nautics and Space Administration

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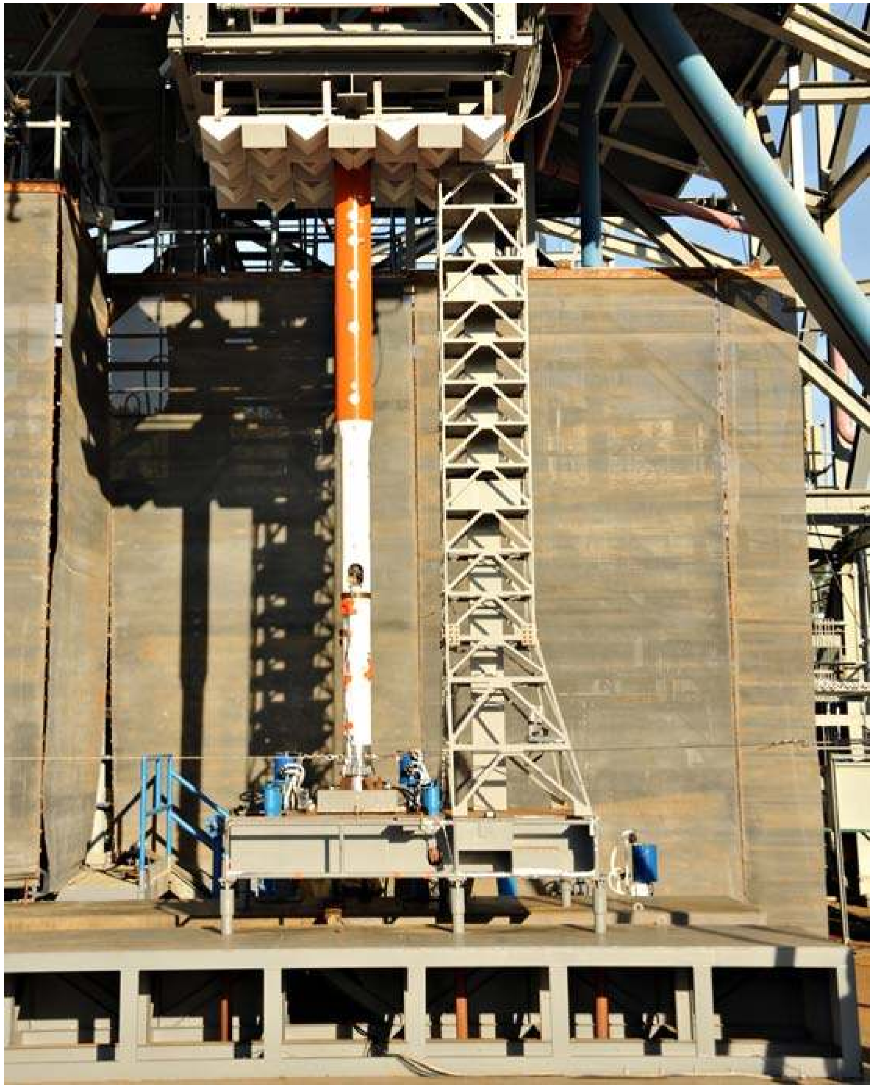
Fluid Dynamics Branch

5 % Ares I Scale Model Acoustic Test Overpressure Characterization and Analysis

September 14, 2011

Configuration

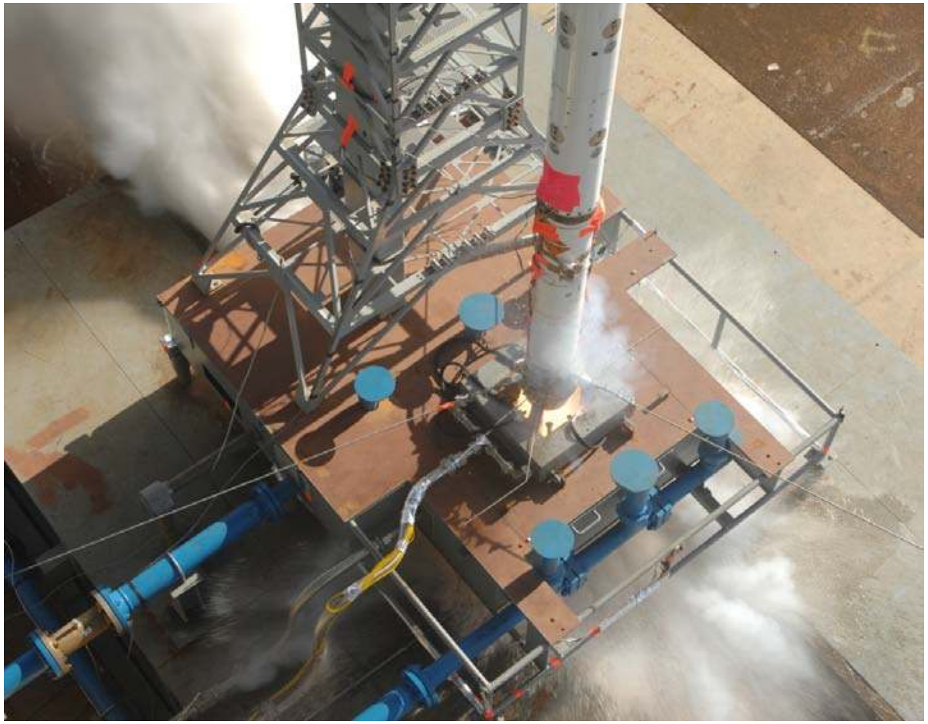
- **Test Configuration and Instrumentation**
  - **The ASMAT IOP Test Series consists of three vertical firings**
    - IOP1: IOP Suppression with Water Bags
    - IOP2: IOP Suppression without Water Bags
    - IOP3: No IOP Suppression
  - **IOP instrumentation suite comprised of 78 unsteady pressure sensors**
    - Vehicle (31)
    - Tower (14)
    - Mobile Launcher (10)
    - Exhaust Duct (14)
    - Flame Trench (9)
  - **Chamber pressure (2) and RATO mounted strain gage (4) measurements used for ballistics profile**
  - **Measurement Sample Rate: 256,000 Samples Per Second (sps) and 4,000 sps**



ASMAT Test IOP2 (Pre Test)
Marshall Space Flight Center – Test Stand 116
November 10, 2011

Objectives

- **Test Objectives**
  - **Primary Objectives**
    - Data for use in Ares I overpressure environments
    - Determine the effect of the IOP suppression system for overpressure reduction on Ares I
    - Determine the effectiveness of water bags for IOP reduction on Ares I
  - **Secondary Objectives:**
    - Obtain overpressure data for CFD validation and analytic model improvements (KSC/MSFC)



ASMAT Test IOP2 (Ignition Overpressure Suppression System without Water Bags
Marshall Space Flight Center – Test Stand 116
November 10, 2010

Suppression System Design

- **Current Space Shuttle IOP Suppression System (IOPSS) was designed in 1981 and installed for STS-2 launch**
- **ASMAT water suppression system components**
  - Water Bags
  - Rainbirds (not run during IOP tests)
  - Main Flame Deflector/Crest Water
  - Below Deck IOPSS
    - Launch Mount Injected Duct Water
    - Mobile Launcher Injected Duct Water
- **Water bag configuration**
  - MSFC designed and fabricated
  - Tested in IOP-1 (not baselined in Ares I design)
- **Water flow rates**
  - Crest Water (North Trench): 640 gpm
  - Crest Water (South Trench): 233 gpm
  - Exhaust Duct (Launch Mount): 146 gpm
  - Exhaust Duct (Mobile Launcher): 146 gpm

