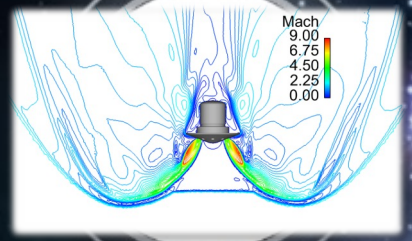
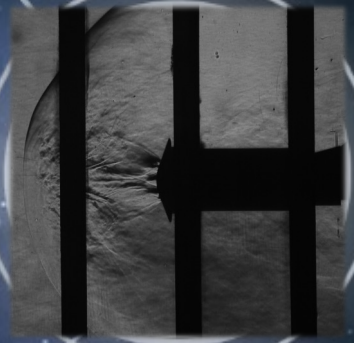
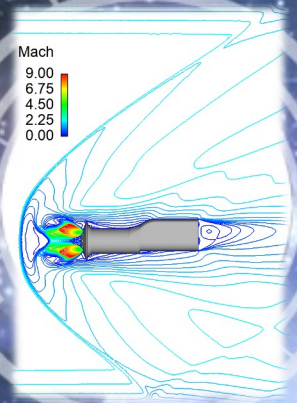
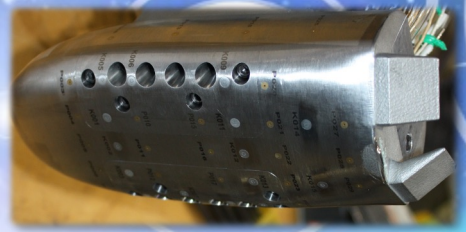
National Aeronautics and Space Administration

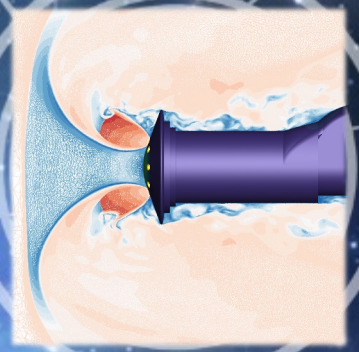












Space Technology Mission Directorate
Game Changing Development Program

Karl Edquist | Ashley Korzun | FY23 Descent Systems Study Annual Review Presentation | 09.21.23
karl.t.edquist@nasa.gov

Project Overview

Technology Development Needs Addressed by Project		
Stakeholder (i.e. HLS)	Description of how the project addresses strategic stakeholder vision and needs	STARPort Capability Area(s) and Gap ID(s)
HEOMD	The DSS project, in partnership with ARMD/AETC “CFD as Surrogate for High Supersonic Wind Tunnel Testing”, provided Propulsive Descent (PD) supersonic wind tunnel data and CFD predictions at conditions relevant for High-Mass Mars Entry Systems	Gap ID 322: “Supersonic Retropropulsion (SRP) Modeling & Simulation”

Project Goals	
Goal #1	Improve methods for Earth-based testing of PD systems
Goal #2	Develop best practices for calculating CFD-based PD aerodynamics at Mars conditions
Goal #3	Establish baseline uncertainties for CFD-based PD aerodynamics models
Goal #4	Reduce overall high-mass Mars EDL risks associated with PD

Project Objectives		
Objective #1	Complete CFD analysis to support ARMD wind tunnel model and test matrix design	✔ Completed
Objective #2	Complete CFD solutions for a range of planned conditions in the Langley UPWT environment (model configurations, tunnel Mach number, model attitude, and model thrust)	✔ Partially Completed
Objective #3	Quantify the differences between the CFD results and wind tunnel data	✔ Partially Completed

Team Members / Project Org Slide

Descent Systems Study

CFD Solvers:
- **FUN3D**
- **OVERFLOW**
- **Loci-CHEM**

GCD Program Manager

GCD Program Element Manager
Wade May, NASA Langley

DSS Project Manager
Karl Edquist, NASA Langley

NASA Langley (FUN3D)
Chris Glass Bil Kleb
Ashley Korzun Bill Wood

NASA Ames (OVERFLOW)
Robert Childs Joseph Garcia
Logan Halstrom Veronica Hawke
Kristen Matsuno Tom Pulliam

