National Aeronautics and Space Administration

Overview of the High Reynolds Number Ascent Wind Tunnel Test of the Space Launch System at the National Transonic Facility

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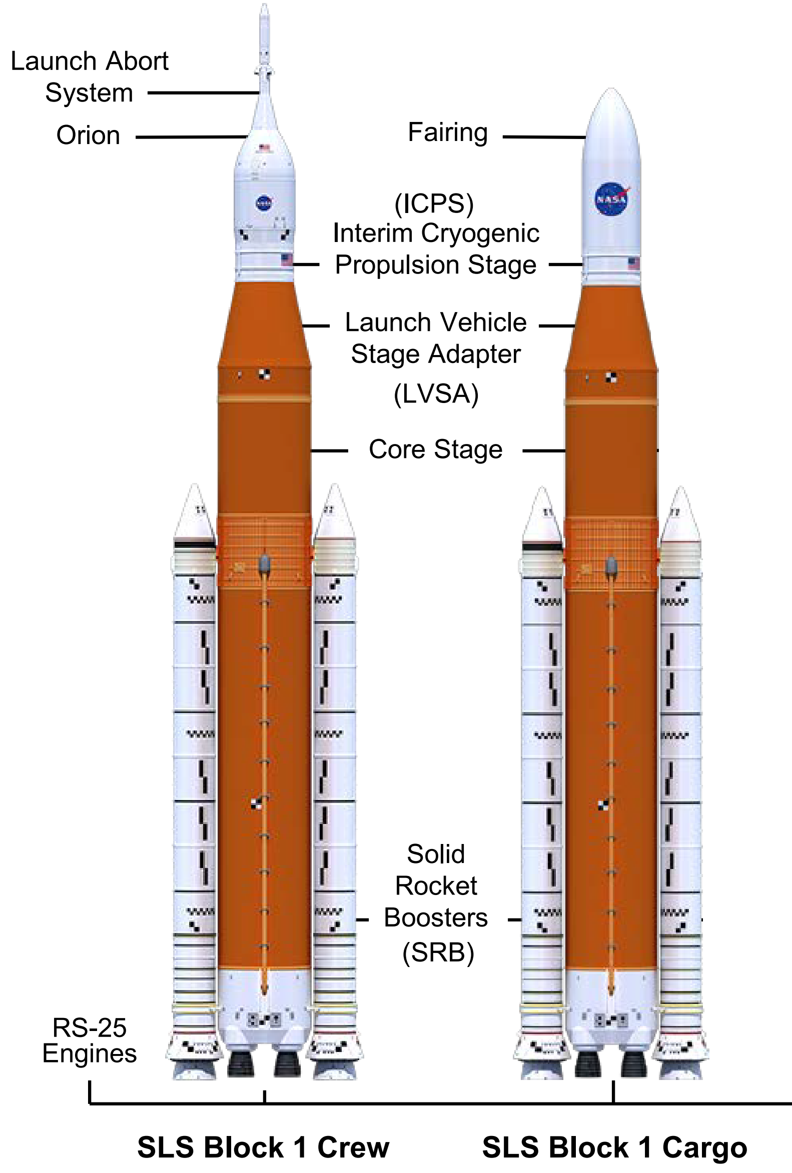
OUTLINE

- Background and Motivation
- Wind Tunnel Facility and Test Article Description
- Experiment Summary
- General Test Results Summary
- Final Remarks

BACKGROUND AND MOTIVATION

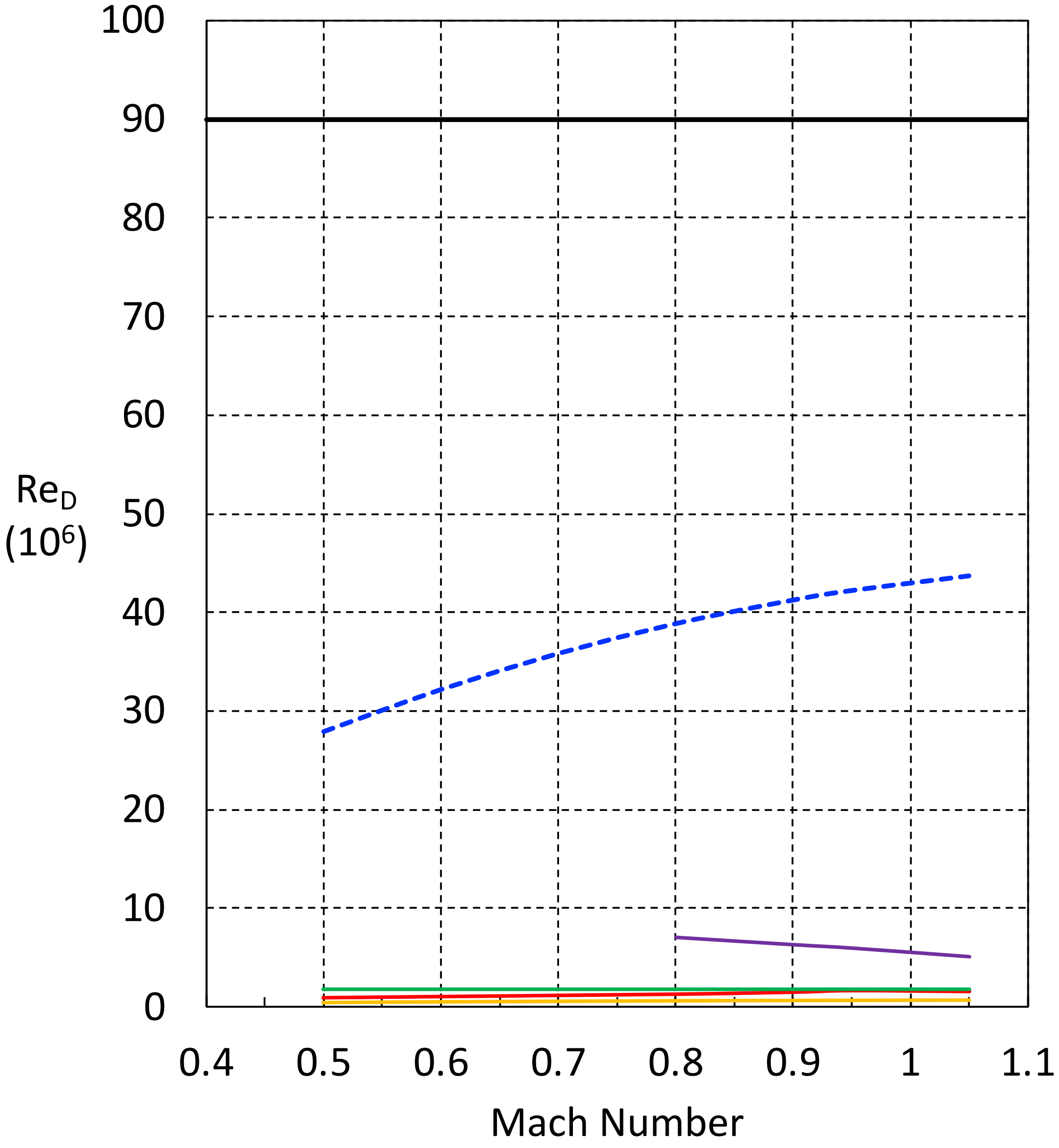
- **NASA Space Launch System (SLS)**
  - Family of launch vehicles for future crew and cargo missions beyond low-Earth orbit
  - Common core stage powered by four RS-25 engines
  - Two five-segment Solid Rocket Boosters (SRB)
- **Accurately characterizing SLS ascent aerodynamics in transonic flight regime is critical**
  - Transonic flow physics can change rapidly
  - Vehicle experiences maximum aerodynamic loading
  - Flight control stability margins are generally lowest in this portion of flight
- **Effect of Reynolds number on ascent aerodynamics had been an open question for complex, multibody SLS vehicle**
  - CFD simulations at ground and flight conditions were the only data available to assess Reynolds number effects
  - Implications on control margins (pitching and yawing moment)
  - Implications on performance and payload capacity (drag)

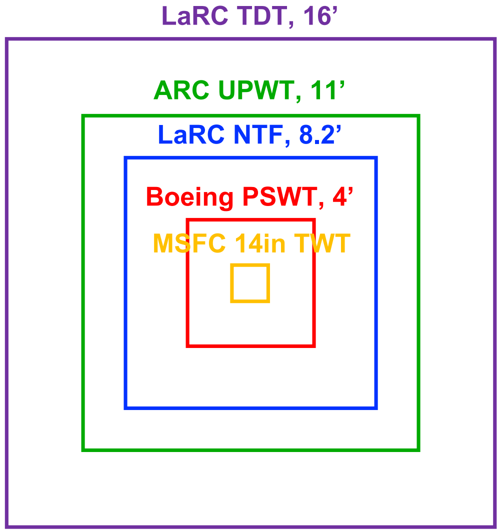


BACKGROUND AND MOTIVATION

- **SLS will reach Reynolds numbers (*Re*$_D$)* as high as 90x10^6 during ascent flight**

- **Previous SLS ascent wind tunnel tests were conducted at low *Re*$_D$**
  - Limited to 5x10^6 (1-2 orders of magnitude lower than flight)
  - National Transonic Facility (NTF) can achieve range of *Re*$_D$ up to 45% of flight levels





TWT – Trisonic Wind Tunnel
PSWT – Polysonic Wind Tunnel
UPWT – Unitary Plan Wind Tunnel
TDT – Transonic Dynamics Tunnel
NTF – National Transonic Facility

➔ **SLS High *Re*$_D$ Test at the NTF**
  - Sponsored by SLS program and NASA Engineering and Safety Center (NESC)

