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Update on Risk Reduction Activities for a Liquid Advanced Booster for NASA's Space Launch System

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Overview and Introduction to ABEDRR

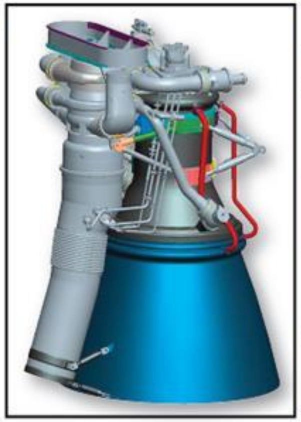
- **Goals of NASA's Advanced Booster Engineering Demonstration and/or Risk Reduction (ABEDRR) are to:**
  - Reduce risks leading to an affordable Advanced Booster that meets the evolved capabilities of SLS
  - Enable competition by mitigating targeted Advanced Booster risks to enhance SLS affordability
- **SLS Block 1 vehicle is being designed to carry 70 mT to LEO**
  - Uses two five-segment solid rocket boosters (SRBs) similar to the boosters that helped power the space shuttle to orbit
- **Evolved 130 mT payload class rocket requires an advanced booster with more thrust than any existing U.S. liquid- or solid-fueled boosters**

Scope of This Presentation

- In October 2012 and February 2013, NASA awarded a contract to Dynetics, Inc. (with Aerojet Rocketdyne as a major subcontractor):
  - To demo the use of modern manufacturing techniques to produce and test several primary components of the F-1 rocket engine originally developed for the Apollo Program, including an integrated powerpack
  - To demo innovative fab techniques for metallic cryo tanks
- Early 2014, NASA and Dynetics agreed to move additional large liquid oxygen/kerosene engine work under Dynetics
  - Originally had been its own ABEDRR prime contract to Aerojet
- Led by Aerojet Rocketdyne, work is focused on an Oxidizer-Rich Staged Combustion (ORSC) cycle engine
  - Can apply to both NASA's Advanced Booster and other launch vehicle applications, including Atlas V booster engine
  - Effort will demonstrate combustion stability and performance of a full-scale ORSC cycle main injector and chamber
- This presentation will discuss the Dynetics ABEDRR engine task (both efforts) and structures task achievements to date

Dynetics Risk Reduction Task Summary

A



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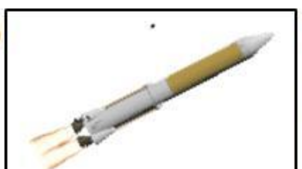

Engineering Demonstrations and Risk Reduction Tasks	*Benefit of Proposed Effort/Status at Start of DDT&E*
F-1B Engine Risk Reduction	
Aerojet Rocketdyne Lead	
• Gas Generator Build and Test	• Full-Scale, Low-Cost, Production-Like, Throttling GG Hot-Fired
• Turbopump Build	• Full-Scale, Low-Cost, Production-Like, Throttling TPA Built
• Powerpack Build and Test	• Full-Scale, Low-Cost, Production-Like, Throttling PPA Hot-Fired
• Thrust Chamber Assembly Design and Build	• Full-Scale, Low-Cost, Production-Like, HIP-Bonded TCA Demonstrated
Structures Risk Reduction	
Dynetics Lead	
• Cryotank Assembly Build	• Full-Scale 18-ft Diameter Flight-Like Tank and Intertank Verified
• Cryotank Proof and Thermal Cycle	• Full-Scale Design,Tooling, and Build Processes Verified
ORSC Cycle Engine Risk Reduction	
Aerojet Rocketdyne Lead	
• Main Injector and Thrust Chamber Assembly Design, Build, and Test	• Full-Scale Demonstration of Combustion Stability and Performance Measurement

