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

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67th International Astronautical Congress, Guadalajara, Mexico, Sept 26-30, 2016



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)



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 |

(B)



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 |

(A)



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 |
|---|--|



Overall F-1B Engine Risk Reduction Summary

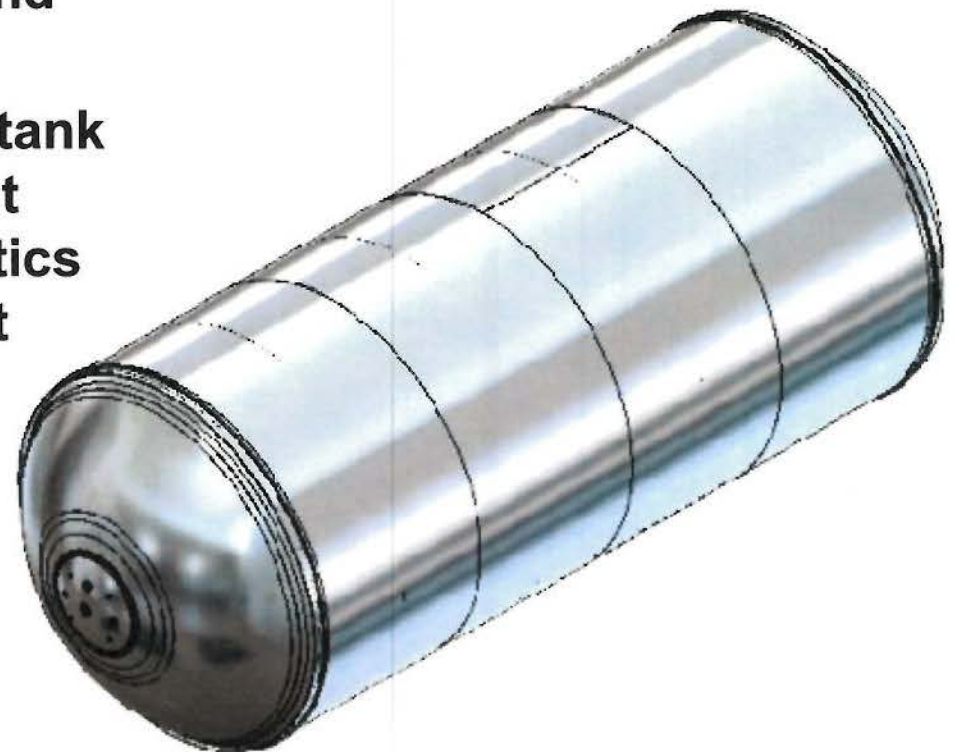
- **Program objective was to reduce F-1B engine development risks—despite funding challenges, the effort met this objective:**
 - Demonstrated F-1B engine and component understanding and readiness
 - Completed a heritage gas generator (GG) hot-fire test series, proving throttling capability
 - Completed an additively manufactured GG injector 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 LN₂