* *Re*$_D$ – Reynolds number based on core stage diameter

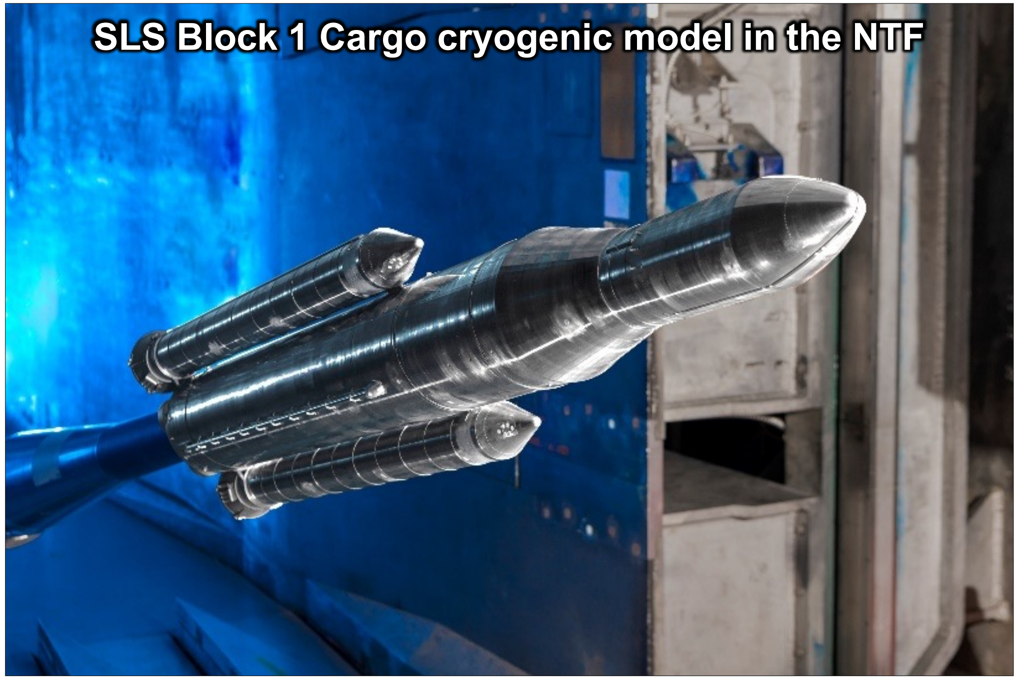
SLS

TEST OBJECTIVES

- **Assess the effect of Reynolds number on SLS ascent aerodynamics**
  - SLS Block 1 Cargo configuration was focus of test, but results relevant for entire SLS family
  - Range of Reynolds numbers up to 45% of flight
  - Mach numbers between 0.5 and 0.95
  - Angle of attack (α) and sideslip (β) over the range of -8 to 8 degrees

- **Specific measurement objectives**
  - Obtain 6-component static force and moment data
  - Obtain static surface pressure data
  - Obtain Pressure Sensitive Paint (PSP) measurements around SRB forward attach region

- **Goals and outcomes**
  - Determine if updates needed for SLS Ascent Aerodynamics databases
    - Force & Moment and Partial Derivatives databases
  - Improve CFD simulations at high Re_D and help inform future CFD-based ground-to-flight increments



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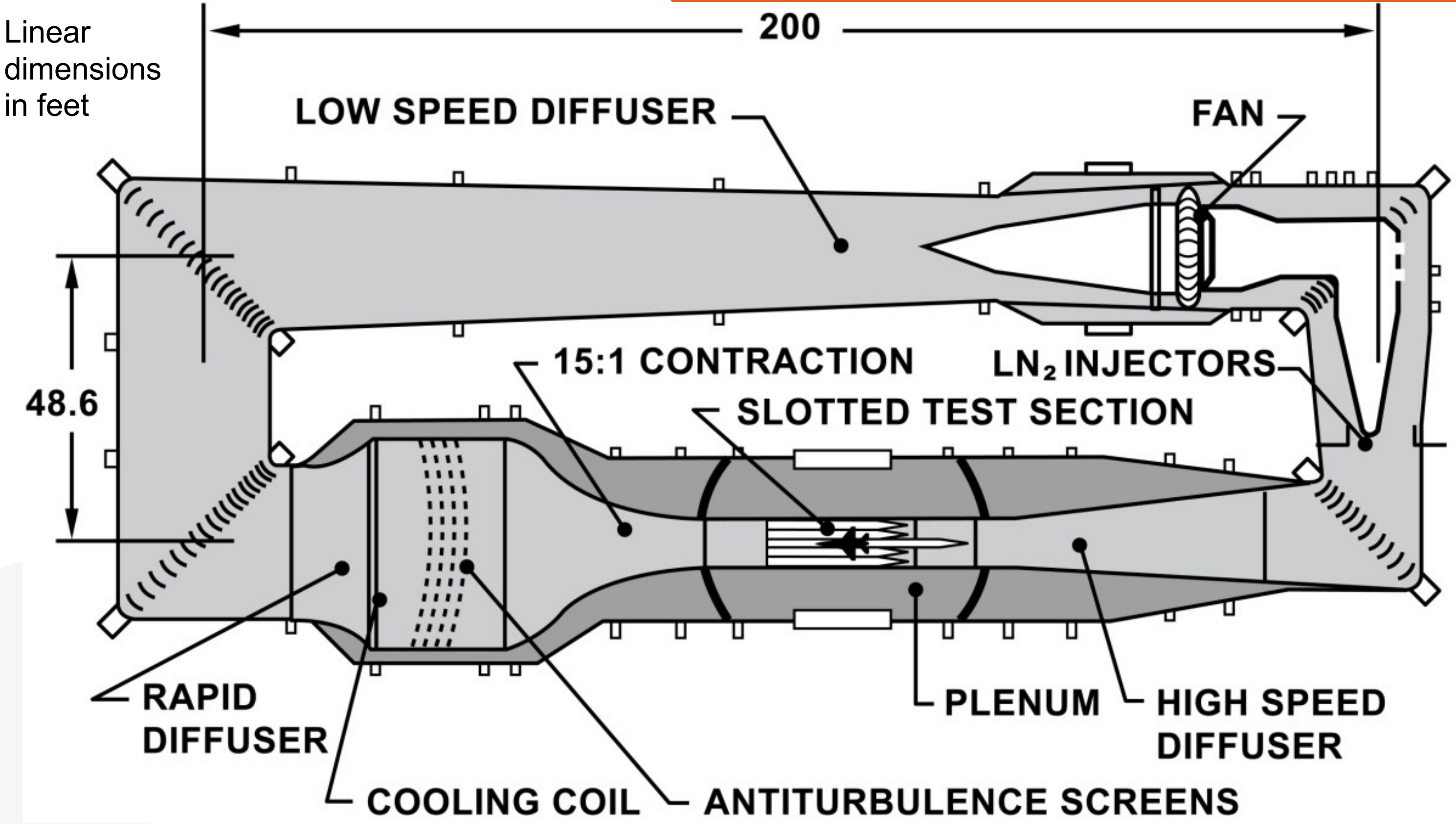
SLS

NATIONAL TRANSONIC FACILITY (NTF)



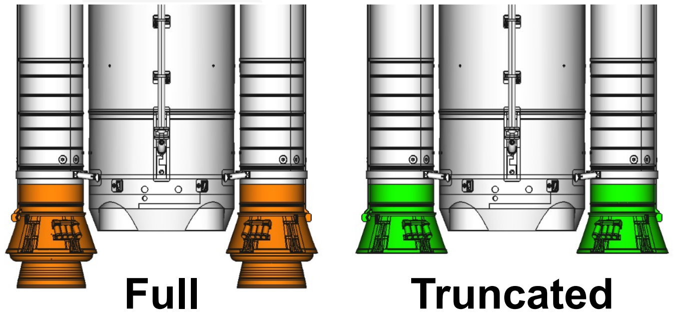
Photos : NASA

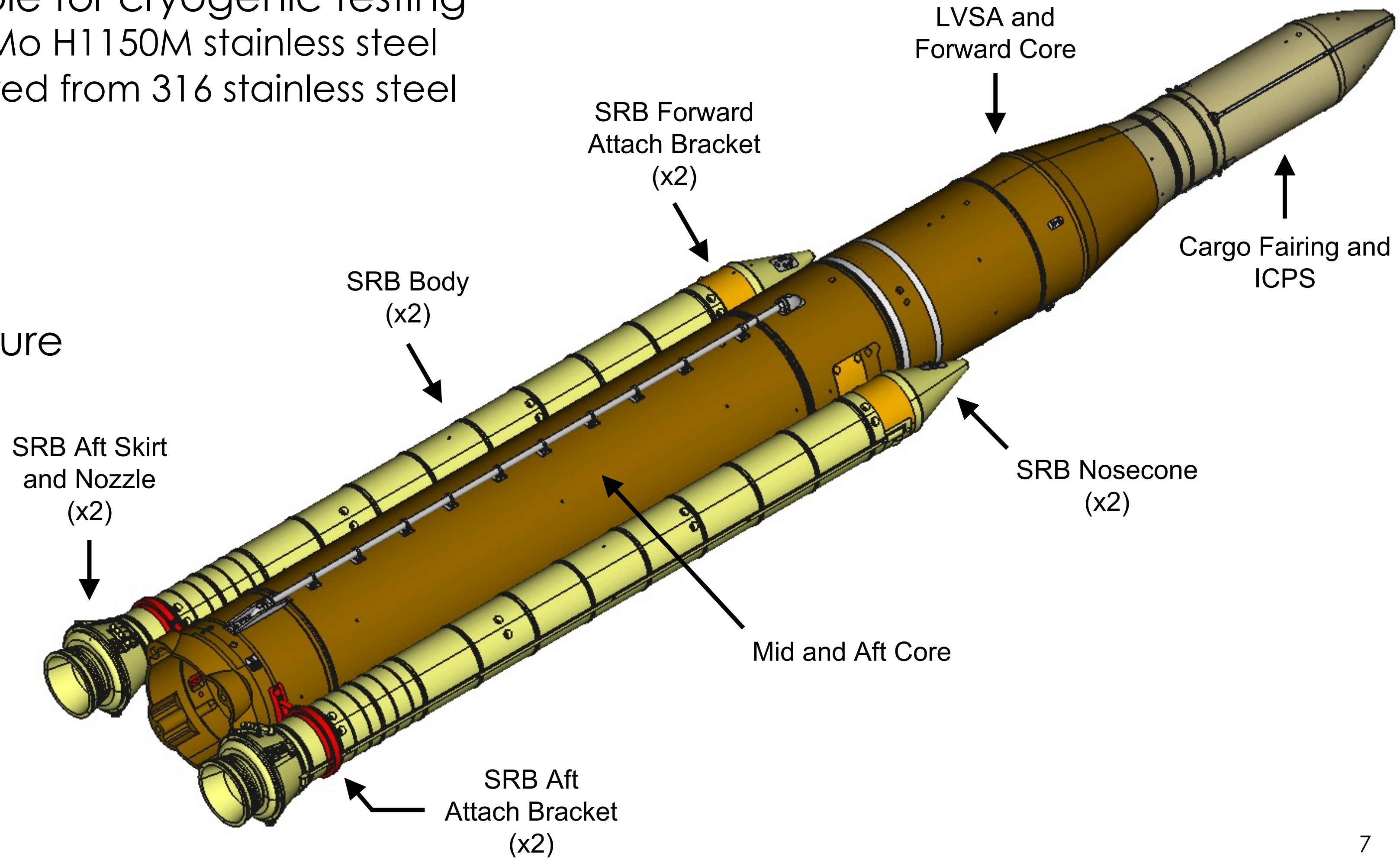
- Located at the NASA Langley Research Center
- Pressurized, cryogenic wind tunnel
- Operate in dry air or gaseous nitrogen
- Achieve very high Reynolds numbers
  - Flight or near-flight for many vehicles