NASA Marshall (Loci-CHEM)
Francisco Canabal

Partner Project

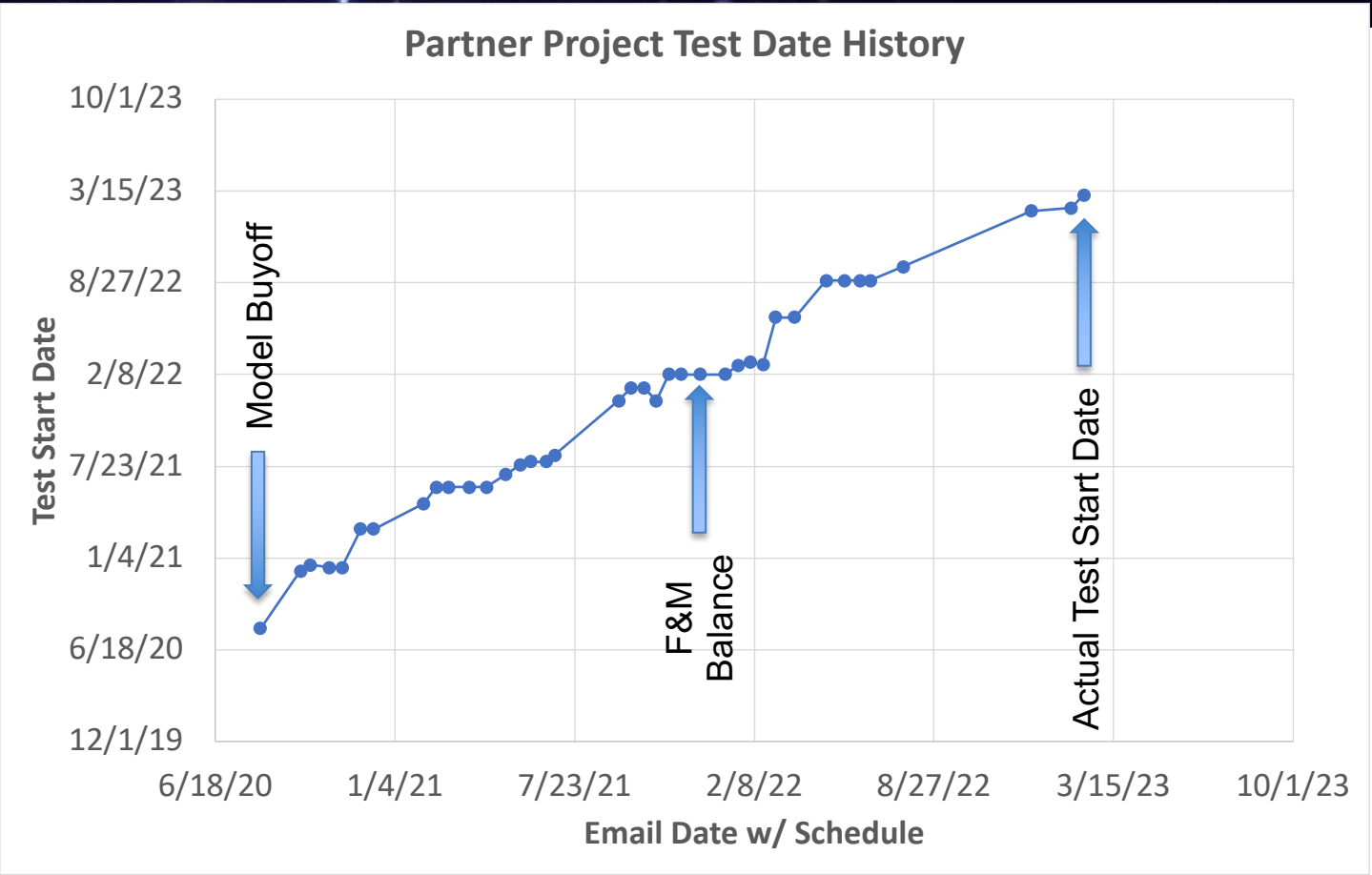
ARMD Aerosciences Evaluation & Test Capability (AETC) Portfolio Office

CFD as Surrogate for High Supersonic Wind Tunnel Testing
PM Jim Ross, Ames

Propulsive Descent Test
PI Karl Edquist, Langley

Partner Project Test Date History

- The wind tunnel models were inspected and approved for testing in August 2020, within days ahead of the original test start date
- The partner project and existing Langley funding allowed the design/fabrication of a new flow-through force and moment (F&M) balance, giving them the opportunity to attempt to measure SRP F&M for the first time



>2.5 year delay in the partner project test (COVID-19, facility repairs) allowed the project to design and fabricate a new force and moment balance, but effectively eliminated the time needed for DSS to analyze the data and do another cycle of CFD analysis and uncertainty quantification (UQ) as planned, since the project is ending and only will be able to close out high-level analysis in FY24

Accomplishments

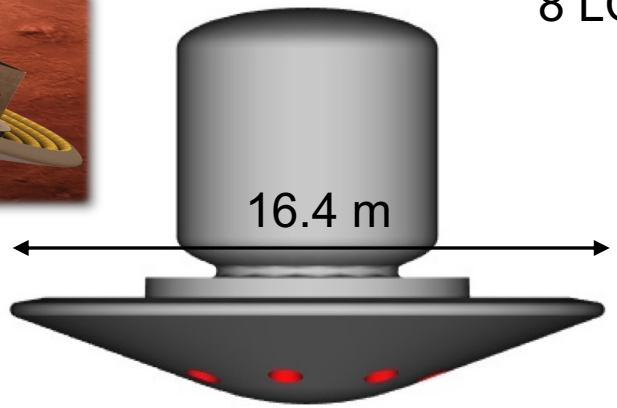
- The partner project “CFD as Surrogate for High Supersonic Wind Tunnel Testing” completed the Propulsive Descent (PD) Test #1933 in the Langley Unitary Plan Wind Tunnel between 3/15/23 and 5/12/23
  - The test was designed to provide PD aerodynamics data to the DSS project, which has been tasked with running high-fidelity CFD at wind tunnel conditions and comparing results to the test data to form the basis of PD aerodynamic uncertainties at Mars entry conditions
- DSS has received:
  - Final high-speed video, discrete pressure, and pressure-sensitive paint (PSP) test data
  - Uncertainty quantification of major test variables
  - Preliminary force & moment test data from flow-through balance, more analysis is required, but not funded, to answer questions that data raise
- Since May 2023, DSS has:
  - Completed initial comparisons between existing CFD solutions and discrete pressure and PSP data
  - Proposed 6 papers for the 2024 AIAA Aviation conference, but mostly will include only CFD analysis that was completed prior to the test
  - Proposed remaining FY24 tasks using no-cost extension

>2.5 year delay in the partner test (COVID-19, facility repairs) has severely limited to time available for DSS to analyze the data and for any go-backs on the CFD analysis side, since the project is ending and only will be able to close out short-term analysis in FY24