Moments after tank burst

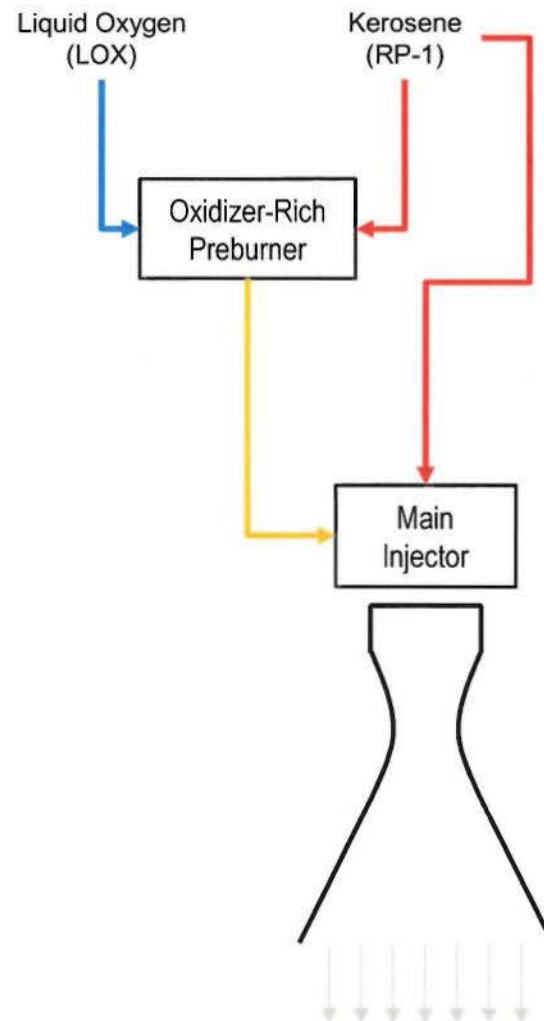
Burst Test





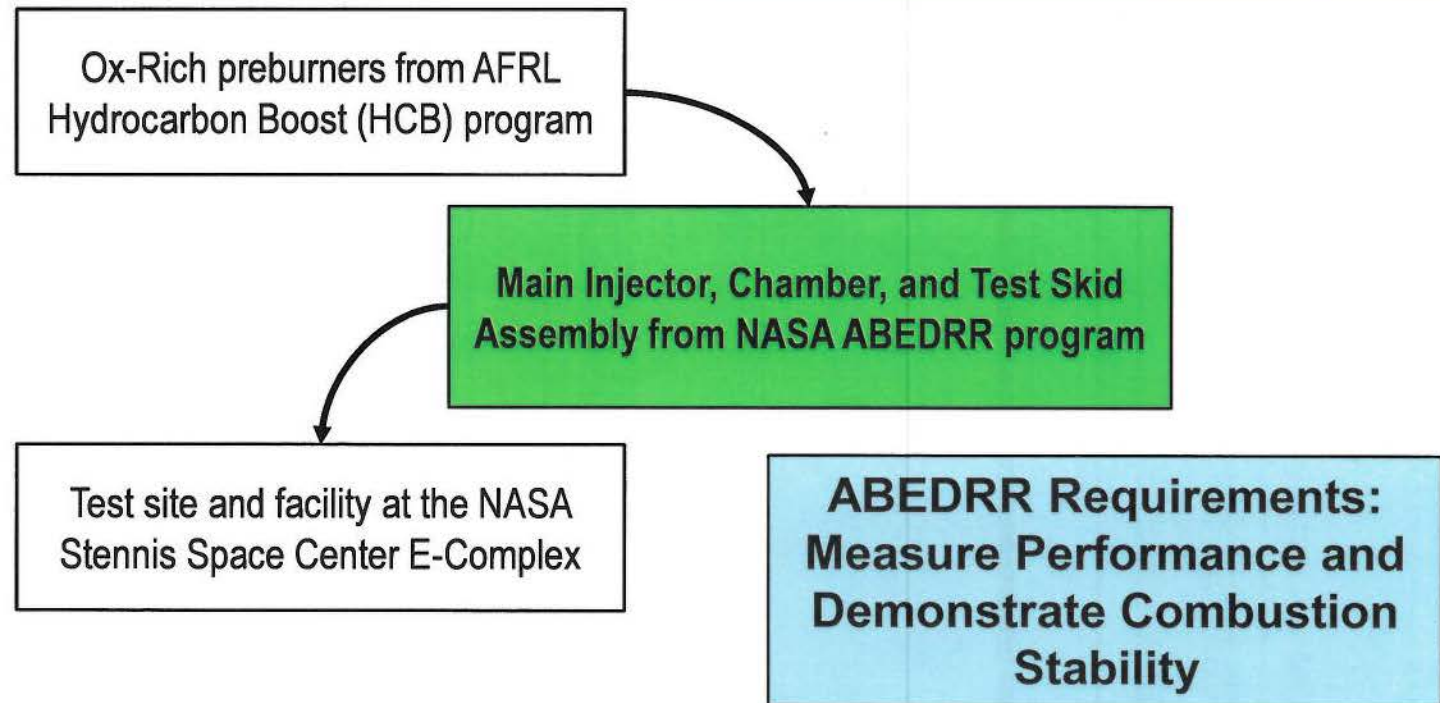
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Ox-Rich Staged Combustion (ORSC) Cycle Engine