Test Gas	Air	Nitrogen
Mach Number	0.1 – 1.10	0.1 – 1.20
Max Unit Reynolds Number	20×10^6 / ft	145×10^6 / ft
Total Pressure	1 – 8.3 atm	1 – 8.3 atm
Total Temperature	80°F to 130°F	-250°F to 80°F

TEST ARTICLE DESCRIPTION

- **1.75%-scale model of SLS Block 1 Cargo configuration**
  - Large enough for detailed protuberances, but under 0.5% blockage ratio recommended by NTF
  - Withstand aerodynamic loads at 4000 psf dynamic pressure
  - Fabricated from materials suitable for cryogenic testing
    - Most parts machined from 13-8 Mo H1150M stainless steel
    - Some parts additive-manufactured from 316 stainless steel or Inconel 718
- **Two sets of SRB nozzles**
  - Full and truncated nozzles
  - Used to examine SRB base pressure environment

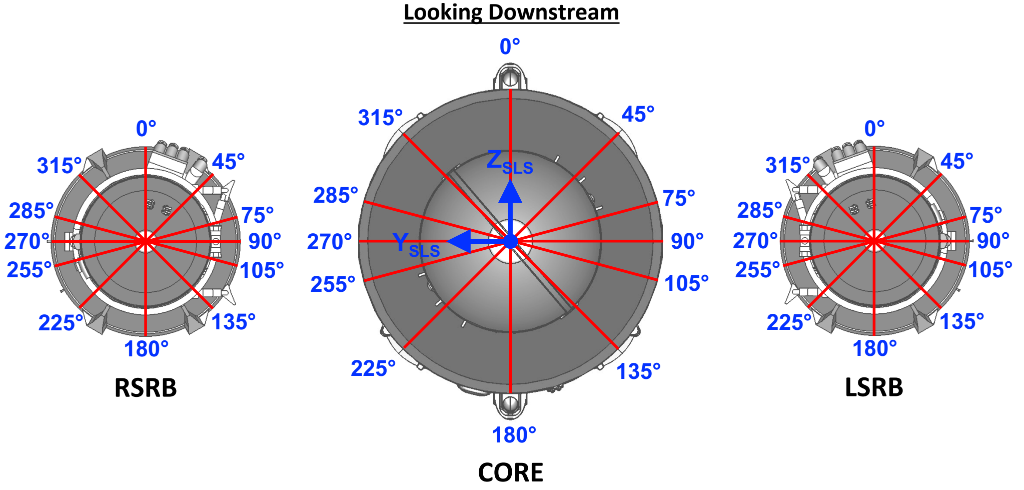


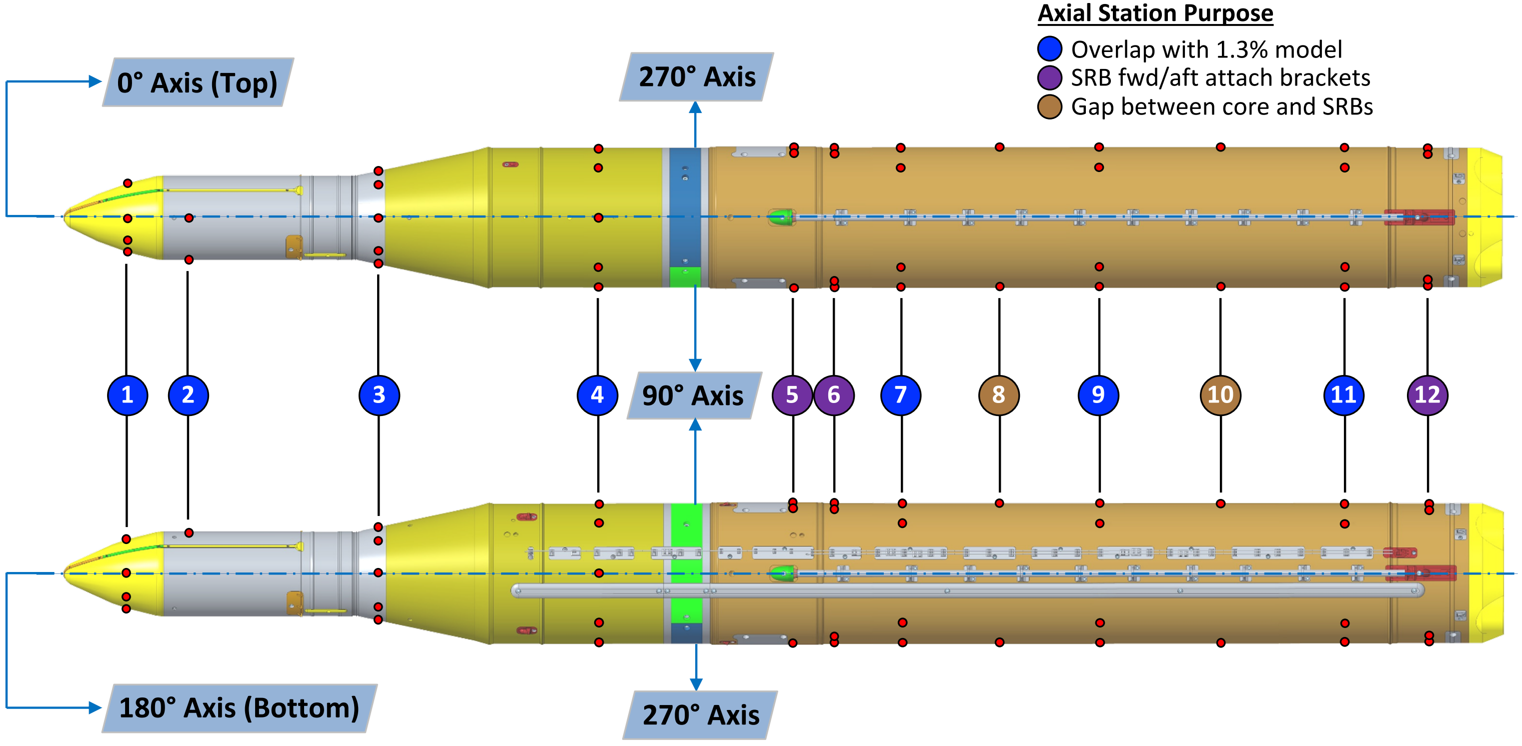


SLS

SURFACE PRESSURE TAPS

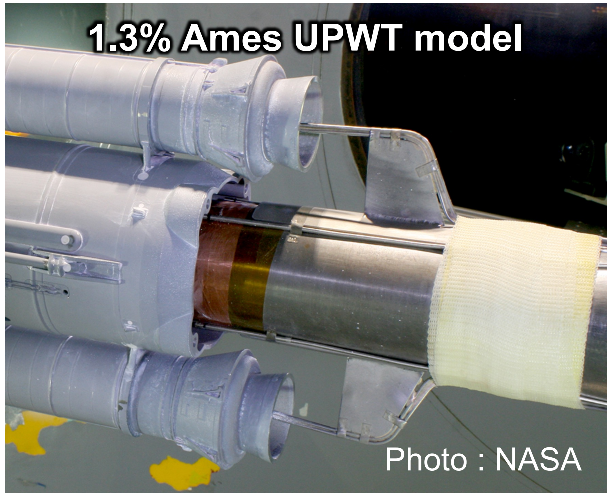
- **Total of 124 static pressure taps**
  - Ring of pressure taps at various axial stations along length of model
  - Radial locations and axial stations chosen with different objectives including comparisons to CFD
    - Overlap with 1.3% scale model (for comparison to Ames UPWT)
    - Additional taps around SRB forward and aft attach brackets (for investigating Re_D effects)
    - Additional taps in the gap between core and SRBs (for investigating Re_D effects)



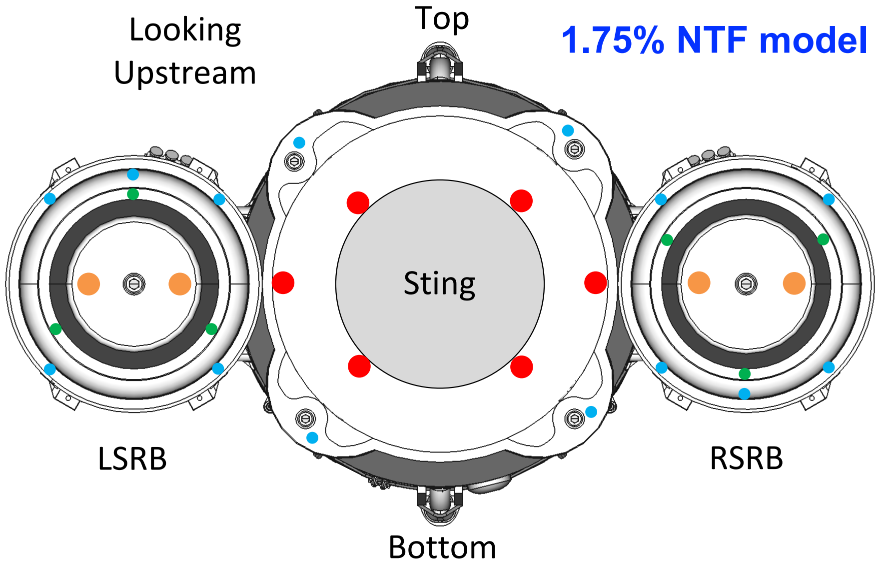


BASE AND CAVITY PRESSURES

- **Base pressure environment in wind tunnel does not represent flight conditions**
  - Corrections applied using measured base and cavity pressures
  - Previous SLS models only had 4 core cavity pressures and 2 cavity pressures for each SRB
  - CFD showed large pressure gradients on complex SRB nozzle geometry
  - Using only 2 SRB cavity pressures could reduce accuracy of base pressure correction
- **NTF model instrumented with more base and cavity pressures to examine base pressure environment**
  - 10 pressure taps each for core and SRBs
  - Several pressure taps directly on aft-facing base surfaces
  - Pressure flowpaths integrated into SRB nozzle parts using additive manufacturing