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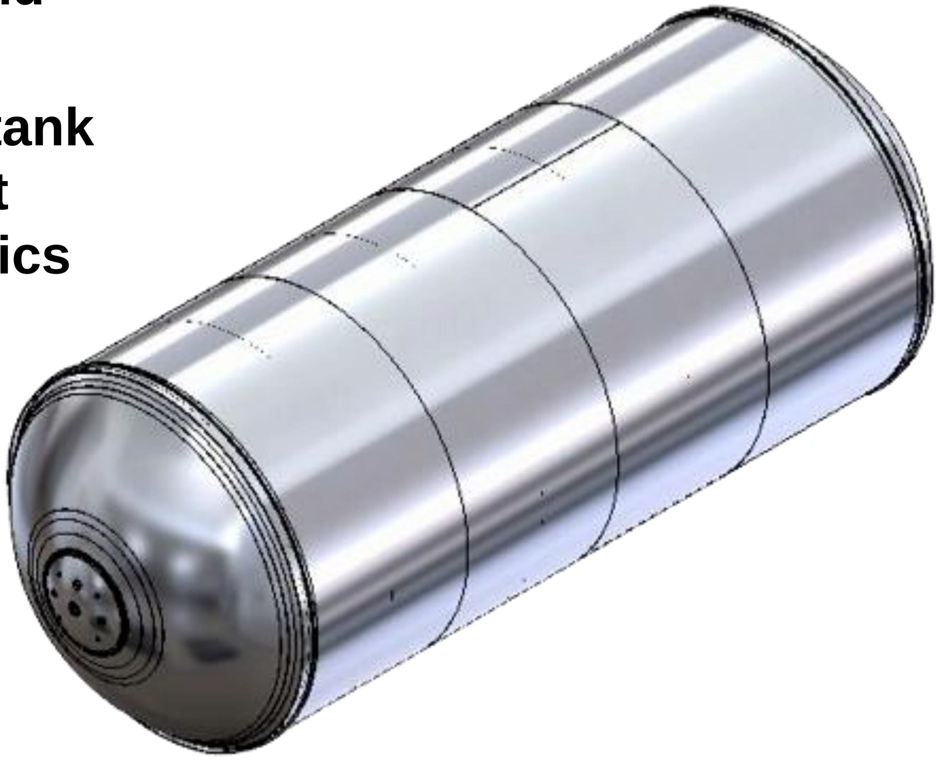
Overall F-1B Engine Risk Reduction Summary

- **Program objective was to reduce F-1B engine development risks—despite funding challenges, the effort met this objective:**
  - Demonstrated F-1B engine and component understanding and readiness
  - Completed a heritage gas generator (GG) hot-fire test series, proving throttling capability
  - Completed an additively manufactured GG inejctor hot-fire test series, proving similarity to heritage
  - Disassembled and reverse engineered existing Mk-10A turbopump
  - Demonstrated long-term affordability through full-scale demonstrations of an additively manufactured GG injector and a cast LOX volute, turbine blades, and turbine manifold
  - Prepared main propellant valves for test
  - Integrated engine loads and design, developed transient operational models, and designed interfaces with the facility for Powerpack testing
  - Developed a new MCC design focused on dramatic cost reductions

Structures Risk Reduction – Cryotank Build

- **Structures risk reduction task planned to validate the designs, materials, equipment, and processes to produce robust and affordable structures**
- **The task created a full-scale cryotank assembly that was verified by proof pressure and cryo-thermal cycle testing**
- **Original plan was to build a tank with four barrel sections, but NASA negotiated with Dynetics to reduce schedule and cost by building a tank with a single cylindrical barrel**
  - **Circumferential welding still demonstrated, and testing still completed**



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Structures Risk Reduction – Testing