NASA/USAF-Funded Integrated Ox-Rich Test Article



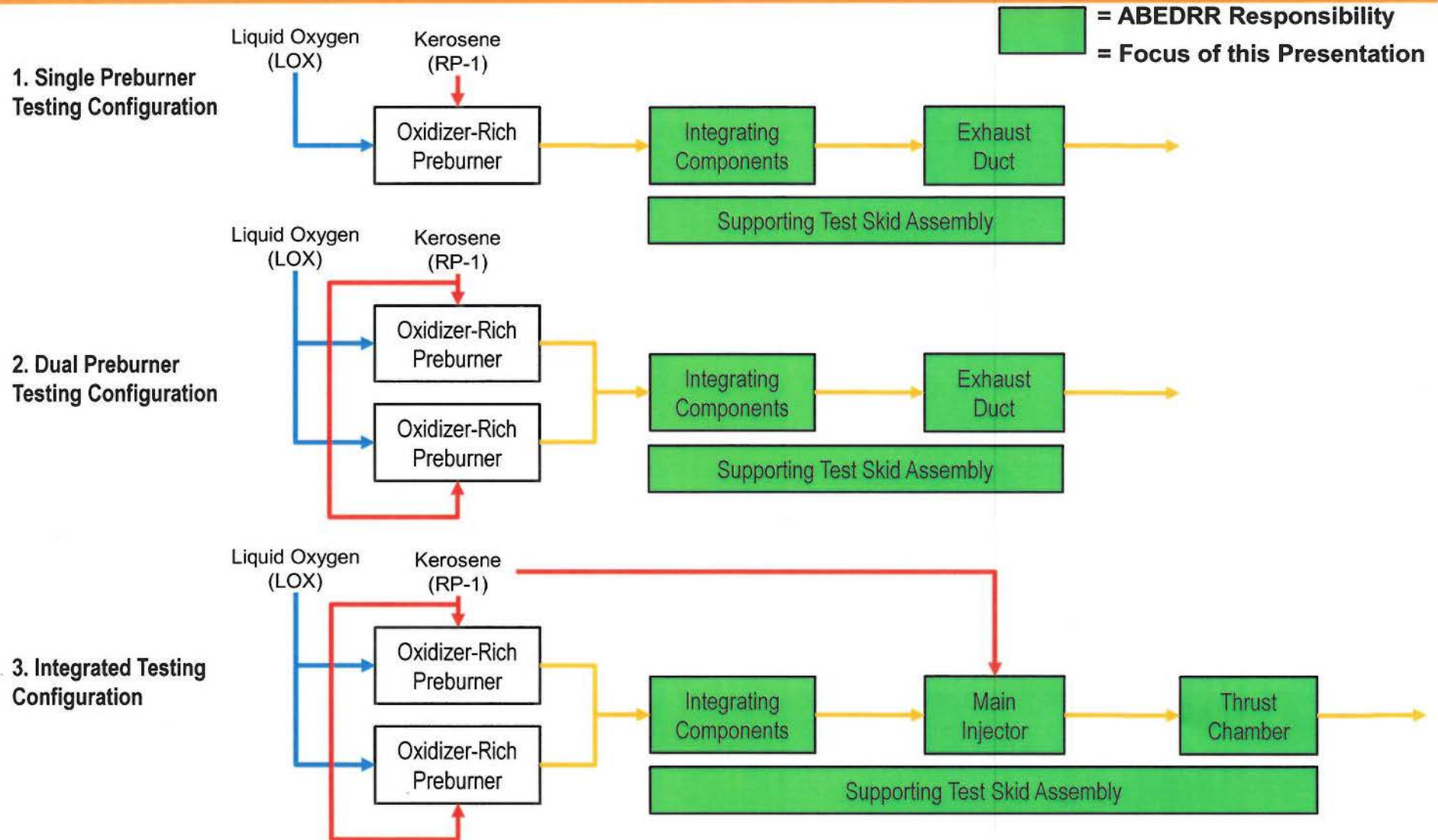
- Preburner testing at the 250 klbf thrust level. ORSC main injector combustion stability and injector performance results at 500 klbf thrust level. Direct design information and model validation data.