1.75% NTF model

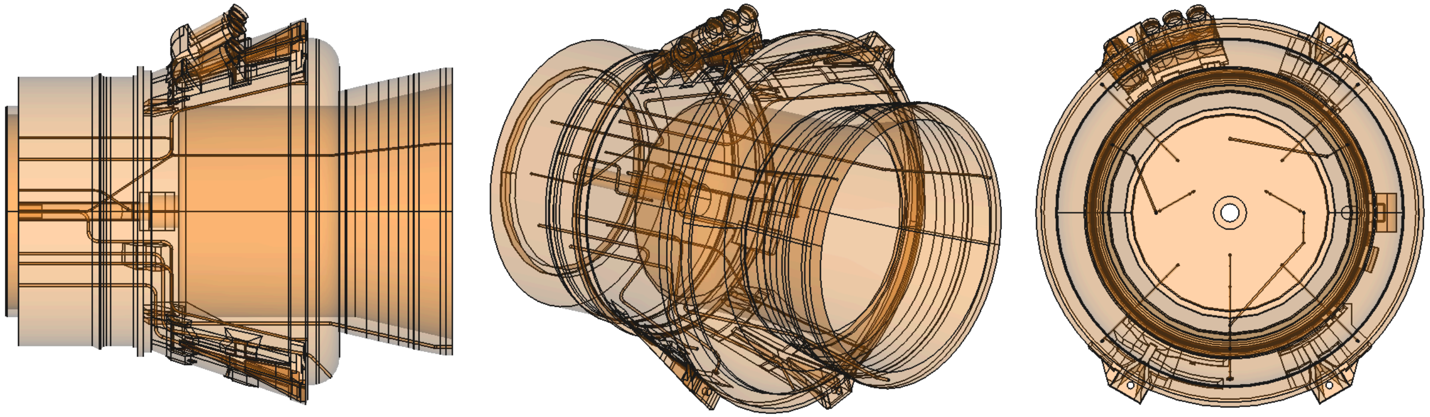


- Base Pressure Tap (Core and SRB Aft Skirt)
- Base Pressure Tap (SRB Nozzle)
- SRB Cavity Pressure Tap
- Core Cavity Pressure Tube

ADDITIVE MANUFACTURING

- **Direct Metal Laser Sintering (DMLS) additive manufacturing technique was used to fabricate the SRB nozzles and attach brackets**
  - Necessity based on design requirements, NOT cost or rapid prototype capability
  - Inco718 powder used for SRB attach brackets and 316 SS powder used for SRB nozzles
  - Materials chosen for strength & ductility properties, and compatibility at cryogenic temperatures

- **Design requirement to maintain geometric fidelity and small details of outer mold line, while also integrating internal flowpaths for the SRB base and cavity pressure taps**
  - Would have been very difficult or impossible to do with traditional machining methods



Full SRB nozzles

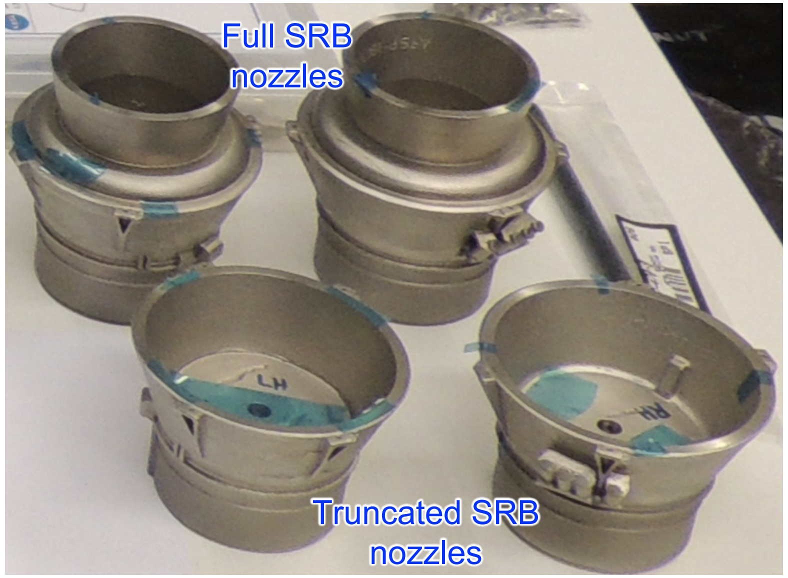


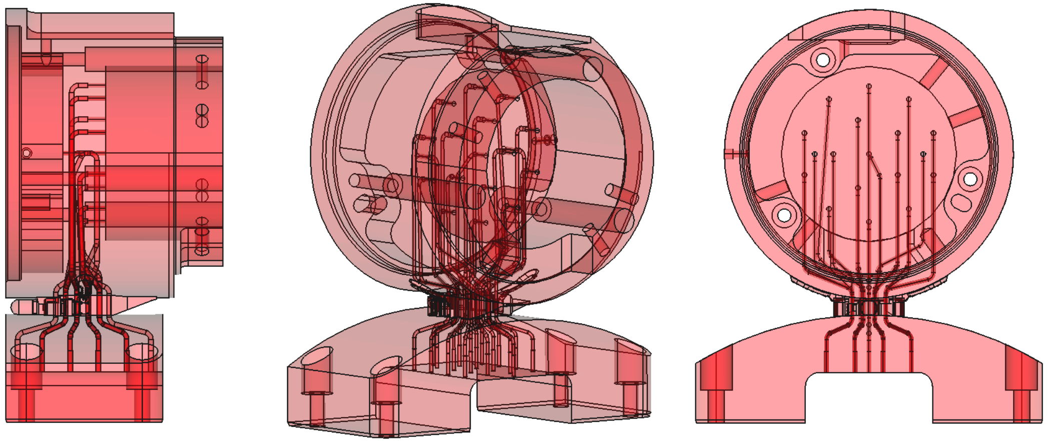
Photo : NASA

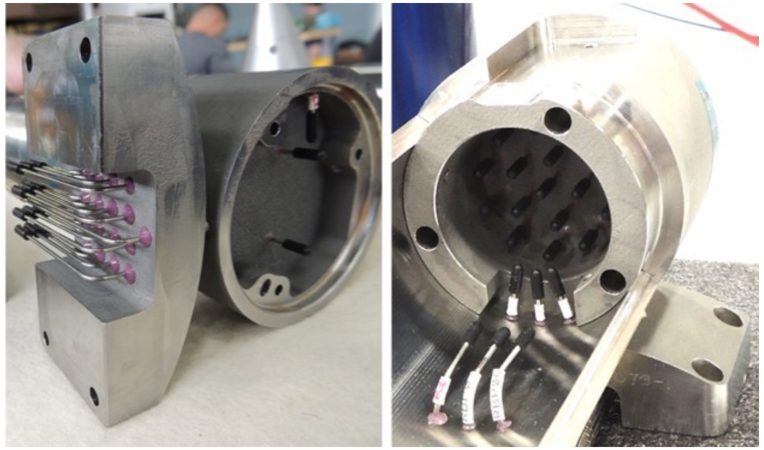
ADDITIVE MANUFACTURING

- **SRB forward and aft attach brackets**
  - Structural components on model used to attach SRBs to the core
  - Pass SRB pressures (body, base, cavity) through to core where pressure transducers reside
  - Stainless steel tubes attached to ends of flowpaths for easy connection to flexible tubing

<u>SRB fwd attach brackets</u>

- 18 pressures passed through separation mechanism





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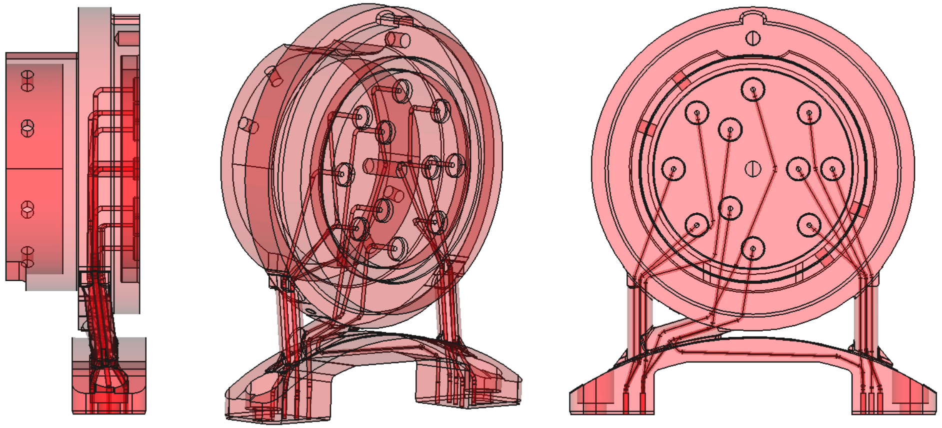
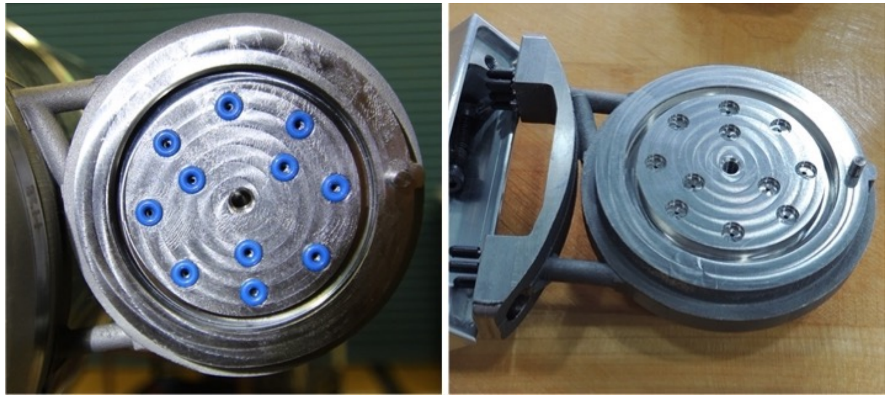
<u>SRB aft attach brackets</u>