Reference Vehicles and Wind Tunnel Models

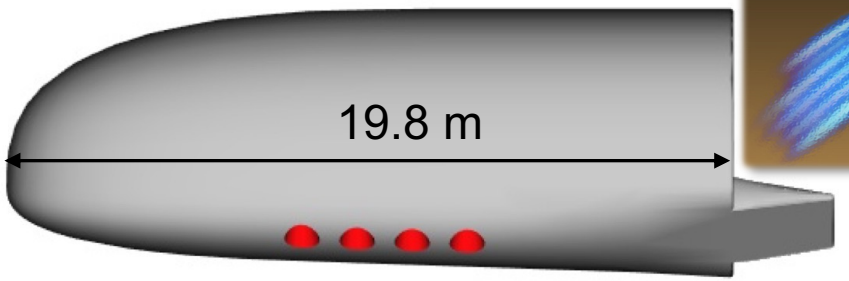
Low-L/D (HIAD Entry Vehicle)

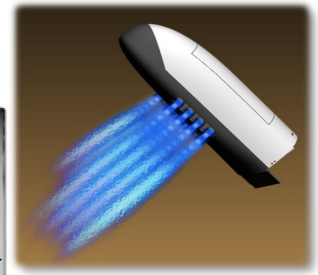




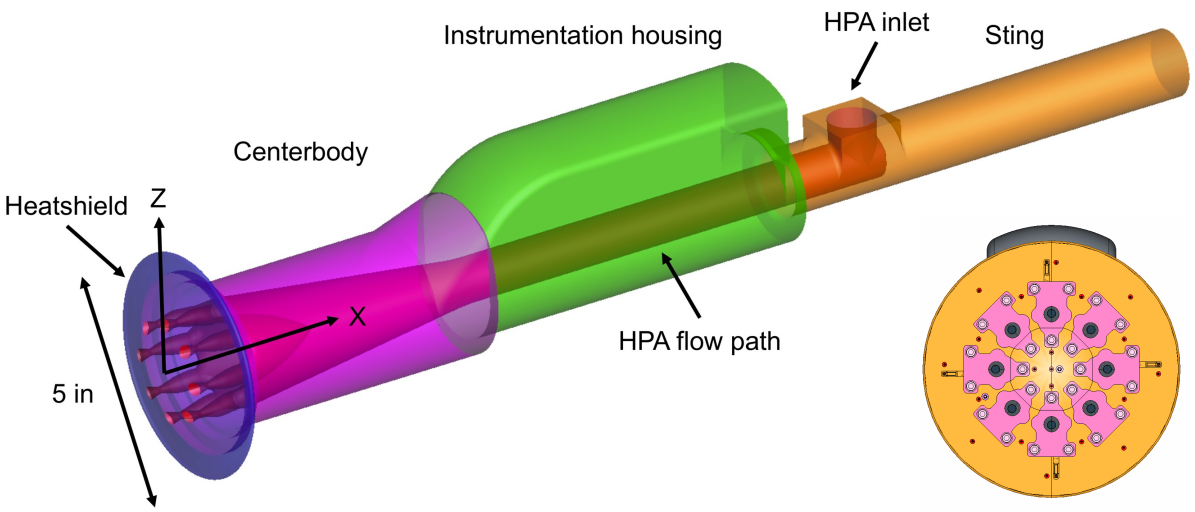
Mid-L/D (Rigid Entry Vehicle)

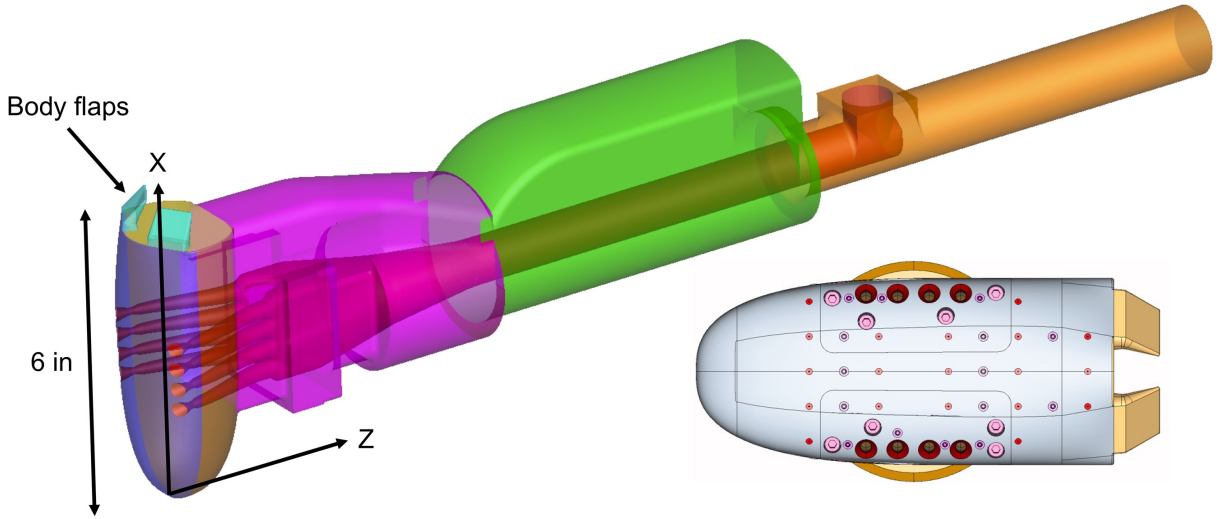
8 LO_2/LCH_4 engines, total thrust = ~100 kN





Engines modeled using high-pressure air (HPA), pressure is adjusted to match thrust coefficient $C_T = T / q_\infty S_{ref}$





AIAA 2022-0911, "Status of Mars Retropropulsion Testing in the Langley Unitary Plan Wind Tunnel"