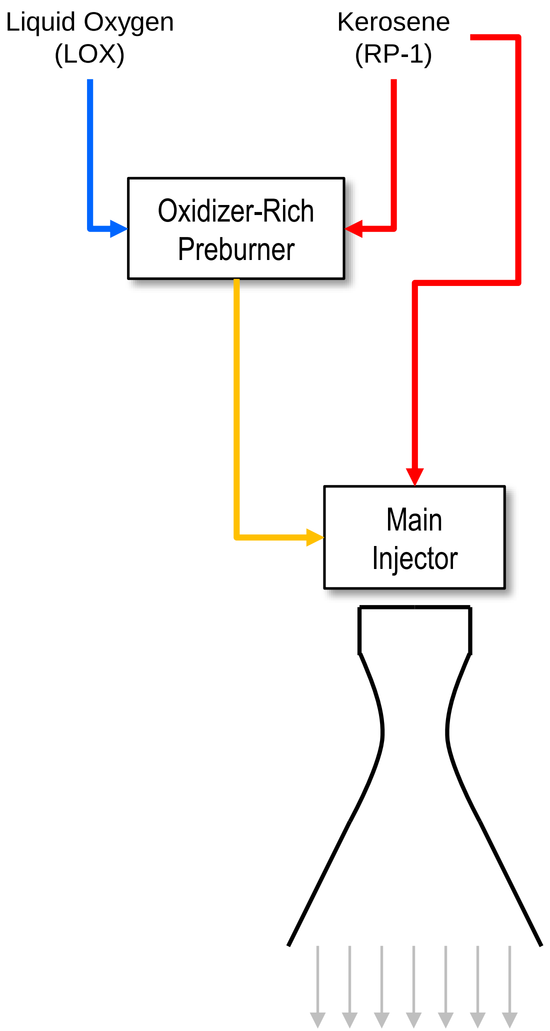
Cryothermal Cycle / Proof Test

Integrated test article chilled with LN_2

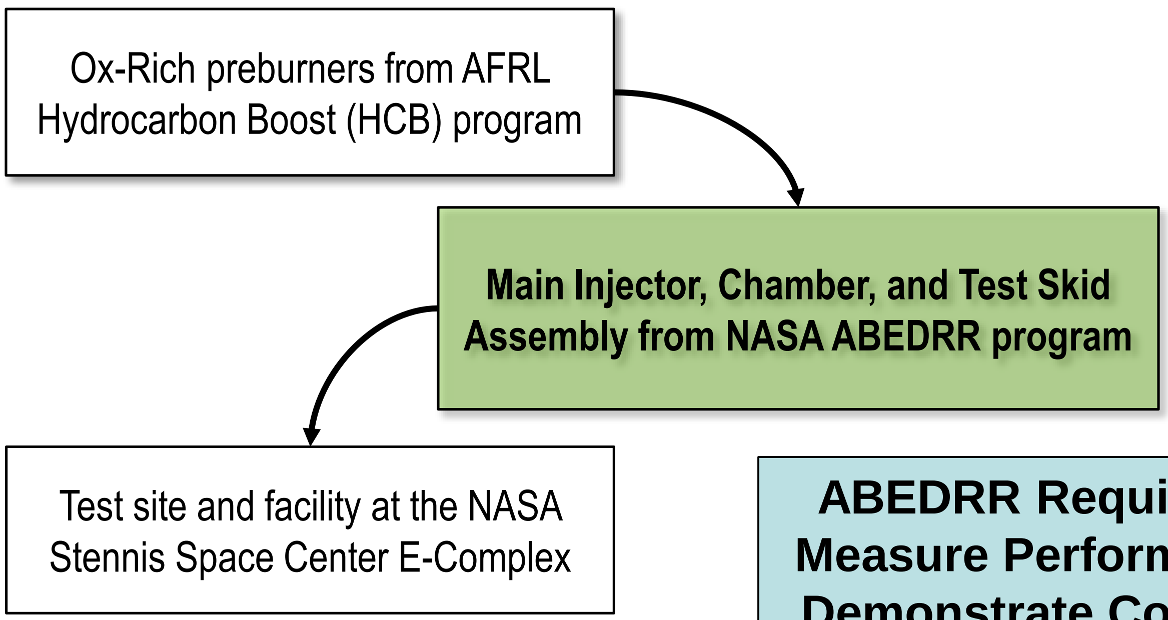
Burst Test

Moments after tank burst

Ox-Rich Staged Combustion (ORSC) Cycle Engine



NASA/USAF-Funded Integrated Ox-Rich Test Article

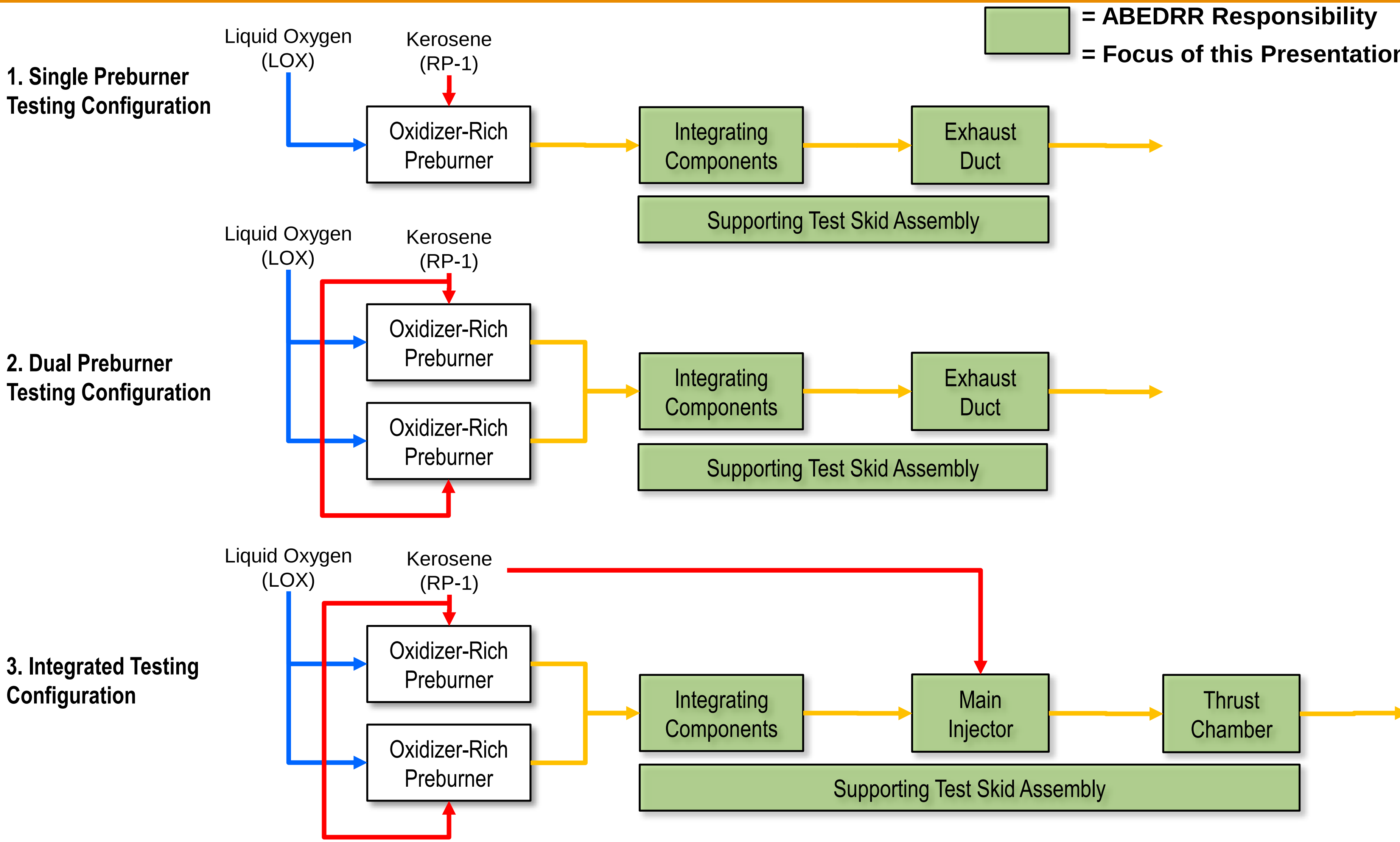


ABEDRR Requirements: Measure Performance and Demonstrate Combustion Stability

- Preburner testing at the 250 klbf thrust level. ORSC main injector combustion stability and injector performance results at 500 klbf thrust level. Direct design information and model validation data.

= Focus of this presentation

Test Configurations



Main Injector Summary Status

- Completed CDR in Mar 2016; Delta CDR in June 2016 with NASA & USAF
- Resolved thermal compatibility issues to eliminate hot spots / streaks
- Performed acoustic analyses to find stable configurations and conditions
- Performed structural analysis to determine injector has positive margins and meets life requirements
- Finalized design of injector elements and injector assembly
- Developed fabrication plan; verified with manufacturing demonstrators
- 100% of drawings completed and released; ~100% out for fabrication
- Completed major forgings and finish machining
- Completed major assembly tasks
- Remaining items include:
  - Material coatings (e.g., thermal barrier coatings)
  - Small component fabrication for parts to be attached to the injector in the final stages of assembly
  - Final assembly and quality inspections

Chamber Summary Status

- Chamber = heat sink with 3 locations for boundary layer cooling injection
- Ran CFD and thermal analysis to determine driving temperatures at various power levels, engine conditions, cooling flows, etc.
- Resolved thermal compatibility issues to eliminate hot spots / streaks
- Performed structural analysis to determine chamber has positive margins and meets life requirements
- Finalized cooling design with thermal/structural and flow requirements
- Finalized design of chamber with features to reduce strain and improve low cycle fatigue; optimized geometry for manufacturability
- Defined and demostrated key manufacturing processes (e.g., brazing)
- 100% of drawings completed and released; ~100% out for fabrication
- Fabrication and machining of hardware nearly all complete
- Completed major assembly tasks
- Remaining items include:
  - Final fabrication steps
  - Final assembly and quality inspections