- 11 pressures passed through attach posts
- O-rings used on SRB nozzle-to-bracket interface



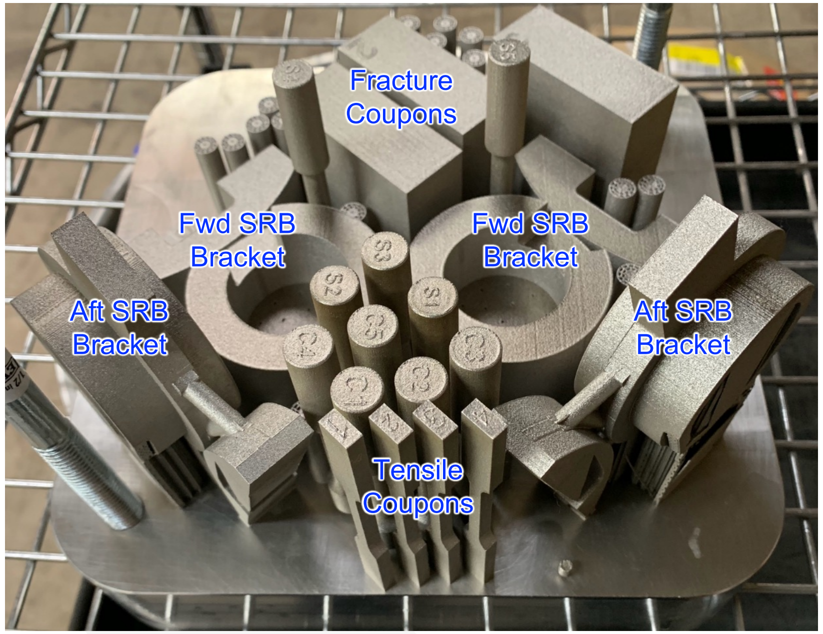


MATERIALS TESTING

- **SRB attach brackets were first use of additive-manufactured parts as <u>structural components</u> on a cryogenic model at NTF**

- **NTF model systems criteria for additive-manufactured structural components**
  - Coupons shall be made alongside each part with the same representative build orientation
  - As-built material properties shall be measured (tensile strength and fracture toughness)
  - Coupon tests shall be performed at both room and cryogenic temperatures
  - Nondestructive evaluation (NDE) inspections shall be performed to ensure no voids or cracks

Build plate



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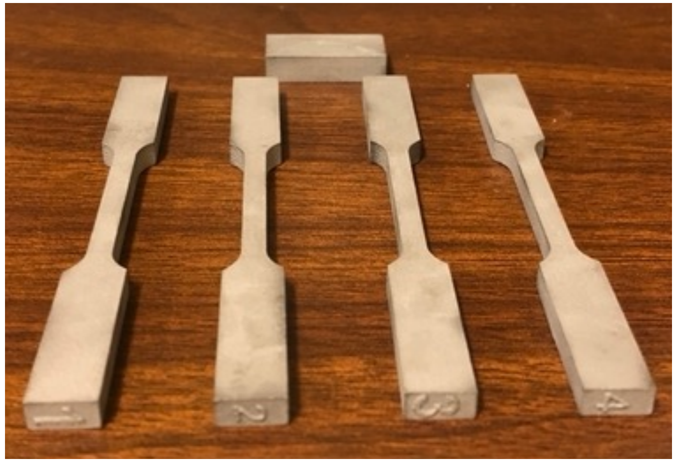
Tensile strength subsize coupons



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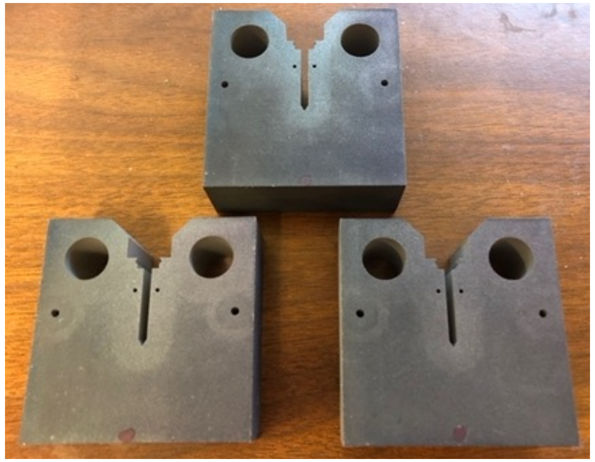
Fracture toughness compact tension coupons



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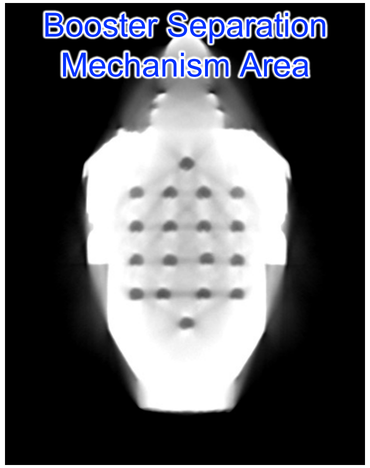
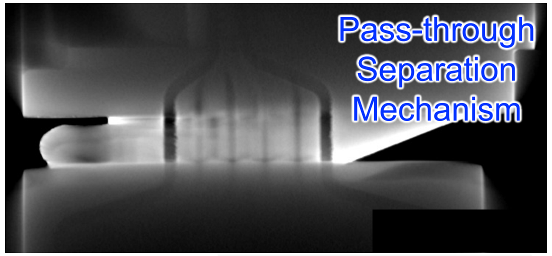
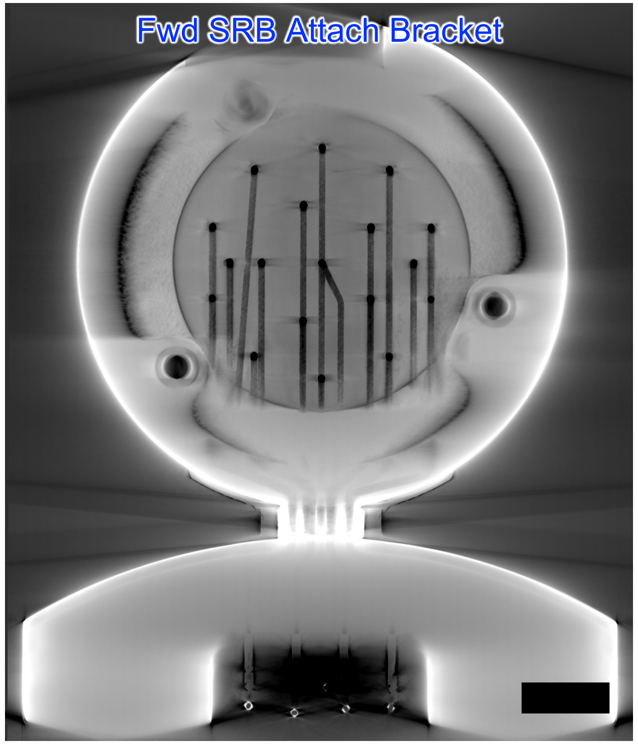
X-RAY INSPECTION

- **Computed Tomography (CT) scans performed on SRB attach brackets**
  - Inspect build integrity and part homogeneity
  - No critical voids or cracks were detected in scans

SRB forward attach bracket







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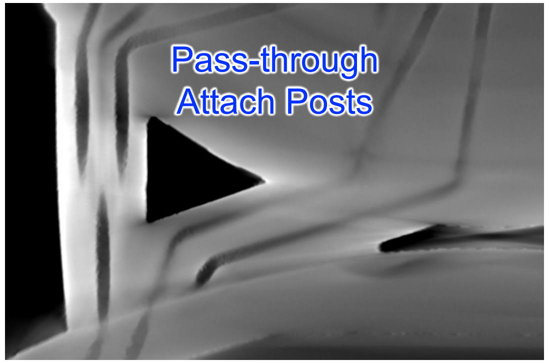
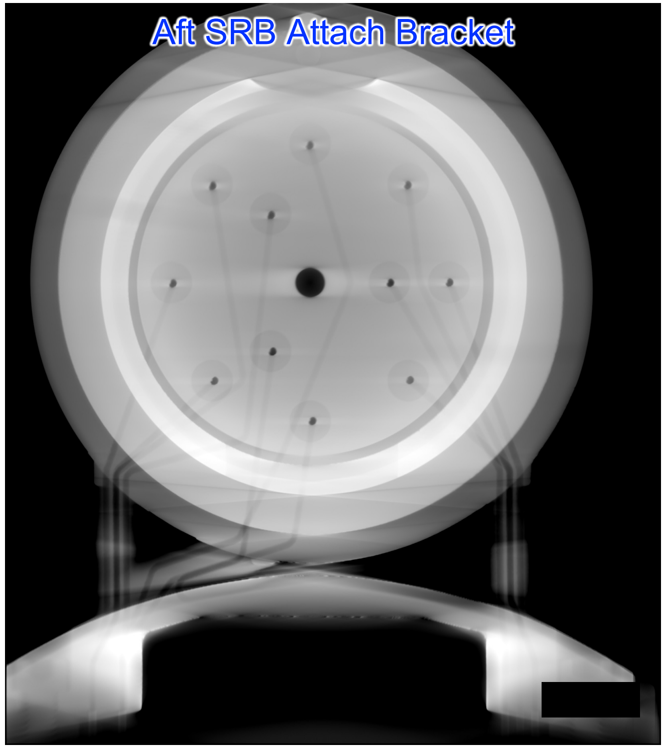
SRB aft attach bracket