Partner Test Summary

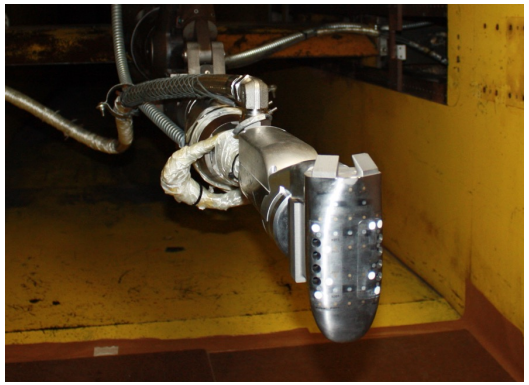
- Test matrix

	Low-L/D Model	Mid-L/D Model
Nozzle configurations	1 (plugged), 1A, 1B, 1C, 1D, 1E, 1F,	2 (plugged), 2A
Mach number	2.4, 3.5, 4.6	
Thrust coefficient	0 to ~2.5	
Angle of attack	-10 to +20 deg	
Roll angle	0 to 180 deg	

- Test data were delivered for a total of 837 runs, with each run containing several model angles of attack
  - ~5000 test points, all points included discrete pressure data
  - 3345 high-speed videos, 1463 PSP files

	Status/Comments
6-component F&M	Delivered, data quality impacted by challenging thermal environment
Discrete static and dynamic pressures	Delivered
PSP	Delivered, data quality impacted by challenging thermal environment
High-speed video	Delivered at frame rates of 3 to 10 kHz

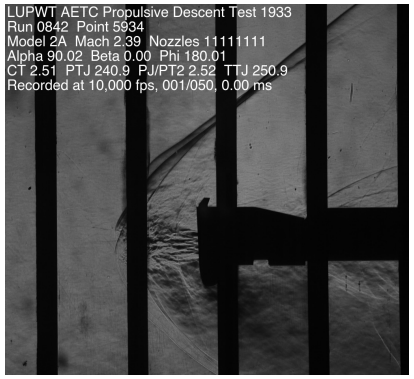






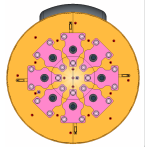
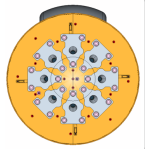
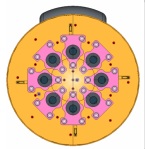
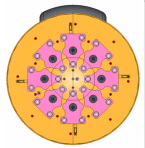
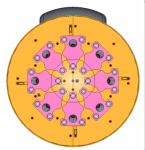
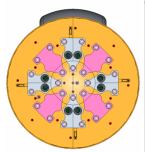
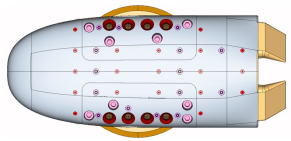






DSS Pre-Test CFD Analysis Matrix

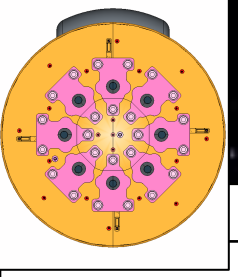
- 7 blowing models, 3 angles of attack, 4 thrust coefficients, 3 tunnel Mach numbers, 3 CFD codes = 156 primary cases and 303 bonus cases completed in FY20-22 for eventual comparison to test data
- Completed 100% of primary cases and 71% of bonus cases prior to test using over 10M CPU hours on the NAS supercomputer, at no direct cost to project