= Focus of this presentation



Test Configurations





Integrating Components (IC) Summary Status

- **Accomplishments**
 - Completed IC CDR in Aug 2015
 - Completed IC Delta CDR in Nov 2015
 - Completed pouring of all cast parts
 - Completed casting process on several key components
- **Status**
 - Drawing status: 74% released
 - All remaining major component machine drawings are in signature cycle
 - Machining of IC hardware on schedule to support testing
- **Upcoming Events**
 - Release remaining IC piece part drawings
 - Complete machining of IC hardware per schedule



Main Injector Summary Status

- **Accomplishments**

- Completed CDR in Mar 2016
- Completed Delta CDR in June 2016
- Ran hydraulic CFD to design flow distribution through manifold and injector elements
- Ran reacting-flow CFD in sub-models and full-sector models to determine driving temperatures at various power levels, engine conditions, cooling flows, etc.
- 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
 - Included stability aids (baffles and cavities) for improved high frequency stability margin
- Developed fabrication plan, and verified / updated with sub-scale injector Manufacturing Technology Demonstrators (MTDs)



Main Injector Summary Status (cont'd)

- **Status**
 - Completing cold flows to determine final propellant flow paths
 - ~80% of drawings released and out for procurement
 - Completed major injector forgings; moved to machining
 - Majority of injector components in fabrication



Chamber Summary Status

- **Accomplishments**

- Ran reacting-flow CFD in sub-models and full-sector models 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
 - Finalized cooling approach
 - Modified features to reduce strain and improve low cycle fatigue
- Optimized geometry for manufacturability
- Baselined braze parameters; demonstrated braze parameters
- Defined and matured manufacturing processes



Chamber Summary Status (cont'd)

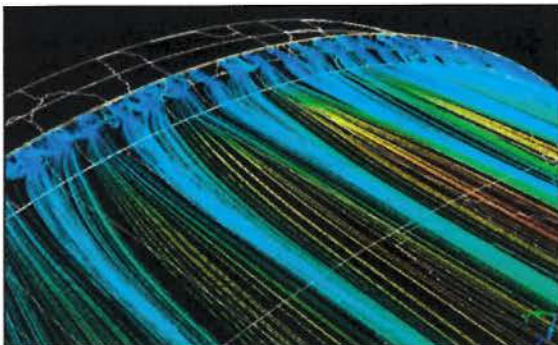
- **Status**
 - Drawings ~70% complete
 - Procurement on schedule
 - Machining of hardware on schedule to support testing

- **Upcoming Events**
 - Complete remaining braze trials
 - Release remaining piece part drawings
 - Complete machining of hardware per schedule

