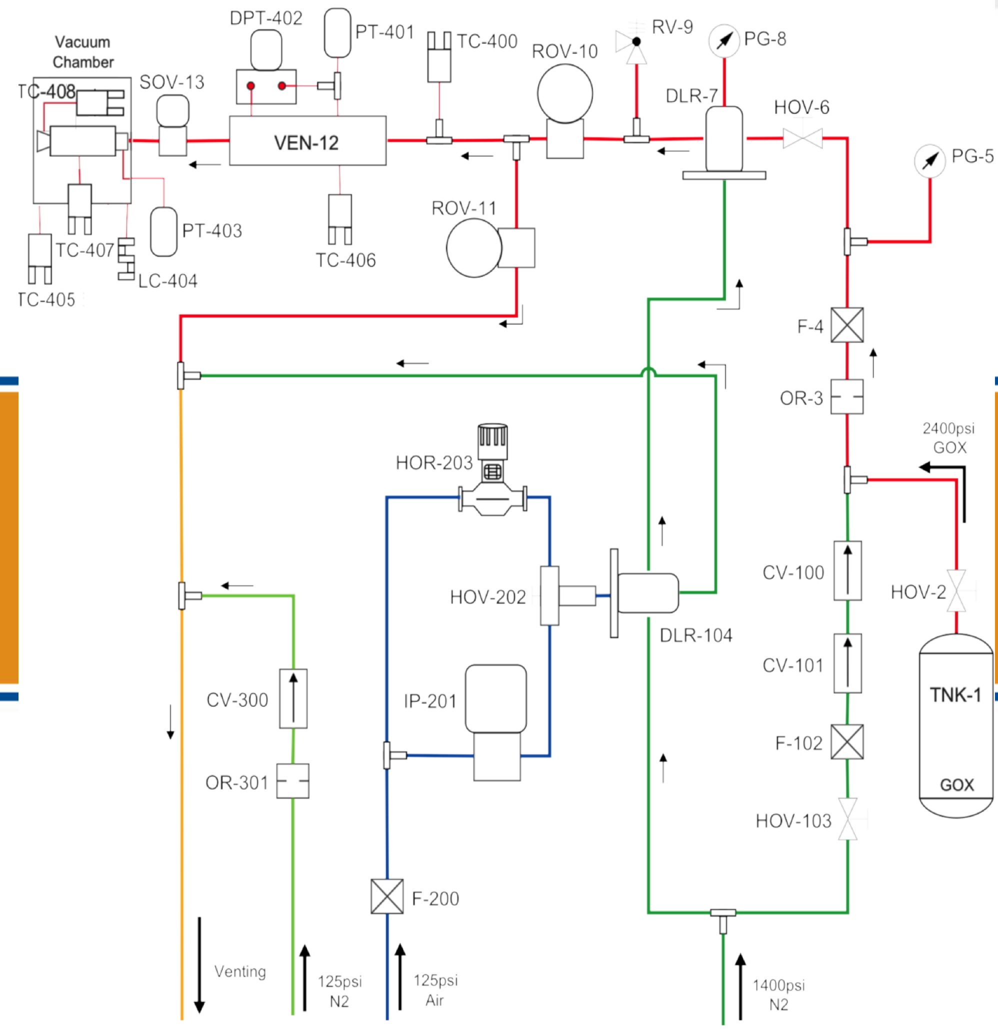
Test Article	Functional Description
TA-200	GOX injector cap
TA-201	Motor case
TA-202	Nozzle cap

Acronyms
- TNK: tank
- HOV: hand-operated valve
- HOR: hand-operated regulator
- VEN: Venturi flow meter
- SOV: solenoid valve
- TA: test article
- TC: thermocouple
- PT: pressure transducer
- LC: load cell

