

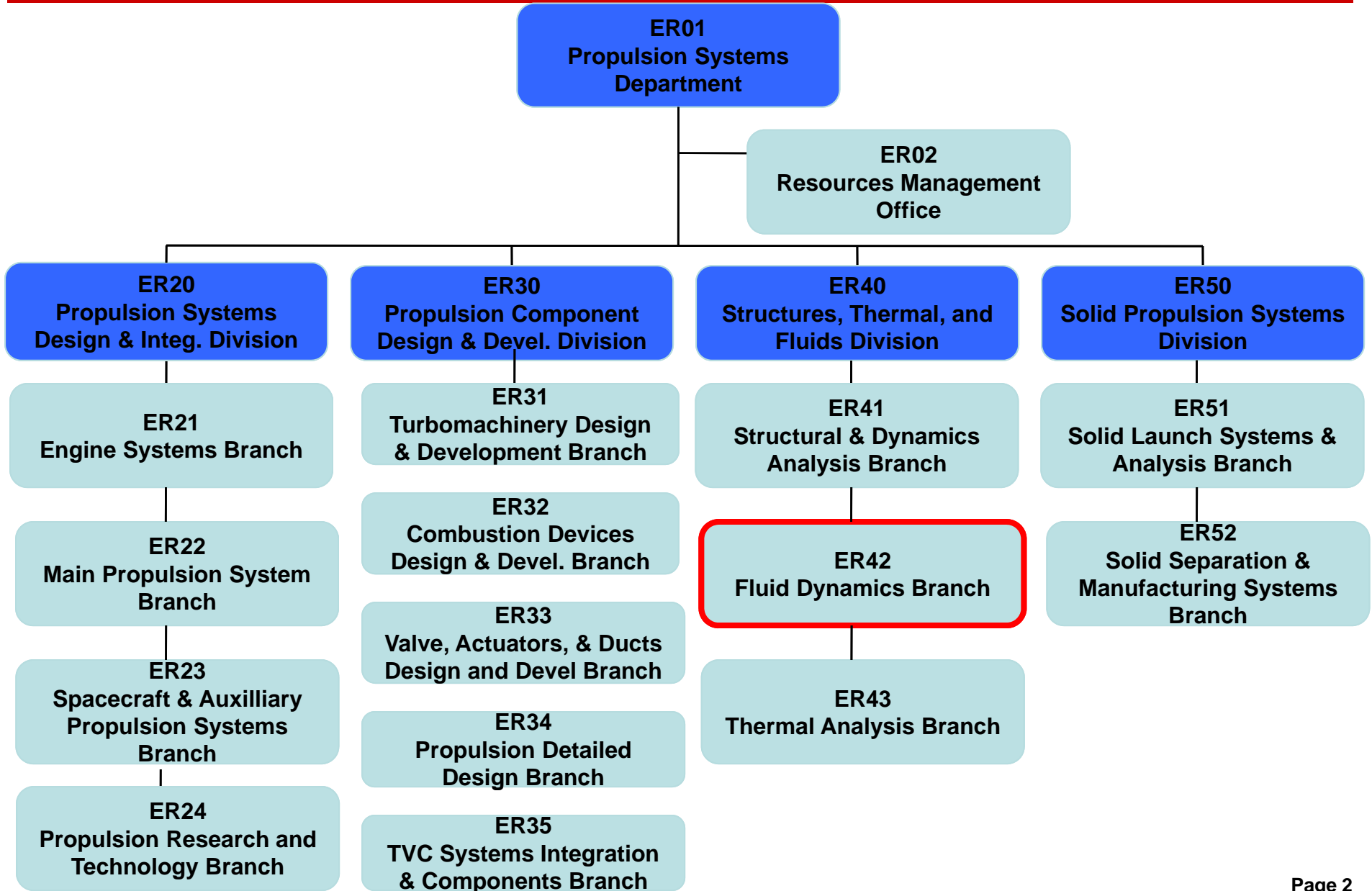


Fluid Dynamics and Propulsion at Marshall Space Flight Center

Marshall Technology Exposition
U.S. Space and Rocket Center
Davidson Center for Space Exploration
October 27, 2014



PROPULSION SYSTEMS DEPARTMENT





FLUID DYNAMICS BRANCH STRUCTURE



Fluid Dynamics Branch

Branch Chief – Lisa Griffin

Assistant Branch Chief – Tom Nesman

Technical Assistant – Denise Chaffee

Technical Assistant - Kevin Tucker

Computer System Administrator – Dennis Goode

**Computational Fluid
Dynamics**
Team Leader: Jeff West

**Unsteady Flow
Environments**
Team Leader: Tom Zoladz

**Acoustics and
Stability**
Team Leader: Jeremy Kenny

ER42 is comprised of three
teams with a total of
approximately 50 employees



FLUID DYNAMICS BRANCH APPLICATIONS



The Fluid Dynamics Branch (ER42) is a discipline centric branch responsible for all aspects of the discipline of fluid dynamics applied to propulsion and propulsion-induced loads and environments.

- ER42 work begins with design trades and parametric studies and continues through hardware development and flight.
- Project support also includes risk assessment, anomaly investigation and resolution, and failure investigation.

Main Propulsion System

- Tank Dynamics
- Cryofluid Management
- Feedline Flow Dynamics
- Valve Flow and Dynamics

Turbopumps

- Pump Dynamics
- Turbine Dynamics

Liquid Combustion Devices

- Injection Dynamics
- Chamber Acoustics
- Combustion Stability
- Nozzle Dynamics

Solid Rocket Motors

- Motor Dynamics
- Nozzle Dynamics
- Combustion Stability

Coupled Systems

- Feed System Dynamics
- Coupled Pump/MPS Dynamics, e.g., Pogo
- Thrust Oscillations and its Impact on the Vehicle
- Tank Slosh and its Impact on Vehicle Stability and GN&C

Launch, Separation, and Plume-Induced Environments and Debris

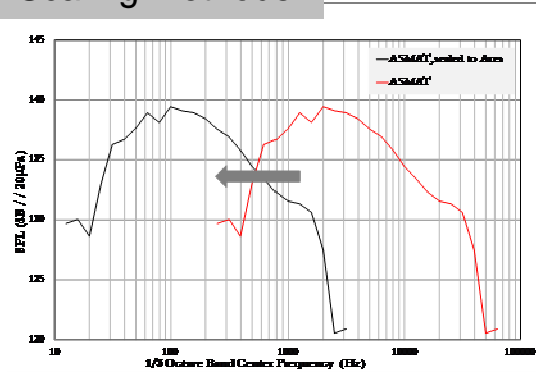
- Liftoff Acoustics
- Separation Acoustics
- Overpressure
- Inflight Plume Generated Noise
- Noise Mitigation
- Hydrogen Entrapment
- Liftoff Debris Transport



