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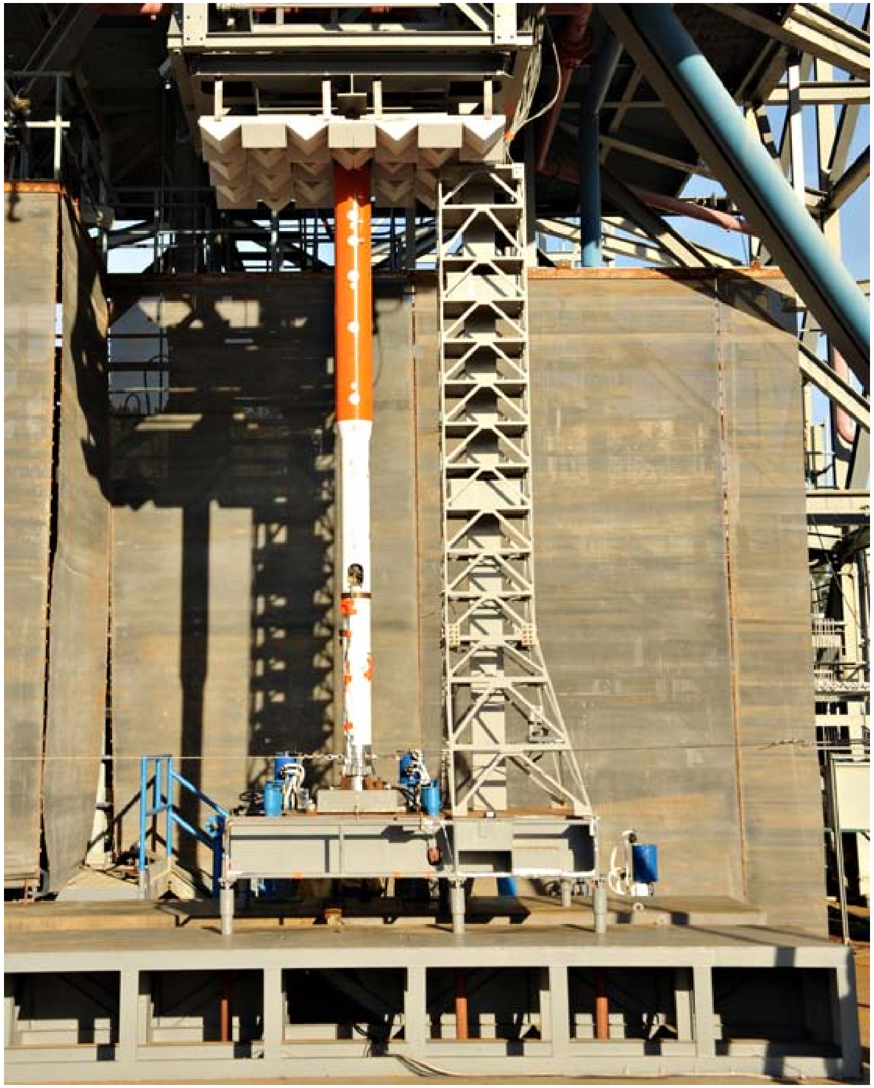
*Fluid Dynamics Branch*

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

**September 14, 2011**

# Configuration

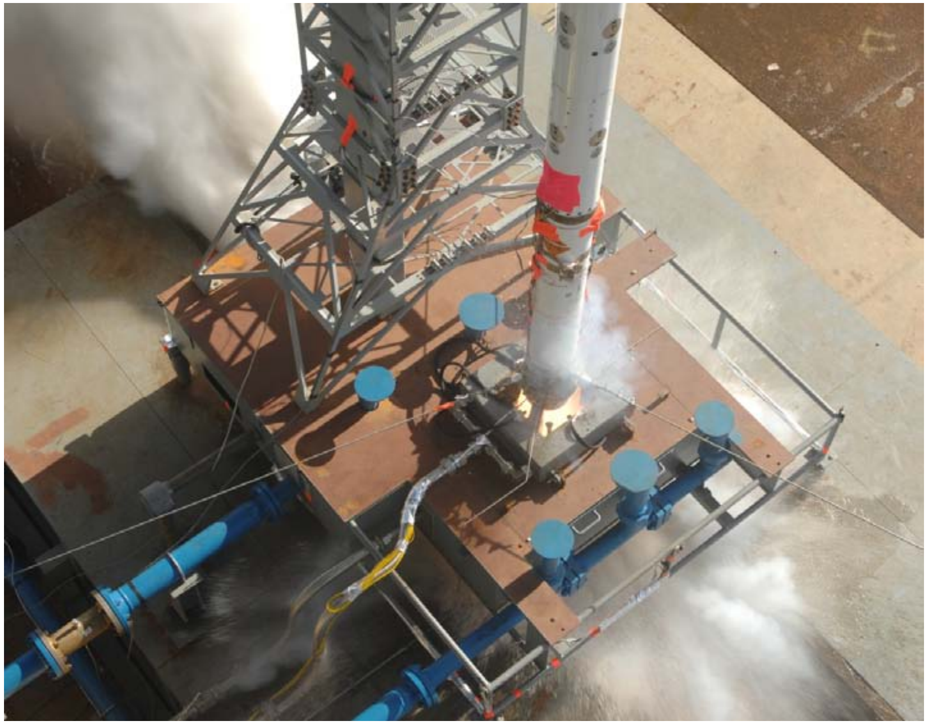
- **Test Configuration and Instrumentation**
  - **The ASMAT IOP Test Series consists of three vertical firings**
    - IOP1: IOP Suppression with Water Bags
    - IOP2: IOP Suppression without Water Bags
    - IOP3: No IOP Suppression
  - **IOP instrumentation suite comprised of 78 unsteady pressure 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

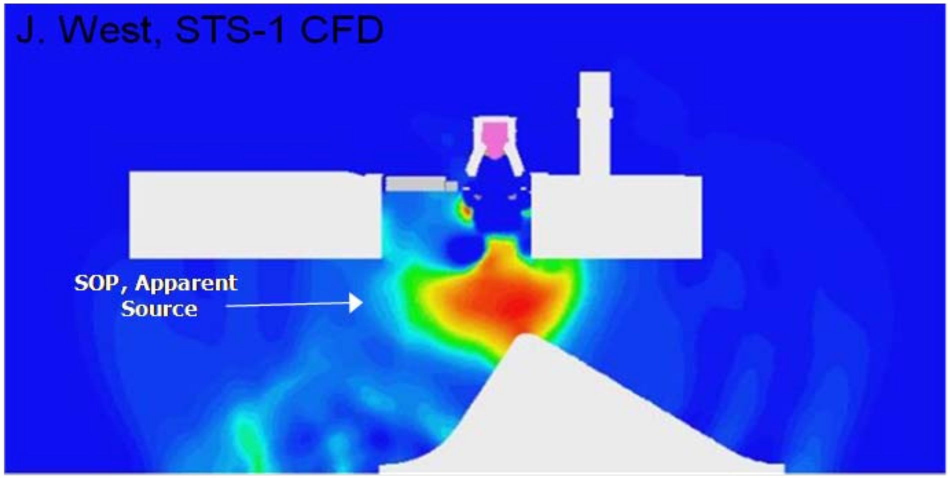
ASMAT Test IOP3 (Main Flame Deflector Crest Water Trench Suppression)

