Aerodynamic and Aeroacoustic Wind Tunnel Testing of the Orion Spacecraft

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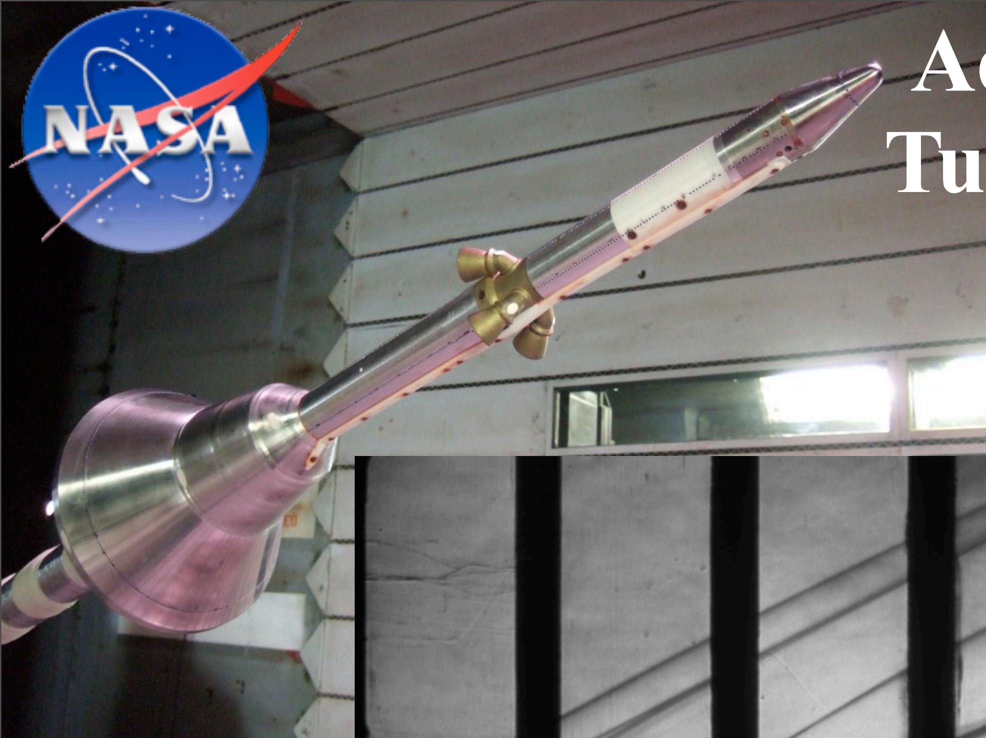


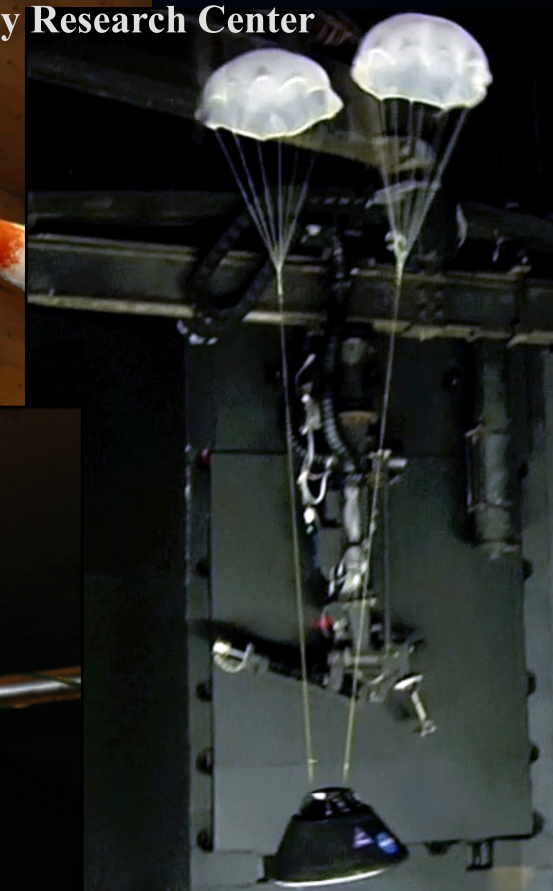


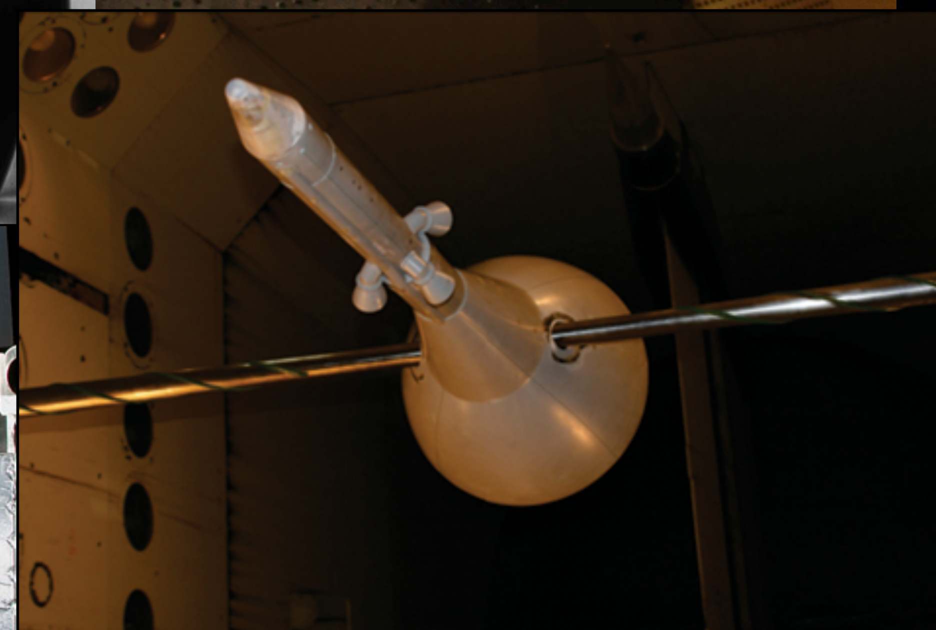
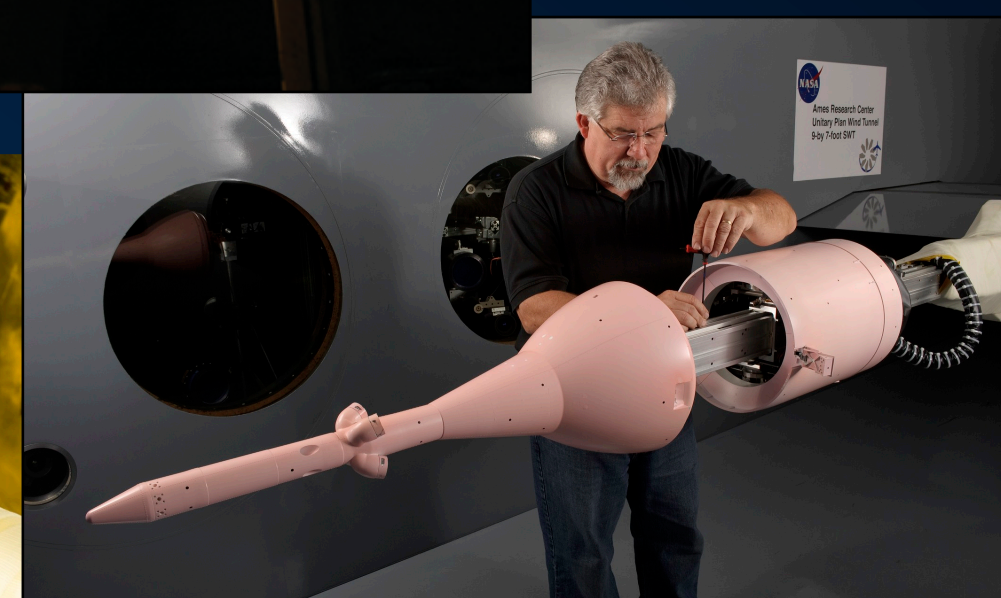
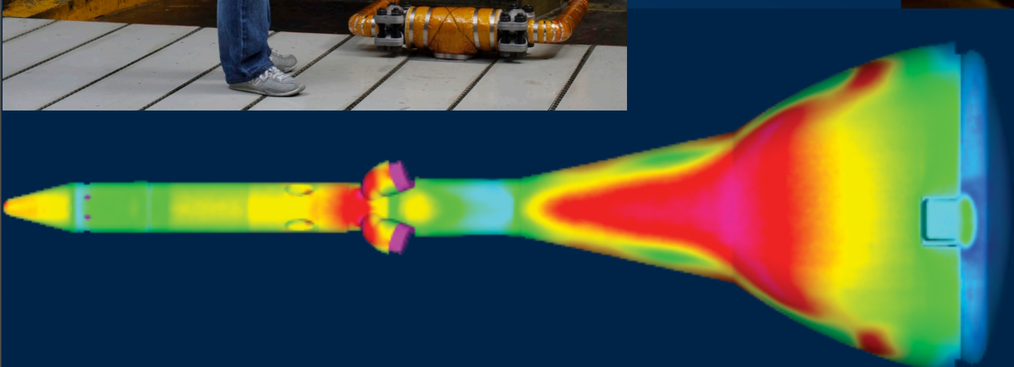