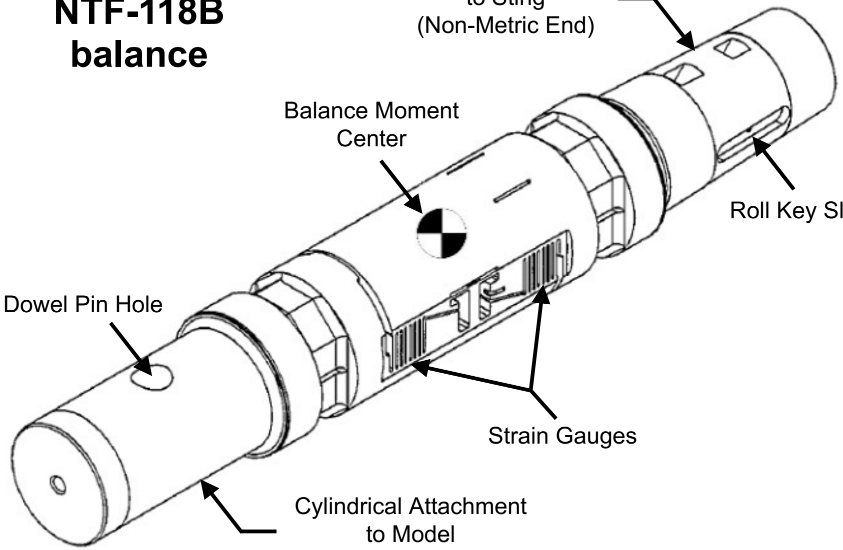
Photos : NASA

INSTRUMENTATION

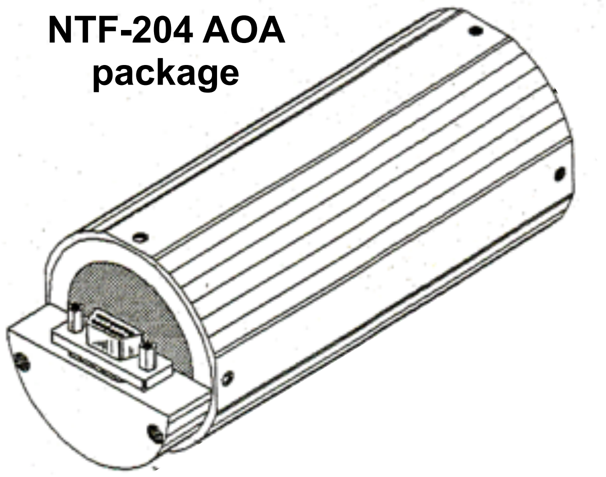
- **Measurement transducers**
  - Force & Moment (F&M) : NTF-118B strain gauge balance
  - Model Orientation : NTF-204 heated AOA package
  - Model Temperatures : 3 Type-T thermocouples
  - Model Pressures : 2 ESP modules housed in heated enclosure
  - Pressure Sensitive Paint

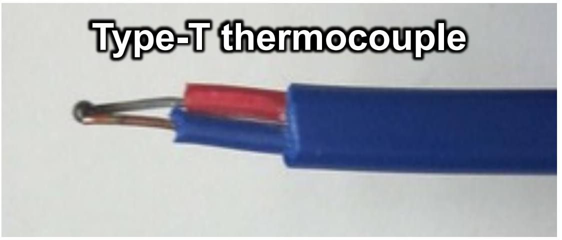
Photo : NASA

NTF-118B balance



NTF-204 AOA package





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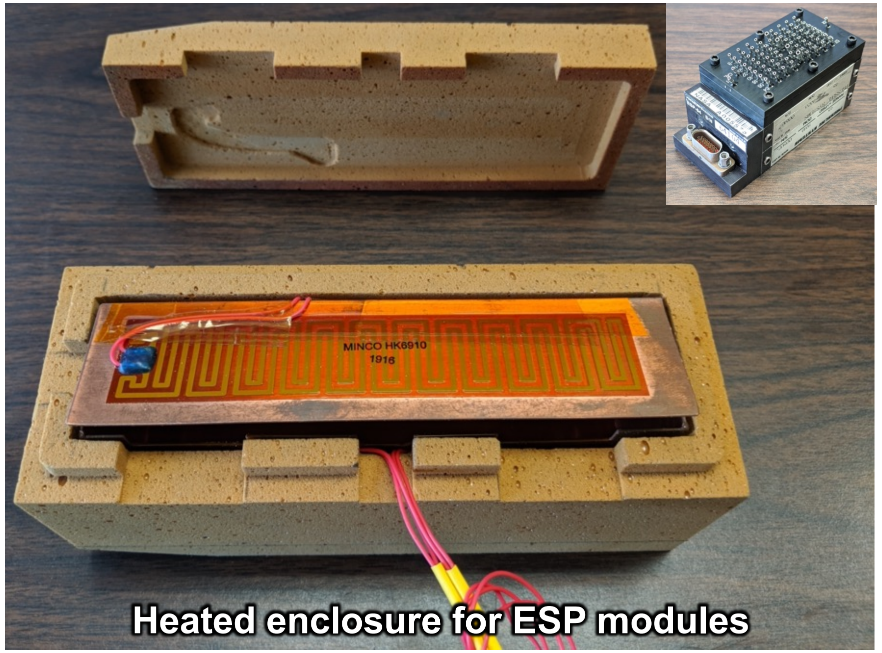

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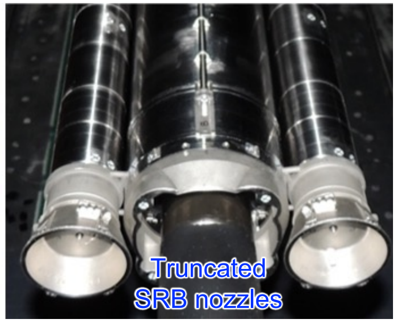
TEST SUMMARY AND METRICS

- **NTF Test 231 – SLS High Re_D Ascent Test**
  - Assess Re_D effects on SLS ascent aerodynamics
- **Test Entry Dates: Dec. 2019 to Apr. 2021**
  - Lost 1 year due to COVID-19 pandemic and recovery / restart
- **1.75% SLS Block 1 Cargo configuration**
  - Full and truncated SRB nozzles
- **Boundary layer transition**
  - Free and fixed (trip dots for low and high Re_D)
- **Data types**
  - 6-DOF forces and moments
  - Static surface pressure
  - Pressure Sensitive Paint
- **Test conditions**
  - Total temperature : -250°F to 120°F
  - Total pressure : 15 to 81 psia
  - Dynamic pressure : 450 to 3500 psf
- **Metrics**
  - 589 user occupancy hours, 245 wind-on data runs
  - 22,387 tons of LN_2, 1,601 MW-hrs of power, 3986 klbs of air