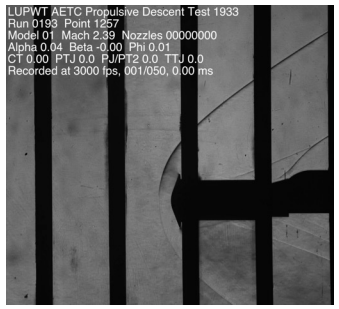
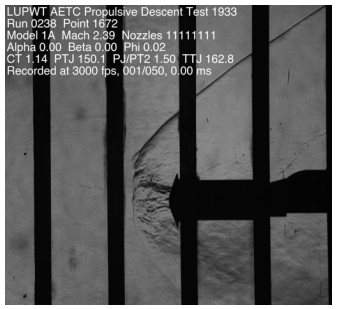
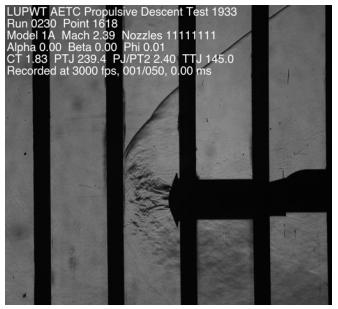
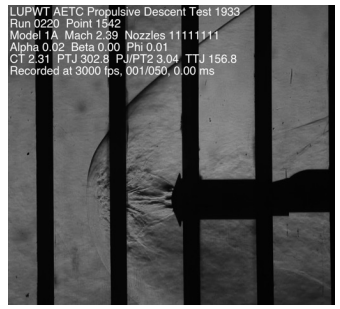
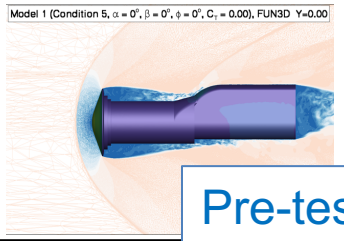
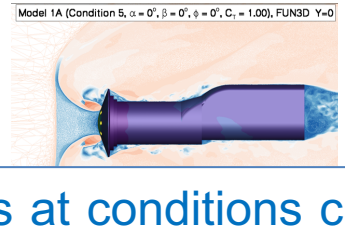
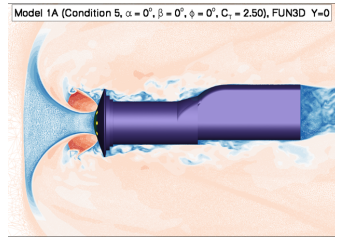
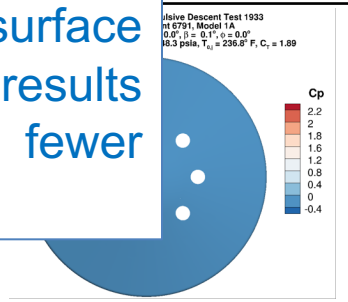
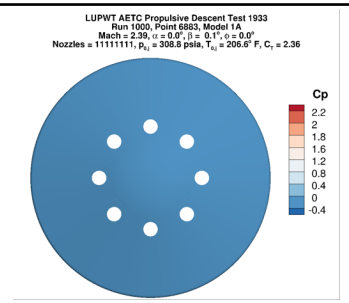
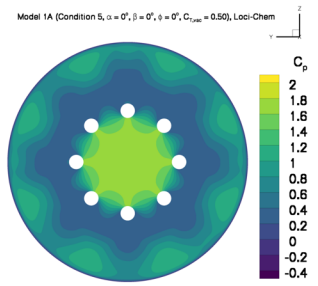
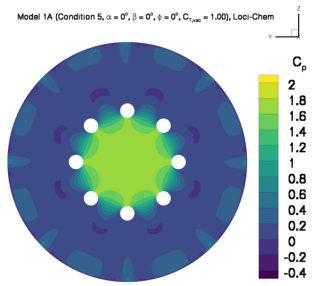
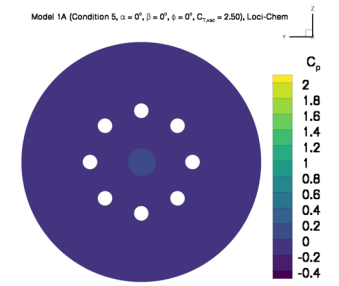
Model	α \ CT	Condition #5 (Mach = 2.386, Re = 1e6 / ft)												Condition #20 (Mach = 3.477, Re = 1e6 / ft)												Condition #35 (Mach = 4.568, Re = 1.5e6 / ft)											
		0			0.5			1			2.5			0			0.5			1			2.5			0			0.5			1			2.5		
		LC	F3D	OF	LC	F3D	OF	LC	F3D	OF	LC	F3D	OF	LC	F3D	OF	LC	F3D	OF	LC	F3D	OF	LC	F3D	OF	LC	F3D	OF	LC	F3D	OF	LC	F3D	OF	LC	F3D	OF
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1B	0				1	2		1	2		1	3					0	0		0	1		0	0					0	0		0	0		0	0	
	5				0	0		0	0		0	0					0	0		0	1		0	0					0	0		0	0		0	0	
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1F	0					0	0		0	0		1	0					0	0		0	0		0	0					0	0		0	0		0	0
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2A	90	1	1	1	0	0	1	0	0	1	0	1	1	1	1	1	0	0	1	0	0	1	0	0	1	1	1	1	0	0	1	0	0	1	0	0	1
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	80	1	1	1	0	0	1	0	0	1	0	0	1	1	1	1	0	0	1	0	0	1	0	0	1	1	1	1	0	0	1	0	0	1	0	0	1

The partner test included conditions that were close to those used for all pre-test CFD simulations, with the highest variability being the actual thrust coefficient achieved during the test due to uncertainties in the ability to control HPA pressure