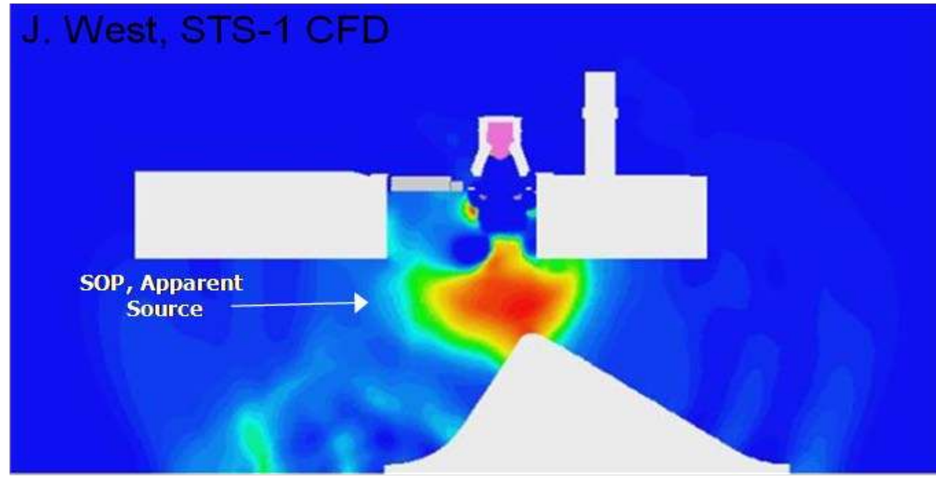
ASMAT Test IOP3 (Main Flame Deflector Crest Water Trench Suppression)

ASMAT Water Flow Testing (Below Deck Suppression Mobile Launcher Duckbill Nozzles)

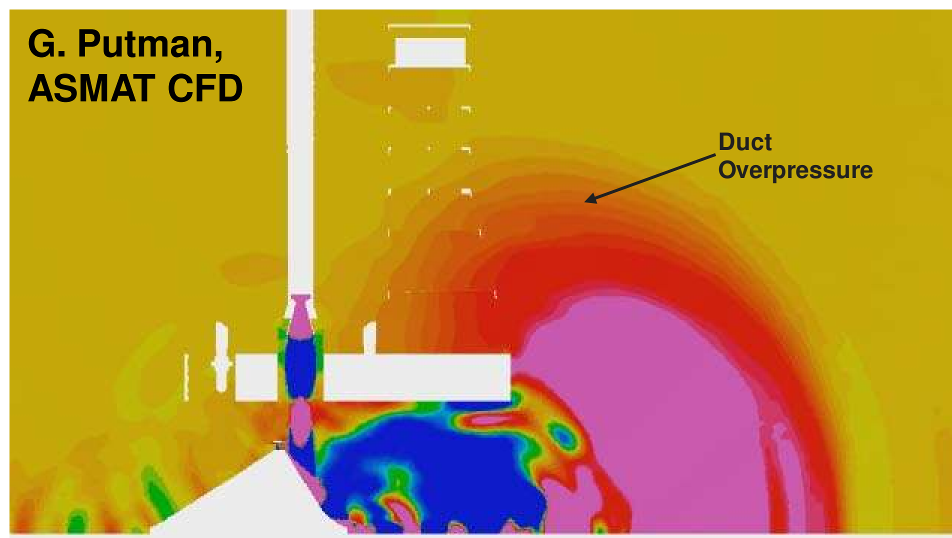
Overpressure Events

- **Overpressure definition**
  - Pressure wave that results from the sudden injection of mass and subsequent compression of the accelerating plume gas in a confined volume
  - Pressure wave propagates out the trench and exhaust duct exits

- **Ignition transient events**
  - Igniter Pulse / Throat Plug Overpressure (TPOP)
  - Overpressure Events
    - **Source Overpressure (SOP)** – overpressure waveform genesis inside of trench and exhaust hole
    - **Ignition Overpressure (IOP)** – pressure wave exiting the top of the exhaust duct
    - **Duct Overpressure (DOP)** – pressure wave exiting the trench exits



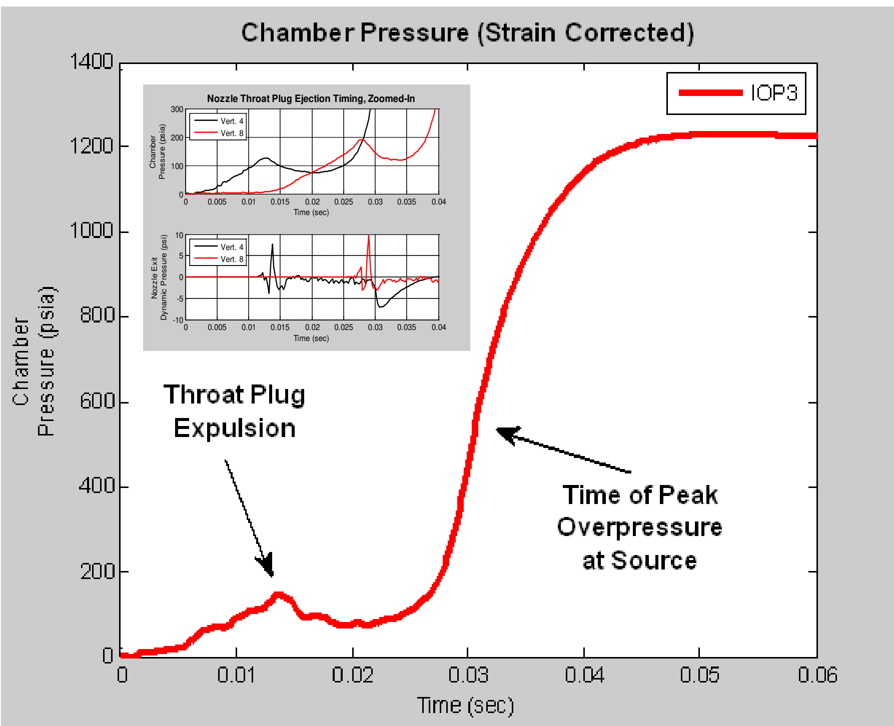
Instantaneous moment in time during SOP Development
Full-scale Unsteady CFD Simulation for STS-1, Summer 2008

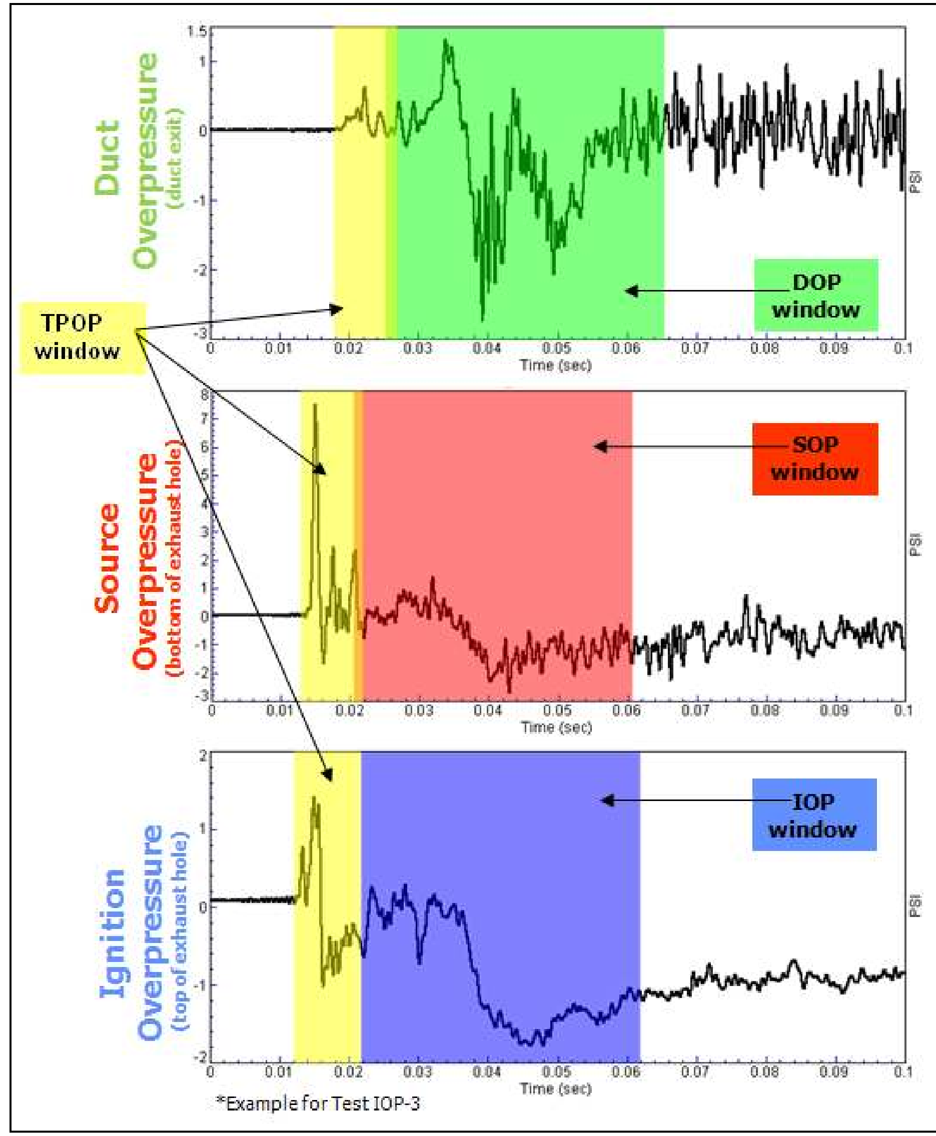


Instantaneous moment in time during DOP Propagation
Unsteady CFD Simulation for ASMAT, Spring 2011