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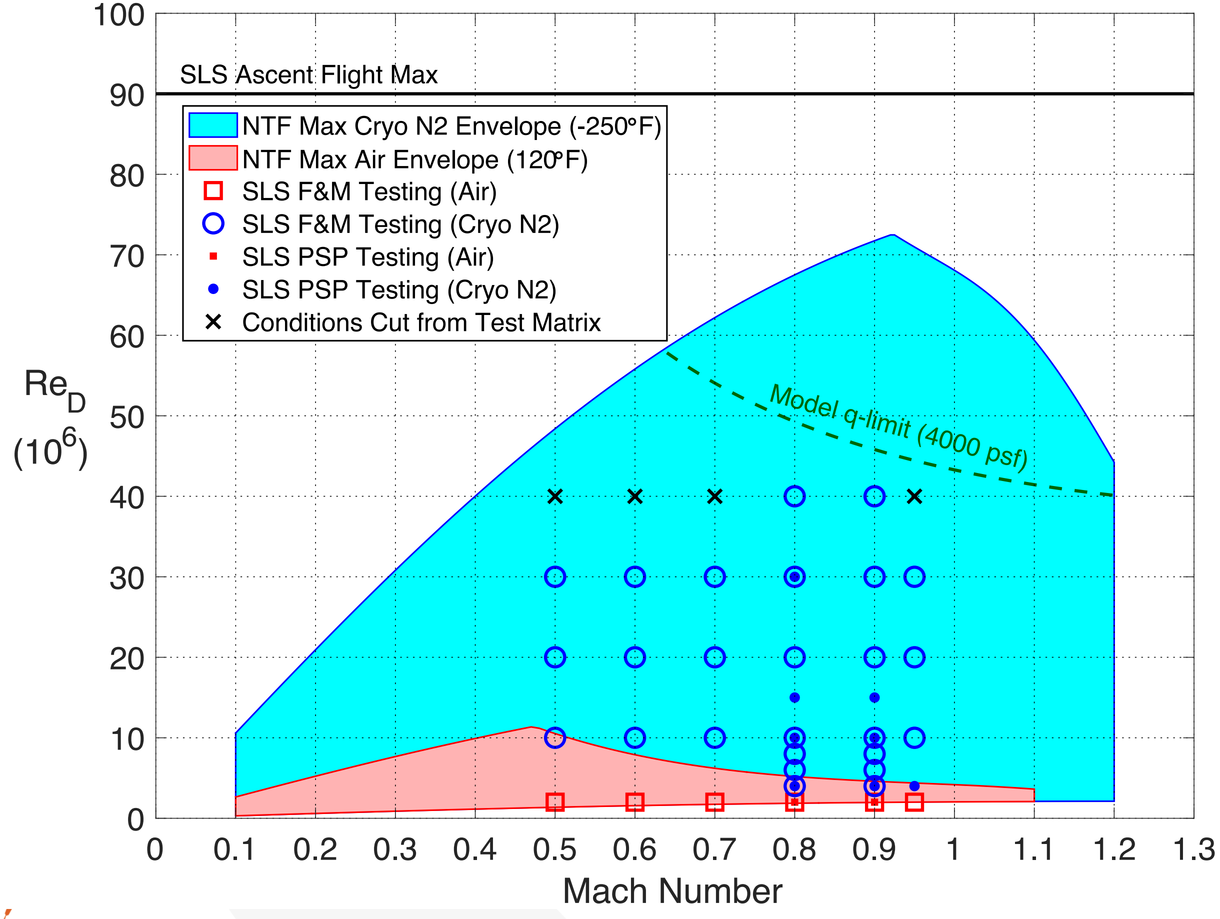
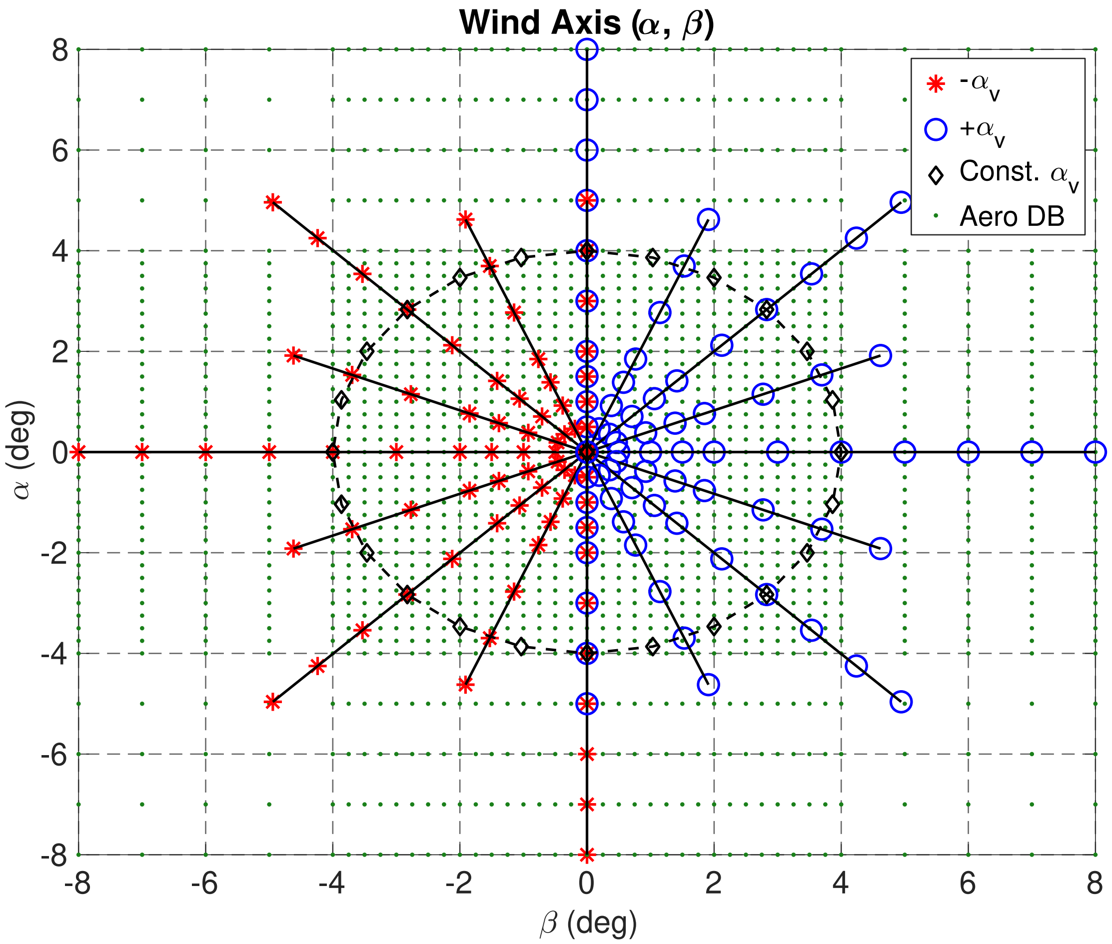
TEST MATRIX

- **Test matrix split between main F&M testing block and PSP testing block**
  - Most of test conducted with truncated SRB nozzles for more stable base pressure environment
  - Pitch and Roll sweeps were used to fill out (α, β) data space





GENERAL RESULTS AND DATA SUMMARY

- **Companion paper* provides more details on test results and data analyses**

- **F&M data showed Reynolds number sensitivity up to Re_D = 40x10^6**
  - Most notable in pitching moment (C_m), yawing moment (C_n), and axial force (C_A) coefficients
  - C_m, C_n can impact flight controller development and C_A can impact payload to orbit

- **Surface pressure data showed SRB forward attach region is sensitive to Reynolds number**
  - May be region that is contributing to the changes in the integrated F&M
  - This region must be modeled carefully for experimental test hardware and for CFD simulations

- **For ascent testing, the truncated SRB nozzles are preferred over the full SRB nozzles**
  - Provides a more stable base pressure environment with a limited number of pressure taps
  - For ascent low α, β range, differences in F&M data are minimal between the two sets of nozzles

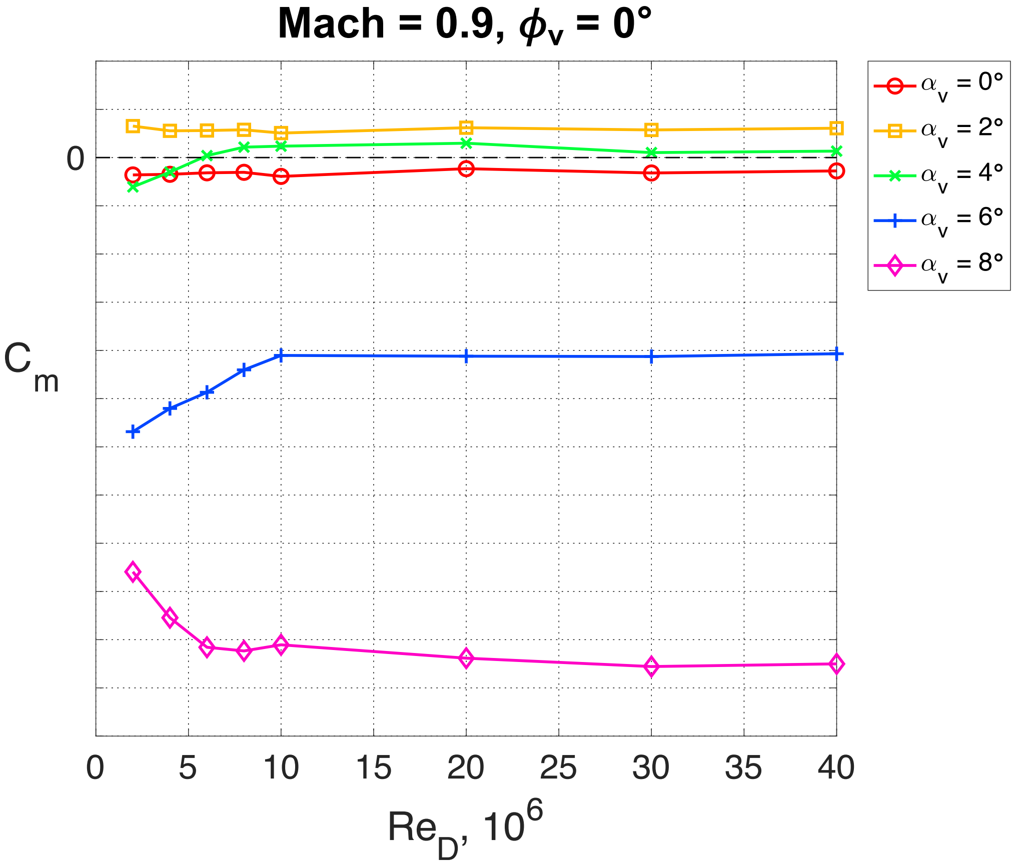
- **PSP data in NTF compared favorably with PSP data at Ames UPWT at similar conditions**
  - However, further development at NTF is needed to obtain results at high Re_D under difficult cryogenic conditions

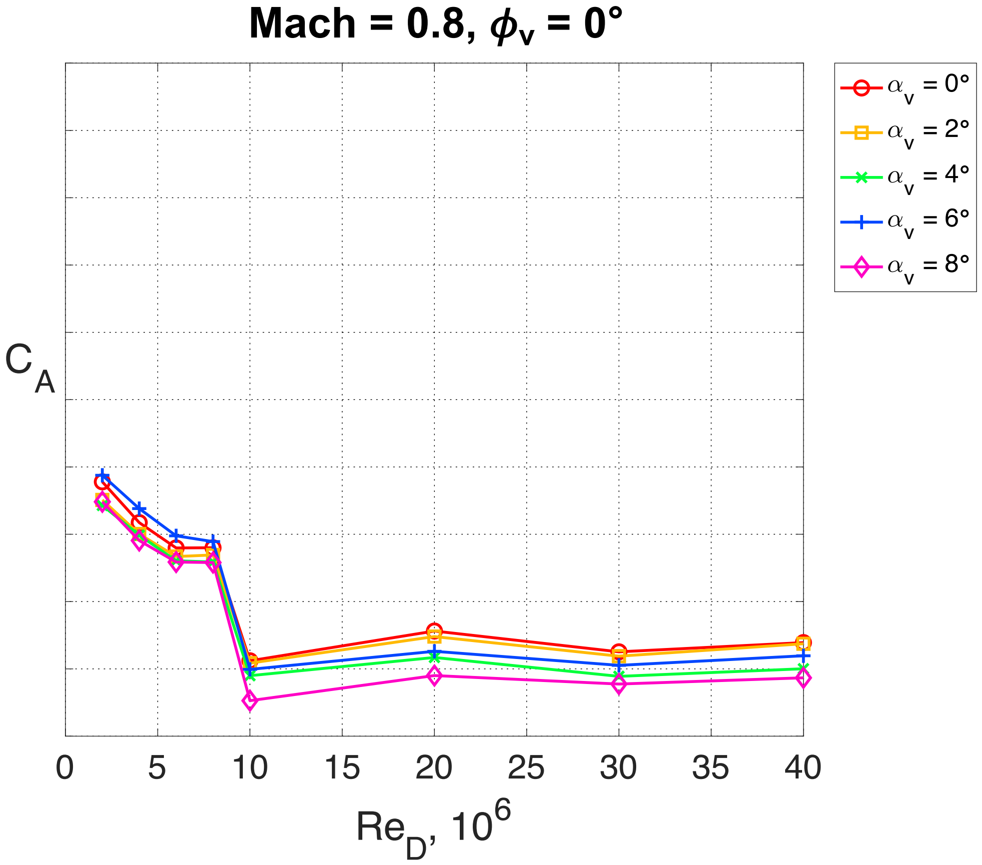
* Patrick Shea, et al., "Force & Moment Analysis for the High Reynolds Number Wind Tunnel Test of the Space Launch System at Ascent Conditions"