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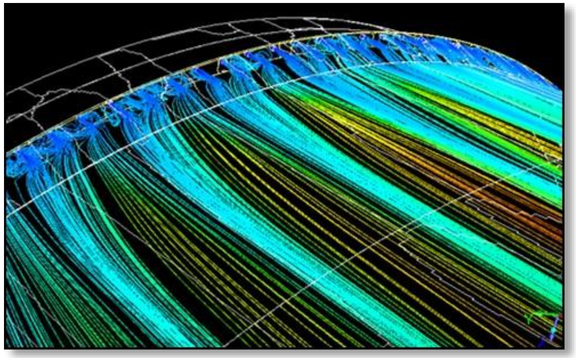
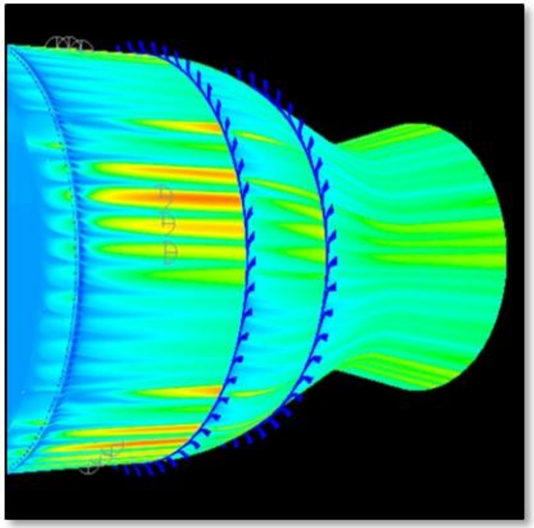
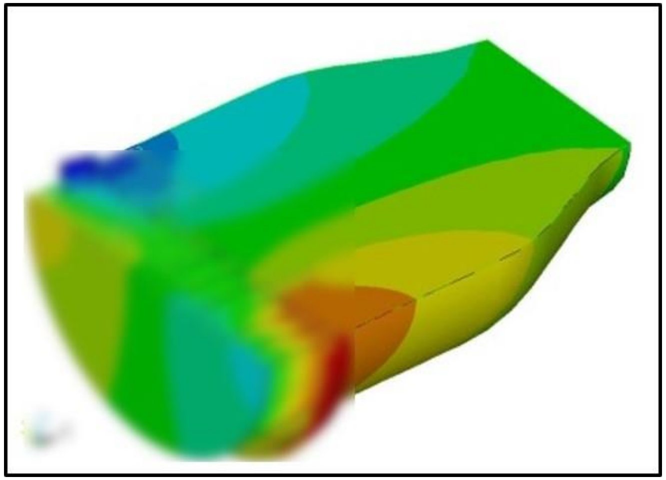
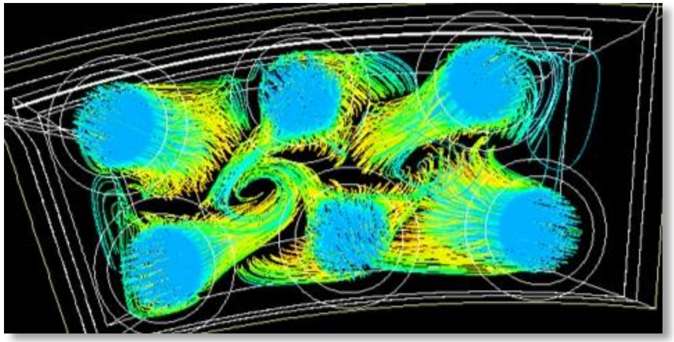
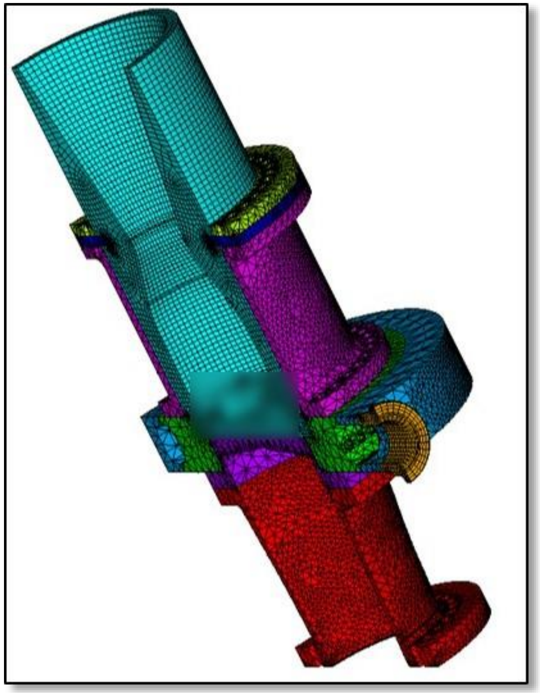
Examples of Fluid, Thermal, Structural, and Acoustic Analyses


Analysis of coolant flow along chamber wall


Chamber wall temperature analyses using CFD


Stability analysis / acoustic modeling of injector and chamber


Reacting flow CFD of injector streamlines


Structural model of thrust chamber assembly

Integrating Components (IC) Summary Status

- Integrating components = components that direct the hot gas flow from the customer-provided preburners to the exhaust duct (without the injector or TCA) or to the injector and TCA
- Completed CDR in Aug 2015; Delta CDR in Nov 2015
- 100% of drawings completed and released; 100% out for fabrication
- Completed pouring and casting of all cast parts
- Started all additively manufactured parts; some already completed
- Machining of hardware on major parts nearly complete
- Most major components have already finished fabrication and are in storage at AR’s NASA Stennis Space Center (SSC) location
- Remaining items include:
  - Complete fabrication on remaining components
  - Complete quality inspections