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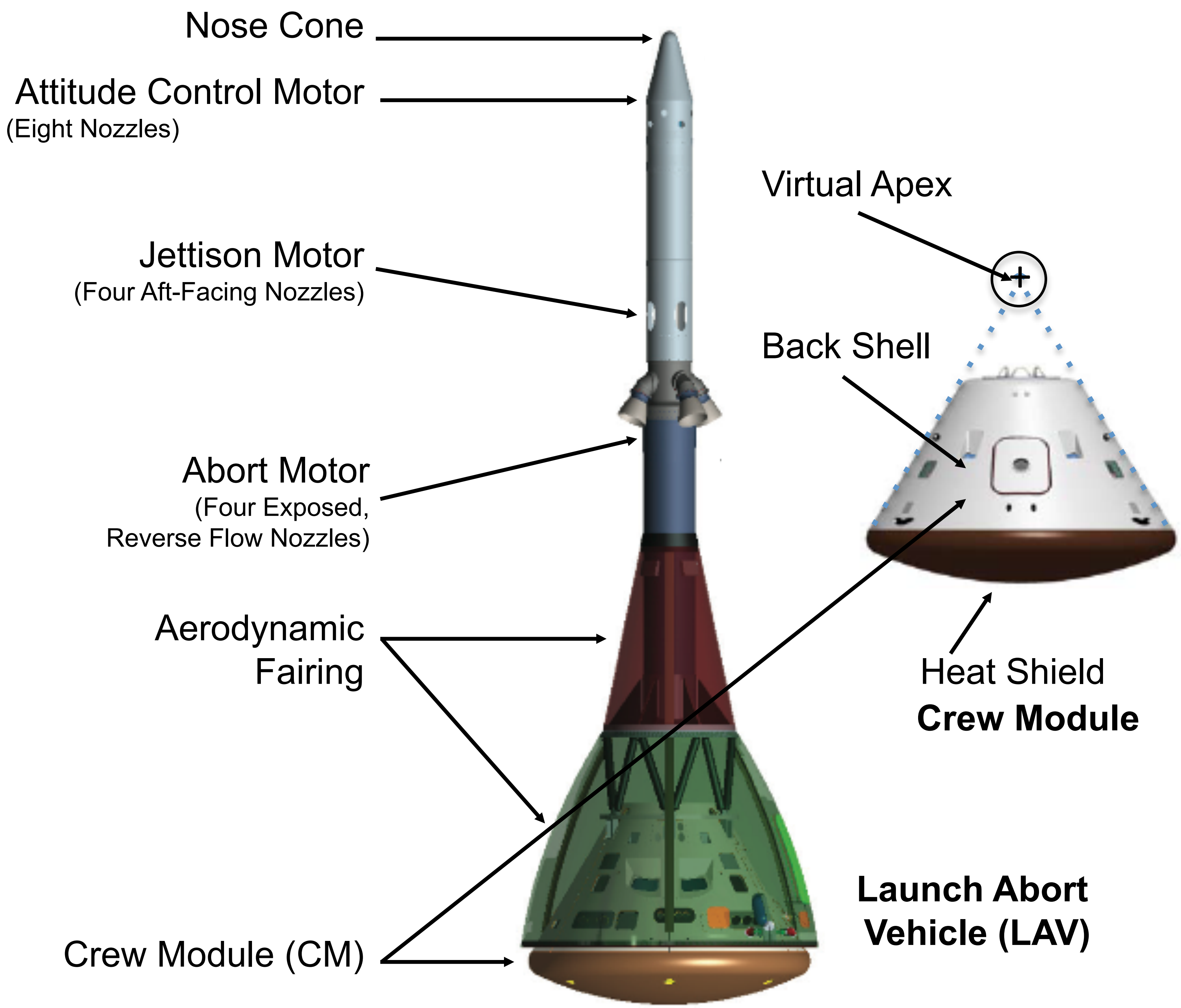
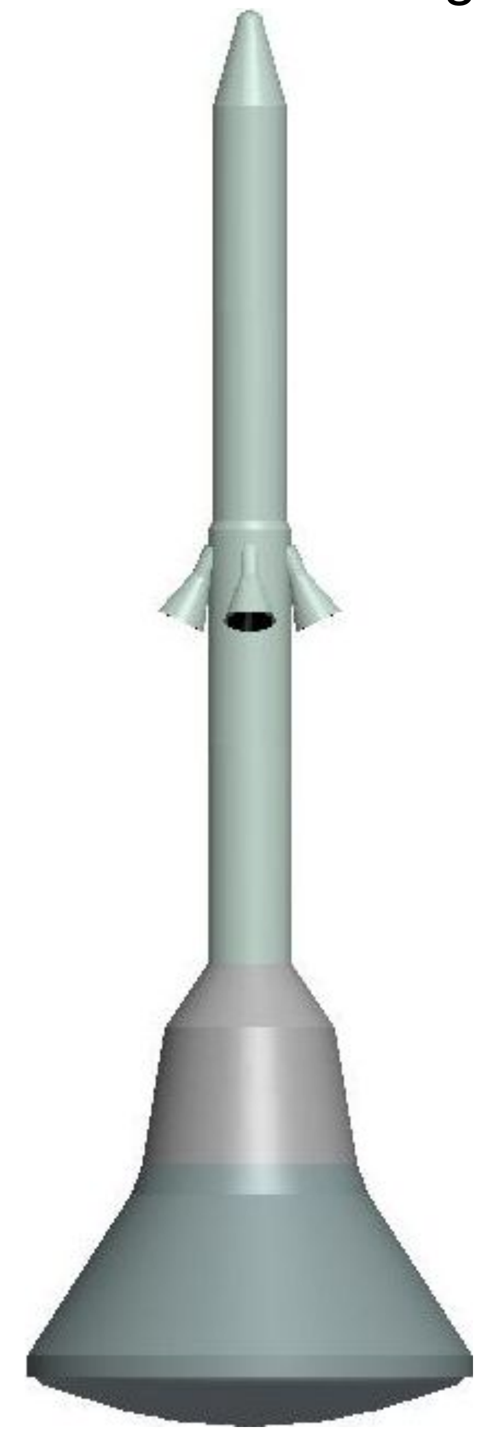
Outline

- **Vehicle description and phases of flight requiring aerodynamic data**
- **Database strategy and role of testing**
- **Types of tests**
  - Static Aerodynamics - Crew Module (CM) & Launch Abort Vehicle (LAV)
  - Dynamic Stability - CM, LAV, and Launch Abort Tower (LAT)
  - Powered Aerodynamics - LAV
    - Plume modeling
    - Jettison Motor (JM), Attitude Control Motor (ACM), and Abort Motor (AM) jet interactions
    - Separation - LAV from launch vehicle and LAT from CM
  - Aeroacoustics - Aerodynamic and Plume-Induced Noise (Unsteady Pressure Loads)
- **Descriptions of selected tests**
- **Summary**

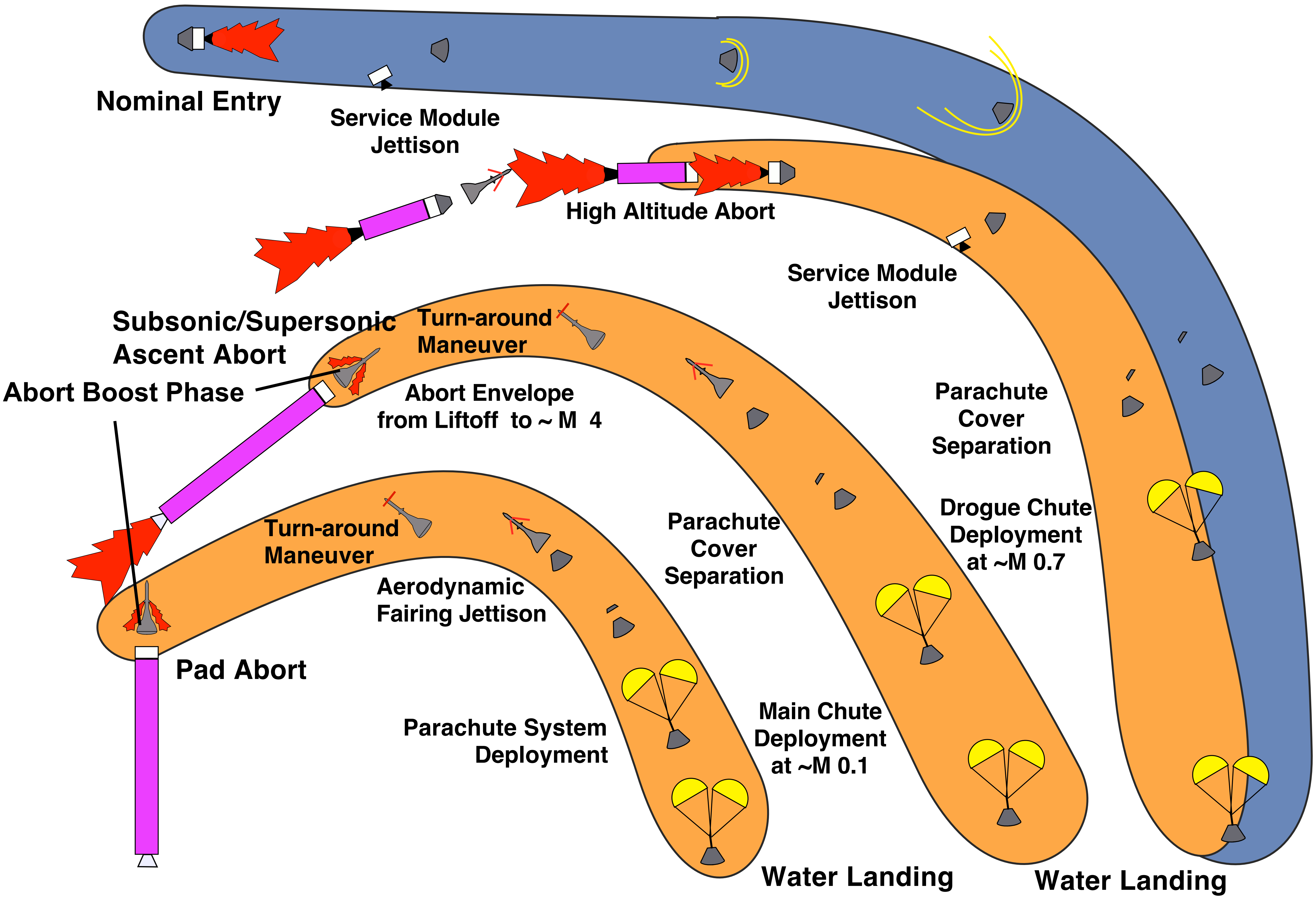
Orion Crew Module & Launch Abort Vehicle