System P&ID



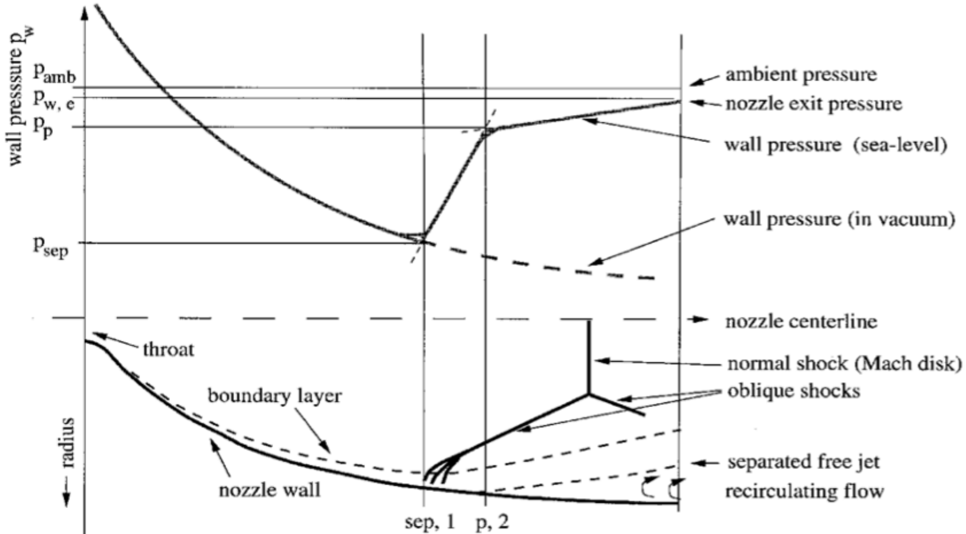
MSFC Test Facility (Bldg. 4305)



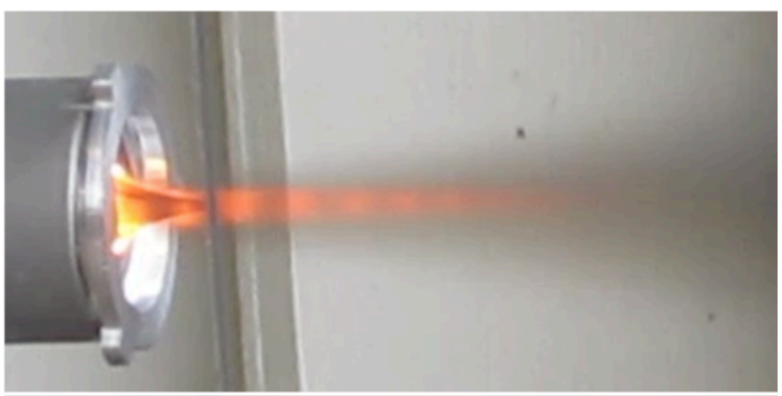
System P&ID

Ambient Tests, Logan UT

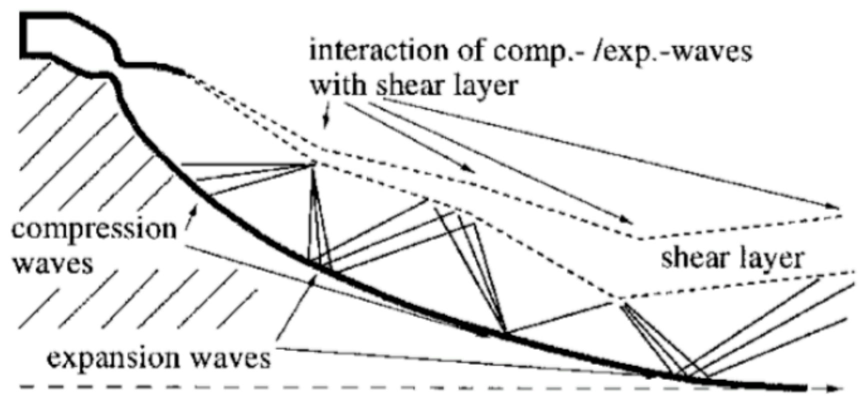
(a) *Over-expanded Conical Nozzle Exit Plume.*



(b) *Over-expanded Conical Nozzle Pressure Profile, and Flow Phenomenon Interpretation.*