LC = Loci-CHEM
F3D = FUN3D
OF = OVERFLOW



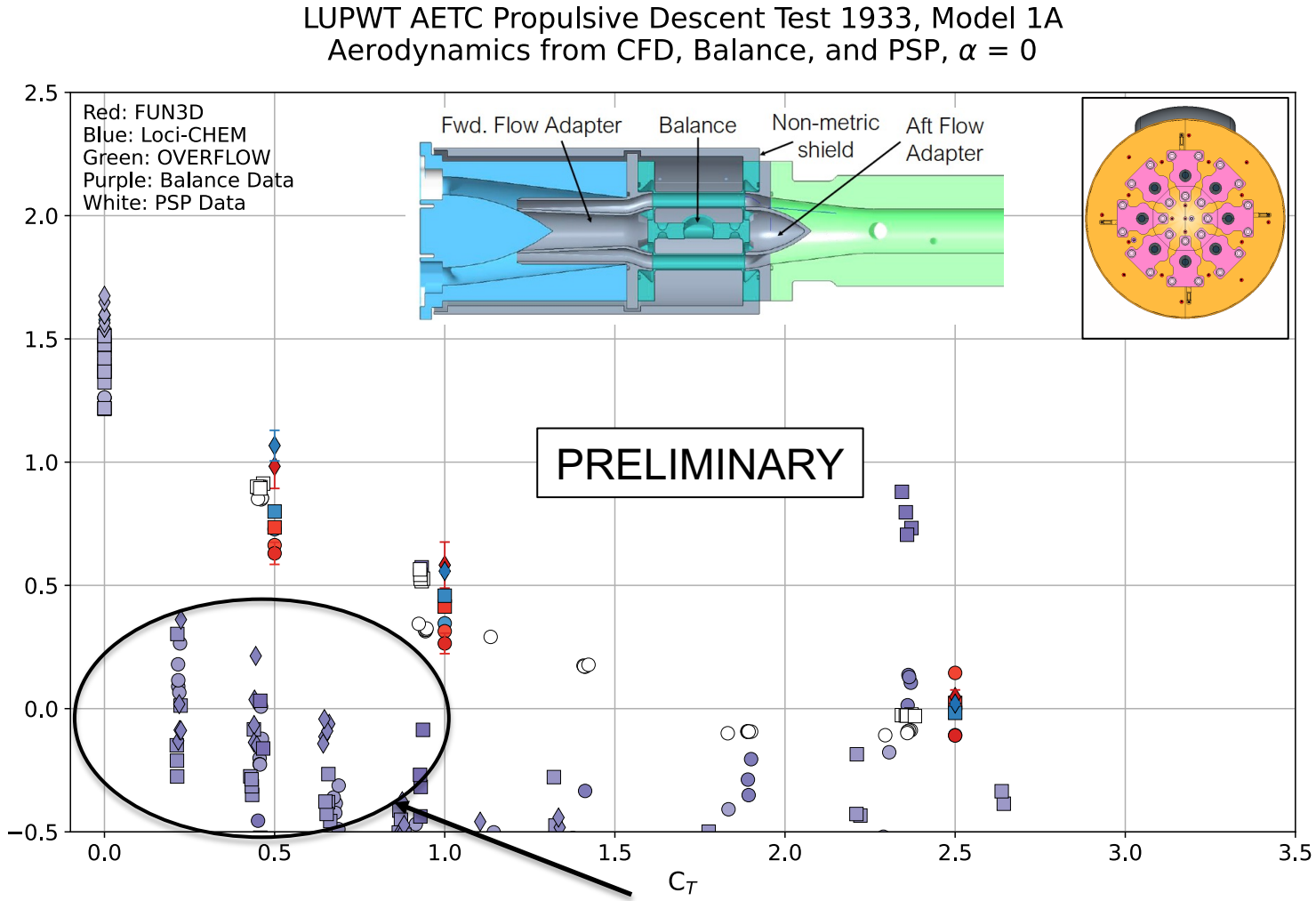
Sample Results for Model 1A

C_T →	0	0.5	1	1.5	2	2.5
High-Speed Video @ 3 to 10 kHz						
CFD Solution, Time-Averaged						
PSP Average Surface Pressure Coefficient						
CFD Average Surface Pressure Coefficient						

Pre-test CFD simulations at conditions close to what were tested show that gross flowfield trends (shock standoff and surface pressure vs. C_T) are captured, which is consistent with results from testing and CFD from 2010/2011 on models with fewer nozzles

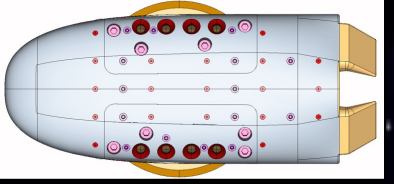
Preliminary PD Aerodynamics Results for Model 1A

- Plot shows the heatshield aerodynamic axial force coefficient = non-dimensional total axial force minus thrust axial force
- Two methods were used to derive this parameter from the test data
  - From the PSP data
  - From the Langley-designed flow-through force and moment balance that was added after model fabrication
- Repeat runs were made at the same C_T values
- The CFD results (red/blue/green symbols) are in family with the PSP-derived data (white symbols), with both sets of results showing a gradual decrease of axial force with increasing C_T
- There is a bias and scatter in the balance data (purple symbols) that likely are a result of the thermal environment being different from the environment during wind-off thrust tares → more analysis may be done in FY24 to investigate other data reduction methods, but more questions than answers are expected