Ignition Transient Characterization

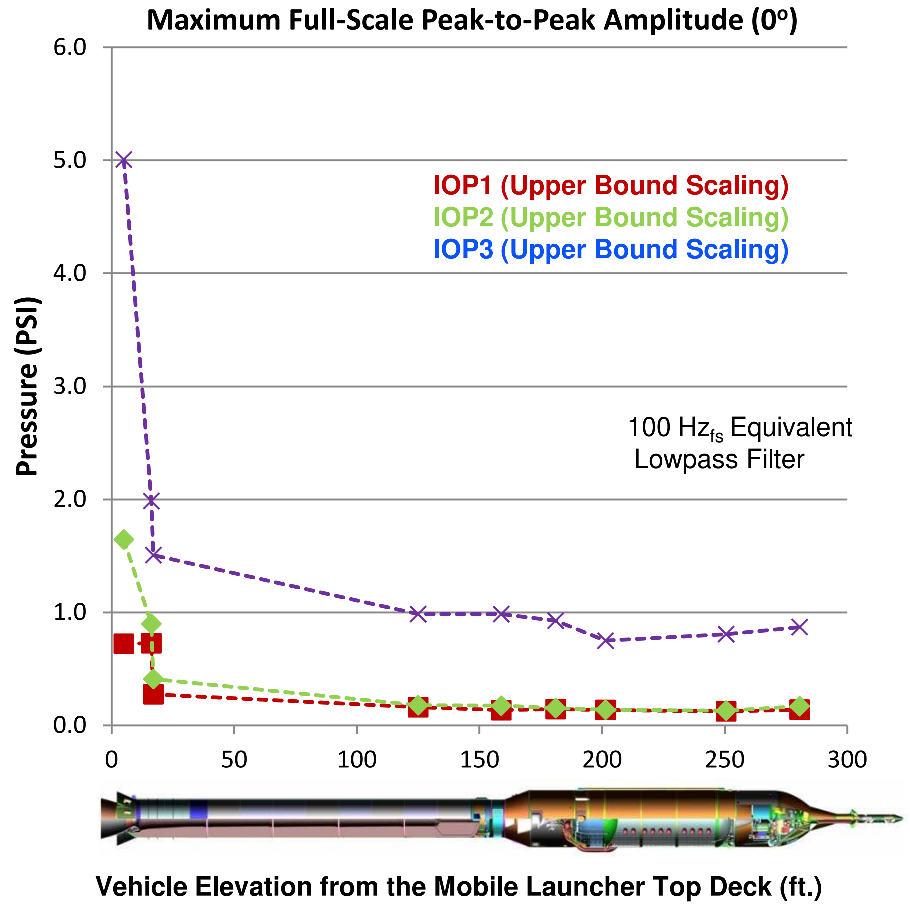
- **Method of Identification**
  - TPOP – nozzle pressure sensors
  - SOP – 1st laws
  - IOP & DOP – propagation speed
- **Characterization**
  - Meticulous tracking of waveform features for every measurement





Ares I Vehicle Environment

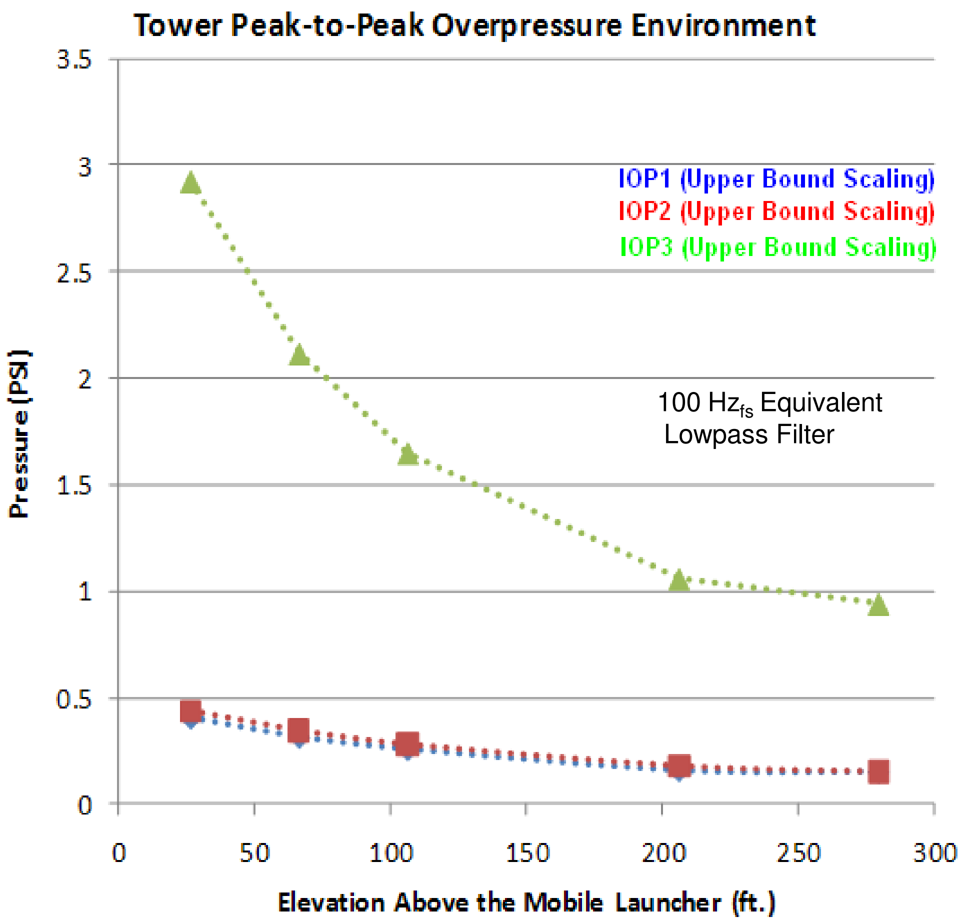
- **Ares I Vehicle Environment**
  - **TPOP**
    - Propagates through the LM up the vehicle
    - Strongest at the thermal curtain
    - Frequency content peaks at 10 – 15 Hz_{fs}
  - **IOP**
    - Propagates through the LM up the vehicle
    - IOP wave encounters the DOP wave near the forward skirt (upper section of first stage)
    - Frequency content peaks at ~9 Hz_{fs}
  - **DOP**
    - Propagates out the north end of the flame trench, diffracting around the ML towards vehicle
    - The dominant overpressure event for the frustum, interstage, and crew module
    - Aft end of the vehicle has no direct impingement
    - Frequency content peaks at ~4 Hz_{fs}



Note – Above amplitudes and figure only consider IOP and DOP. Does NOT include peak amplitudes associated with the throat plug pulse.