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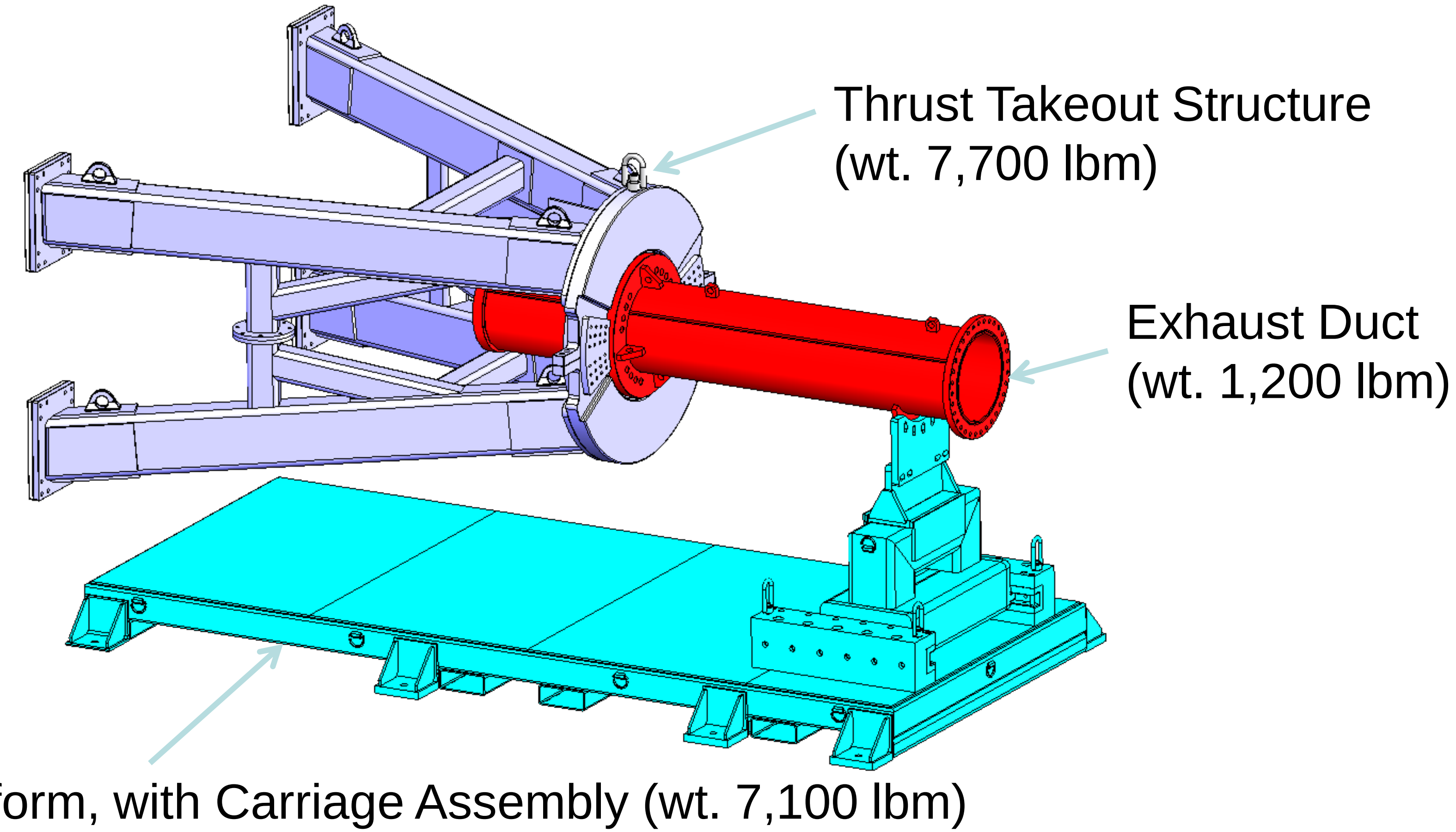
Test Skid Assembly Summary Status

- **Test skid assembly = test article support structure that provides the structural interface for the test article(s) to the test facility**
- **Finalized the design and analysis, completing a Detailed Design Review (DDR) in Feb 2016**
- **Completed manufacture, assembly, and testing of all hardware**
- **Conducted Hardware Acceptance Review (HAR) in Jan 2017**
  - **Verified that the assembly and all associated hardware met requirements**
  - **Delivered thrust takeout structure, test skid (with mounted carriage assembly), and primary exhaust duct to SSC**
- **Conducted Delta HAR in Apr 2017**
  - **Delivered secondary (backup) exhaust duct to SSC**
- **All waiting in storage waiting to be installed**

Test Skid Assembly Design Status

- **Completed CoDR in Oct 2015, PDR in Dec 2015, DDR in Feb 2016**
- **Completed HAR in Jan 2017 and Delta HAR in Apr 2017**