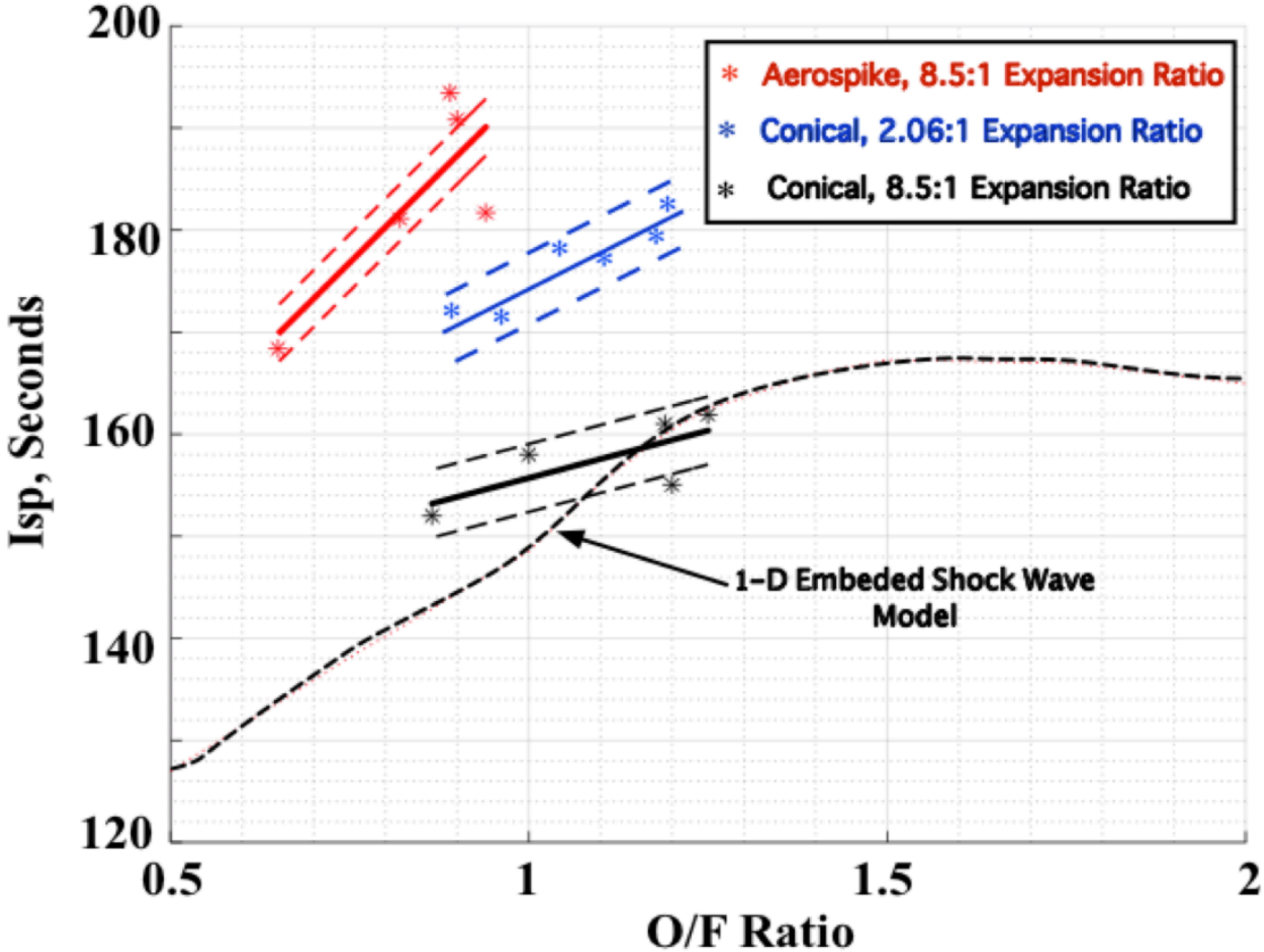


(a) *Over-Expanded Aerospike Nozzle Exit Plume.*



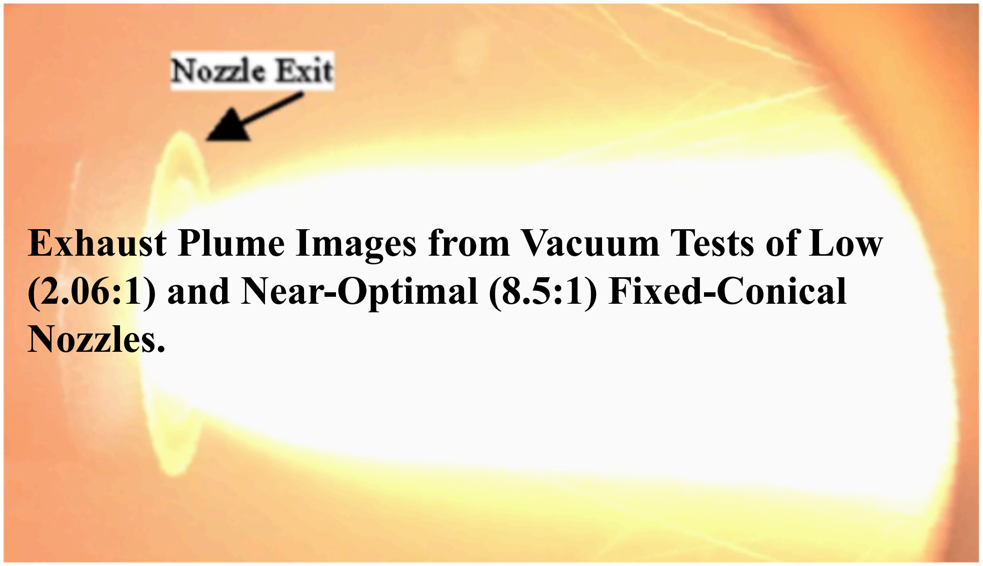
(b) *Over-Expanded Aerospike Nozzle Flow Phenomenon Interpretation.*[10]