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

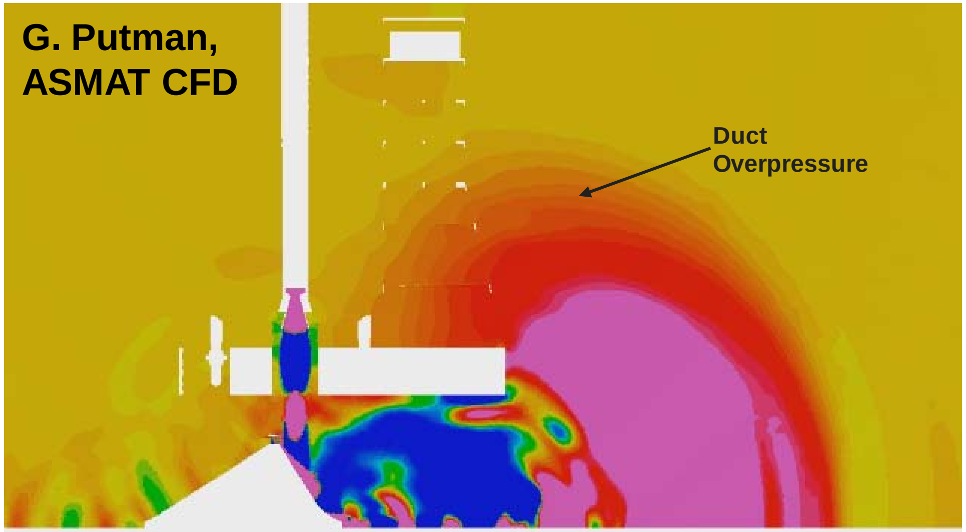
# Overpressure Events

- **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



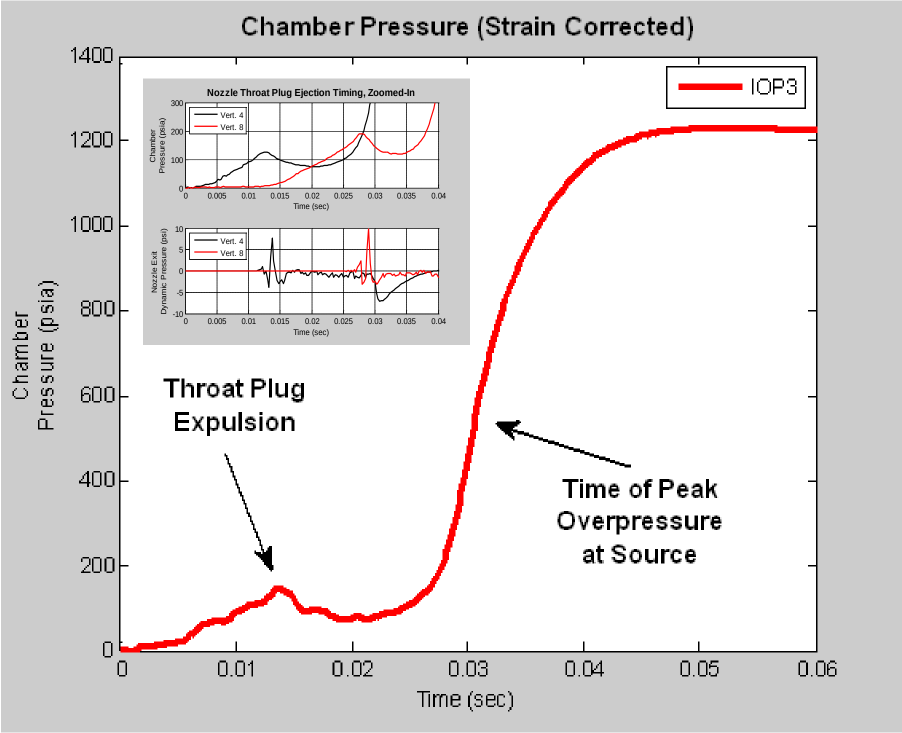

Instantaneous moment in time during SOP Development
Full-scale Unsteady CFD Simulation for STS-1, Summer 2008