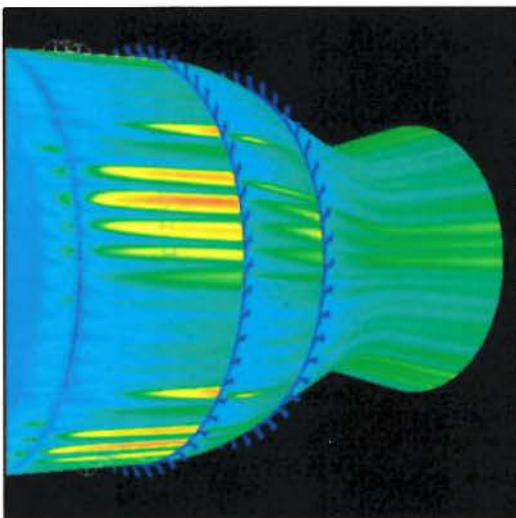


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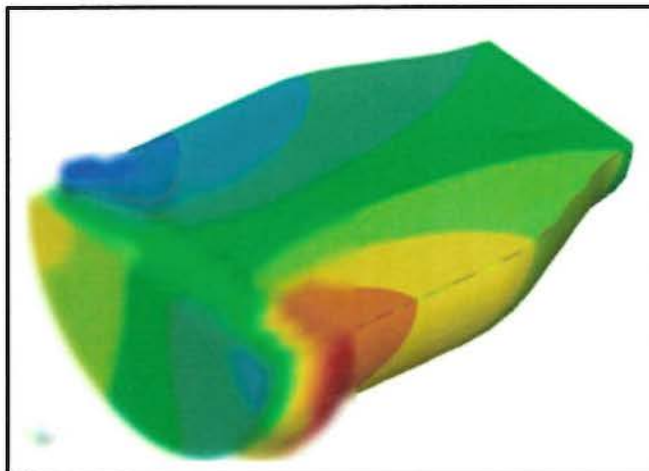
Examples of Fluid, Thermal, Structural, and Acoustic Analyses



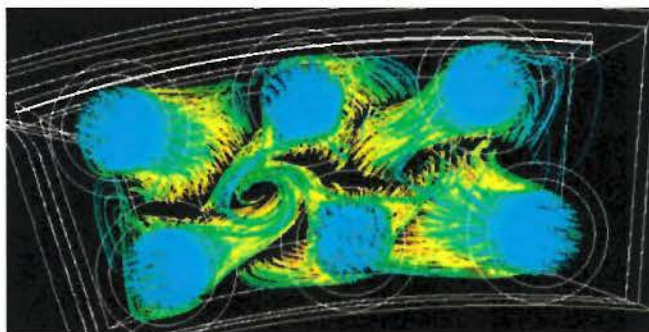
Analysis of coolant flow along chamber wall



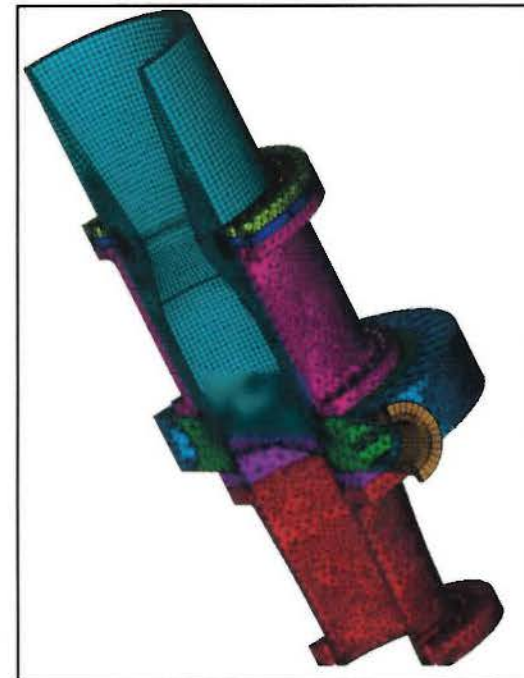
Chamber wall temperature analyses using CFD