FLUID DYNAMICS ANALYSIS

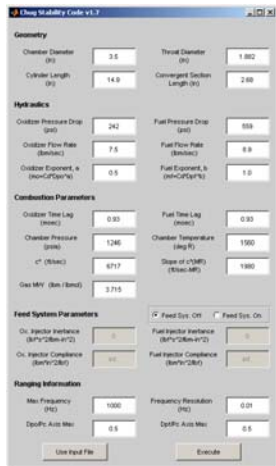
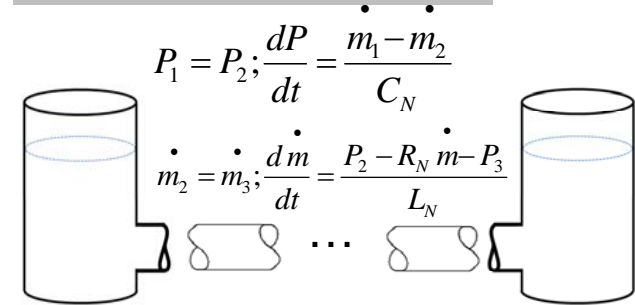


Scaling Methods



ER42 conducts all levels of fluid dynamics analysis from scaling methods through 3D Unsteady CFD

Lump Parameter Modeling

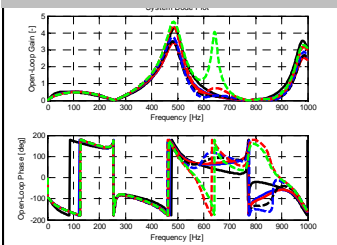


$$x(\omega) = \frac{\bar{X} \sin(\omega(\bar{\tau}_{T,o} - \bar{\tau}_{T,f}))}{\sin(\omega\bar{\tau}_{T,f}) + \theta_g \omega \cos(\omega\bar{\tau}_{T,f})}$$

$$y(\omega) = \omega$$

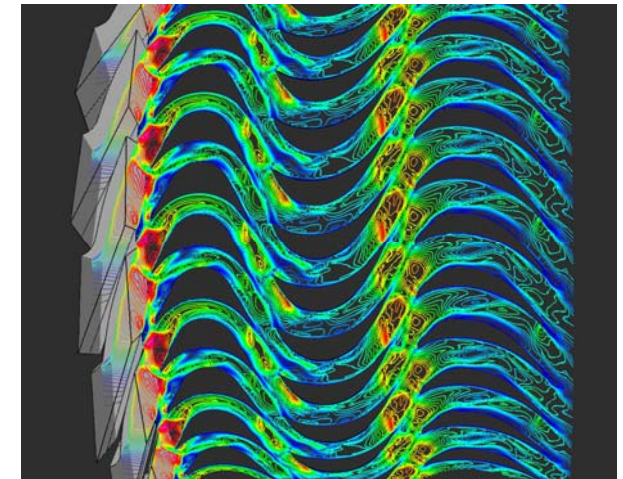
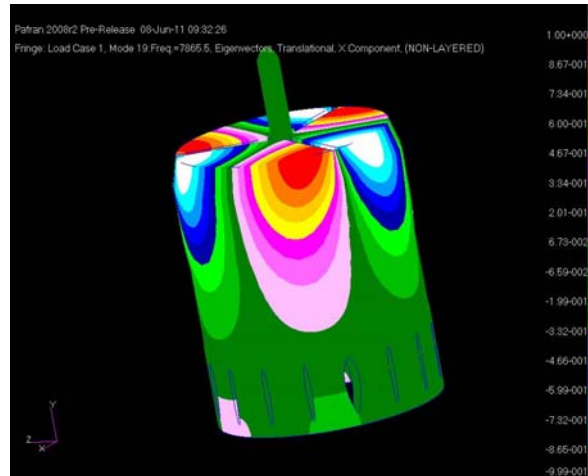
$$z(\omega) = \frac{\bar{F} \sin(\omega(\bar{\tau}_{T,f} - \bar{\tau}_{T,o}))}{\sin(\omega\bar{\tau}_{T,o}) + \theta_g \omega \cos(\omega\bar{\tau}_{T,o})}$$

Gain / Phase Plots



System Stability Modeling

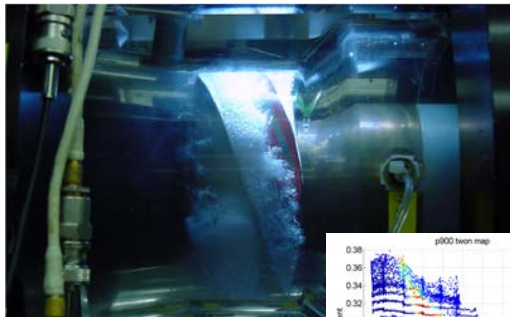
Finite Element Modeling



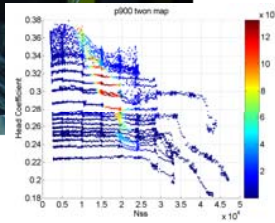
Computational Fluid Dynamics



FLUID DYNAMICS TESTING



Waterflow Testing in Pump Facility

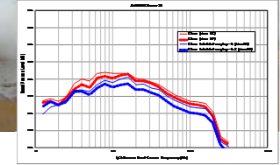


ER42 conducts and supports testing for hardware and technology development and verification, and analysis validation

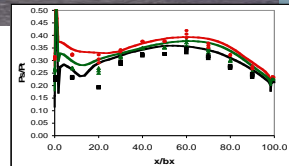
- Primary responsibility for cold flow and scale model acoustics tests
- Secondary responsibility for hot system and component testing



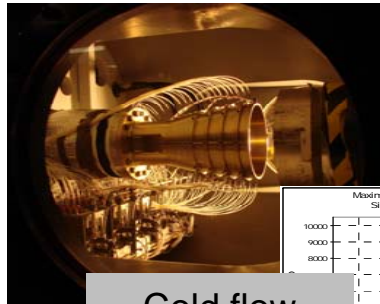
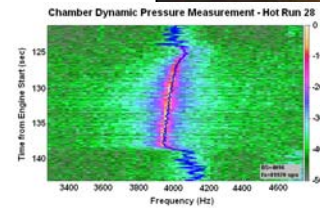
Scale Model Acoustics Testing