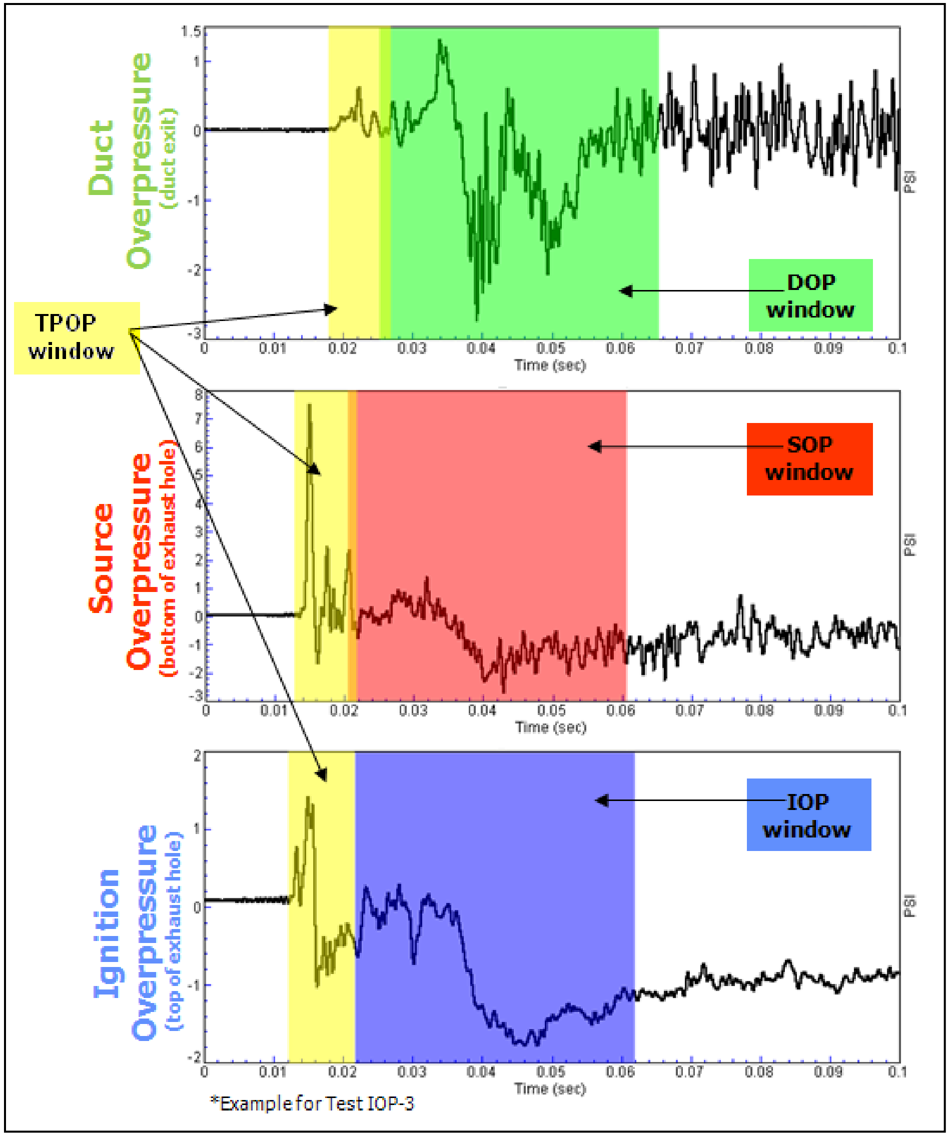



Instantaneous moment in time during DOP Propagation
Unsteady CFD Simulation for ASMAT, Spring 2011

# Ignition Transient Characterization

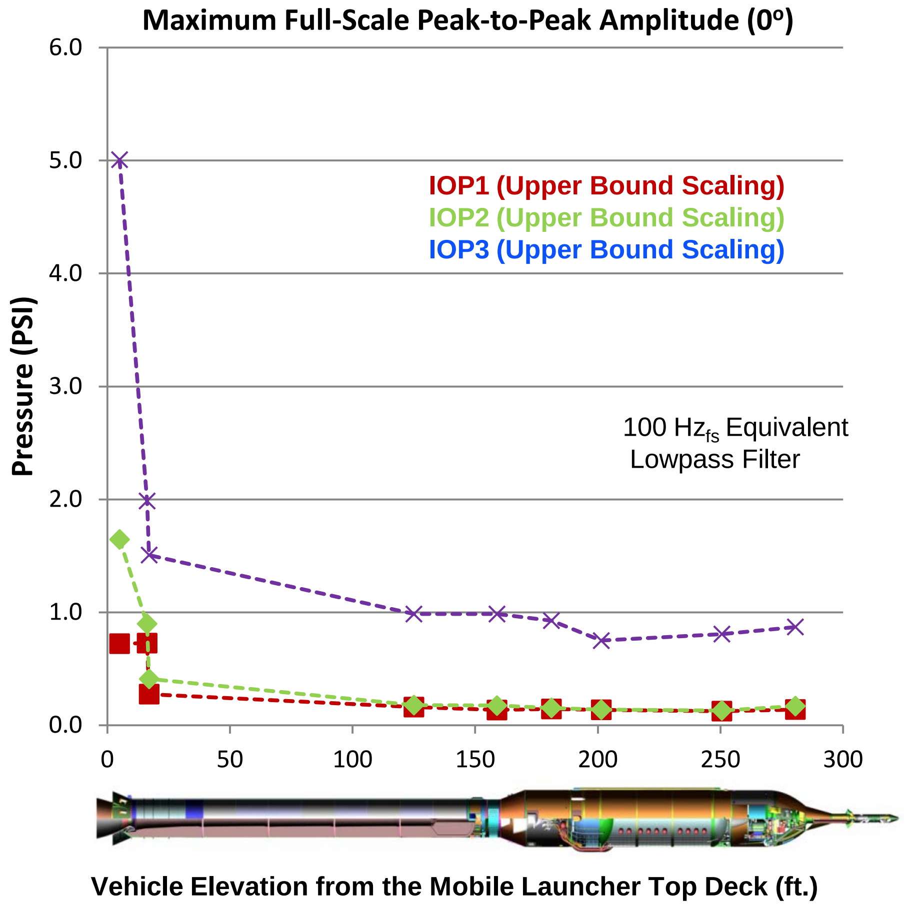
- **Method of Identification**
  - TPOP – nozzle pressure sensors
  - SOP – 1st laws
  - IOP & DOP – propagation speed
- **Characterization**
  - Meticulous tracking of waveform features for every measurement



# Ares I Vehicle Environment

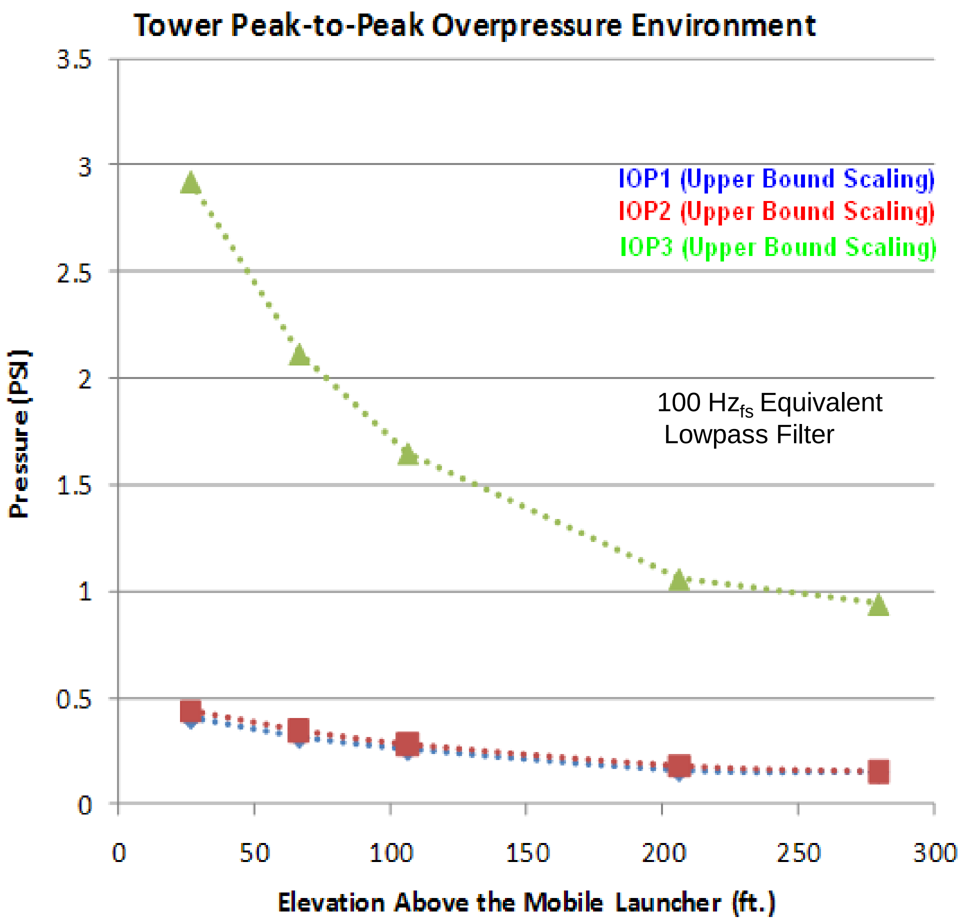
- **Ares I Vehicle Environment**
  - **TPOP**
    - Propagates through the LM up the vehicle
    - Strongest at the thermal curtain
    - Frequency content peaks at 10 – 15 $Hz_{fs}$
  - **IOP**
    - Propagates through the LM up the vehicle
    - IOP wave encounters the DOP wave near the forward skirt (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.*