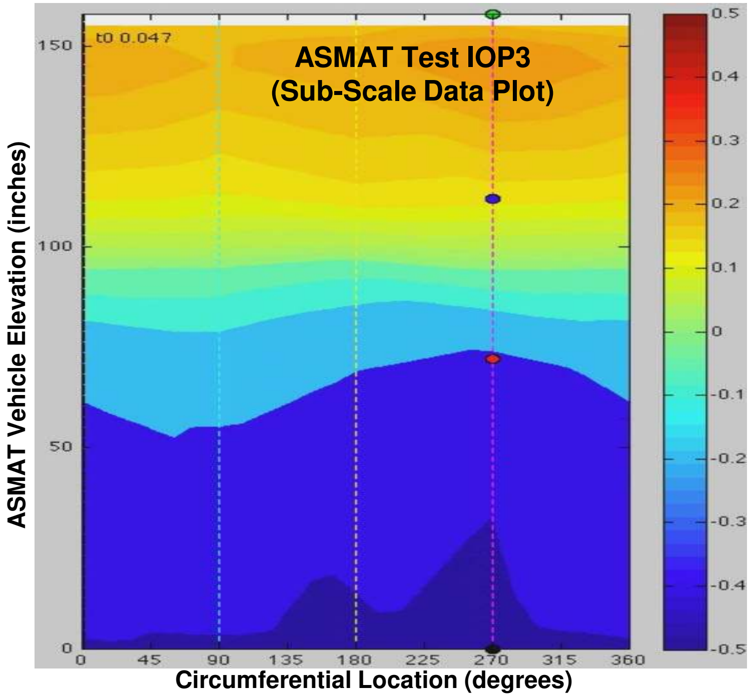
Ares I Tower Environment

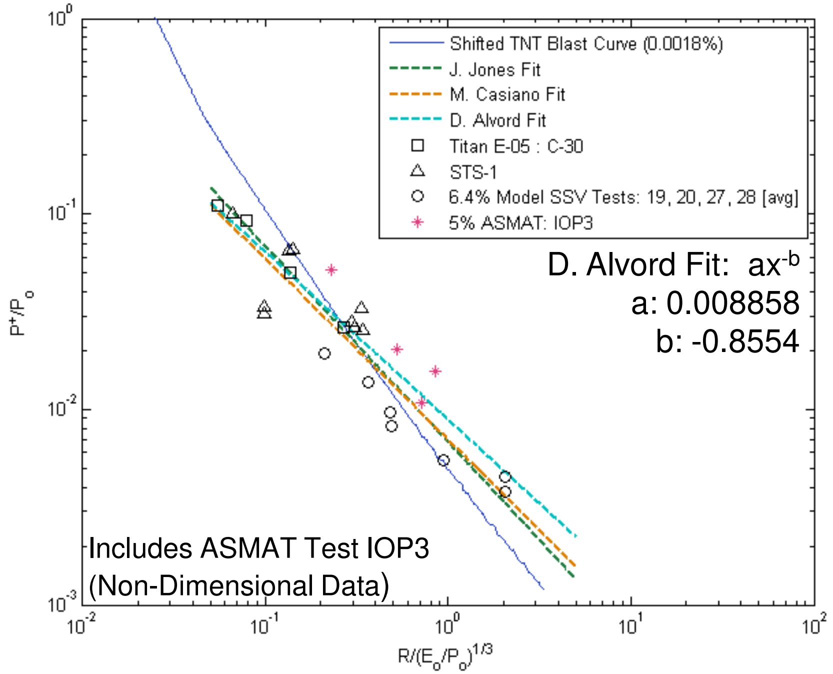
- **Maximum peak overpressure**
  - DOP impingement
  - North side of tower
  - 30' level
- **Full-scale maximum overpressure peak-to-peak amplitude (30' Level):**
  - IOPSS with water bags: **0.4 psi_{fs}**
  - IOPSS without water bags: **0.4 psi_{fs}**
  - Dry Case: **2.9 psi_{fs}**
- **Ares I-X environment comparison (100 Hz LP filtered, peak-to-peak)**
  - Ares I-X VSS at 156' above MLP
    - DOP amplitude: **0.2 psi**
  - Upscaled ASMAT at 156' above ML
    - DOP amplitude (IOP1): **0.2 psi_{fs}**
  - Upscaled ASMAT at 156' above ML
    - DOP amplitude (IOP3): **1.2 psi_{fs}**



Wave Propagation

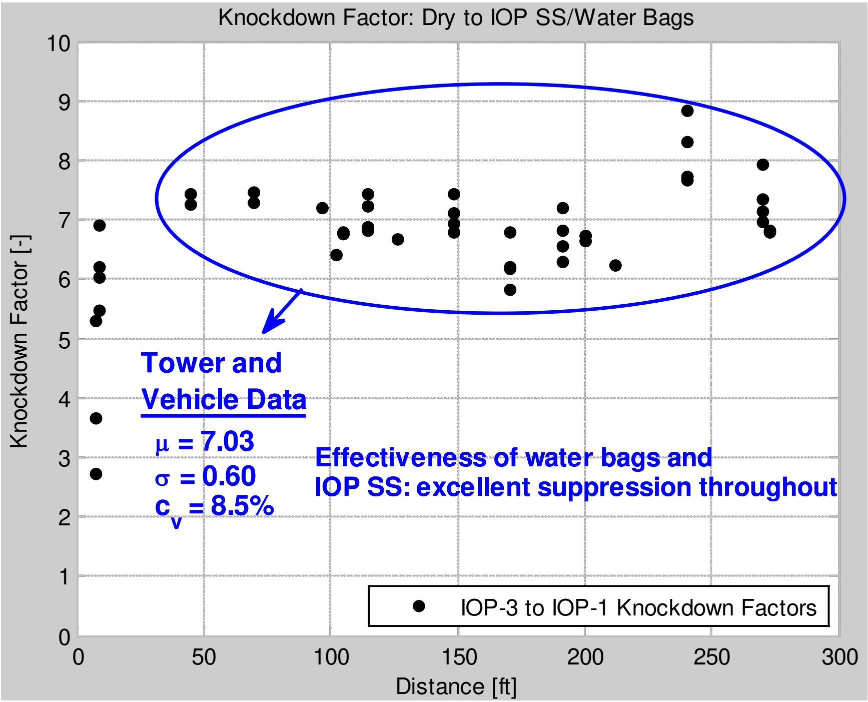
- A Differential Overpressure (ΔOP) from forward to aft of the vehicle of ~2 psi full-scale (psi_{fs}) develops as the IOP and DOP waves propagate up the vehicle



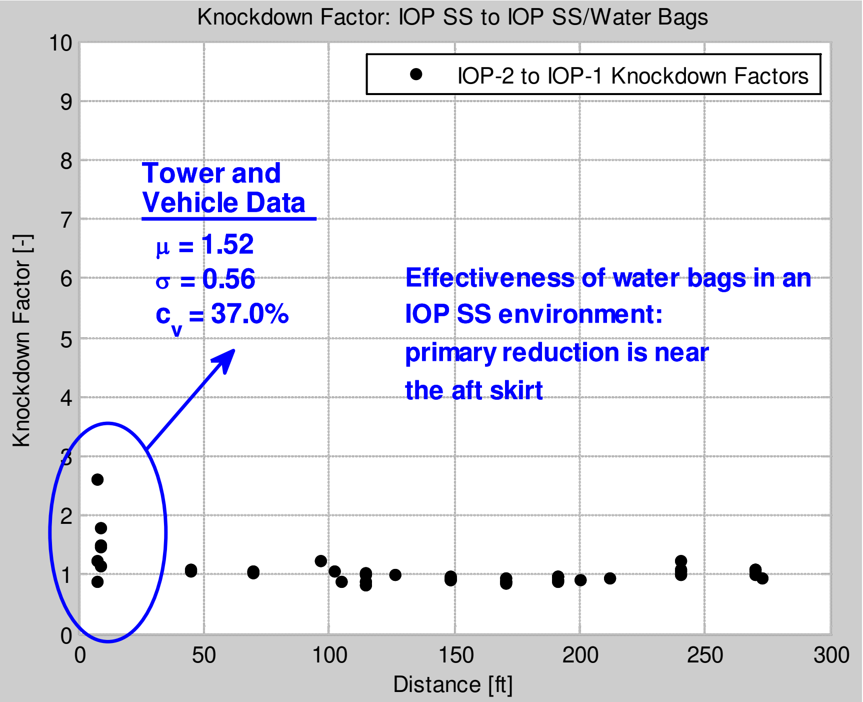


- Sach's blast wave propagation model
  - IOP-3 (dry) data are nondimensionalized and fall within family of heritage data