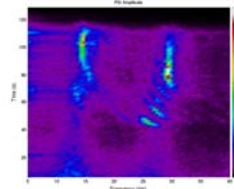
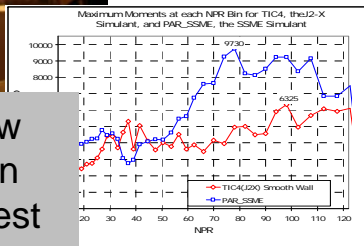
Airflow Testing in Turbine Facility



Engine and Component Testing



Cold flow testing in Nozzle Test Facility



Solid Rocket Testing



FLUID DYNAMICS BRANCH TECHNOLOGY



The Fluid Dynamics Branch is continually improving the state-of-the-practice for fluid dynamics support for propulsion system design & development

- **Why?**

- To enable development of robust propulsion hardware that fully meets design requirements
- To facilitate reductions in the cost of access to space by—
 - Lowering design and development costs
 - Lowering production costs (via evaluation of fluid dynamic impacts of advanced manufacturing techniques)

- **How?**

- Increasing tool/test fidelity via appropriate technology pull from the state-of-the-art
 - Across the entire spectrum of fluid dynamics analysis
 - Tests-cold flow/hot fire, subscale/full scale
 - Test and flight data acquisition capabilities
- Validation of new capabilities
- Integration of validated, high-fidelity capabilities into fluid dynamic support for programs

- **By what means?**

- Strategic partnerships with small business and universities
- Active participation in the NASA SBIR/STTR program
- Internal funding from projects and technology opportunities (e.g. CIF, TIP, Tech Excellence, etc.)



MAIN PROPULSION SYSTEM



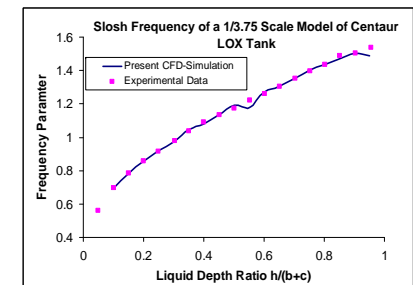
Main Propulsion System (MPS) design & development support encompasses:

- Tanks (including internal components)
 - ✓ Propellant Tank Slosh
 - ✓ Pressurization
 - ✓ Drain
- Valves
 - ✓ Flow Patterns & Mean Pressure Drop
 - ✓ Unsteady & Transient Fluid Environments
- Feedlines (including internal components)
 - ✓ Pressure Drop and Flow Uniformity
 - ✓ Unsteady Pressure Environments

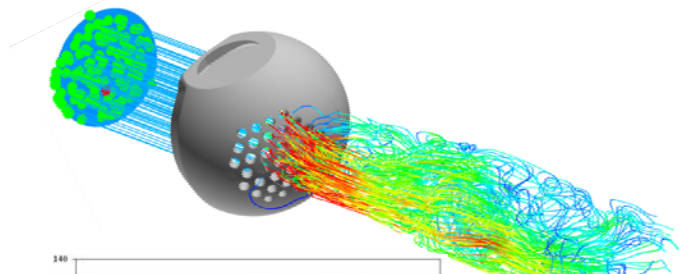
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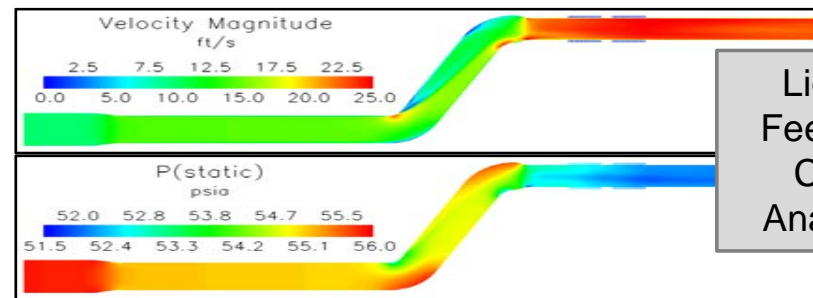
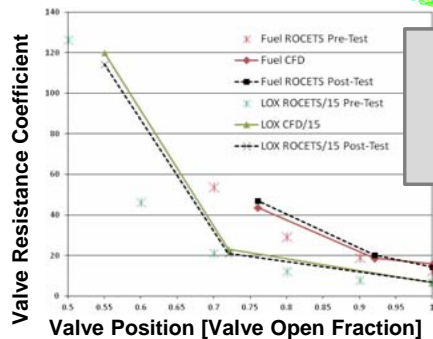
Earth to Orbit Tank Simulation



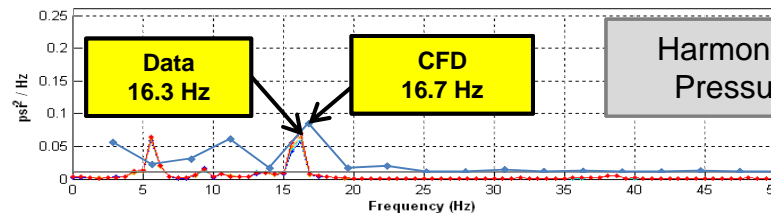
Improvement to Classic Mass-Spring Model



Partially Open Ball Valve Simulation



Liquid Feedline CFD Analysis



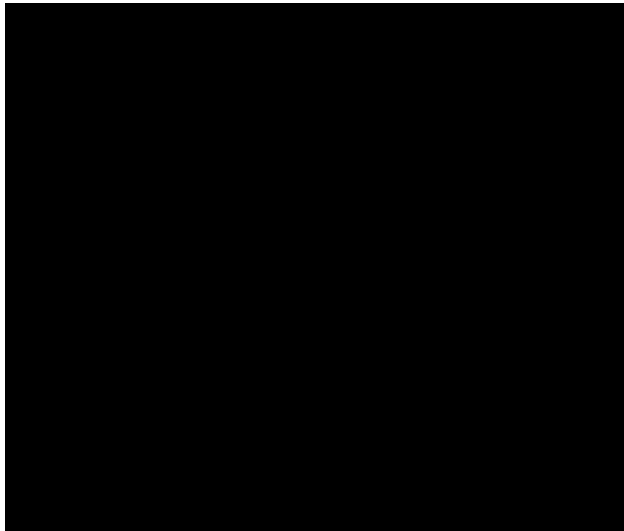
Harmonic Analysis of Pressure Tap Data



TURBOPUMPS Turbines



Turbine
Unsteady CFD
Analysis

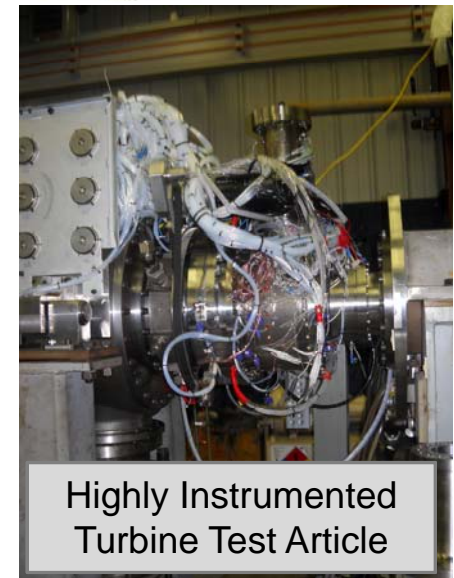


Turbine design & development support includes:

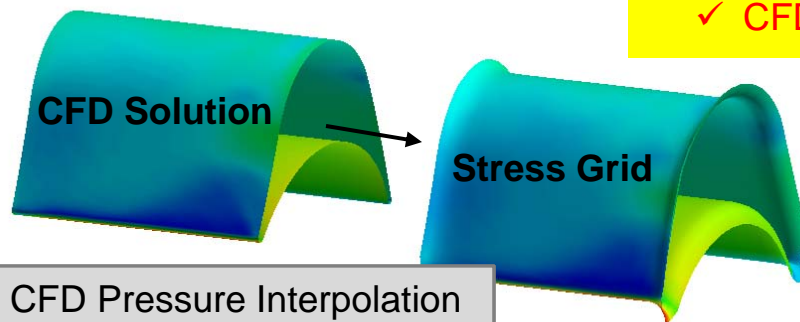
- High-fidelity, unsteady, 3D, full 360° turbine CFD simulations
 - ✓ Quick turnaround design parametrics
 - ✓ All flow features impacting fluid forcing functions are modeled
 - ✓ Unsteady pressure histories delivered in temporal or frequency domains
- Airflow testing of highly instrumented turbine models in scaled air conditions
 - ✓ Steady & unsteady pressure loadings
 - ✓ Interstage cavity pressures
 - ✓ Wide range performance mapping
 - ✓ CFD validation



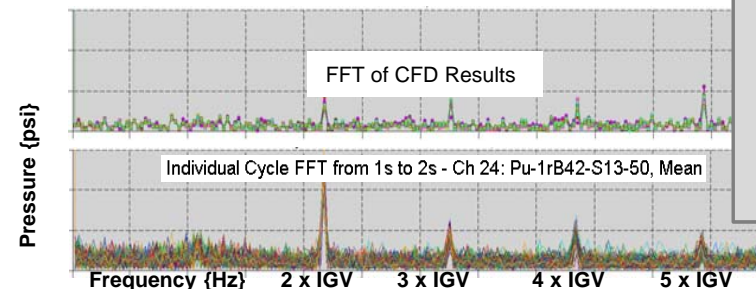
Turbine
Airflow
Rotating
Assembly



Highly Instrumented
Turbine Test Article



CFD Pressure Interpolation
onto Stress Grid



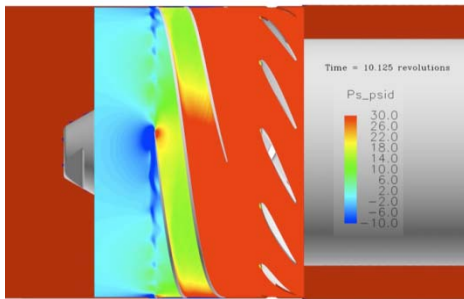
Harmonic
Analysis
of
Pressure
Data



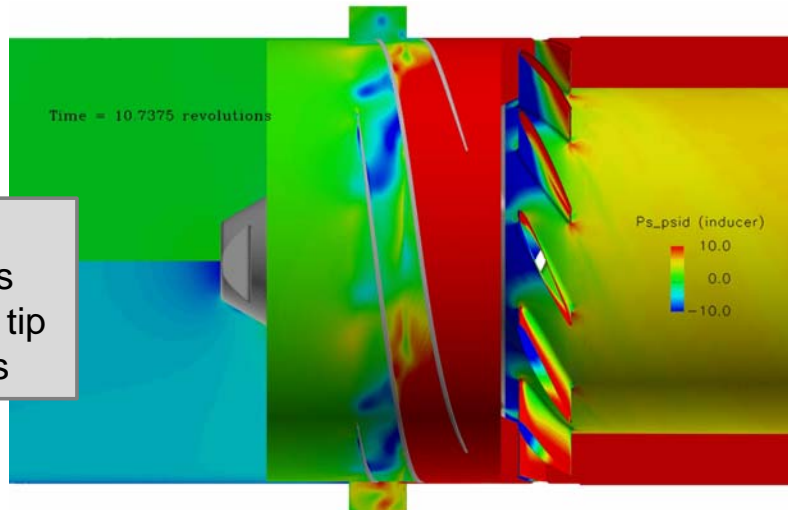
TURBOPUMPS Pumps



Pump Unsteady
CFD Analysis

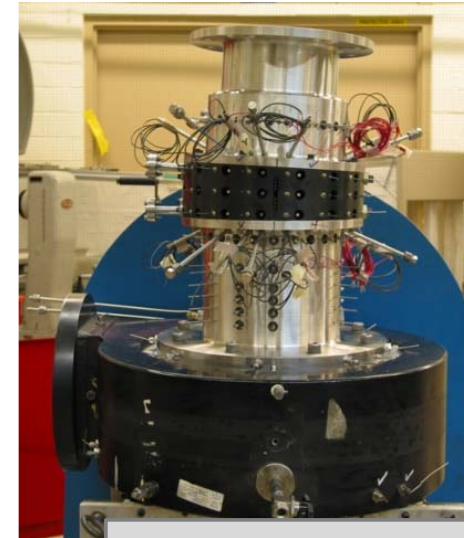


Unsteady pump
CFD simulations
capture inducer tip
vortex dynamics



Pump design & development support includes:

- Comprehensive steady & unsteady pump evaluations
 - ✓ Done at scaled engine conditions via dense instrumentation suites
 - ✓ Cavitation trend identification
 - ✓ High speed flow visualization
- High-fidelity CFD simulations
 - ✓ Time accurate CFD simulations provide insight into cavitation
 - ✓ Used to identify critical unsteady flow interactions between inducer blades and cavitation suppression grooves