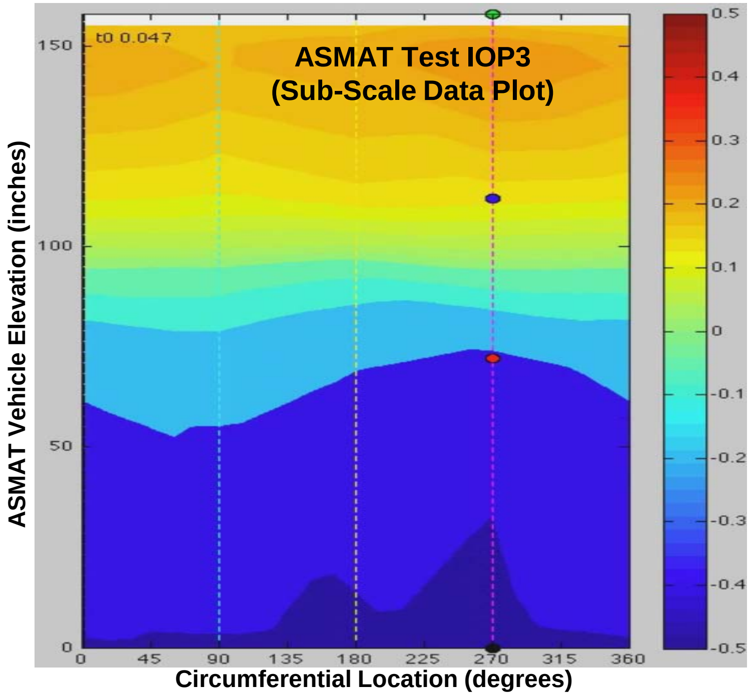
# Ares I Tower Environment

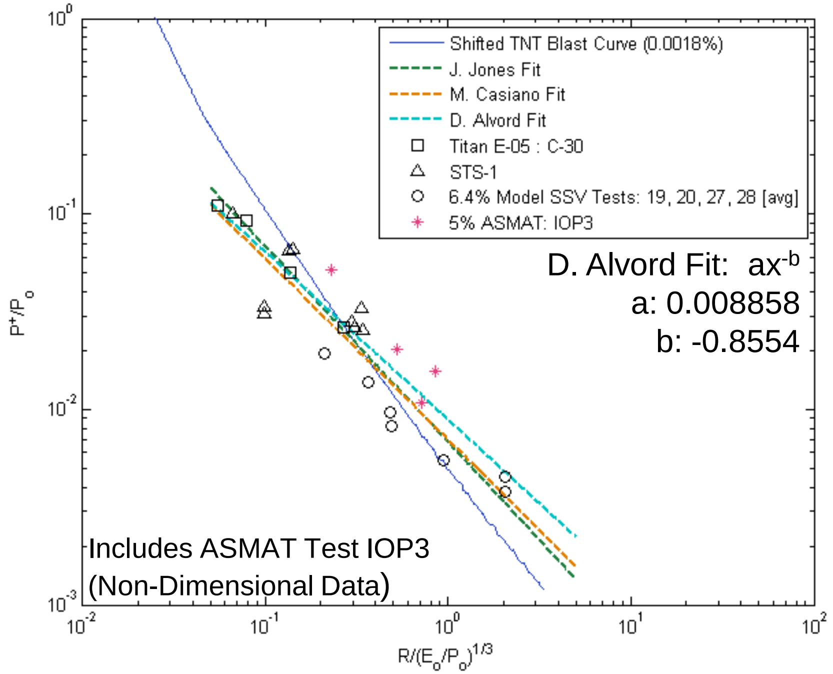
- **Maximum peak overpressure**
  - DOP impingement
  - North side of tower
  - 30' level
- **Full-scale maximum overpressure peak-to-peak amplitude (30' Level):**
  - IOPSS with water bags: **0.4 psi$_{fs}$**
  - IOPSS without water bags: **0.4 psi$_{fs}$**
  - Dry Case: **2.9 psi$_{fs}$**
- **Ares 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

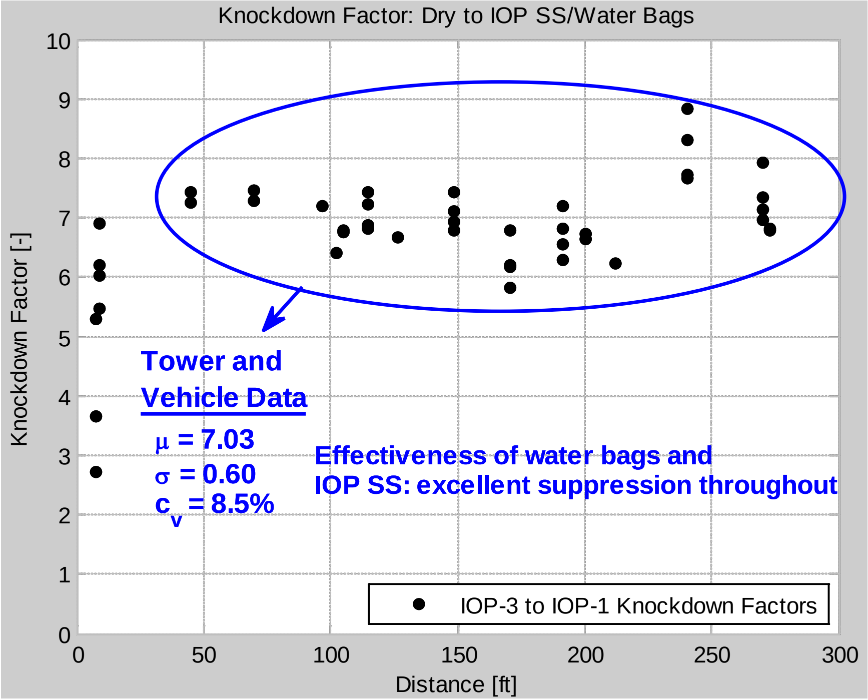
- **A Differential Overpressure (ΔOP) from forward to aft of the vehicle of ~2 psi full-scale ($psi_{fs}$) develops as the IOP and DOP waves propagate up the vehicle**