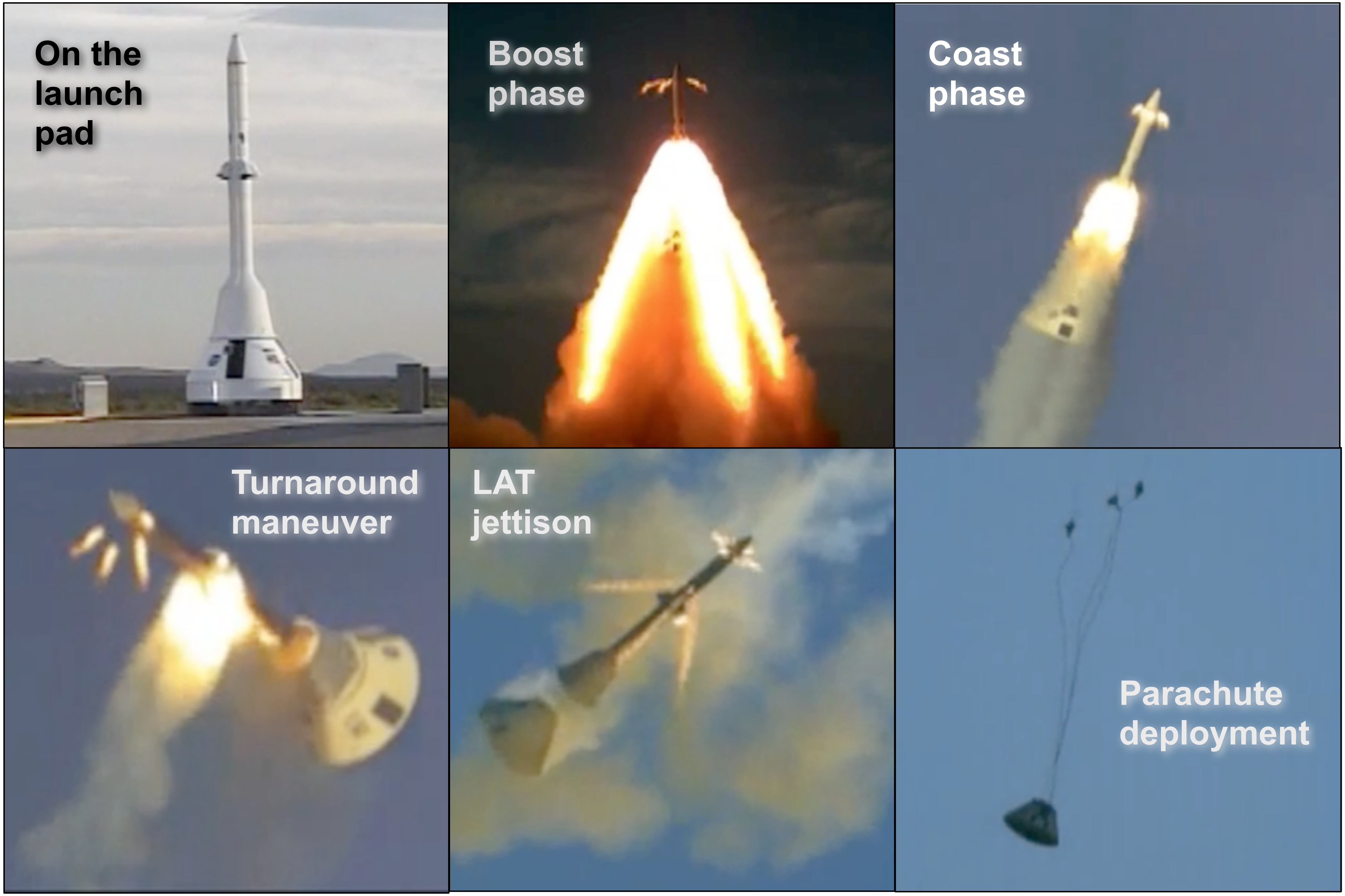
Earlier Aerodynamic Fairing Shape Used for PA-1 Flight Test



Phases of Flight Through the Atmosphere



Launch Abort Phases of Flight
(Images from Pad Abort 1 Test Flight)



Aerodynamic Database

- **Original intent was CFD as primary source with WT test to anchor**
- **Poor CFD results for some flight conditions led to much more testing than planned**
  - Many more production-style tests to fill database
  - Made sure to provide data that aided CFD validation whenever possible
- **Generally sparse coverage of source data (both CFD and WT) due to wide range of possible flight conditions particularly for aborts**
  - Boost Phase $C_x = f(M, q, \alpha, \beta$, AM Thrust, ACM Thrust & direction, LAV/SM separation...)
  - Coast Phase $C_x = f(M, q, \alpha, \beta$, AM Thrust, ACM Thrust & direction...)
  - LAT Jettison $C_x = f(M, q, \alpha, \beta$, AM Thrust, ACM Thrust & direction, LAT/CM separation...)
- **Surface pressure data from WT tests and CFD provide loads information for structural design and analysis**

Wind-Tunnel Testing

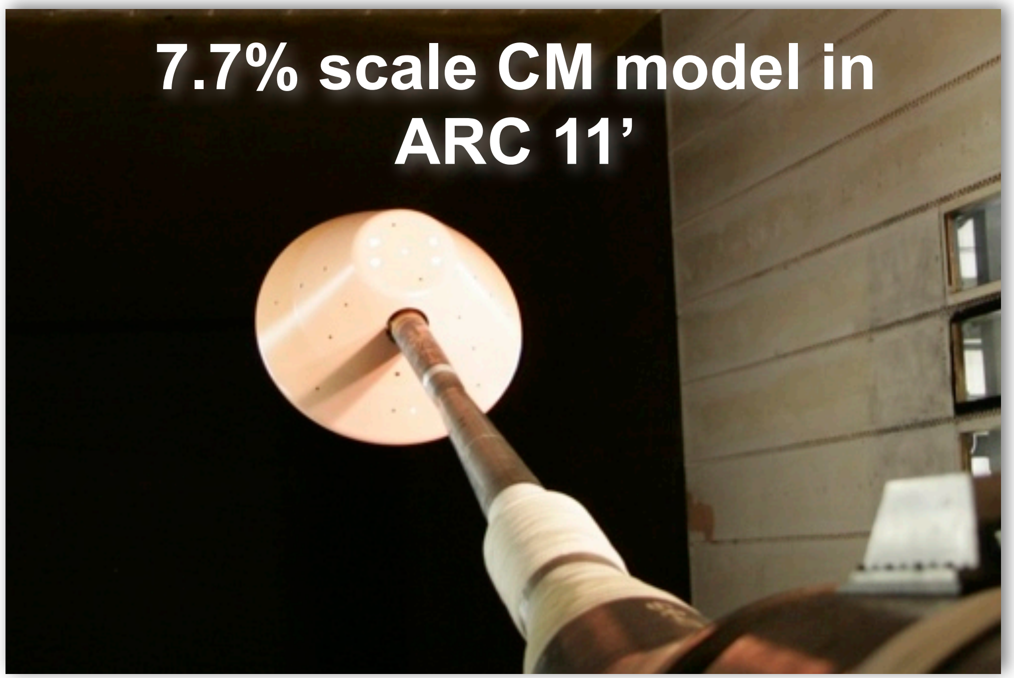
- **Used a wide variety of wind tunnels and other test facilities**
  - 17 different wind tunnels
  - 4 ballistic ranges
  - 2 acoustics laboratories
- **Total of ~44 tests to date**
  - 9 static aero - unpowered (8% of total test time)
  - 18 dynamic stability (23% of test time)
  - 11 powered aero (52% of test time)
    - AM Jet Interactions (JI)
    - ACM JI
    - JM JI
  - 3 ascent acoustics - unpowered (6% of test time)
  - 3 plume acoustics (11% of test time)

General Lessons

- **Take as much data as possible during tests - doesn't seem possible to have enough tests to answer all questions so loads**
- **Make sure CFD validation is factored into both the model design and run matrix**
  - Plume modeling
  - Parameter variations
  - Data types
- **PSP is worth the cost and effort**
  - New self compensating paint is very accurate
  - Integrating pressure distributions matches balance data remarkably well
  - Provides insight into flow phenomena, CFD validation data, and helps explain unexpected results
- **Powered tests need careful consideration to make them accurate enough for the database and easy enough to run without breaking the bank**
  - Plume matching is important and not necessarily clear cut, particularly for noise measurements
- **Schlieren imagery critical for powered tests and generally well worth the effort for unpowered tests**
- **Plan on doing at least some aeroacoustic measurements during aero tests**
  - Often overlooked early but can definitely affect the vehicle shape for both nominal ascent and aborts
  - Better to have quality up-front data than to play catch up

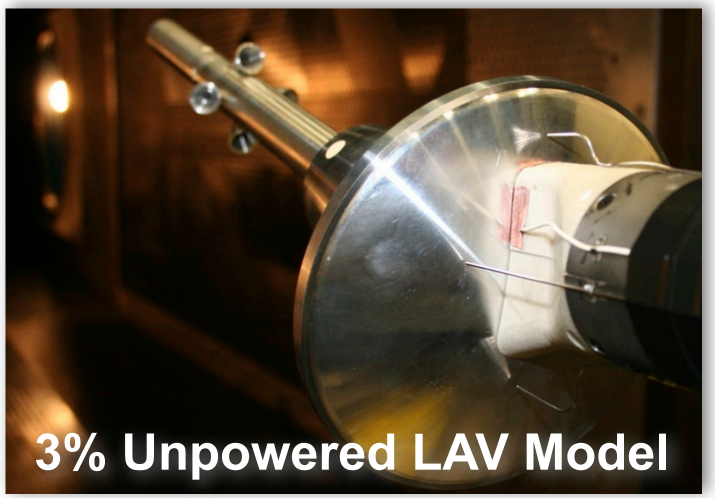
Crew Module Static Aerodynamics

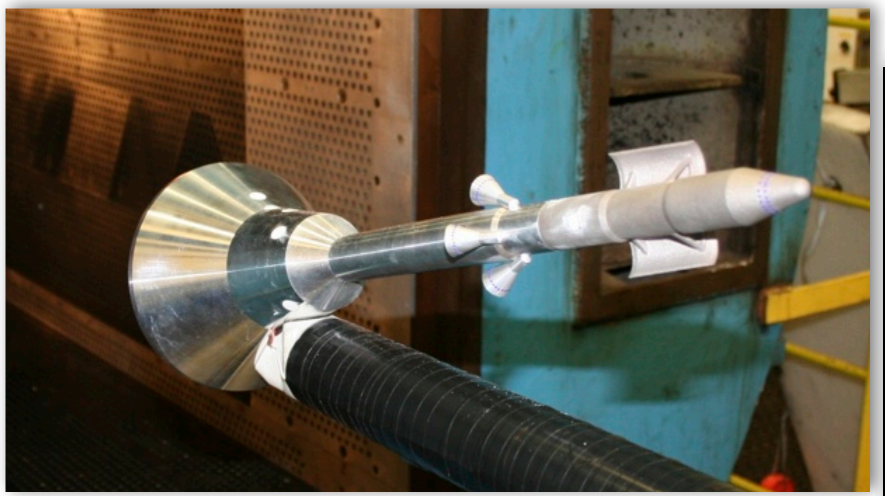
- Needed for both nominal re-entry and abort
- Tests completed from M 0.3 to 6,
- Forces and moments for aero database
- Performed tunnel-to-tunnel comparisons to ensure data quality
- Acquired pressure distributions for loads database
- Looked briefly at heat-shield boundary-layer transition effects
  - Un-tripped b.l. led to very unsteady behavior below M 0.7
  - Some unsteadiness at angles of attack ~140° with untripped BL (reattachment on back shell?)
  - No tripping strategy found to achieve Re-insensitivity for M < 0.9
  - More recent results indicate need for distributed roughness for post entry aerodynamics
- Several tests completed with relatively low Re_D (from 2 to $9x10^{6)}$ - will be running a test at LaRC NTF to get flight Re ($\sim 30x10^6$) up to M 0.9 in a few months