Pump with upstream
MPS element



2-blade inducer
with on-rotor
dynamic force
measurement
system



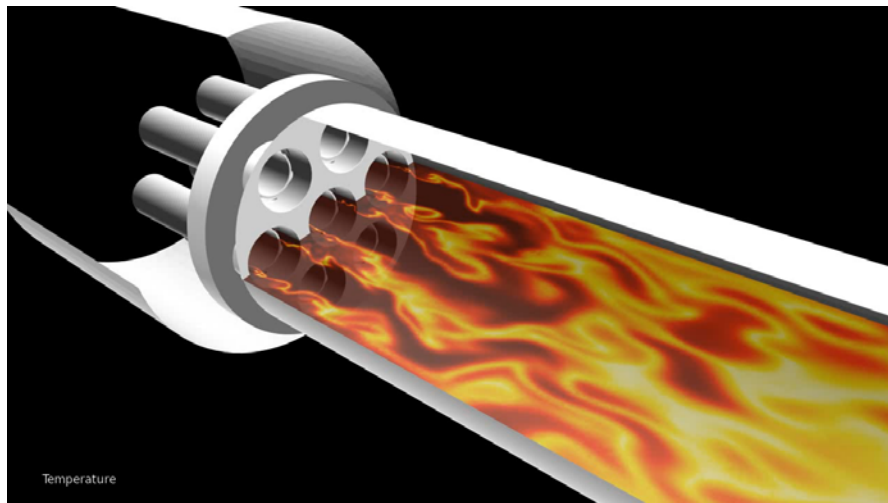
COMBUSTION DEVICES

Injectors and Combustion Chambers



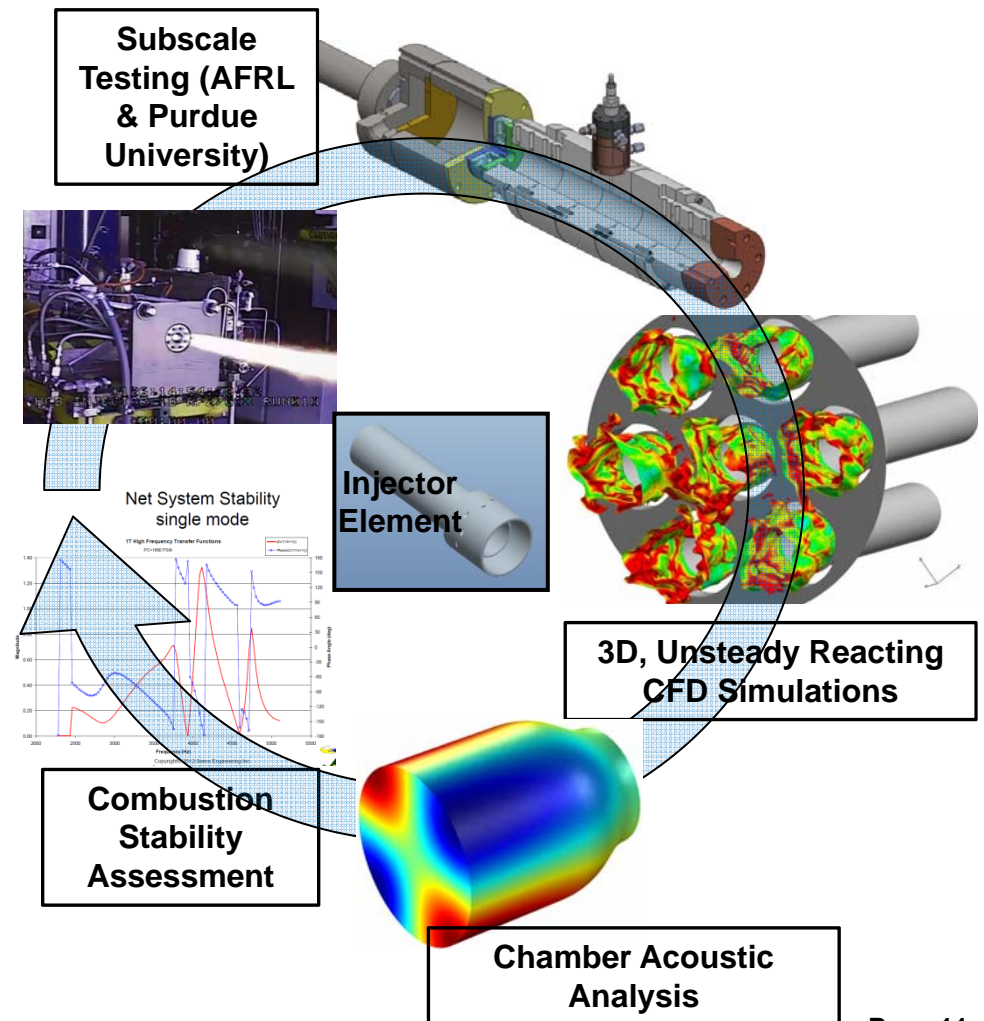
Branch responsibility in support of liquid rocket engine injector/chamber design & development

- Large and small engines
- Design, analysis & test support
 - ✓ Performance
 - ✓ Pressure, acoustic & thermal environments
 - ✓ **Combustion stability—current emphasis**



Reacting flowfield from a 7-element CFD injector simulation

Injector Design & Combustion Stability Assessment Process

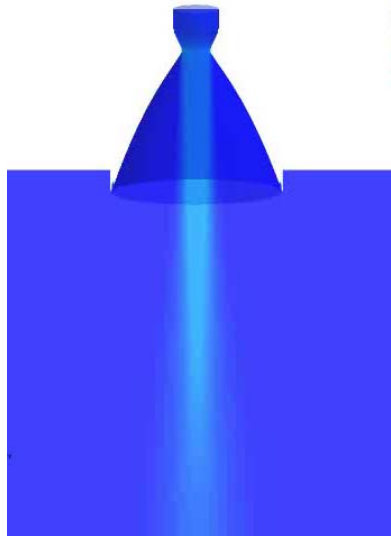




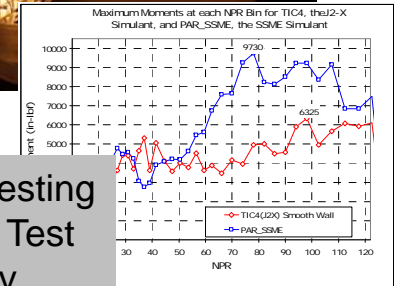
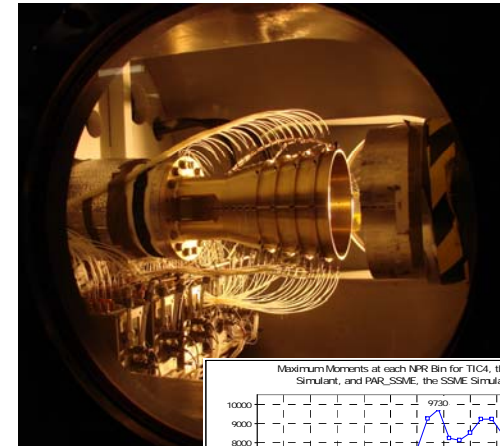
COMBUSTION DEVICES Nozzles