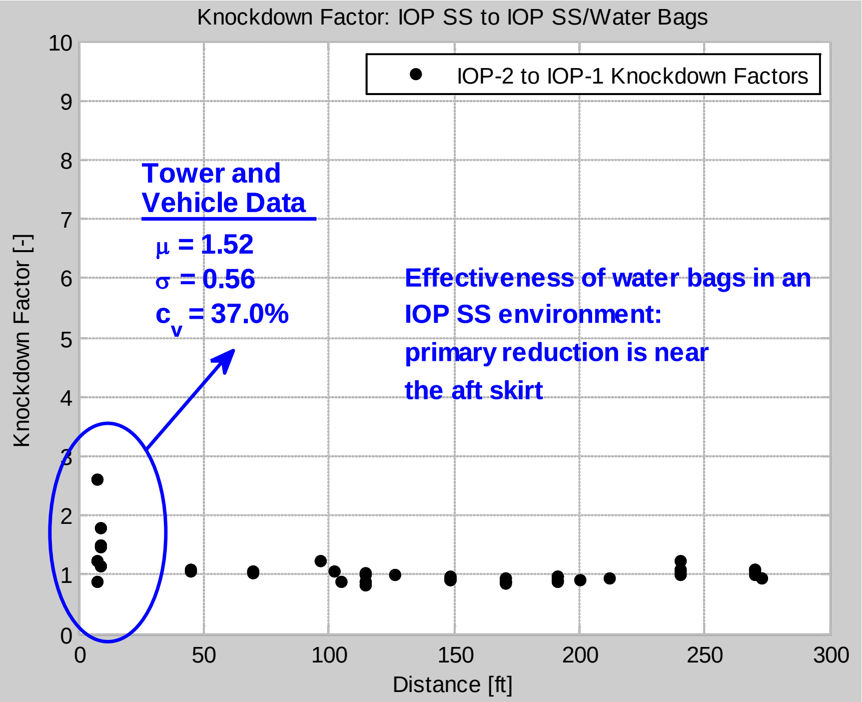




- **Sach's blast wave propagation model**
  - **IOP-3 (dry) data are nondimensionalized and fall within family of heritage data**

# Ares I Amplitude Reduction Factors

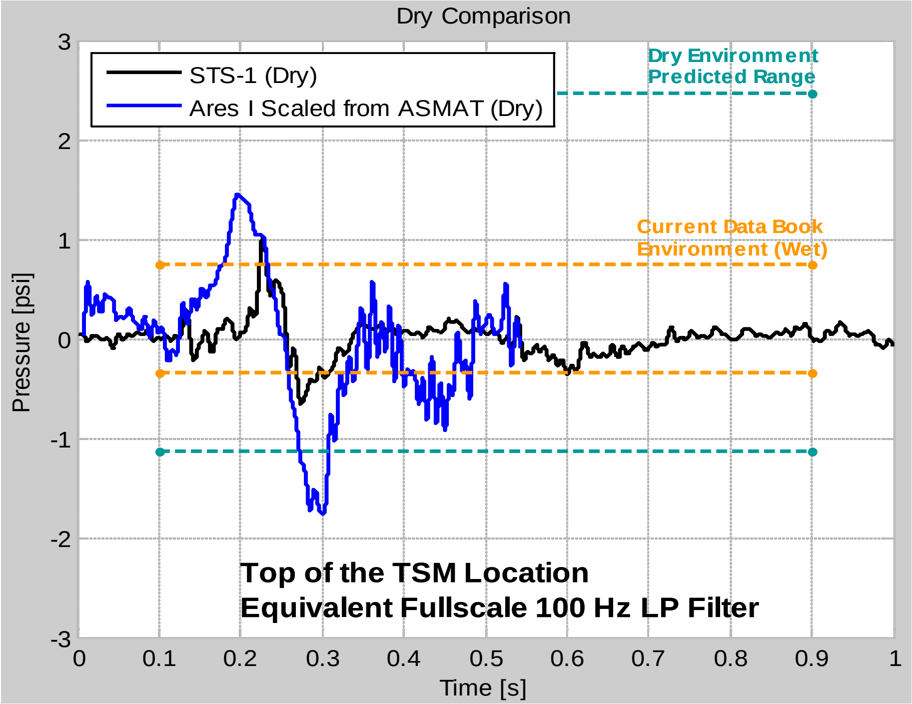



- **Amplitude reduction factors**
  - Also called knockdown factors (KF)
- **IOPSS and water bags show excellent suppression throughout**
  - Water bags are most effective at the aft end of the vehicle

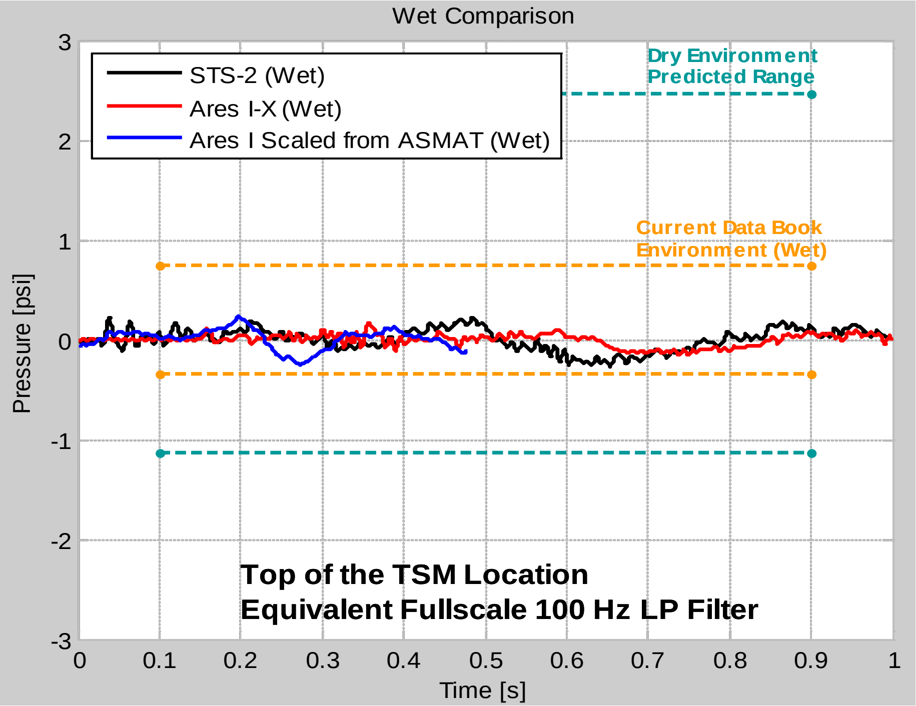



- **Statistics include mean, standard deviation, and coefficient of variation (dispersion)**
  - KF is 7.03x on the vehicle and tower away from the hole due to IOP SS and water bags for Ares I configuration
  - KF is 1.52x near the exhaust hole due water bags in an IOP SS environment in the Ares I configuration