Ares I Amplitude Reduction Factors

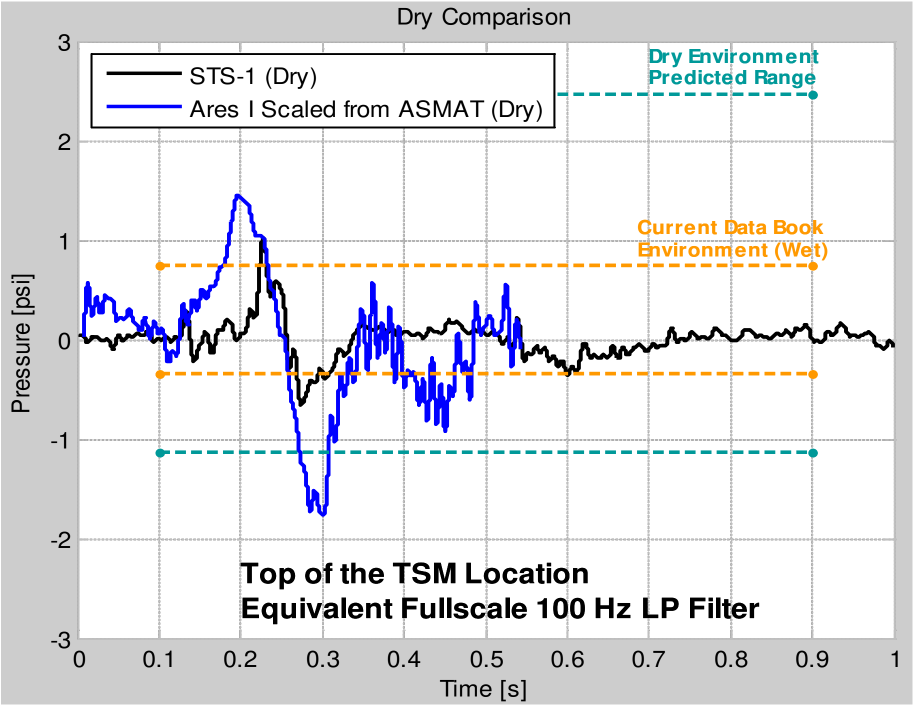


- **Amplitude reduction factors**
  - Also called knockdown factors (KF)
- **IOPSS and water bags show excellent suppression throughout**
  - Water bags are most effective at the aft end of the vehicle



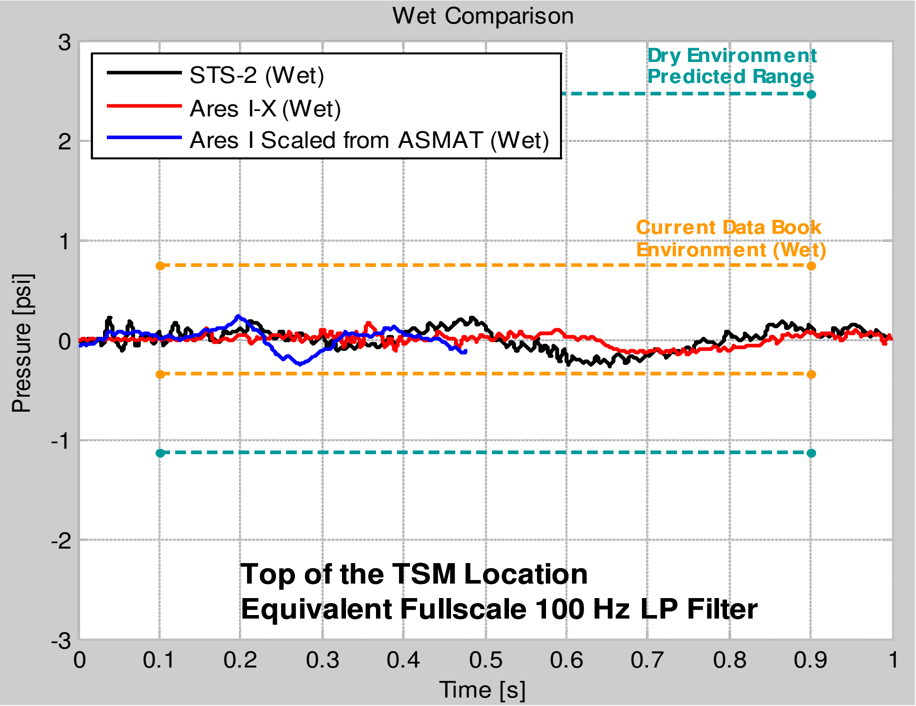
- **Statistics include mean, standard deviation, and coefficient of variation (dispersion)**
  - KF is 7.03x on the vehicle and tower away from the hole due to IOP SS and water bags for Ares I configuration
  - KF is 1.52x near the exhaust hole due water bags in an IOP SS environment in the Ares I configuration

Comparison with Heritage Data



- **Dry Ares I (pred. from ASMAT) has higher amplitudes than the dry STS-1 data**
- **Dry Ares I (pred. from ASMAT) is higher than the wet data book environment**

- **Wet Ares I (pred. from ASMAT) meets the environment specified in the data book**



Conclusions

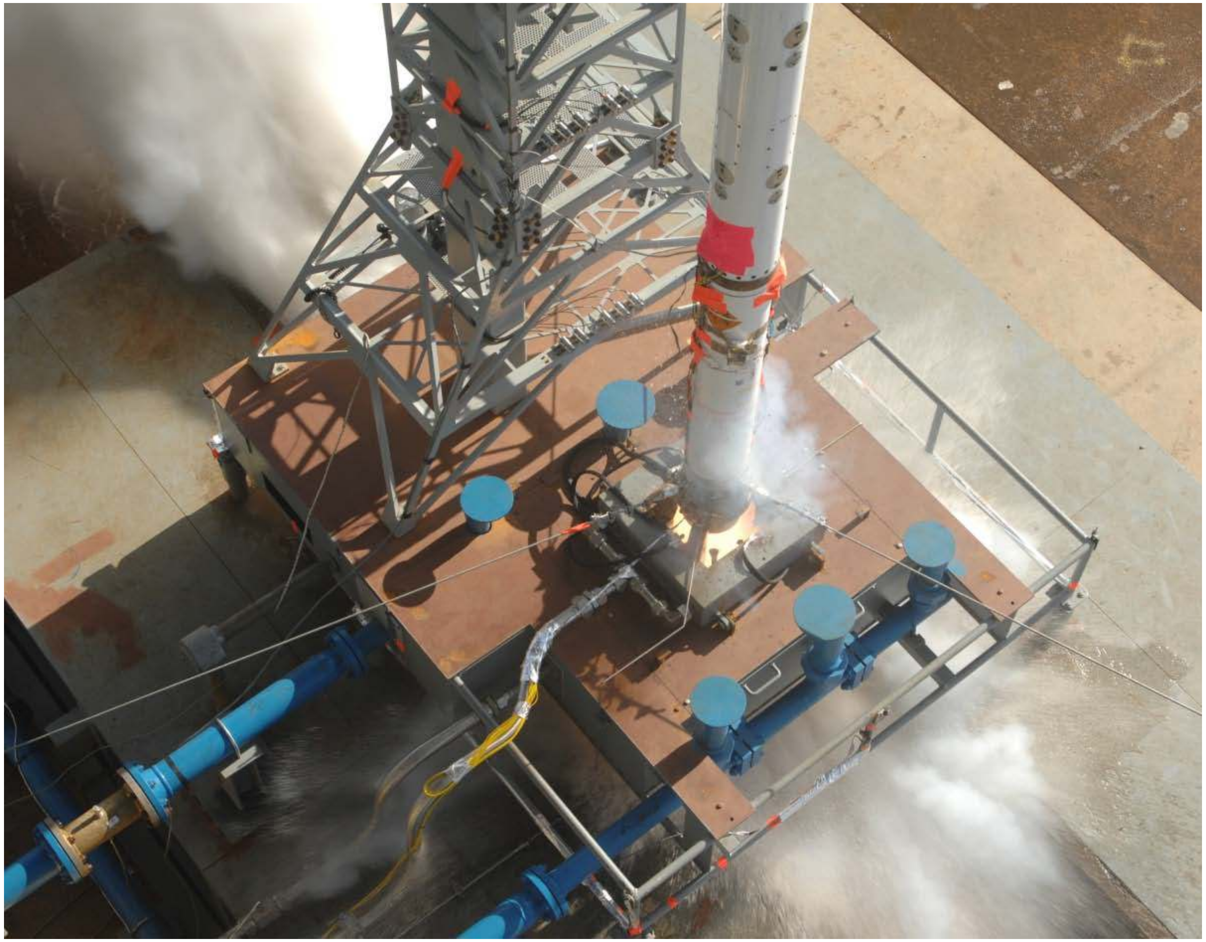
- **ASMAT IOP Results**
  - **Ares I environment (pred. from ASMAT)**
    - The dry, unsuppressed case exceeds both the measured STS-1 and Ares I data book environments
    - The wet, suppressed case meets the environment specified in the data book
  - **Using a Space Shuttle derived suppression system with IOPSS piping and water bags:**
    - An overpressure amplitude reduction of 7.03 was achieved
    - The suppressed environment at the equivalent TSM location is within family of Space Shuttle and Ares I-X
  - **The maximum Ares I environment (pred. from ASMAT)**
    - Measured on the ML underside at 17 psi_{fs}
  - **Frequency content of the dominant wave form is ~4 Hz_{fs}**
    - TPOP Pulse: 10 – 15 Hz_{fs}
    - IOP wave: ~9 Hz_{fs}
    - DOP wave: ~4 Hz_{fs}