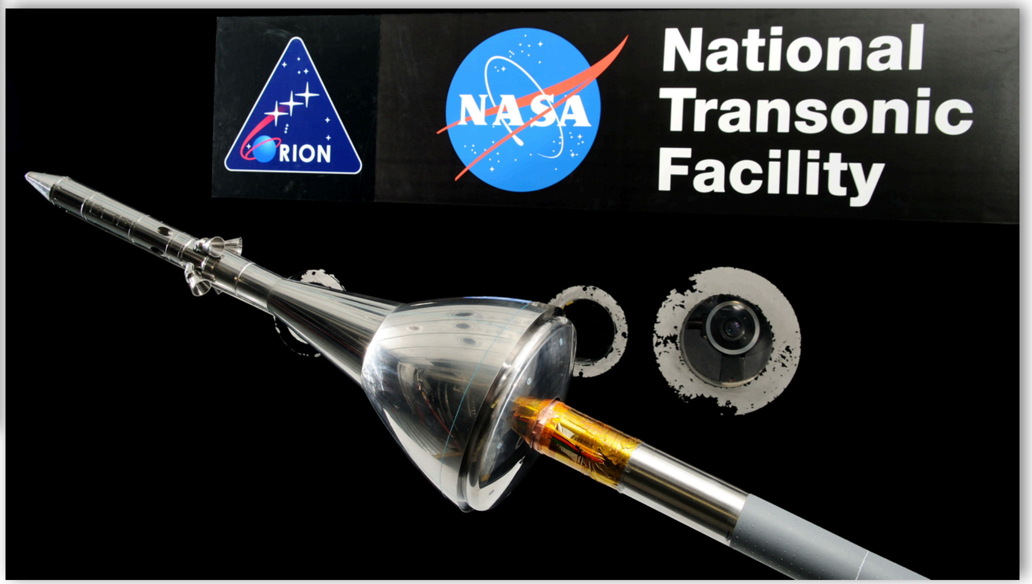


Unpowered LAV Aerodynamics and Aeroacoustics Tests

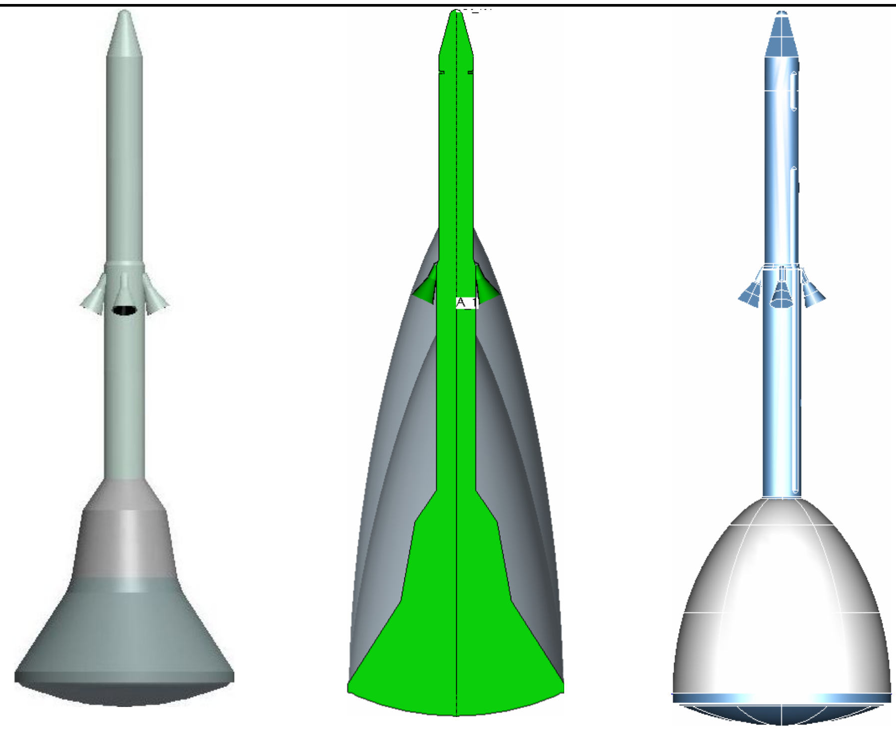
- Initial testing was with unpowered models
- Got full angle of attack data for original LAT configuration
- Looked at LAT fairing shape to reduce nominal ascent acoustic loads (collaboration with NASA Engineering and Safety Center project)
- High-Re test at NTF
- Originally used as basis for aero database - the early databases started with baseline, unpowered data and added increments to account for jet interactions (from Abort Motor and Attitude Control Motor plumes)
- Most of this data has now been replaced with appropriate powered data


3% Unpowered LAV Model

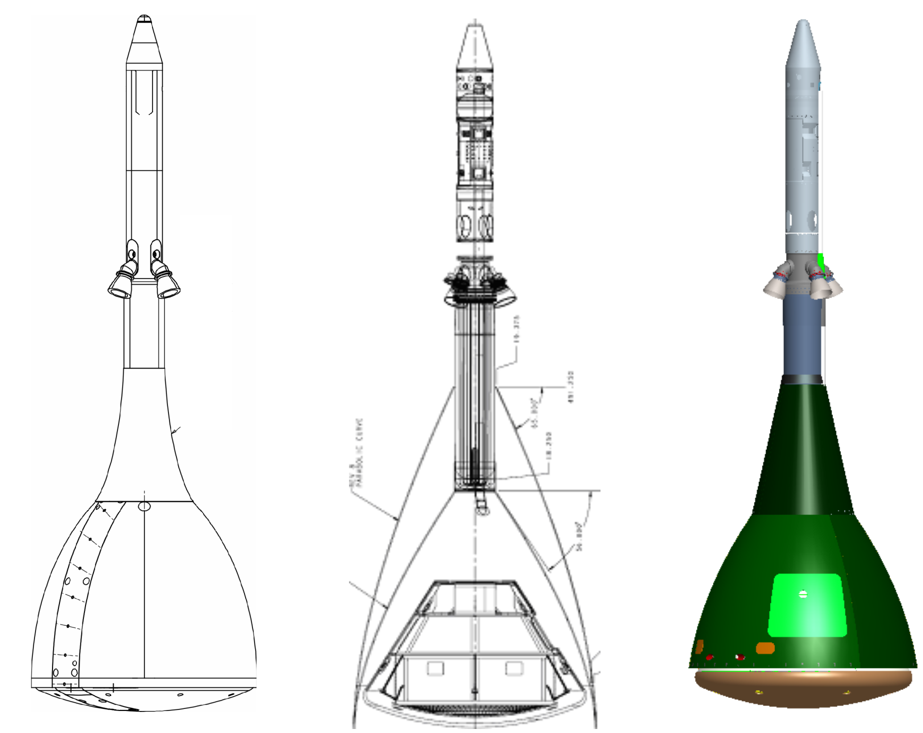




Evolution of LAT Shape



605 config. ALAS 2 & 3 ALAS 11

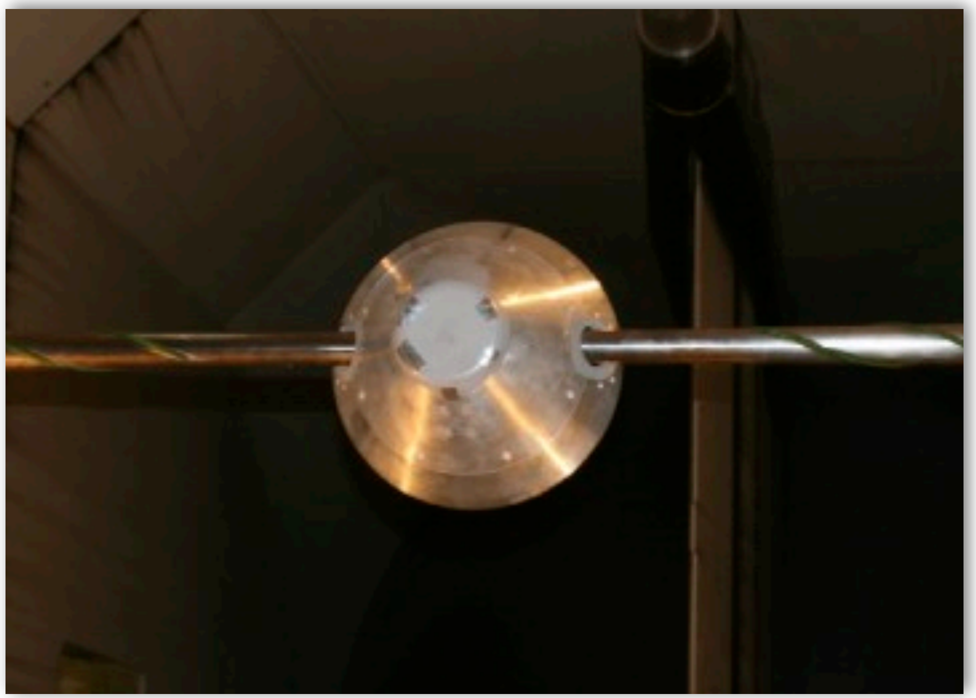


ALAS 11 rev 2 ALAS 11 rev 8 & 10 ALAS 11 rev 3

- 605 configuration was the starting point for the aerodynamic fairing to protect the CM during ascent
- Angular shape produced high aeroacoustic loads
- Alternate Launch Abort System project initiated by NESC led to family of shapes that were tested for acoustic loads and aerodynamics
- ALAS 11 rev 3 was adopted as the LAT design based on reduced acoustic loads and acceptable pitching moment increment (unpowered)

Dynamic Stability Tests

- **17 tests in wind tunnels and ballistic ranges**
- **Primary data obtained from large-amplitude, forced-oscillation testing**
  - Oscillating test rig developed at NASA Langley Transonic Dynamic Tunnel
  - Provided data for M 0.3 to 1.1 at wide range of Re
  - Pitch/yaw damping most critical for subsonic flight of CM
- **Largest number of tests were in the Vertical Spin Tunnel**
  - Free flight
  - Forced oscillation
  - Results in general agreement with TDT but quicker turnaround and lower cost
- ***Overview by Bruce Owens, et al, AIAA-2011-3504***