# 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

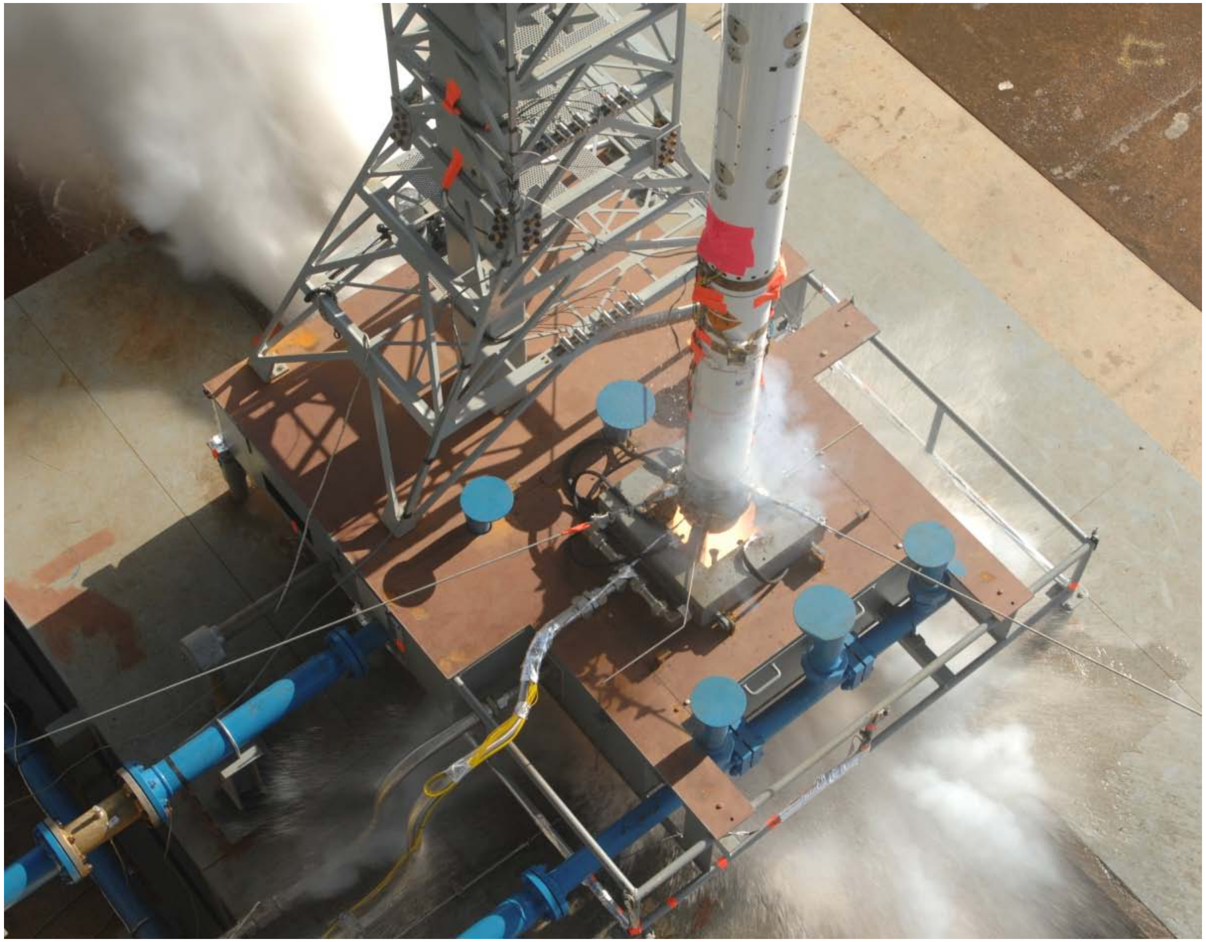
- **ASMAT IOP Results**
  - **Ares I environment (pred. from ASMAT)**
    - The dry, unsuppressed case exceeds both the measured STS-1 and Ares I data book environments
    - The wet, suppressed case meets the environment specified in the data book
  - **Using a Space Shuttle derived suppression system 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**
**Marshall Space Flight Center – Test Stand 116**
**November 10, 2010**