- **ASMAT IOP Observations**
  - IOP suppression system and water bags successfully knockdown the ignition transient events
  - Dominant impingement events:
    - Aft end of first stage – IOP
    - Forward end of the first stage and upward –DOP
  - Asymmetric instantaneous impingement
    - Asymmetrical DOP loading up the vehicle providing a potential moment on the vehicle
      - Overpressure loading on upper stage with underpressure loading on first stage
      - Full-scale ΔOP of +2 psi_{fs}

BACKUP SLIDES

Back Up Slides: Outline

- IOP-1 Configuration
- Data Processing Parameters
- Scaling Methodology
- IOP Suppression System Configuration
- ASMAT Test Matrix



ASMAT Test IOP2 (Ignition Overpressure Suppression System without Water Bags
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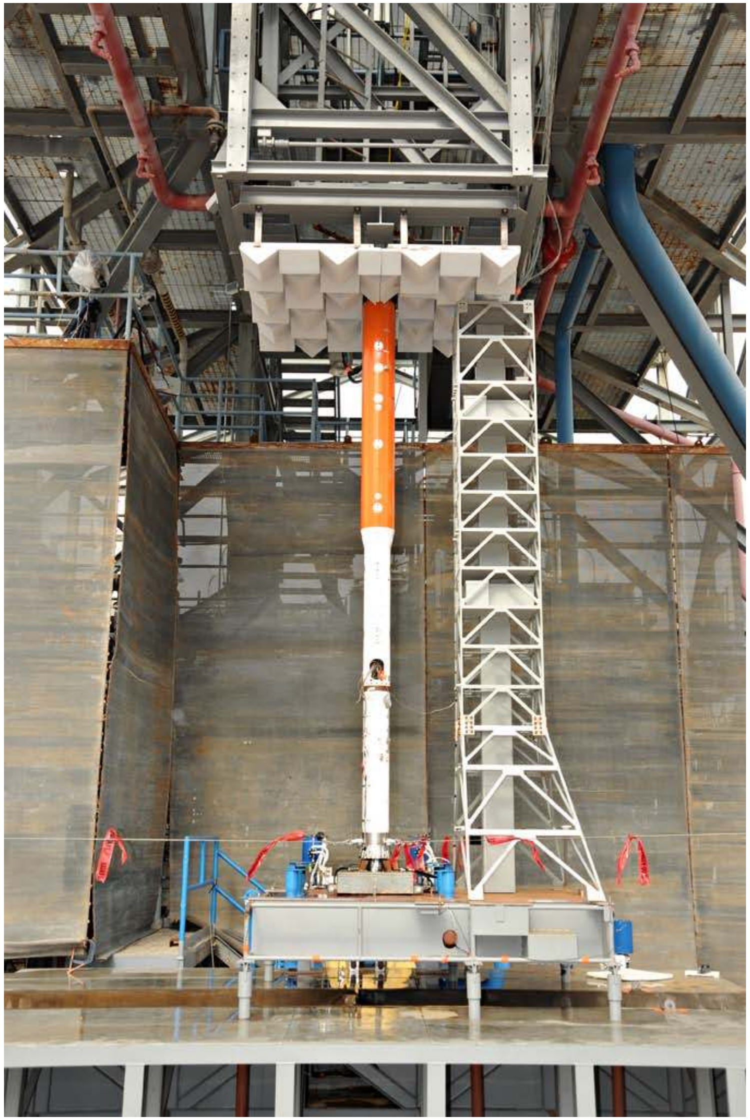
IOP-1 Configuration

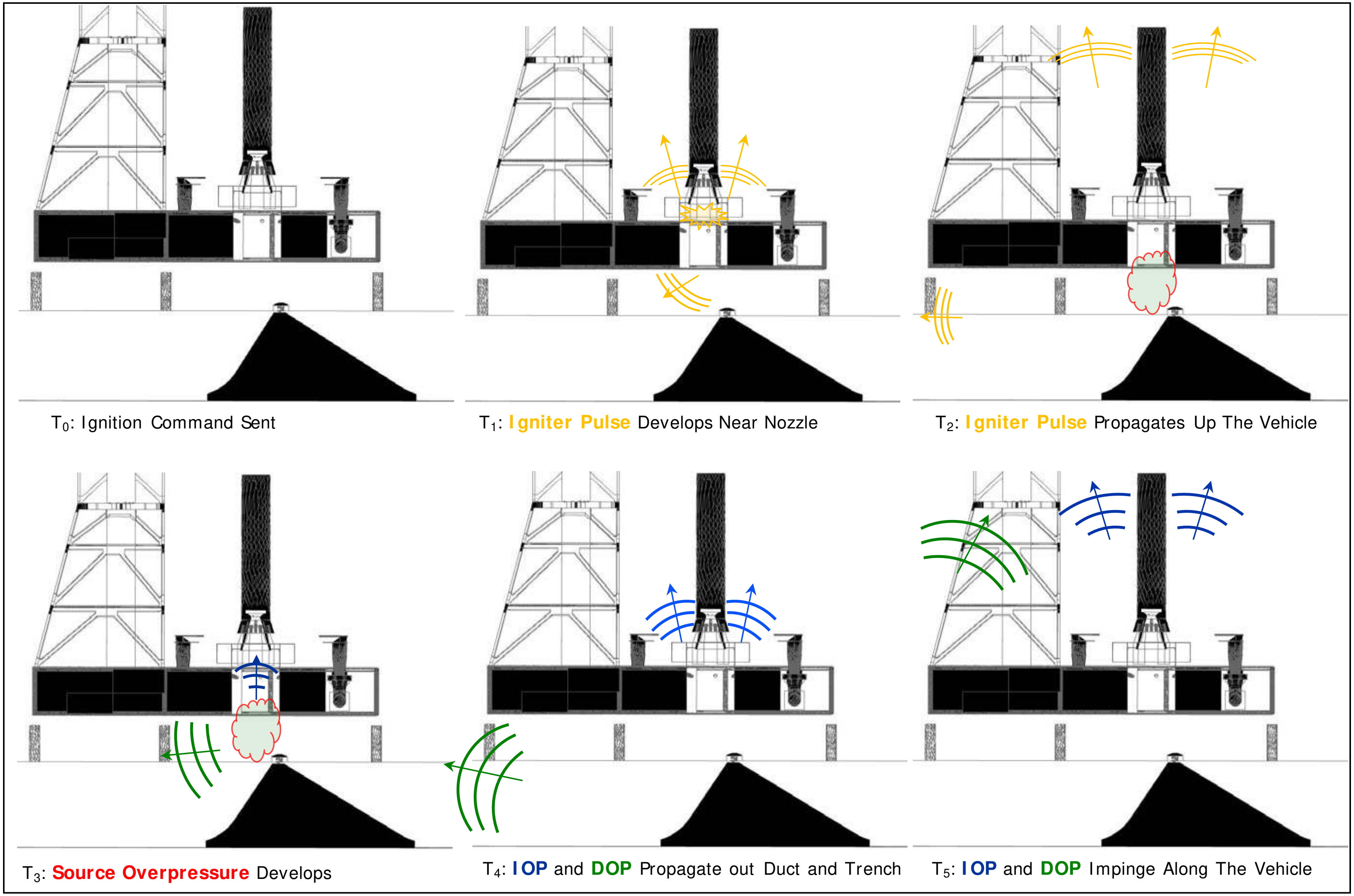
ASMAT Test IOP1 (Hold Down Configuration - South View, Post Test)



ASMAT Test IOP1 (Hold Down Configuration - Side View, Post Test)

ASMAT Test IOP1 (Hold Down Configuration - North View, Post Test)