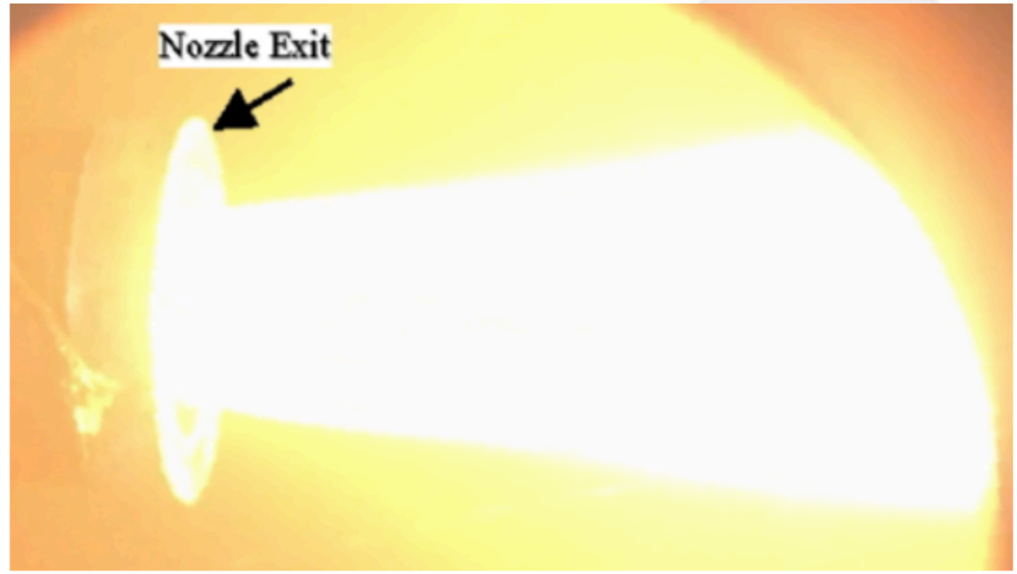
Ambient Tests, Logan UT (2)



Conventional and Aerospike Nozzle Specific Impulse Comparisons for Ambient Test Conditions.

Vacuum Tests, NASA MSFC

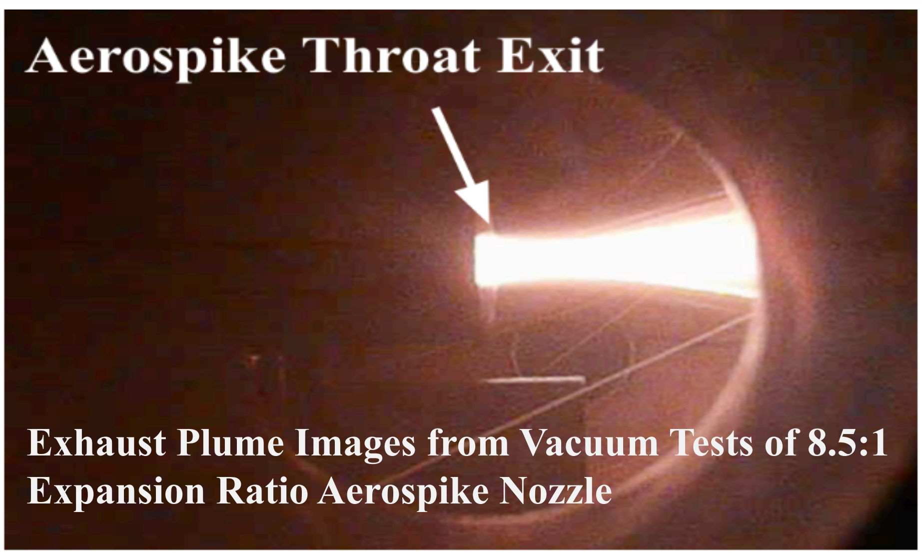




Exhaust Plume Images from Vacuum Tests of Low (2.06:1) and Near-Optimal (8.5:1) Fixed-Conical Nozzles.