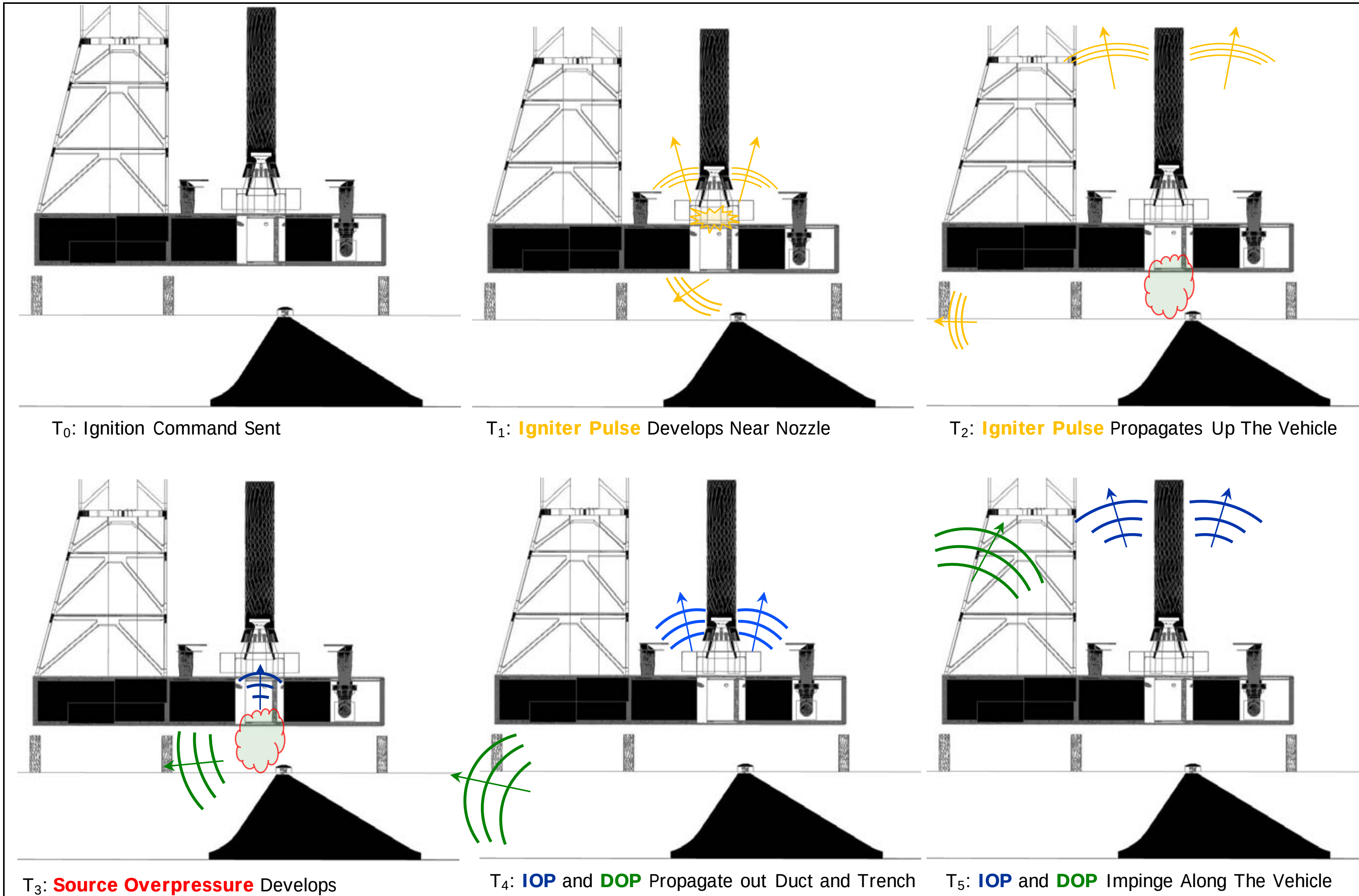
# IOP-1 Configuration

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

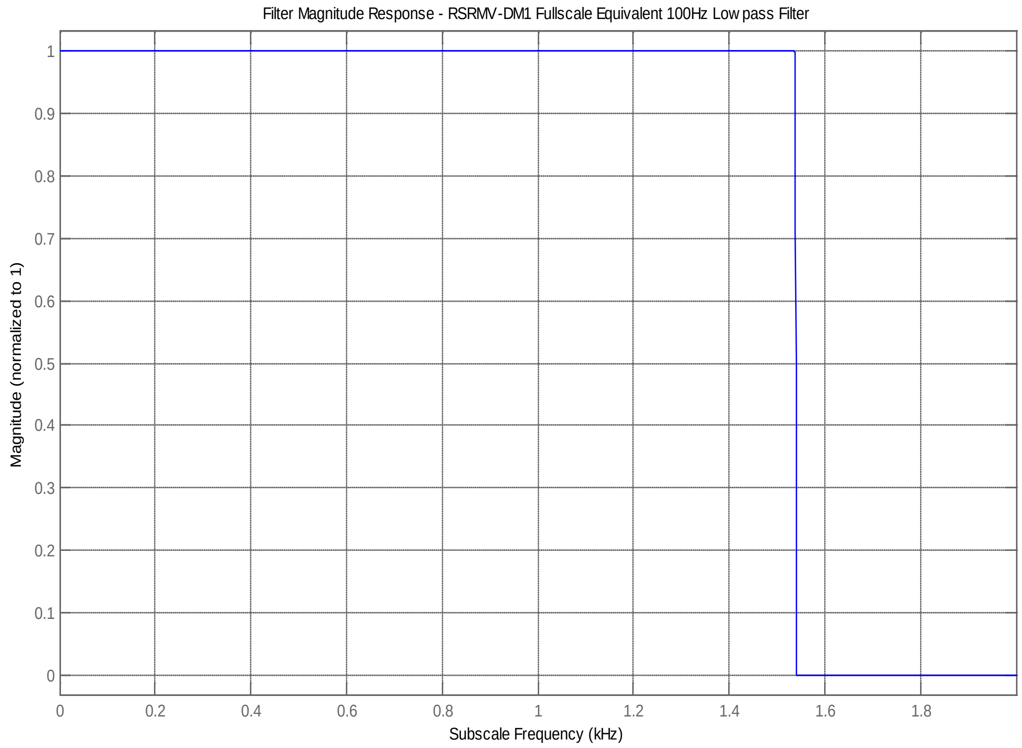


# Data Processing Parameters

- **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

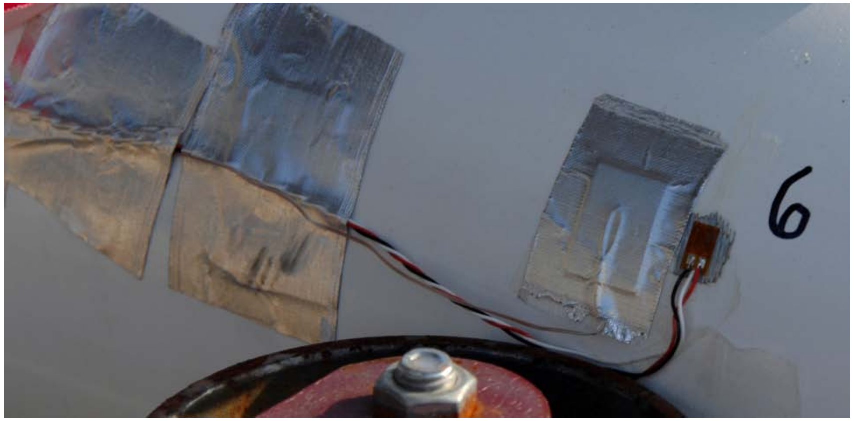
- **The methodology for scaling from ASMAT data to Ares I is based on overpressure physics consisting of two relationships**
  - Geometrical (5% scale)
  - Motor Performance Parameters (variable)

- **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**

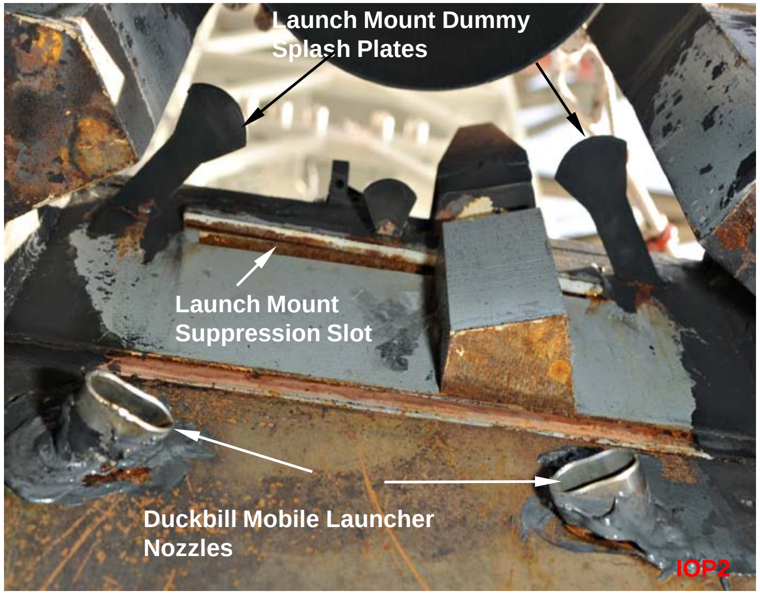
| Configuration | Test | Peak Rise Rate Amplitude | Steady State Pressure | Lower Bound Amplitude Factor (STS09A-LLL) | Nominal Amplitude Factor (DM-1) | Upper Bound Amplitude Factor (TEM006-EHH) |
|---|---|---|---|---|---|---|
| | | psi/sec | psig | - | - | - |
| Horizontal | Subscale Test | 157351 | 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