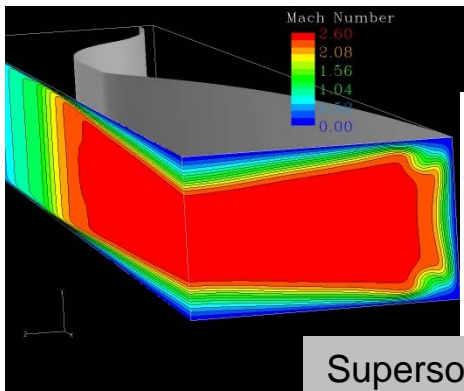
Upper stage engine transients (with stub nozzle)



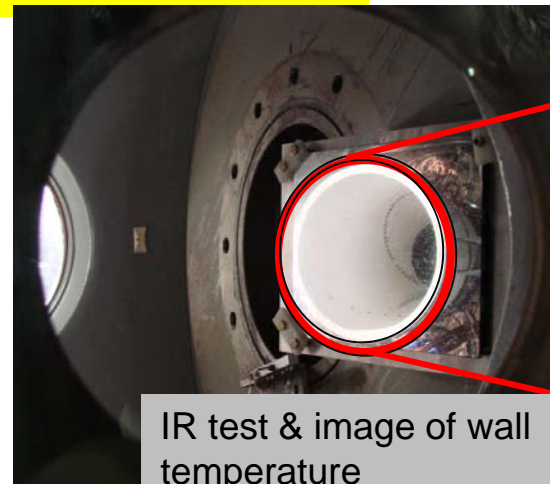
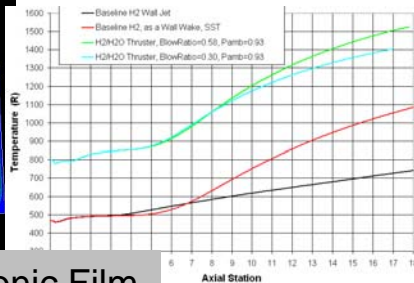
- Nozzle design & development support includes:**
- High-fidelity, unsteady, 3D, full 360° CFD simulations
 - ✓ Performance
 - ✓ Transient side loads
 - ✓ Film Cooling
 - Airflow testing of highly instrumented nozzles in scaled air conditions
 - ✓ Pressure loads & performance
 - ✓ Heat transfer
 - ✓ Evaluation of advanced nozzle concepts—dual bell, aerospike, expansion-deflection, etc.
 - ✓ Data for CFD validation



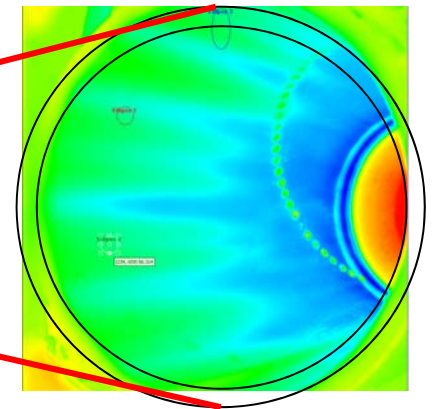
Cold flow testing in Nozzle Test Facility



Supersonic Film Cooling



IR test & image of wall temperature

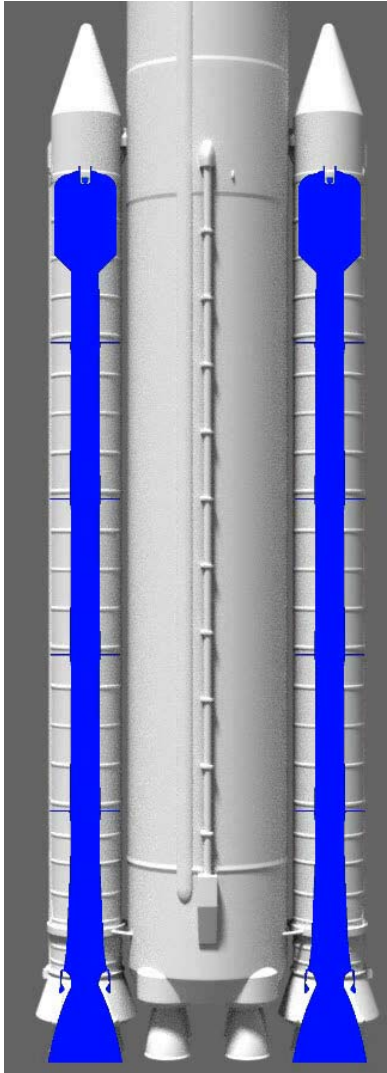




SOLID ROCKET MOTORS



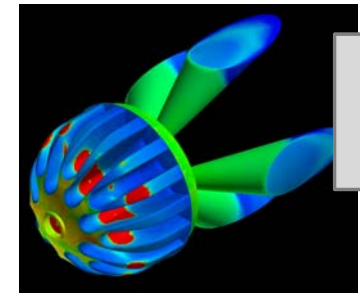
CFD simulation of booster start transient



Solid rocket motor design & development support includes:

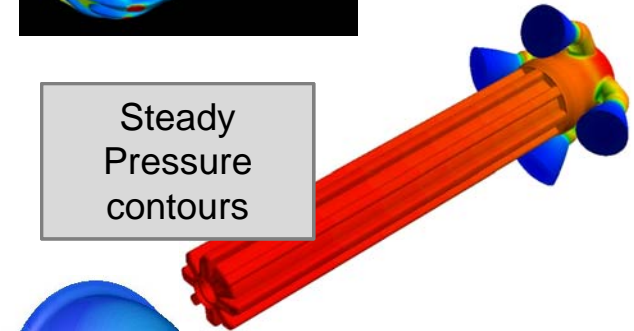
- Large booster-class motors
- Small motors- ullage settling, booster separation & launch abort