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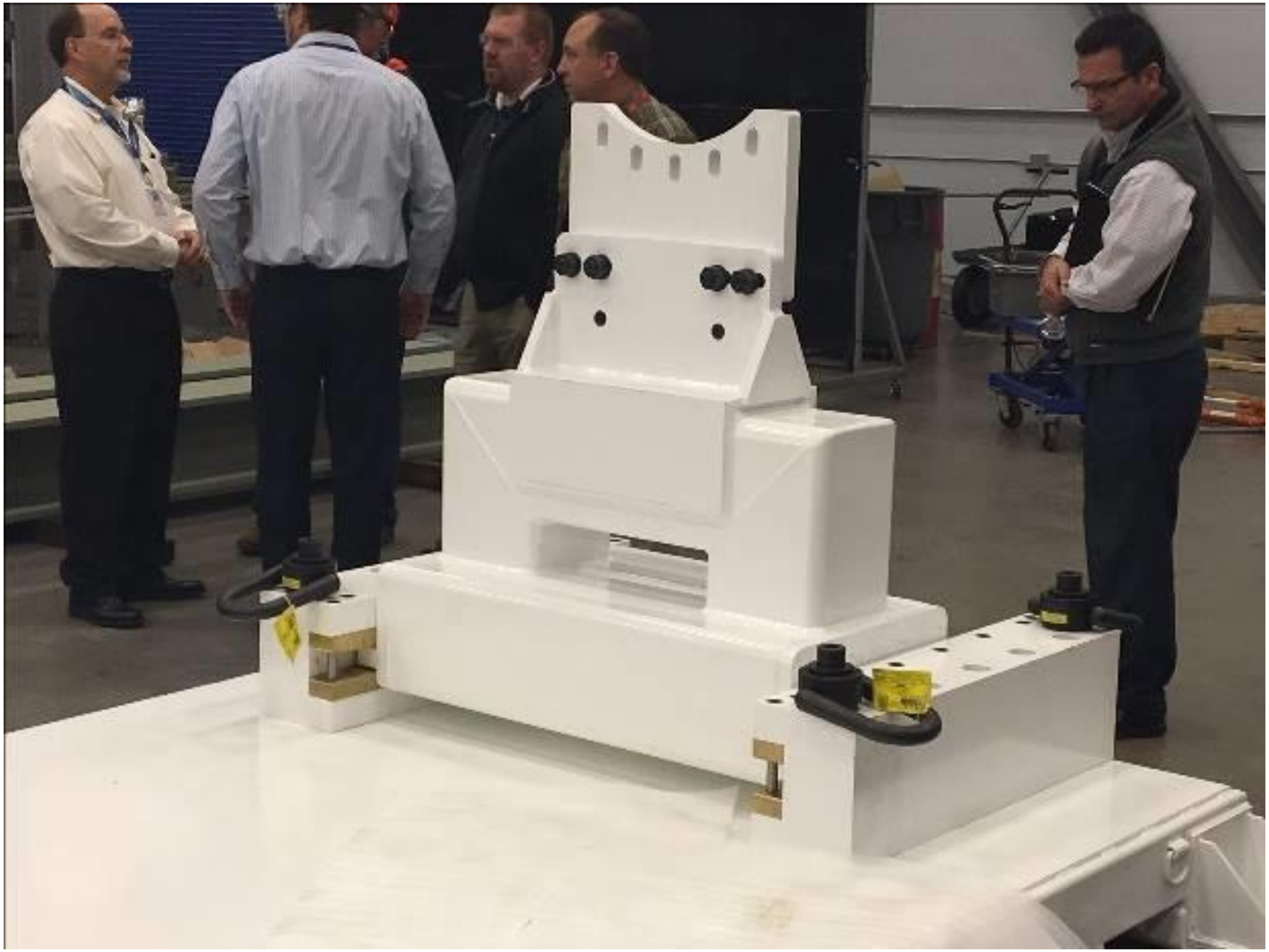
Test Skid Assembly – Manufactured Thrust Takeout Structure