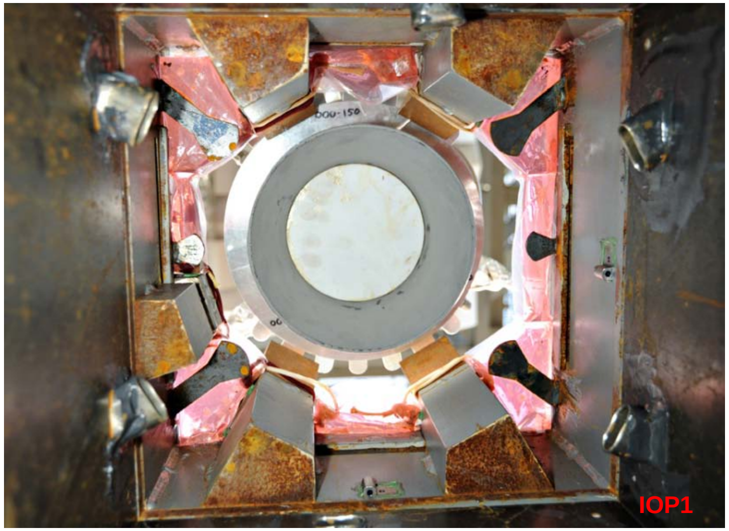
# Suppression System Design



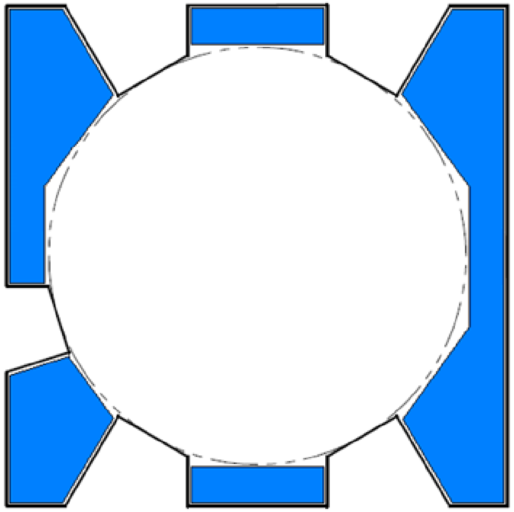


Above: Below deck IOP suppression system (ASMAT – as built)
Below: Installed water bags (top view)

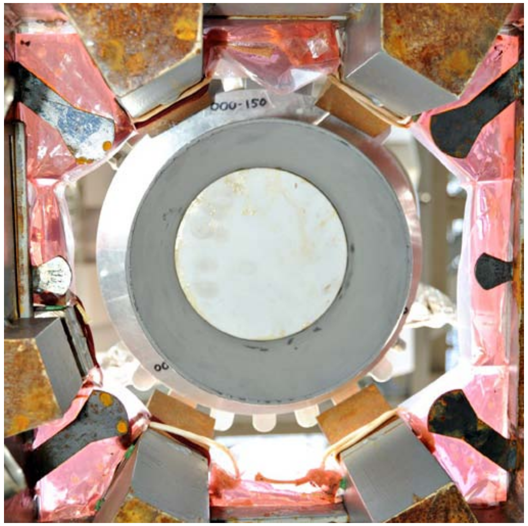
Above: Main flame deflector with crest water
Below: Installed water bags and below deck IOP suppression (exhaust duct view)

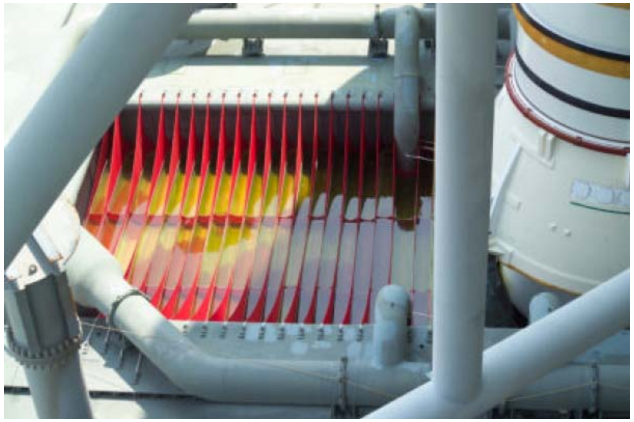
# Suppression System Design



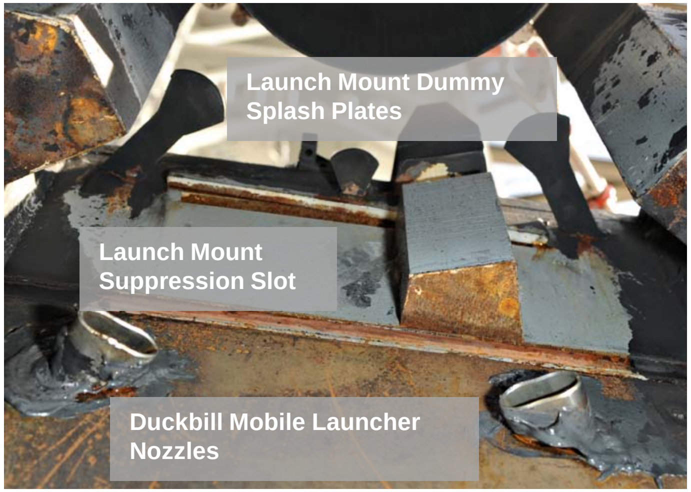
Above: Initial ASMAT water bag coverage/design



Above: Final ASMAT as-built water bag config.



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




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

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

# ASMAT Test Matrix

| Vertical Test | Test Objective | Location | | Water Systems | | | | | | Test Date |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Elevation (Feet) | Drift (in) | Waterbags | Trench Water (gpm) | Exhaust Hole Water (gpm) | Rainbird (gpm) | Total water (gpm) | Rainbird Ww/Wp | |
| 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