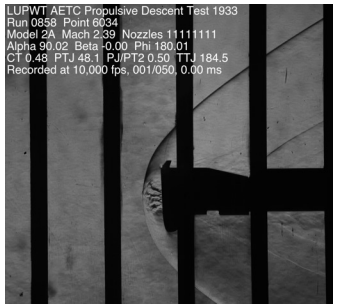
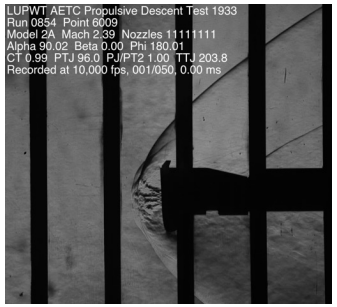
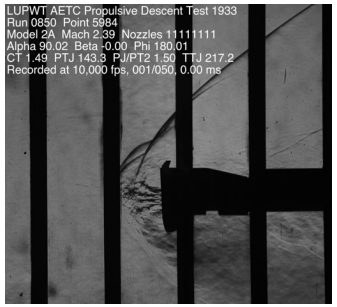
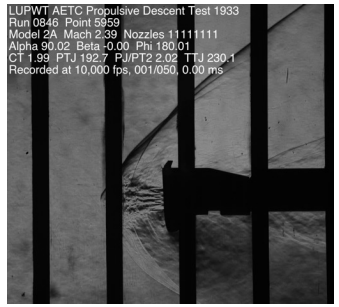
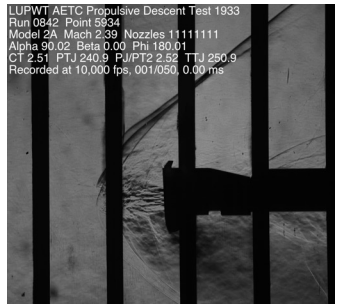
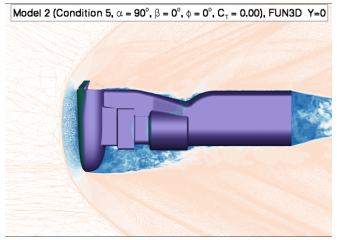
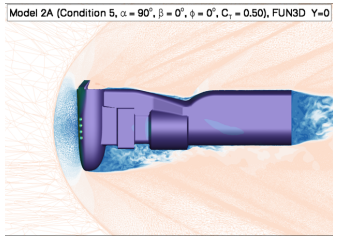
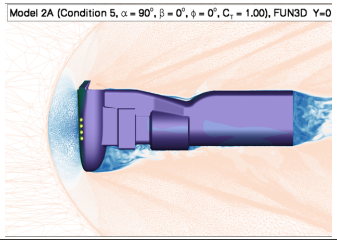
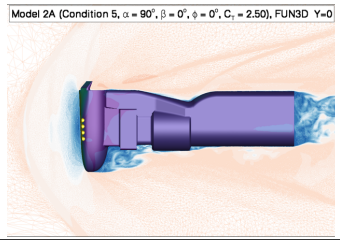
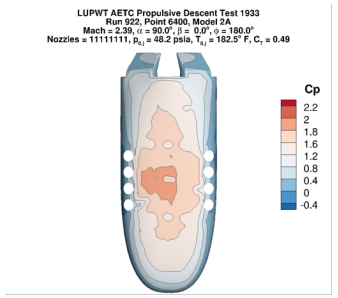
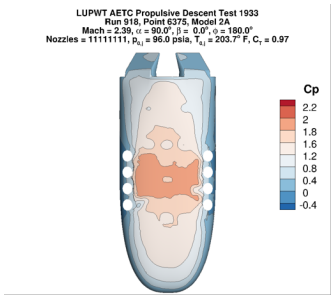
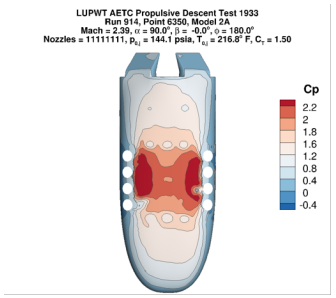
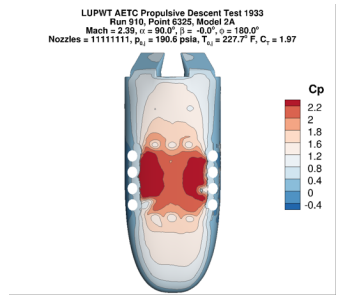
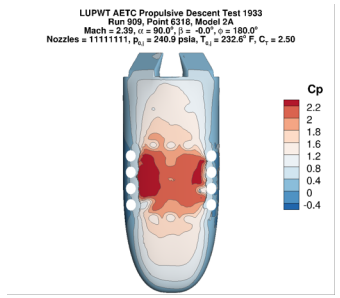
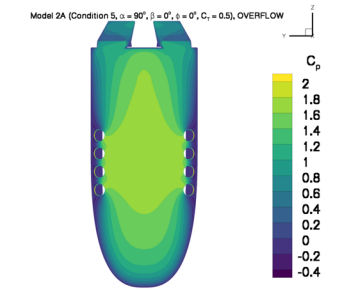
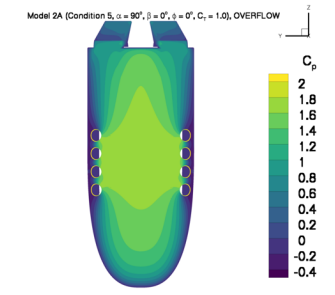
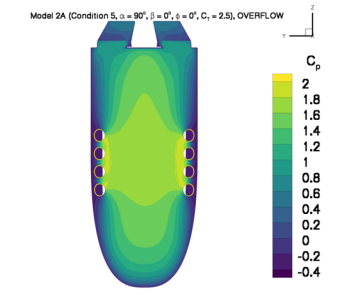


Source of bias needs to be investigated further, but won't be answered by DSS

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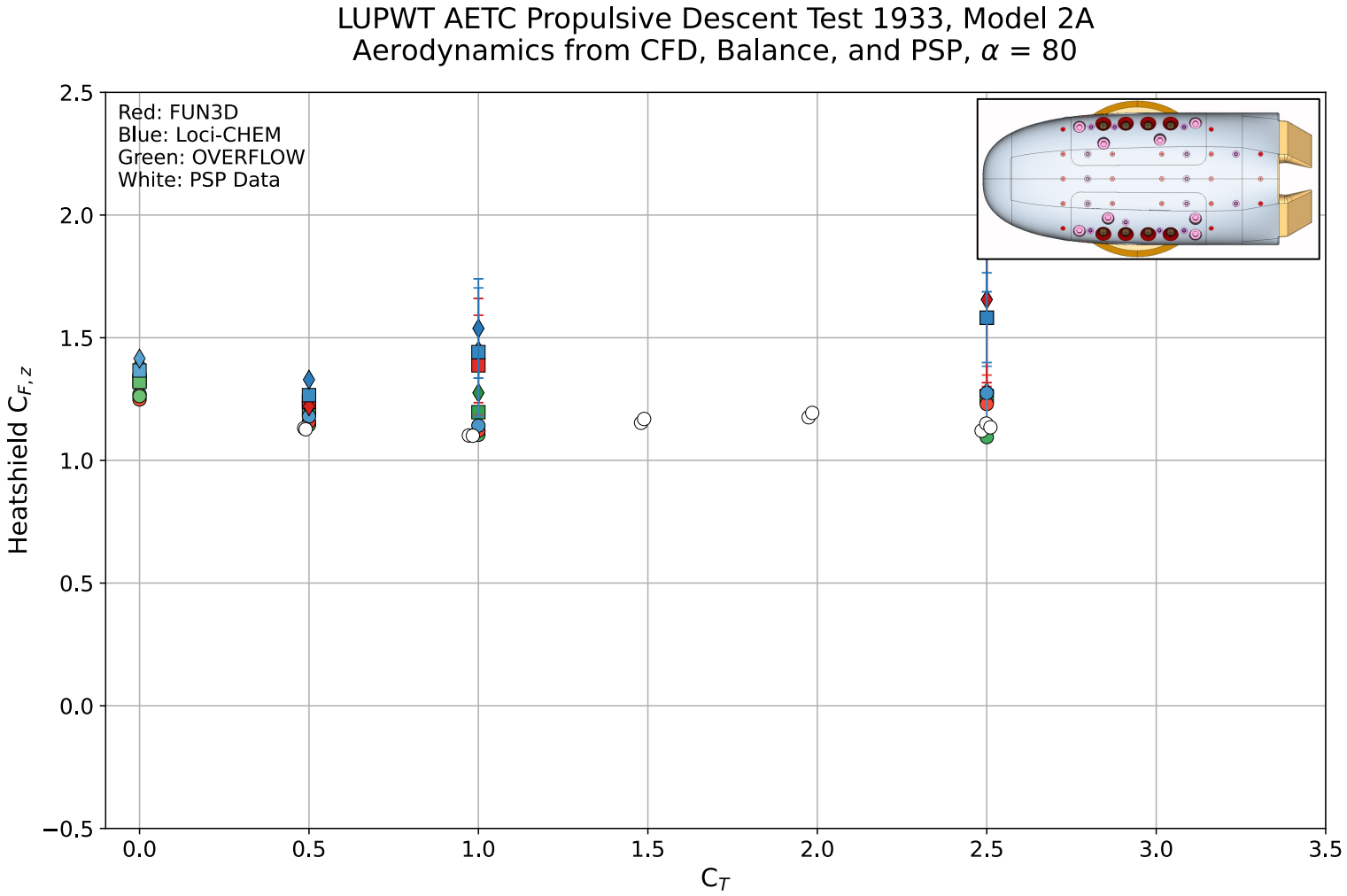