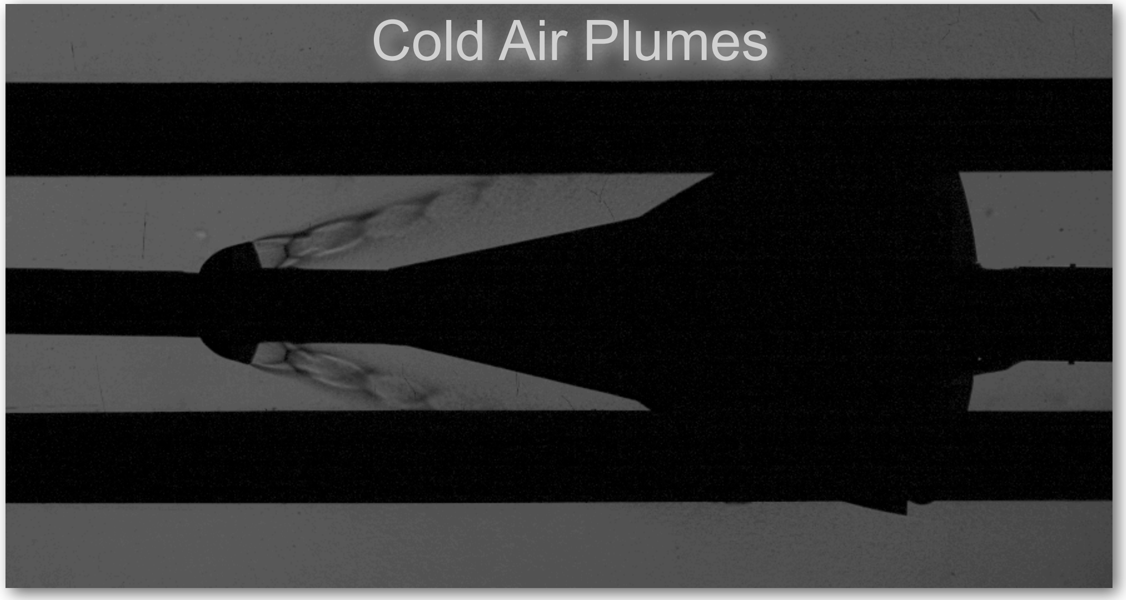


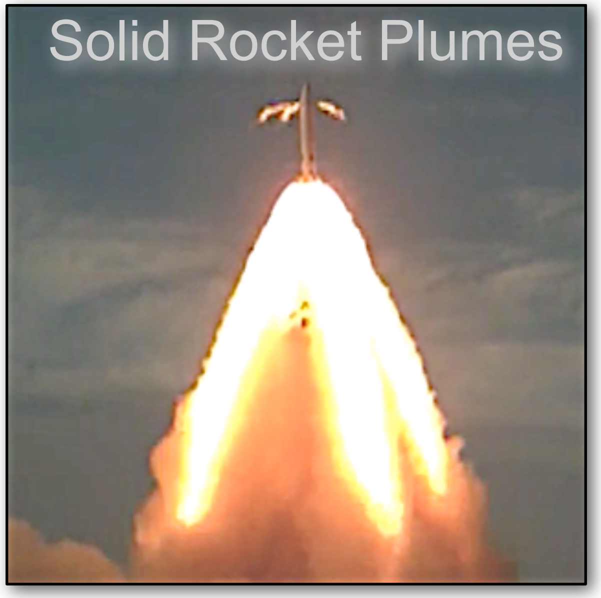
Jet Interaction Tests

- Interaction of the various rocket plumes and the LAV during a launch abort is non-linear, particularly for transonic abort conditions
- Boost phase is the most difficult to characterize - ACM plumes affect AM plumes changing the jet interaction
- ACM operation provides flexible (unlimited) pointing command making full characterization for the database difficult
- Cannot fully match the effect of a hot solid rocket motor plume using cold high-pressure air
- *Plume scaling methodology summary by Greg Brauckmann, et al, AIAA-2011-3341*

Plume Matching Strategy

- **Covered in detail in another paper/presentation**
- **Primarily a concern for launch abort scenarios**
- **Important parameters for aerodynamic interactions are:**
  - Thrust ratio, defined as: $TR = Thrust/(q_\infty S)$
    - q_∞ is free-stream dynamic pressure, S is vehicle reference area
    - Affected by the Mach number and altitude at abort initiation - changing launch vehicles changes the nominal TR to be tested for a given M
    - Thrust of the solid AM and ACM changes with temperature requiring tests over a range of TR
  - Second important parameter to match is either γM_e^2 or $\gamma M_e^2/(1-M_\infty^2)^{\frac{1}{2}}$
    - M_e is plume exit Mach number M_∞ is free-stream Mach number
    - Selection of which to match was made using CFD at wind-tunnel conditions with air plumes compared to CFD at flight conditions with hot solid motor plumes





Launch Abort Tower Jettison

- **After the point in the trajectory when the LAT is no longer needed, it is jettisoned**
  - High Mach number but high enough that dynamic pressure is small and aerodynamics is not a concern
- **During a launch abort the LAT is jettisoned after the turn-around maneuver**
- **Needed to quantify the effect of the Jettison Motor plumes on the CM**
  - At multiple displacements of the LAT from the CM so the integrated effect during the separation event can be modeled
  - At multiple Mach numbers and altitudes (Thrust Ratio of the JM)
- **Three tests to cover conditions from pad abort to maximum dynamic pressure aborts (Mach number 0.05 to 2.5)**

Attitude Control Motor Jet Interactions

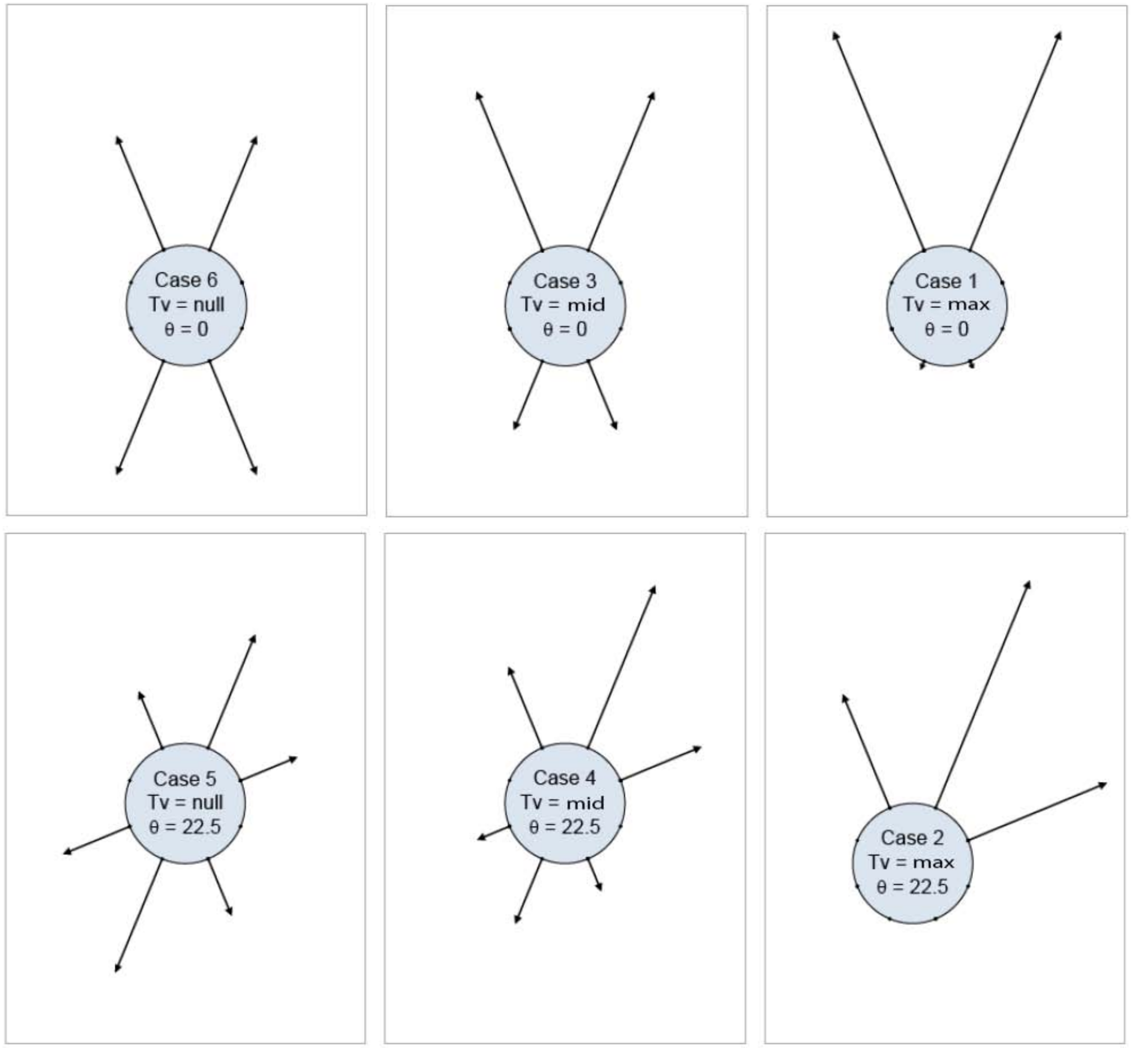
- **ACM operates throughout a launch abort to control the LAV**
- **ACM works by throttling set of 8 nozzles on a single solid fuel combustion chamber**
  - Provides very flexible angular and net thrust control
  - Wind tunnel test can only cover a small subset of the possible conditions
- **ACM plumes interact with the vehicle resulting in reduced effectiveness for many flight conditions**
- **The ACM plumes affect the AM plumes which are downstream, requiring a separate test to examine the combined jet interaction effects**

ACM Operation

- Most pitch/yaw commands can be achieved using a variety of nozzle thrust combinations, each having its own efficiency:

$$Efficiency = \frac{Net\ Moment}{Net\ Thrust \times Moment\ Arm}$$

- Many flight conditions have low efficiency requiring documentation at as many conditions as possible