Test Skid Assembly – Manufactured Exhaust Duct

Test Skid Assembly – Manufactured
Test Skid

Test Skid Assembly – Manufactured Carriage Assembly



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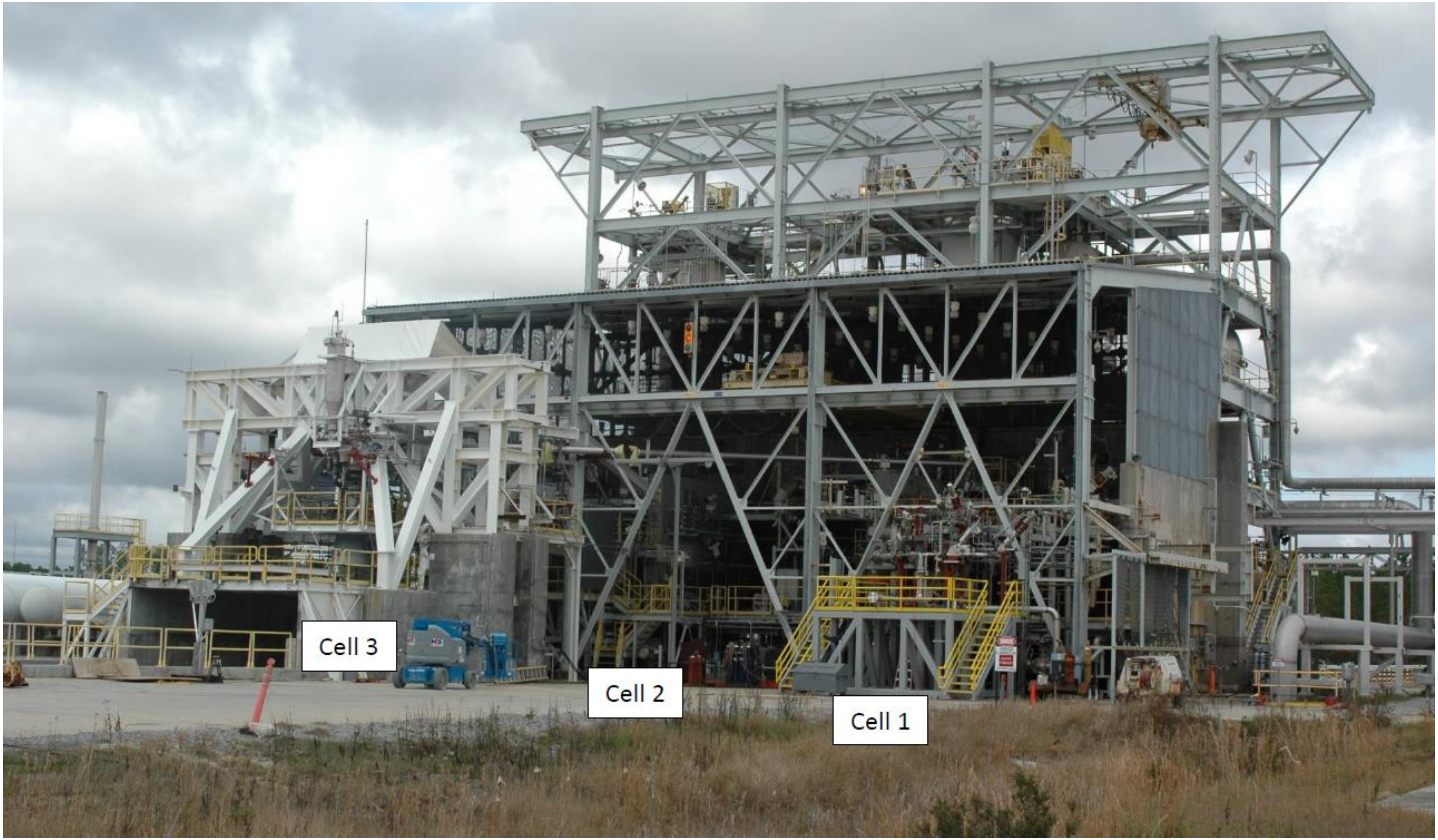
Testing at NASA Stennis Space Center Stand E1



NASA Stennis Space Center Stand E1
Overhead Crane Structure at E1, Cell 1

Test Schedule Summary

- **High thrust, LOX/kerosene rocket engine test facilities are rare, so the capabilities at NASA SSC's E1 test stand are in high demand**
  - **Start of ABEDRR testing has been delayed by the use of the of the same test cell by another engine test program**
  - **In addition, there are other engines to be tested in other cells at E1 that overlap with preburner and ABEDRR testing**
  - **Limited SSC personnel and physical resources available for testing at E1**
  - **Test plans have been stretched to accommodate resource availabilities**
- **E1, Cell 1 is expected to be available by Fall 2017**
- **Skid assembly and ICs are installed, 1st GFE preburner ready: early 2018**
- **Reconfigure for testing 2nd preburner; continue through late 2018**
- **Dual preburner testing through early 2019**
- **Then configure to accommodate main injector and TCA**
  - **Conduct testing to demo combustion stability and measure performance**
  - **Planned to continue through end of 2019**

Summary

- **Dynetics has designed innovative structure assemblies; manufactured them using FSW to leverage NASA investments in tools, facilities, and processes; conducted proof and burst testing, demonstrating viability of design/build processes**
- **Dynetics/AR has applied state-of-the-art manufacturing and processing techniques to the heritage F-1, reducing risk for engine development**
- **Dynetics/AR has also made progress on technology demonstrations for ORSC cycle engine, which offers affordability and performance for both NASA and other launch vehicles**
  - **Full-scale integrated oxidizer-rich test article**
  - **Testing will evaluate performance and combustion stability characteristics**
  - **Contributes to technology maturation for ox-rich staged combustion engines**