Sample Results for Model 2A

C_T →	0	0.5	1	1.5	2	2.5
High-Speed Video, Average of 100 Frames						
CFD Solution, Time-Averaged						
PSP Surface Pressure Coefficient from Test						
CFD Surface Pressure Coefficient						

Preliminary PD Aerodynamics Results for Model 2A

- Plot shows the heatshield aerodynamic axial force coefficient = non-dimensional total axial force minus thrust axial force
- The force and moment balance was not designed to be used with model 2A, so only the PSP method was used
- The CFD results (red/blue/green symbols) are in family with the PSP-derived data (white symbols), with both sets of results showing no loss of aerodynamic axial force for C_T up to 2.5



Project Assessment Summary

Descent Systems Study	Performance				Comments
	C	S	T	P	
Mid Year					Technical – No issues Cost – Under-runs in labor costs due to late start of partner project wind tunnel test Schedule – Partner project wind tunnel test had not started as of the MYR, giving the DSS project less time than needed to understand and analyze the data before the end of the FY. Programmatic – A late start date for the partner project test means that test data will be delivered late in the FY, making it more difficult to understand and analyze the data and to meet scheduled milestones for full project success.
Annual					Technical – No issues for DSS, but F&M balance test data not as expected due to test thermal environment, so must revert to pressure-sensitive paint for some metrics Cost – Under-runs in labor costs due to late start of partner project wind tunnel test. A no-cost extension was requested and granted using $330K. Schedule – Partner project wind tunnel test started in 3/15/23 and ended 5/12/23, giving DSS much less time than planned to understand and analyze the data, and for any go-backs on the CFD analysis. Programmatic - Partner project was executed from March to May 2023 (COVID-19 and multiple unscheduled facility repairs), more than 2.5 years later than originally expected. The very late test start date means that data were delivered late in the FY, which made it difficult to understand and analyze the data and to meet scheduled milestones. Limited analysis and documentation are planned in FY24 to complete the project, but no additional rounds of CFD analysis can be done to answer detailed questions. Test dataset is very large and should be made publicly available to other stakeholders for further detailed analysis outside of DSS.

Plans Forward and Transition / Infusion Plan

- DSS was approved for a no-cost extension into FY24 ($330K) due to the arrival of test data late in FY23 and the need to complete quick-look documentation of test and in-hand CFD results
  - Very little new CFD is planned due to impending end of project, remaining funds will be used for quick-look comparisons between what CFD has been completed and the data
  - Deep dive analysis of the data and associated CFD are out of scope at this point
- Six AIAA conference papers will be written for the 2024 Aviation conference
  - Test overview, CFD overview, detailed CFD (4)
- The test data will be provided to an existing ESI researcher for further analysis
  - “Physics-informed Modeling of Multi nozzle Plume Physics with Quantifiable Uncertainties from Supersonic Retropropulsion Tests,” Matthias Imhe, Stanford U.
- Archive test data for public availability
- Recommend ESI and NSTGRO topics to perform deep dive analysis of the test data
- Further improvements in test techniques will be proposed to bridge the gaps between wind tunnel and flight environments i. e. cold vs. hot gas engines, high expansion ratio nozzles, Earth flight testing, etc.
- Will continue to work with EDL Capability Leads on follow-on activities within STMD and potential commercial partners

Education/Public Outreach

EPO Involvement

- Partial support of Emily Jewell, Stanford University, NASA Space Technology Graduate Research Opportunity
- Partial support of Justin Shafner, Stanford University, NASA Space Technology Graduate Research Opportunity
- NASA Research Collaborator for Matthias Imhe, Stanford University, for NASA Early Stage Innovation research under NASA Grant Number 80NSSC22K0257, “Physics-informed Modeling of Multi-nozzle Plume Physics with Quantifiable Uncertainties from Supersonic Retropropulsion Tests”
  - Presentation was given at 20th International Planetary Probe Workshop, August 2023
  - Partner project test data will be used in the research

EPO Calendar Outlook (High Priorities):

6 Month Look-Ahead	

Summary

- Final high-speed video, discrete pressure, and PSP data from partner project test have been received
- Force & moment test data from flow-through balance have been received in preliminary form, more analysis will need to be done outside of DSS to answer questions about suspect data
- Initial comparisons between existing CFD solutions and matching test points have been made against discrete pressure and PSP data
- Preliminary comparisons between test data and CFD show general agreement in aerodynamics trends with increasing thrust – no surprises yet
- Will write 6 papers for the 2024 AIAA Aviation conference to close out DSS project