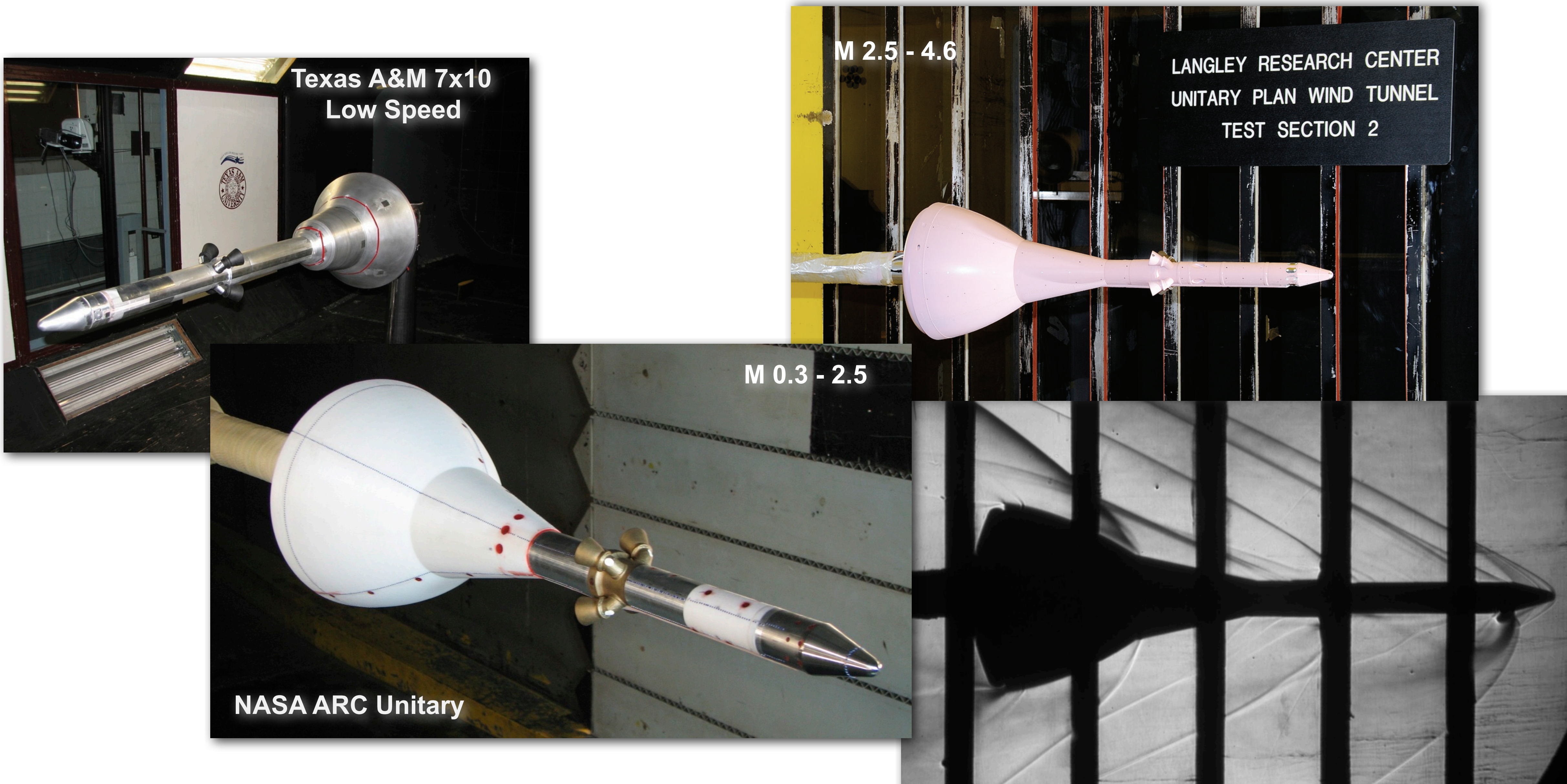


- Examples of three moment command levels in two directions
- Null commands look nothing alike

  Both have zero moment command (*Net Thrust* x *Moment Arm*) but not necessarily zero resulting moment due to jet interactions

Attitude Control Motor Tests

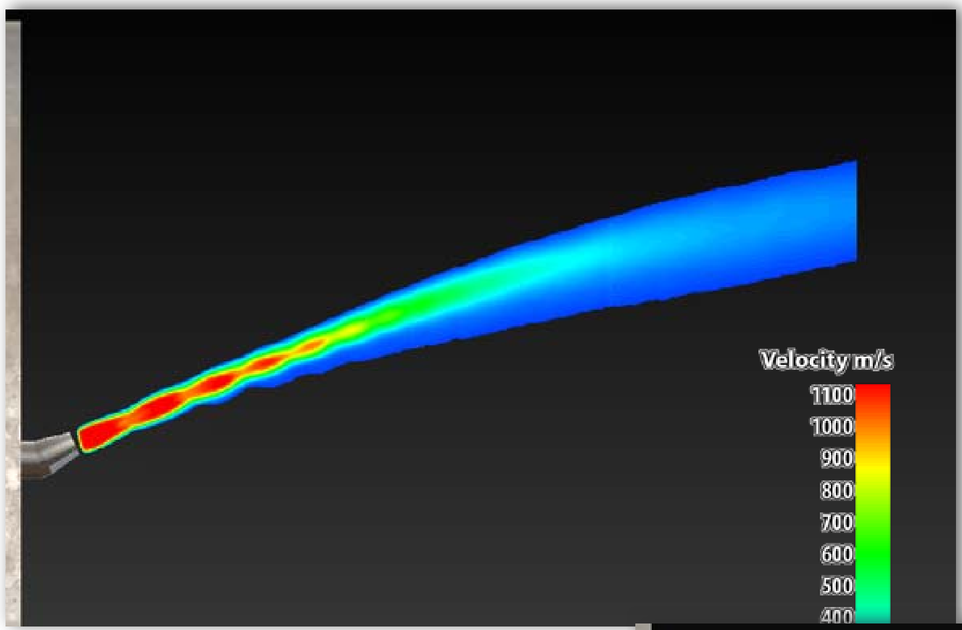
- 4 coast phase tests completed to cover necessary Mach number range
- Summary of coast-phase tests presented by *Kelly Murphy, et al, AIAA-2011-3343*



CFD Validation for Abort Motor Jet Interactions

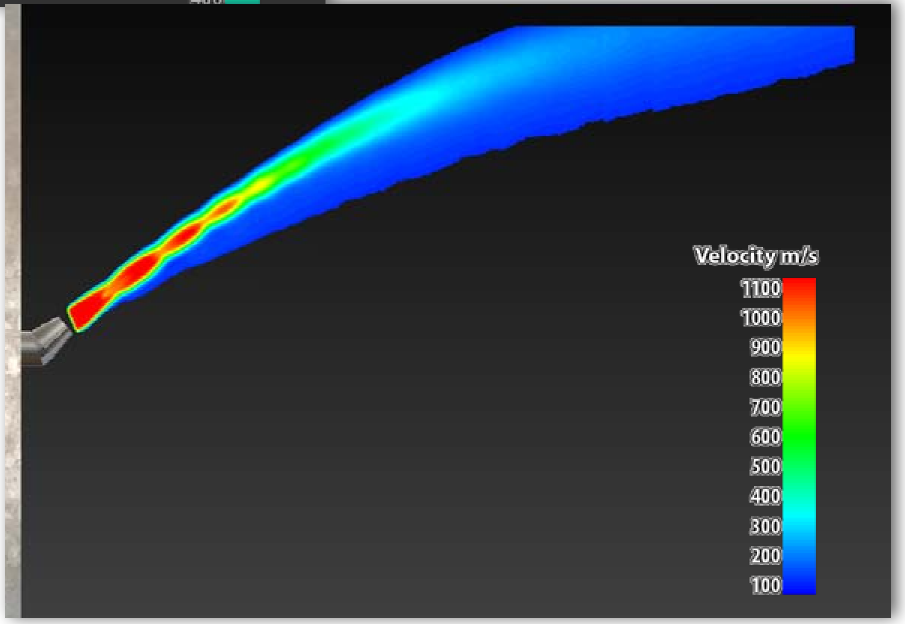
- During the time the database was built on increments, several tests were run to characterize the effect of the AM plumes on the LAV aerodynamics
- One major test at GRC dedicated to providing validation data for CFD
- *Summary of test by Mark Wernet, et al, AIAA-2010-1031*

Single nozzle running with heated air (~800°F) in a co-flowing free stream (Mach 0.3). Plume exit is at ~M 3



Nozzle deflected 25° relative to free stream

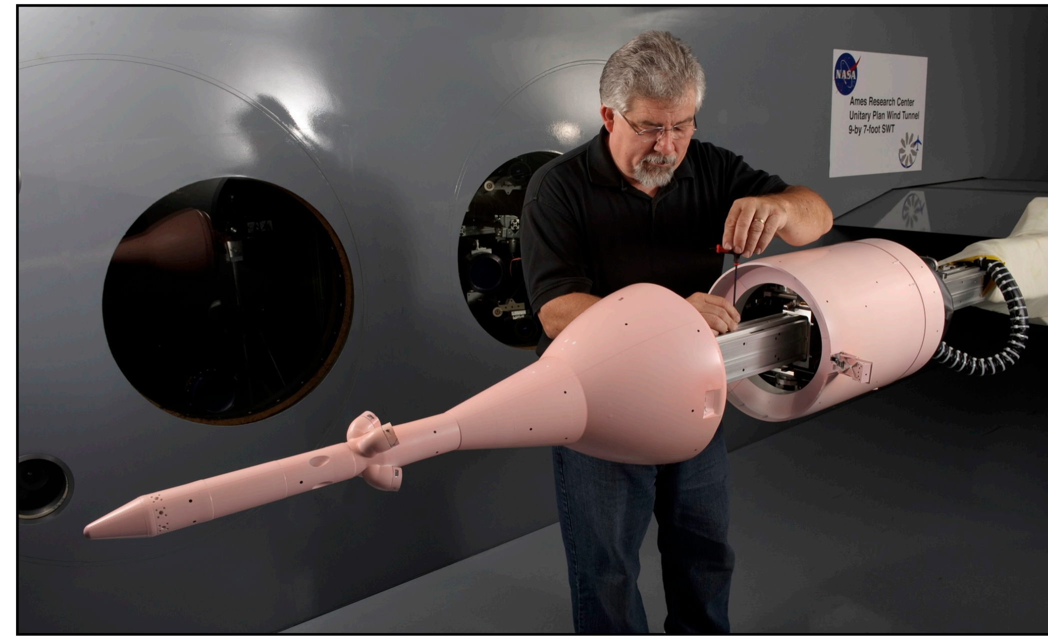
Particle Image Velocimetry data acquired in a plane centered on the plume (shown here without the LAV model present)