(a) 2.06:1 Conical Nozzle

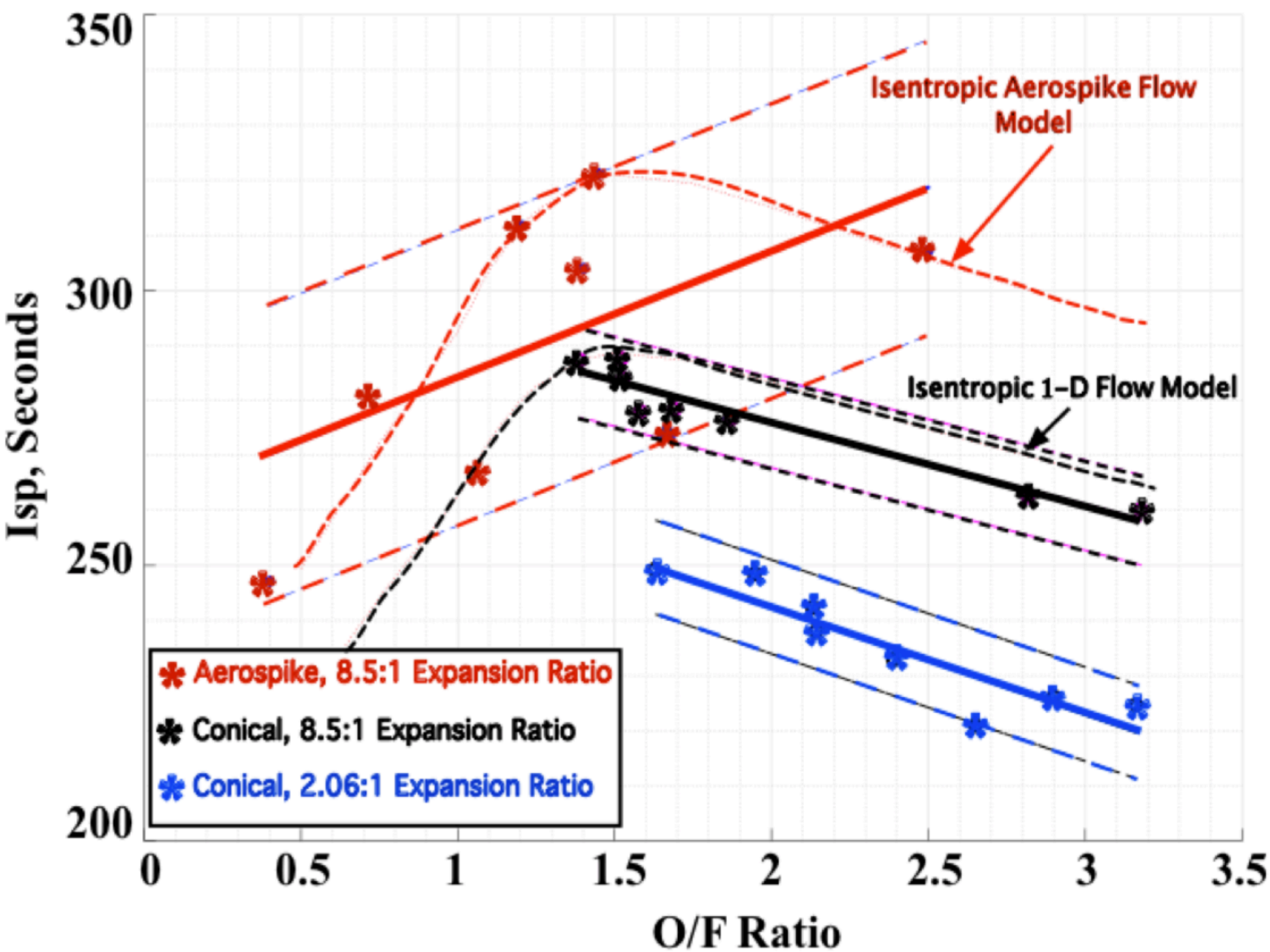
(b) 8.5:1 Conical Nozzle



Exhaust Plume Images from Vacuum Tests of 8.5:1 Expansion Ratio Aerospike Nozzle

Aerospike Compensates to Near-Optimal Exit Pressure

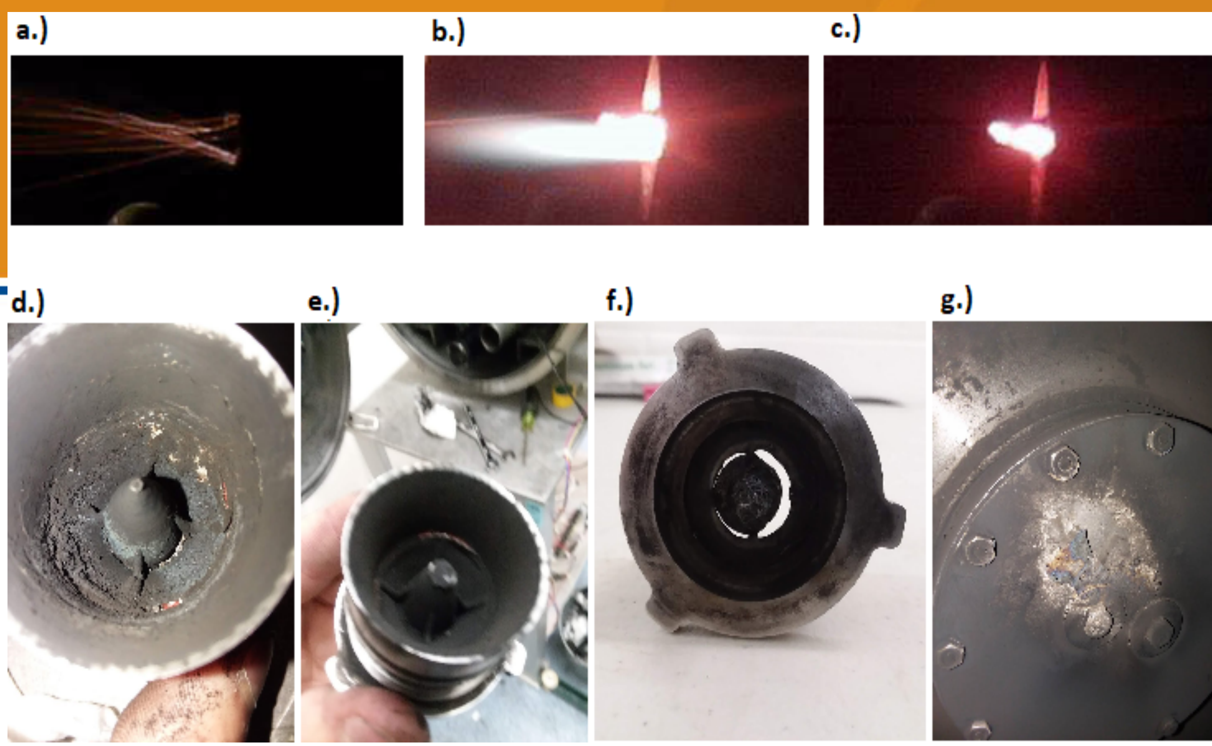
Vacuum Tests, NASA MSFC (2)



Conventional and Aerospike Nozzle Specific Impulse Comparisons, Vacuum Test Conditions.

Nozzle Survivability

- **3-D Printed Nozzle Failed after 16 seconds total burn time**
- **Machined Graphite Designs Survived for Duration of Testing Testing Campaign**
- **Fixed-Conical Nozzle Exhibited no Thermal Issues**



Thermal Failure of 3-D Printed Inconel Aerospike

Conclusion

- Graphite aerospike performed in line with established theory in over-expanded regime.
- Aerospike Nozzle exhibited Superior Isp, Thrust Levels compared to Fixed-Cone nozzle.
- Normal shockwave formation, observed visually and verified via shock model, reduced performance of 8;5:1 Fixed-cone nozzle during ambient tests.
- Aerospike Exhibited superior vacuum performance at the 8.5:1 expansion ratio, exhibiting ability to compensate.
- **Ability to print Aerospike as 3-D Monolithic Structure demonstrated**
- Thermal stress resulted in failure of 3-D Printed Inconel Nozzle after 16 seconds of total burn time.

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Proposed Future Work

- **3D printed Tungsten or other Refractory Metals**

- **Optimize O/F ratio for Higher Flame temperatures**
- **Test Multiple Units to Failure to Evaluate Thermal Capacity of Design**

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