✓ Performance
✓ Environments- pressure, acoustic & thermal
✓ Stability

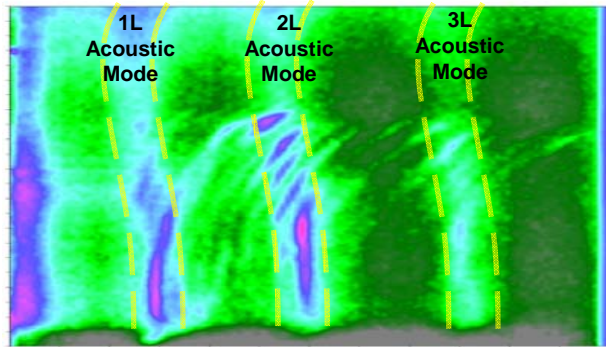
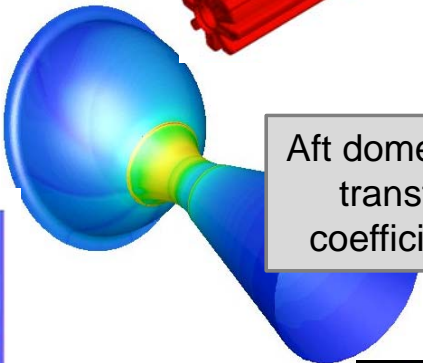


Temperature contours during ignition

Steady Pressure contours

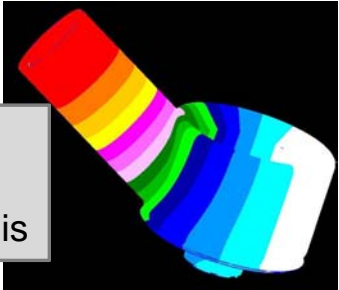


Aft dome heat transfer coefficients



Hot Fire Test Oscillatory Pressure Characteristics

Mode shapes from finite element analysis

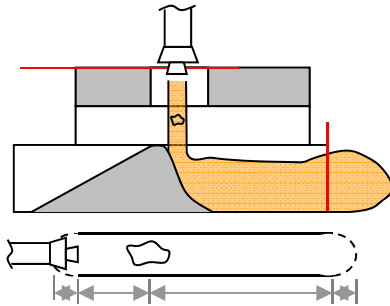




LAUNCH ENVIRONMENTS



1D Linearized
Physics Models



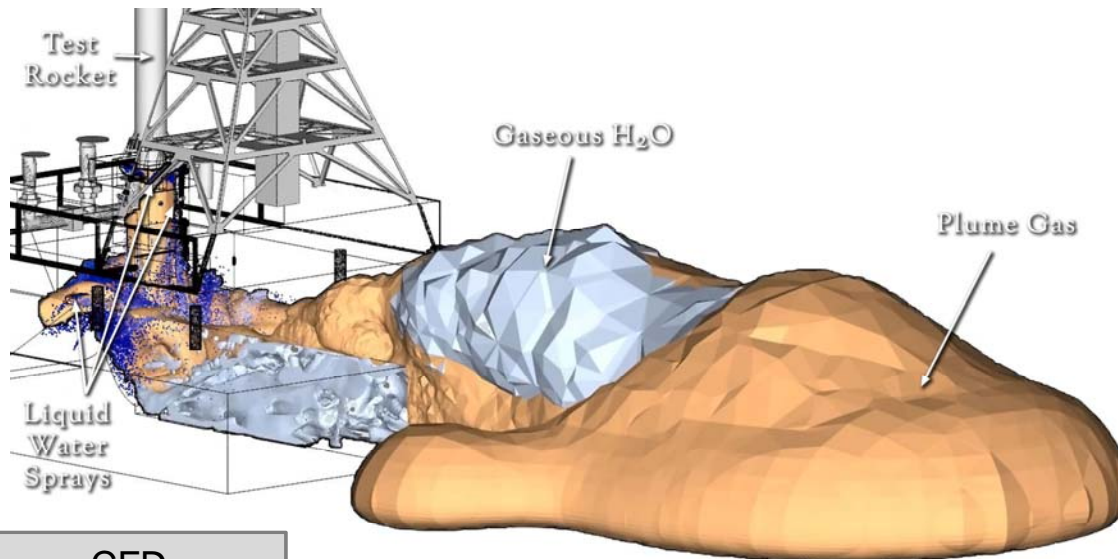
ER42 Develops the Fluid and Acoustic Environments for Launch

- ✓ Liftoff Acoustics
- ✓ Overpressure
- ✓ Sound Suppression
- ✓ Liftoff Debris Transport
- ✓ Hydrogen Entrapment