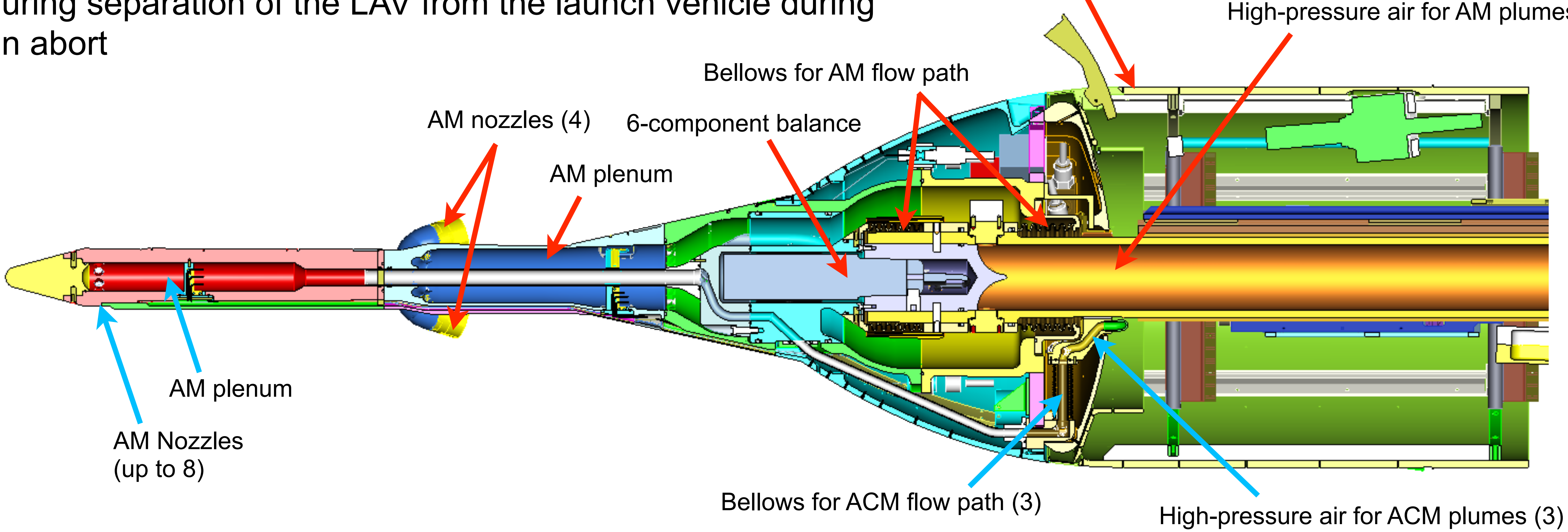


Nozzle deflected 40° relative to free stream

AM/ACM Combined Plume Jet Interactions

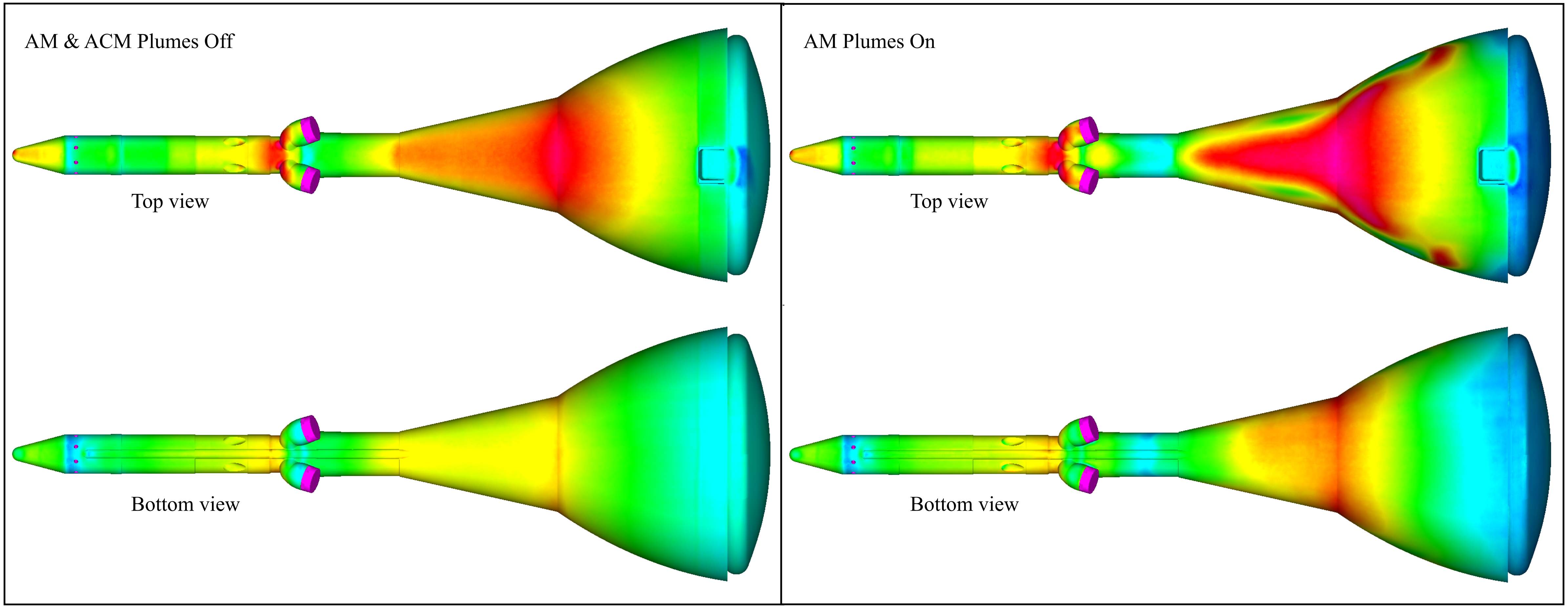
- **The mutual interactions of the ACM and AM plumes were shown to be very non-linear by a number of CFD results**
- **One test was done to document as many conditions as possible**
- **The test also documented the aerodynamics on the CM as it separates from the launch vehicle during the initial stages of an abort**
  - Service Module model remotely reposition-able in axial and vertical directions and could rotate relative to the LAV model
  - AM plumes running because they would always be present during separation of the LAV from the launch vehicle during an abort





AM/ACM JI and Separation Aerodynamics Test Highlights

- **Integration of balance and bellows was difficult**
- **Developing bellows for the pressures required proved difficult**
- **Calibrating out all of the pressure tares proved difficult**
- **Current state of the art for Pressure Sensitive Paint is excellent (*Summary paper by Marvin Sellers, AIAA-2011-3166*)**
  - Integrated forces and moments in good agreement with balance when pressure tares are properly accounted for
  - Used integrated PSP to correct some of balance data where the residual pressure tares were excessive

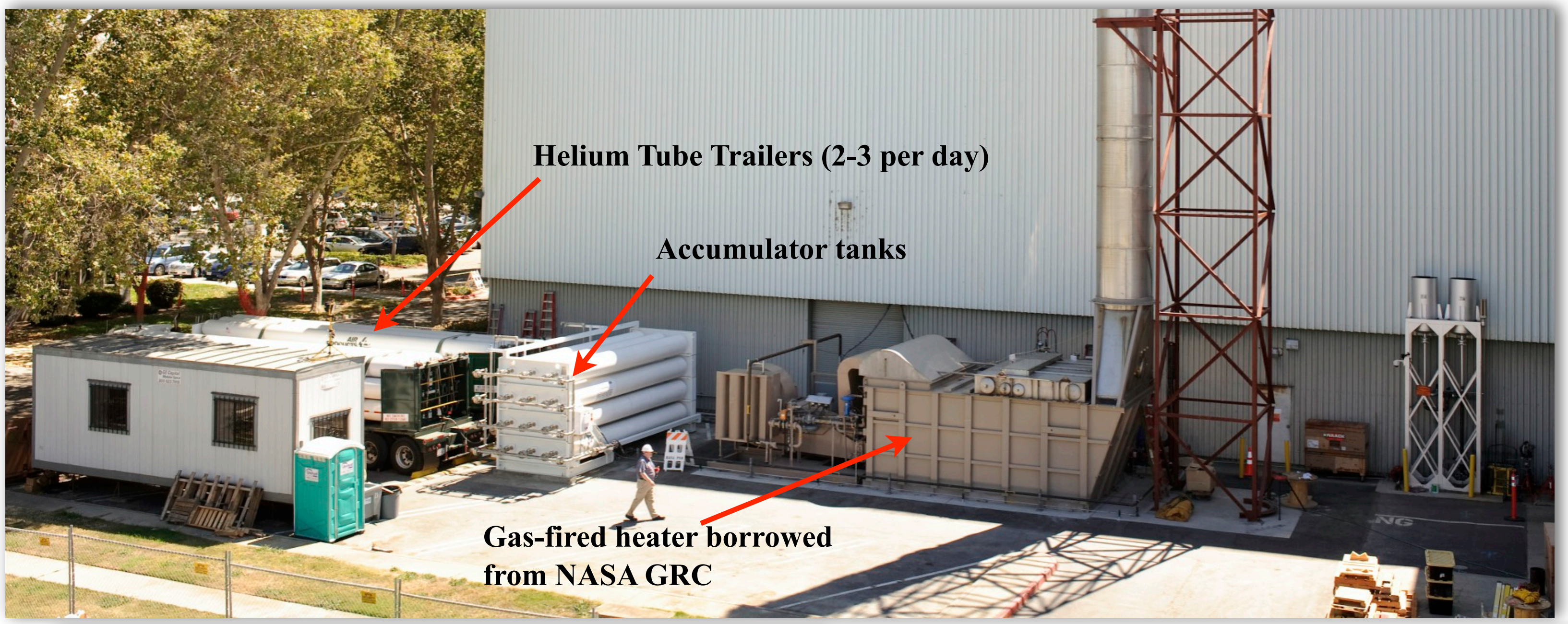


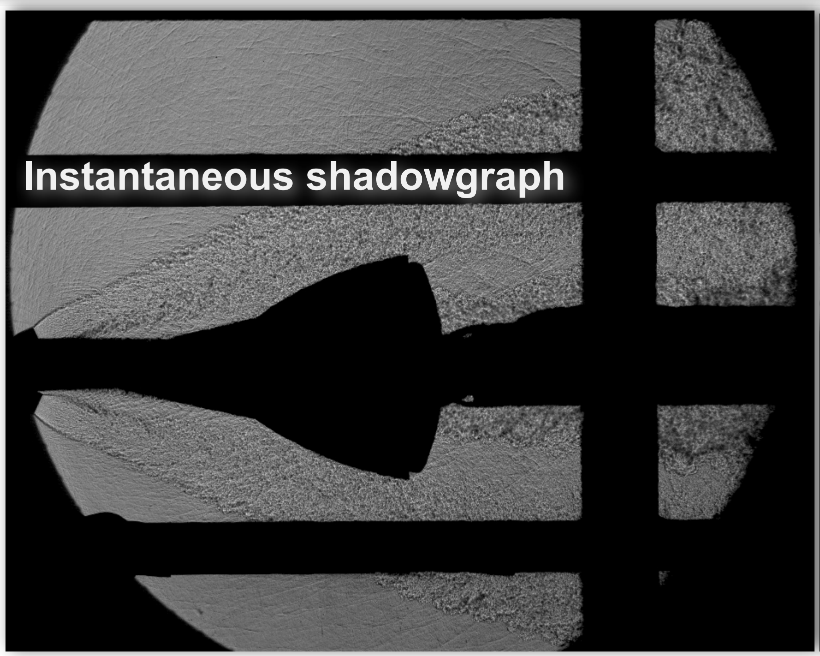
Aeroacoustic Testing

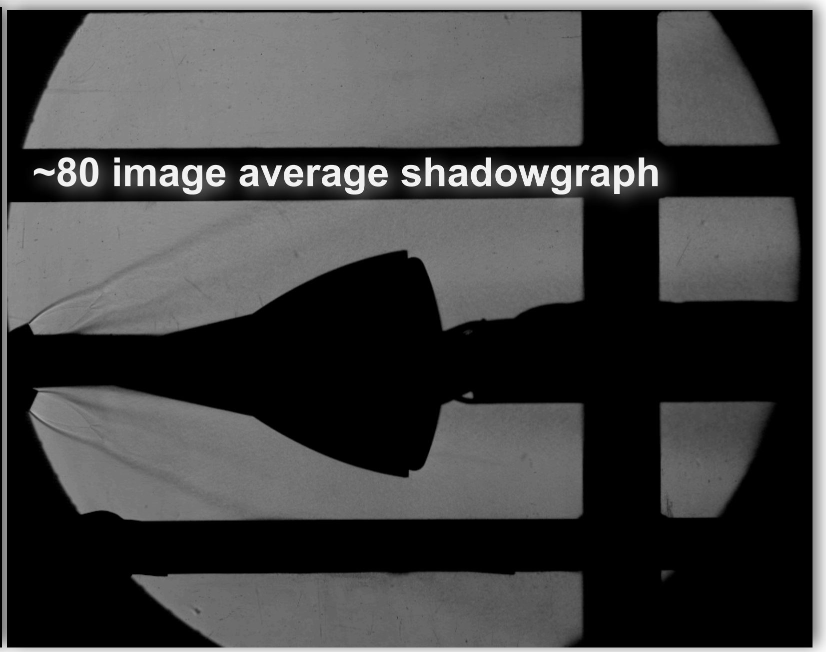
- **Necessary to define the loads environment for the vehicle during nominal ascents as well as during launch aborts**
- **Series of tests and CFD analyses to refine the shape (ALAS) and to define the nominal ascent loads with unpowered models**
- **Powered (AM plume simulation) models to develop abort loads cases**
  - Initial estimates from cold air plumes
  - High-fidelity results using hot Helium as the simulant gas
- **Helium accurately simulates the hot solid motor plume**
  - Primary matching parameter for acoustics is plume exit velocity
  - Secondary matching of density ratios of the He plume to rocket plume and free-stream flight to wind-tunnel
  - Does not include effects of after-burning, Al_3O_2 particles, and different γ than rocket plume
  - Matched the flight measurements from PA-1 test
  - *Summary by Jay Panda, et al, AIAA-2011-2901*