Ignition Transient Event Timing

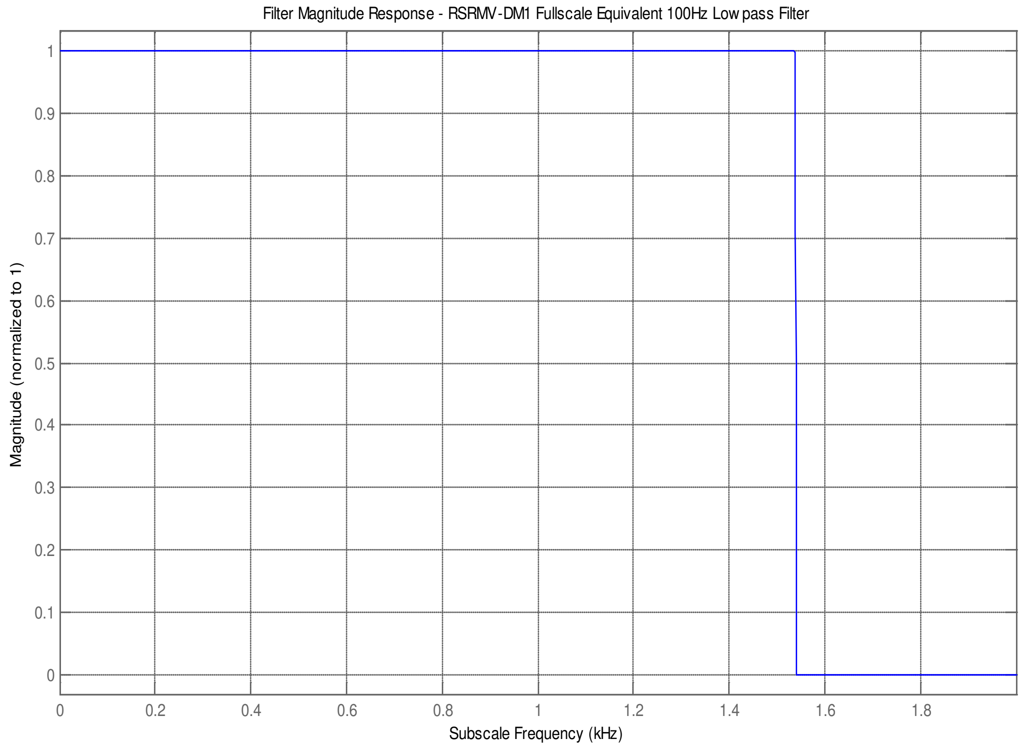


Data Processing Parameters

- **IOP Unsteady Pressure Sensors**
  - Kulite XTL-123B-190-30SG
  - Kulite XTL-123B-190-65SG
- **Sample Rate – 256,000 samples per second**
- **Lowpass Filter**
  - Filter Type – Infinite Impulse Response Chebyshev Type II
  - Transition Band Frequency – Test dependent
  - Required Stopband Attenuation – 60 dB
- **Time Interval – 0 to 0.1 seconds**

- **Data also adjusted to accommodate variation in test-to-test motor variance**
  - Adjustments reference IOP3 motor performance
  - IOP1 adjustment: 1.02x
  - IOP2 adjustment: 1.08x

$$\frac{P_1^+}{P_2^+} = \frac{D_1}{D_2}\frac{\overline{\dot{P}_1}}{\overline{\dot{P}_2}}\frac{\overline{P_{c,2}}}{\overline{P_{c,1}}}$$



Normalized Type II Chebyshev Lowpass Filter Magnitude Response Function

Scaling Methodology

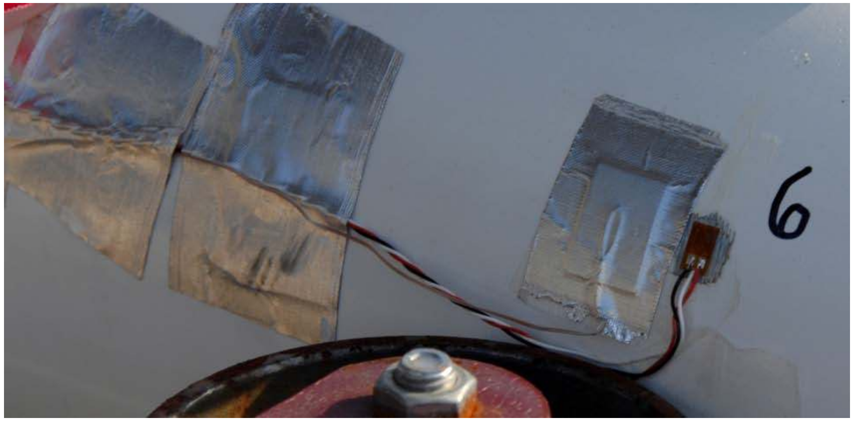
- **The methodology for scaling from ASMAT data to Ares I is based on overpressure physics consisting of two relationships**
  - Geometrical (5% scale)
  - Motor Performance Parameters (variable)

- **The ballistic scale factors are calculated for every test using sub-scale RATO motor (ASMAT) and full-scale RSRMV (Ares I) performance data**
  - These scale factors account for external geometrical influence of the size of the LM, the motor's steady state chamber pressure ($P_{C,SS}$), and the peak chamber pressure rise rate ($P_{C,RR}$)
  - To account for the igniter pressure measured by the RATO head end chamber pressure sensors, four case mounted strain gages were used to determine the effective ballistic profile
  - Scaled to measured RSRMV DM-1 P_C data
  - Full-scale upper and lower bounds determined from the approved RSRMV MODEL5V ballistics dispersion curves based on heritage flight data

IOP Scaling methodology accounts for both geometrical scaling and differences in motor performance

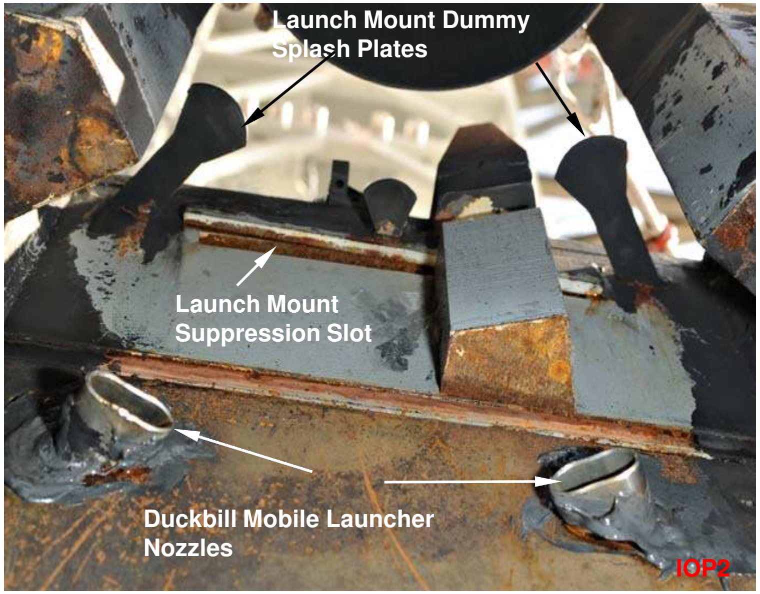
Configuration	Test	Peak Rise Rate Amplitude	Steady State Pressure	Lower Bound Amplitude Factor (STS09A-LLL)	Nominal Amplitude Factor (DM-1)	Upper Bound Amplitude Factor (TEM006-EHH)
		psi/sec	psig	-	-	-
Horizontal	Subscale Test	157351	1280	1.47	1.51	2.46
Vert01	Subscale Test	152243	1205	1.43	1.46	2.39
Vert02	Subscale Test	162423	1209	1.35	1.38	2.25
Vert03	Subscale Test	153162	1231	1.46	1.49	2.43

Configuration	Test	Peak Rise Rate Amplitude	Steady State Pressure	Upper Bound Cutoff Frequency (STS09A-LLL)	Nominal Cutoff Frequency (DM-1)	Lower Bound Cutoff Frequency (TEM006-EHH)
		psi/sec	psig	Hz	Hz	Hz
Horizontal	Subscale Test	157351	1280	1358	1329	814
Vert01	Subscale Test	152243	1205	1395	1365	836
Vert02	Subscale Test	162423	1209	1484	1452	889
Vert03	Subscale Test	153162	1231	1374	1345	823