Multiple Levels of Analysis and Testing Used to Accomplish this Work



Flight Tests



CFD



Scale Model Tests

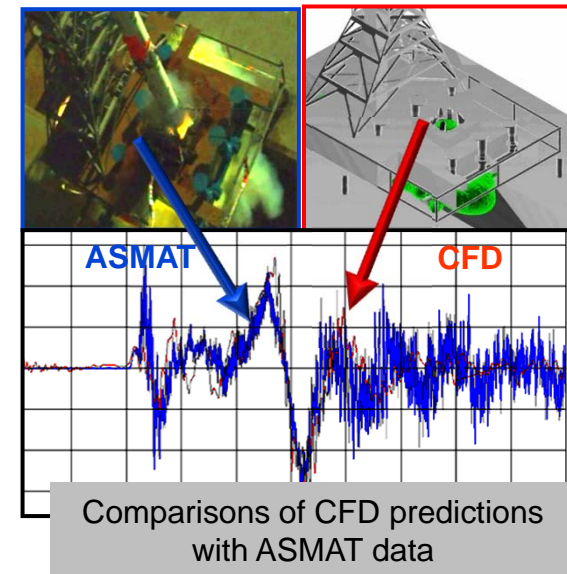
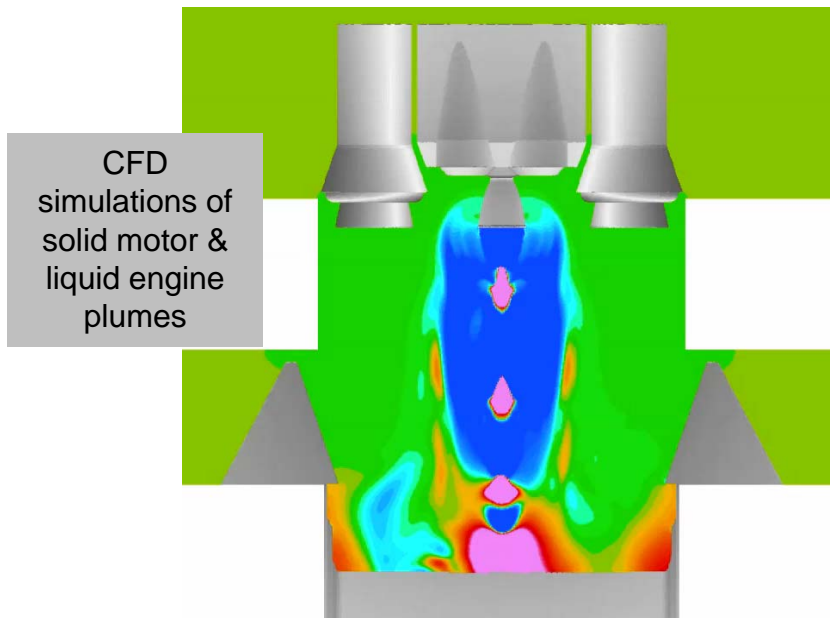
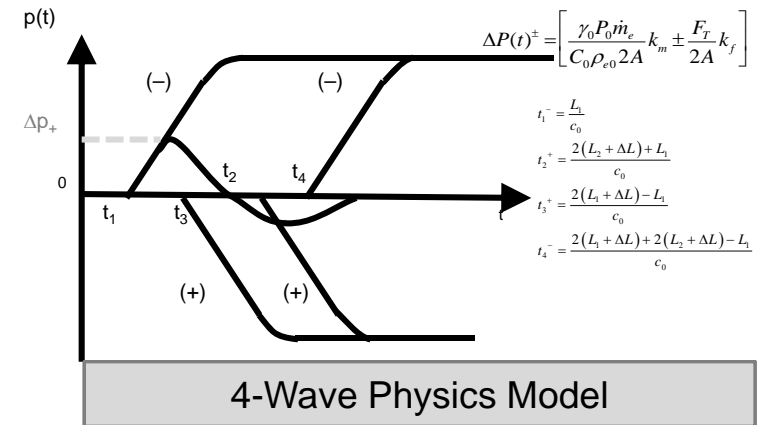


LAUNCH ENVIRONMENTS Overpressure



Overpressure Predictions

- Made by use of a combination of analytical models, CFD simulations and test/flight data
- CFD has recently shown to represent overpressure very accurately without the inclusion of water
 - ✓ Demonstrated ability to capture IOP and DOP waves at several locations for dry tests
 - ✓ Addresses limitations of analytical models
 - ✓ Accounts for complex flow scenarios and three-dimensional launch pad geometry
 - ✓ Provides understanding where unknowns exist





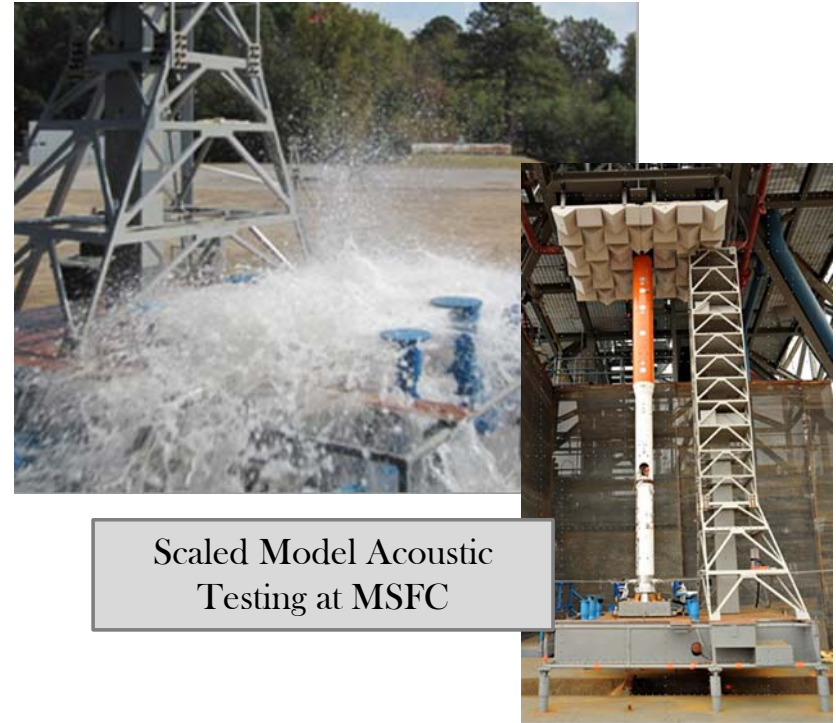
LAUNCH ENVIRONMENTS

Liftoff Acoustics

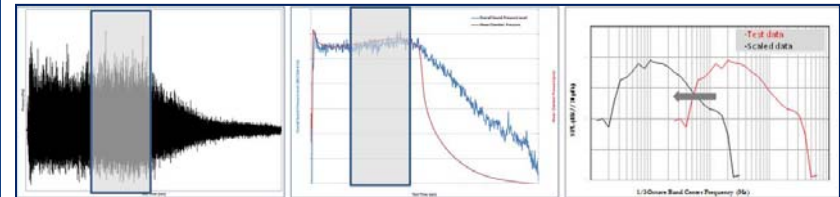


Liftoff Acoustics

- Liftoff noise is generated by rocket exhaust mixing with surrounding atmosphere & its interactions with surrounding launch structures
- ER42 Liftoff Environment Definition Process
 - ✓ Initial liftoff acoustic environment derived from previous/historical flight test data
 - ✓ Acoustic scale model designed and tested to validate liftoff acoustic environments and water sound suppression system design.



Scaled Model Acoustic Testing at MSFC



Typical pressure time history with

- Analysis window (a)
- Analysis window overlaid on chamber pressure measurement and RMS OASPL time history (b)
- A one third octave plot for the test data compared to the scaled data (c).



SUMMARY



- The Fluid Dynamics Branch at MSFC has the mission to support NASA and other customers with discipline expertise to enable successful accomplishment of program/project goals
- The branch is responsible for all aspects of the discipline of fluid dynamics, analysis and testing, applied to propulsion or propulsion-induced loads and environments, which includes the propellant delivery system, combustion devices, coupled systems, and launch and separation events
- ER42 supports projects from design through development, and into anomaly and failure investigations
- ER42 is committed to continually improving the state-of-its-practice to provide accurate, effective, and timely fluid dynamics assessments and in extending the state-of-the-art of the discipline