Heated Helium Test

- Summary paper presented by Jay Panda at the AIAA Aeroacoustics Conference in Portland
- Plume simulation required heating He to ~700°F with a flow rate of ~5 lbm/sec







Model mounted in 11' test section
~250 Kulite transducers

Summary

- **Aerodynamic and acoustic testing for Orion was necessary to develop the static/dynamic loads and aero databases**
- **Non-linear behavior of LAV to plume effects led to a wide variety of tests to sufficiently cover the potential abort trajectories**
- **Could not build the databases solely from experimental data**
  - Requires correction to flight conditions
  - CFD filled in many areas that could not be tested
  - Those who build databases can do amazing things with sparse data!

Backup

Unpowered Static Aerodynamics

Test Number	Type	Date	Facility	Description
1-CA	**CM Static Aero**	2/10/06	LaRC UPWT	Study of BL trip techniques on 3%-scale CM model.
3-CA	**CM Static Aero**	3/10/06	LaRC UPWT	3%-scale CM force and moment test.
7-CA	**CM Static Aero**	3/10/06	LaRC UPWT	3%-scale pressure distributions, with apex cover on/off.
5-CA	**CM Static Aero**	3/22/06	ARC UPWT	Force & moments and pressure data on 7.7%- and 3%-scale models. Provided tunnel-to-tunnel comparisons between LaRC and ARC UPWT.
9-CA	**CM Static Aero**	4/20/06	LaRC Mach 6 Tunnel	3%-scale CM test for alpha from 0 to 180°.
1-CA	**CM Static Aero**	12/8/06	LaRC UPWT	Boundary layer transition measurements with IR thermography and Temperature Sensitive Paint.
19-AA	**LAV Static Aero**	1/29/07	Boeing PSWT	3%-scale transonic test of PA-1 LAV configuration for 0-180° angle of attack.
54-AA	**LAV Static Aero**	4/13/07	Lockheed High-Speed Wind Tunnel	Quantify the roll coupling with angle of attack caused by the clocking of the abort motor nozzles on the PA-1 configuration. Study effectiveness of various nozzle fairings in relieving the roll interaction.
88-AA	**LAV Static Aero**	10/20/07	LaRC VST	Test of the PA-1 Launch Abort Tower alone to define the post-jettison aerodynamics.
83-AA	**LAV Static Aero**	6/1/08	LaRC National Transonic Facility	High-Re effects on unpowered LAV aerodynamics.
122-PA	**Static Aero**	11/8/10	ARC TC-2	Small-scale test of Forward Bay Cover aerodynamics to validate CFD and engineering models of the FBC jettison event.

Dynamic Stability Tests

Test Number	Type	Date	Facility	Description
11-CD	**Dynamic stability**	4/8/06	US Army Aberdeen Test Range	Proof of concept test to evaluate the Aberdeen Research Laboratory telemetry technique for ballistic range test data acquisition and analysis of CM flight.
8-CD	**Dynamic stability**	5/10/06	NASA Langley Research Center (LaRC) Transonic Dynamics Tunnel (TDT)	Small-amplitude forced oscillation test of CM w/ some unsteady pressures.
12-CD	**Dynamic stability**	6/19/06	US Army Aberdeen Test Range	Evaluation of improved sabot designs for CM testing at the Aberdeen Test Range
13-CD	**Dynamic stability**	7/6/06	US Air Force Eglin Ballistic Range	Transonic and supersonic dynamic aero data for zero L/D CM model
15-CD	**Dynamic stability**	9/2/06	US Army Aberdeen Test Range	Lifting and non-lifting CM models for dynamic aero database development
14-CD	**Dynamic stability**	10/5/06	NASA Ames Research Center Hypersonic (ARC) Free-Flight Aerodynamics Facility	Transonic and supersonic dynamic aero data of CM at non-zero L/D
18-CD	**Dynamic stability**	1/1/07	LaRC TDT	Demonstration of Oscillating Turn Table test technique in the TDT to obtain dynamic stability of the CM at high Reynolds numbers. Comparisons with ballistic range data and previous small-amplitude forced oscillation test (8-CD)
48-CD	**Dynamic stability**	3/1/07	LaRC Vertical Spin Tunnel (VST)	Free-flight test of CM at low Mach number to provide dynamic stability estimates for the Pad Abort flight test.
52-CD	**Dynamic stability**	3/1/07	ARC Fluid Mechanics Laboratory Test Cell 2 (TC-2)	Test technique development to examine issues related to Free-to-Oscillate testing. Will duplicate the conditions of 48-CD test of the CM.
45-AD	**Dynamic stability**	3/9/07	LaRC VST	Low-Mach number test of LAV in support of PA-1 Flight Test
23-AD	**Dynamic stability**	4/1/07	US Army Aberdeen Test Range	Transonic and supersonic dynamic stability data for LAV using ARL telemetry method
29-CD	**Dynamic stability**	6/1/07	ARC Gun Development Facility	Phase 2 of CM dynamic stability at large angles of attack.
82-AD	**Dynamic stability**	12/21/07	LaRC VST	Forced Oscillation test of LAV in the Vertical Spin Tunnel
27-AD	**Dynamic stability**	3/21/08	LaRC TDT	Forced oscillation (subsonic and transonic) test of LAV and CM through as much of the 0-180 deg. range as possible.
108-CD	**Dynamic stability**	8/25/09	Bihrle Research VST	Low-speed dynamic stability test to support Orion decisions on backshell changes.
109-CD	**Dynamic stability**	11/15/09	LaRC VST	Dynamic stability of CM under parachutes.
117-CD	**Dynamic stability**	4/1/10	LaRC VST	Phase 2 of dynamic stability test of CM under parachute
46-AD	**Dynamic stability**	6/1/10	US Air Force Eglin Ballistic Range	Ballistic range test of LAV.

Powered Aerodynamics/Jet Interaction

Test Number	Type	Date	Facility	Description
53-AA	**Jet Interaction (JI)**	5/21/07	Texas A&M 7x10 Foot Wind Tunnel	First test of subsonic interactions between the ACM plumes and the LAV. Primarily to validate CFD and to provide some data on coast-phase ACM increments for the PA-1 flight test aero database.
16-AA	**JI**	6/22/07	ARC UPWT	Abort loads on the CM due to AM plume JI and proximity to Service Module
59-AA	**JI**	9/14/07	ARC UPWT	High fidelity ACM JI for both Pad Abort-1 flight test article and production ALAS-11rev3B configuration.
60-AA	**JI**	1/30/08	ARC UPWT	Preliminary separation aerodynamics during abort initiation on PA-1 and ALAS-11 rev3B configurations. Preliminary aeroacoustics for nominal ascent (with SM) and abort (LAV only) with cold air plume simulation.
85-AA	**JI**	8/20/08	GRC Aero-Acoustic Propulsion Laboratory	CFD validation test documenting flowfield associated with single AM nozzle at M < 0.3 using PIV. Nozzle at 0°, 25°, and 40° relative to free stream. With and without simplified LAV model.
61-AA	**JI**	12/1/08	LaRC 14- by 22-Foot Wind Tunnel	Subsonic 6%-scale Jettison Motor Jet Interaction test around alpha = 180°.
24-AA	**JI**	6/25/09	AEDC 16T	Transonic/supersonic test of Jettison Motor Jet Interation for LAS jettison during a launch abort (i.e. heat shield forward).
75-AA	**JI**	7/24/09	ARC UPWT	Subsonic, transonic, and low-supersonic ACM Jet Interaction test.
76-AA	**JI**	11/24/09	LaRC UPWT	Supersonic ACM Jet Interaction test (M 1.6 to 4.6).
25-AA	**JI**	2/26/10	ARC UPWT	Supersonic (M 1.6 to 2.5) Jettison Motor Jet Interaction and Jettison LAS/CM Proximity aerodynamics.
26-AA	**JI**	8/9/10	ARC UPWT	Subsonic, transonic, and supersonic AM and ACM Jet Interactions including separation effects data for the LAV. PSP to document pressure loadings during launch aborts.

Aeroacoustic Tests

Test Number	Type	Date	Facility	Description
50-AS	**Ascent acoustics**	5/17/07	Boeing Polysonic Wind Tunnel (PSWT)	A preliminary investigation into the aeroacoustic loads generated by the Pad Abort Test (PA-1) LAV configuration and the potential reduction in those loads provided by an alternate Launch Abort System configuration (ALAS-2 mod-1) developed by the ALAS project of the NESC.
58-AA	**Ascent acoustics**	10/8/07	Arnold Engineering and Development Center (AEDC) 4T	Test to identify LAV configuration to adopt for flight. Down-select between ALAS-11 rev 3, rev 8, and rev 10. Approximately 12 flush mounted microphones
57-AS	**Ascent acoustics**	11/1/07	NASA Glenn Research Center (GRC) 8x6	LAV Ascent Aeroacoustics comparing PA-1 and ALAS-11 rev. 3 configurations with approximately 100 surface mounted microphones
55-AS	**Plume Acoustics**	9/28/07	Florida State Jet Noise Laboratory	Series of hot- versus cold-jet acoustic experiments to possibility develop scaling laws to allow the use of cold plume tests for the LAV with AM firing. Phase 1 - 2" 2,000°F jet versus 2" cold jet. Phase 2 - Same 2 jets with more measurement locations. Phase 3 - ~1" D nozzle exit hybrid rocket. Phase 4 - Sounding rocket motor plume noise measurements at NASA Wallops Flight Facility.
51-AS	**Plume Acoustics**	10/30/08	ARC Unitary Plan Wind Tunnel (UPWT)	6%-scale LAV model test to determine the aeroacoustic loading generated by cold air simulation of the AM plumes. ~200 flush microphones.
80-AS	**Plume Acoustics**	9/20/10	ARC UPWT	Hot Helium simulation of AM plumes for acoustic loads. ~200 flush microphones.