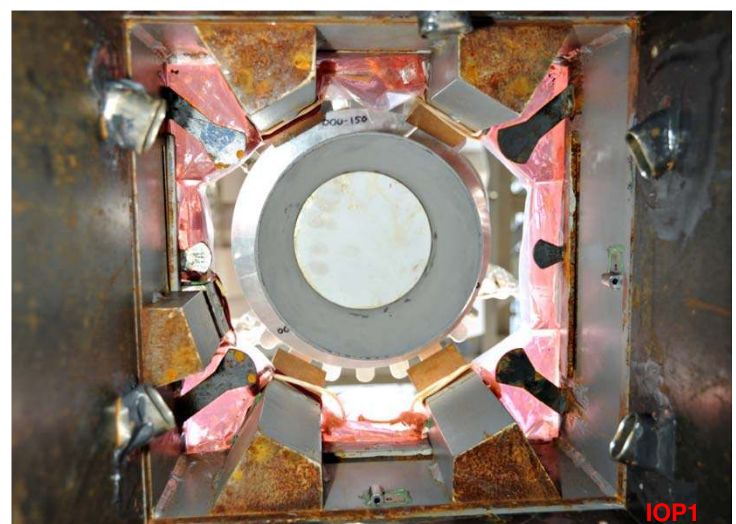
Strain Gage attached to the RATO SRM

Suppression System Design

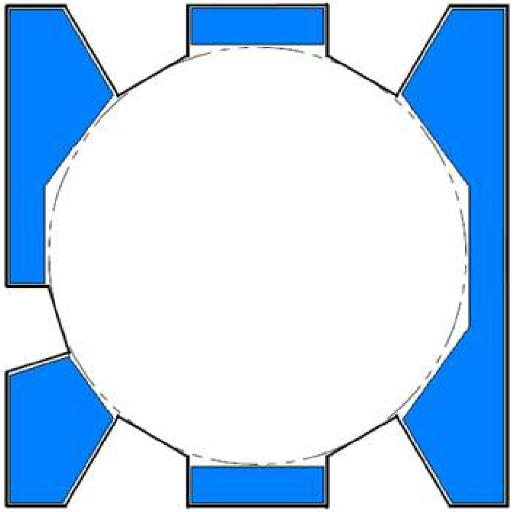


Above: Below deck IOP suppression system (ASMAT – as built)
Below: Installed water bags (top view)

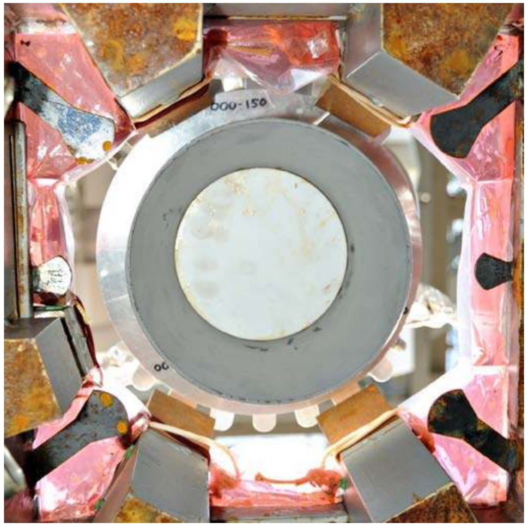
Above: Main flame deflector with crest water
Below: Installed water bags and below deck IOP suppression (exhaust duct view)



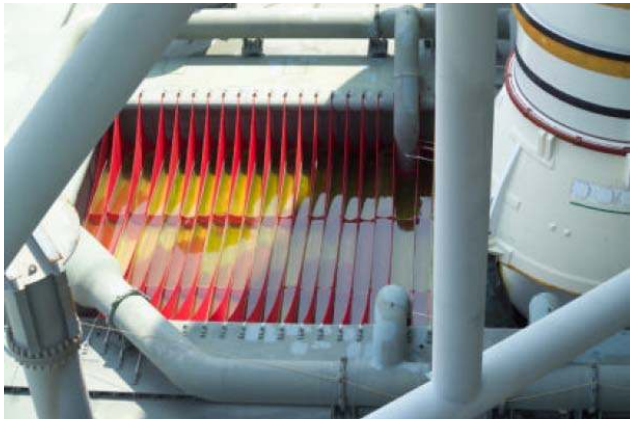
Suppression System Design



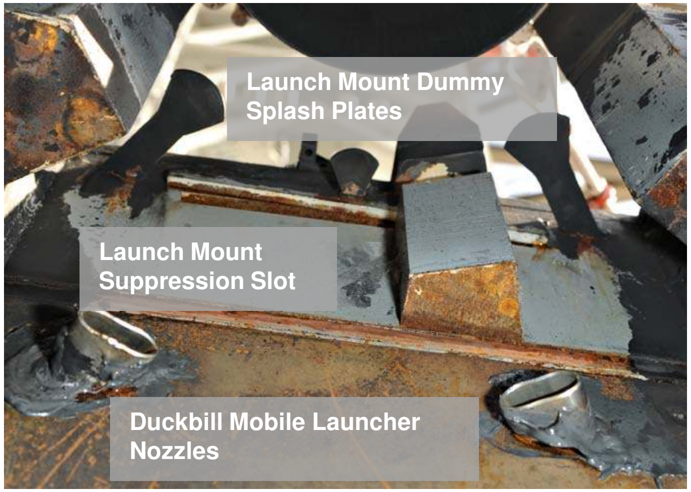
Above: Initial ASMAT water bag coverage/design



Above: Final ASMAT as-built water bag config.



Above: KSC full-scale Shuttle/Ares I-X water bag configuration (2009)



Above: KSC full-scale Shuttle MLP flow testing (2004)

Above: Below deck IOP suppression (ASMAT – as built)
Left: Initial flow testing to optimize configuration

ASMAT Test Matrix

Vertical Test	Test Objective	Location: Elevation (Feet)	Location: Drift (in)	Water Systems: Waterbags	Water Systems: Trench Water (gpm)	Water Systems: Exhaust Hole Water (gpm)	Water Systems: Rainbird (gpm)	Water Systems: Total water (gpm)	Rainbird Ww/Wp	Test Date
0	**Horizontal Firing.** Static horizontal firing to characterize the RATO motor performance.									7/30/2010
1	**IOP Series.** Hold down case with water bags.	0		Yes	873	291		1164		11/5/2010
2	**IOP Series.** Hold down case without water bags.	0		No	873	291		1164		11/10/2010
3	**IOP Series**. Dry case. Test primarily for IOP measurements.	0						0		11/18/2010
4	**Elevation Series.** Purpose is to find the elevation of max SPL. No rainbird water.	2.5 (50)	4.625		873	291		1164		1/20/2011
5	**Elevation Series.** Purpose is to find the elevation of max SPL. No rainbird water.	5 (100)	6.875		873	291		1164		1/28/2011
6	**Elevation Series.** Purpose is to find the elevation of max SPL. No rainbird water.	7.5 (125)	8.375		873	291		1164		2/3/2011
7	**Elevation Series**. Purpose is to find the elevation of max SPL. No rainbird water.	5 (100)	6.875		873	291		1164		2/15/2011
8	**Rainbird Series.** Purpose is to find effective flow rate of rainbirds at max SPL.	5 (100)	6.875		873	291	566	1730	2	2/23/2011
9	**Rainbird Series.** Purpose is to find effective flow rate of rainbirds at max SPL.	5 (100)	6.875		873	291	991	2155	3.5	3/2/2011
10	**Modified Rainbird Series.** Purpose is to find influence due to the presence of the LM with water.	5 (100)	6.875		873	175	991	2039	3.5	5/12/2011
11	**Modified Elevation Series**. Purpose is to repeat at max SPL without the LM. No rainbird water.	5 (100)	6.875		873	175		1048		5/19/2011
12	**Modified Rainbird Series**. Purpose is to find influence due to the presence of the LM with water.	5 (100)	6.875		873	175	1275	2323	4.5	5/24/2011
13	**Modified No Drift Series**. Purpose is to find LOA with vehicle drifted directly over the exhaust duct.	5 (100)	0		873	175	991	2039	3.5	6/8/2011
14	**Modified No Drift Series**. Purpose is to find LOA with vehicle drifted directly over the exhaust duct.	5 (100)	0		873	175		1048		6/14/2011
15	**Modified Elevation Series**. Purpose is to find LOA for max elevation without the LM. No rainbird water.	10 (150)	9.875		873	175		1048		6/27/2011
16	**Modified Rainbird Series**. Purpose is to find influence due to the presence of the LM with water.	10 (150)	9.875		873	175	991	2039	3.5	6/30/2011
17	**Modified No Drift Series**. Purpose is to find LOA with vehicle drifted directly over the exhaust duct.	5 (100)	0							7/12/2011

IOP Test Series (tests 1–3)