SLS SPACE LAUNCH SYSTEM

EFFECT OF REYNOLDS NUMBER

- **Pitching moment coefficient (C_m) sensitivity to Reynolds number**
  - Above α = 2°, noticeable trend from Re_D = 2x10⁶ to 10x10⁶, then less variation up to Re_D = 40x10⁶
- **Axial force coefficient (C_A) sensitivity to Reynolds number**
  - For all α, decrease from Re_D = 2x10⁶ to 8x10⁶, then sharper decrease at Re_D = 10x10⁶, then less variation up to Re_D = 40x10⁶

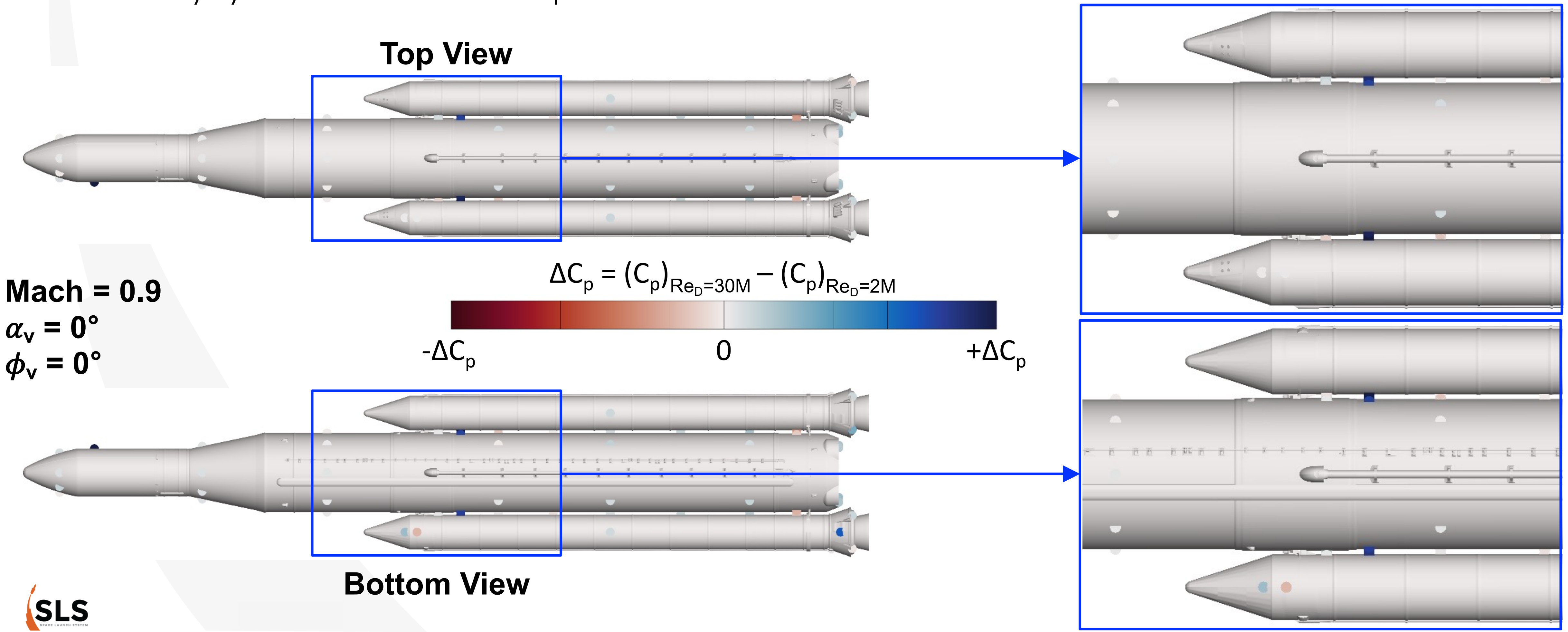




F&M forebody coefficients with base pressure correction applied

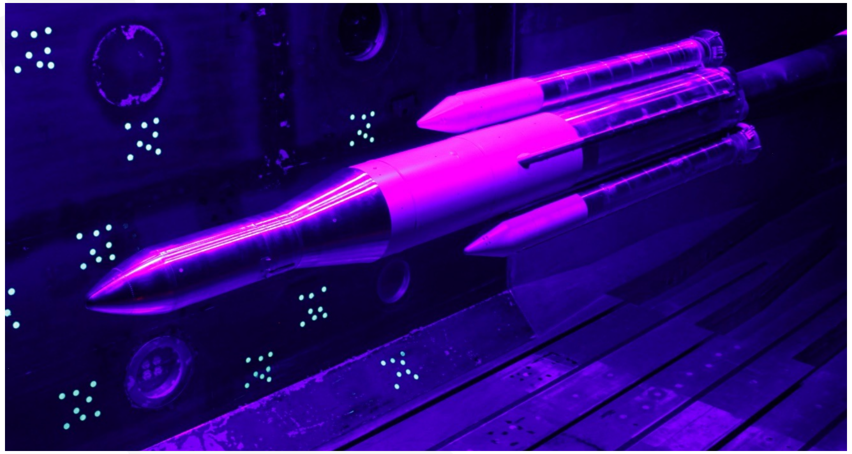
EFFECT OF REYNOLDS NUMBER

- **Surface pressure data showed SRB forward attach region was sensitive to Re_D**
  - Large ΔC_p between Re_D = 2×10^6 and 30×10^6 in SRB forward attach region and cargo fairing
  - Some smaller differences in SRB aft attach region and SRB aft skirt
  - Mostly symmetric between top and bottom of vehicle



PRESSURE SENSITIVE PAINT

- **Air PSP data at NTF compared well with similar PSP data acquired at Ames UPWT**
  - Large scale flow features on core and SRBs compare well
  - Some slight lateral asymmetries in the NTF results
  - NTF data had higher spatial resolution
- **Cryogenic PSP was attempted at several high Re_D conditions**
  - Effort was derailed by several challenges/issues
  - Further development and improvements are needed



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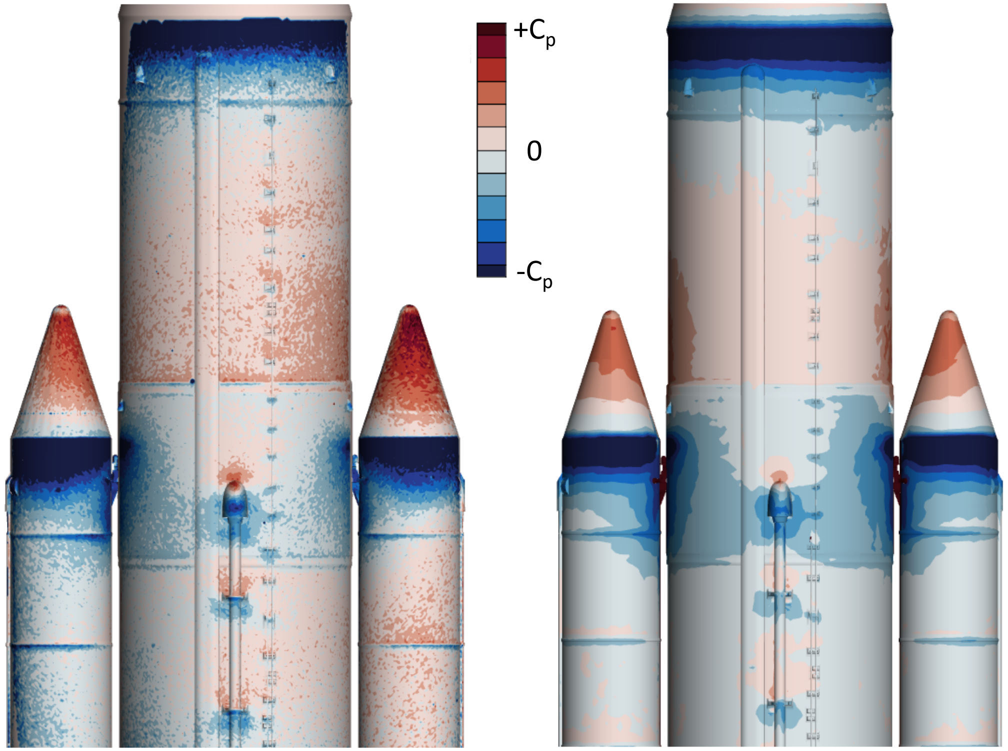
Mach = 0.8, α_v = 0°, ϕ_v = 0°



NTF at $Re_D = 2.00 \times 10^6$ **Ames UPWT at $Re_D = 1.44 \times 10^6$**

FINAL REMARKS

- **Transonic, high Reynolds number ascent wind tunnel test of the SLS Block 1 Cargo configuration was successfully conducted in the NTF**

- **SRB base pressure measurements with integrated pressure flowpaths were a success**
  - Allowed for more detailed study of base pressure environment
  - Truncated SRB nozzles provided a more stable base pressure environment than full SRB nozzles

- **SRB attach brackets were first use of additive-manufactured parts as structural components on a cryogenic model at NTF**
  - Preserve geometric fidelity and include internal pressure flowpaths
  - As-built material testing and NDE inspection were required to satisfy safety criteria

- **Reynolds number effects identified that could not have been measured in other facilities**
  - Most notable effects on pitching moment, yawing moment, and axial force coefficients
  - SRB forward attach region is sensitive to Reynolds number and may contribute to F&M changes

- **PSP data acquisition was successful in air mode at low Reynolds numbers**
  - Further development is needed at high Reynolds numbers under difficult cryogenic conditions

QUESTIONS?

Photo : NASA