Stability analysis / acoustic modeling of injector and chamber



Reacting flow CFD of injector streamlines

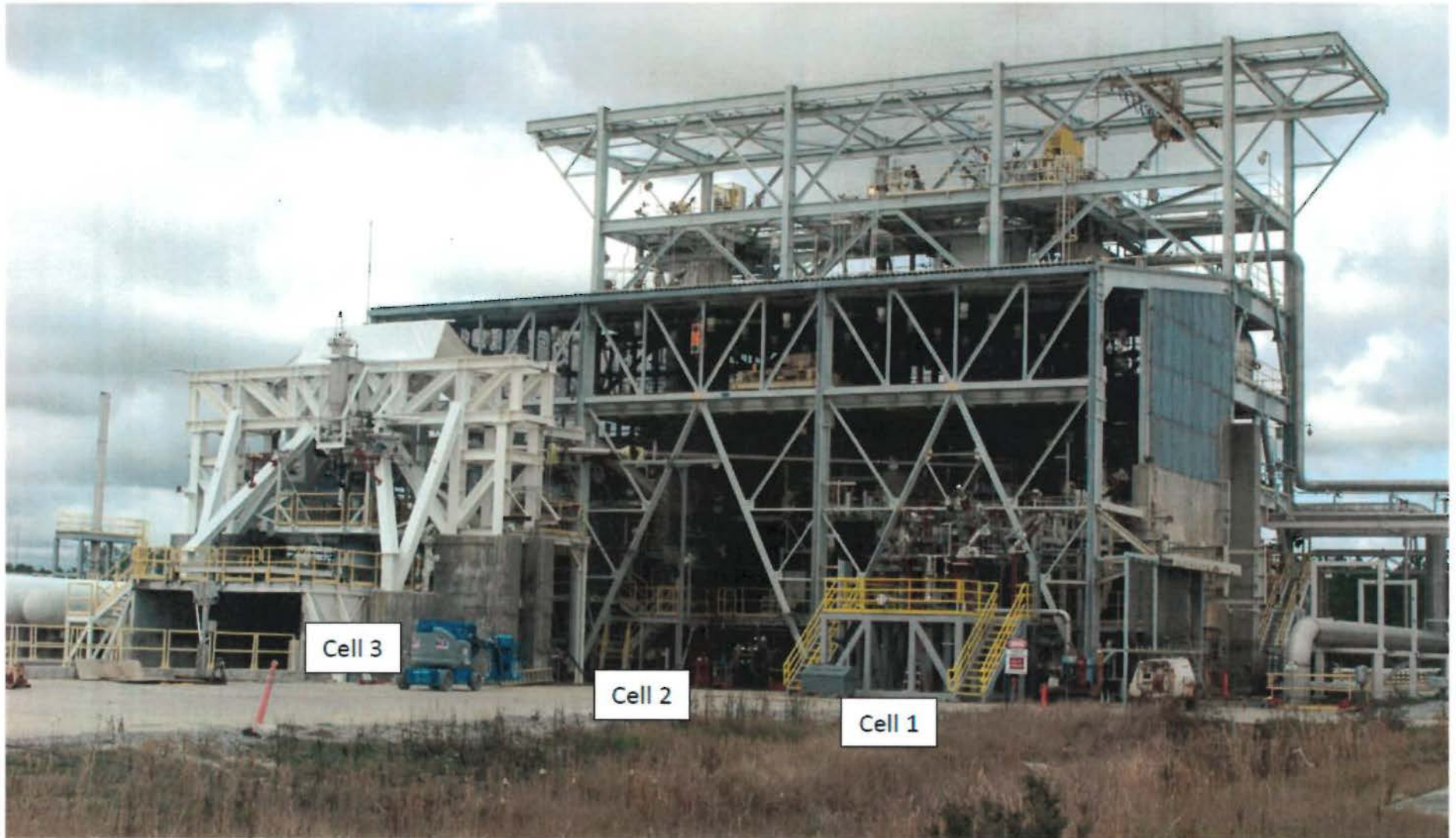


Structural model of thrust chamber assembly



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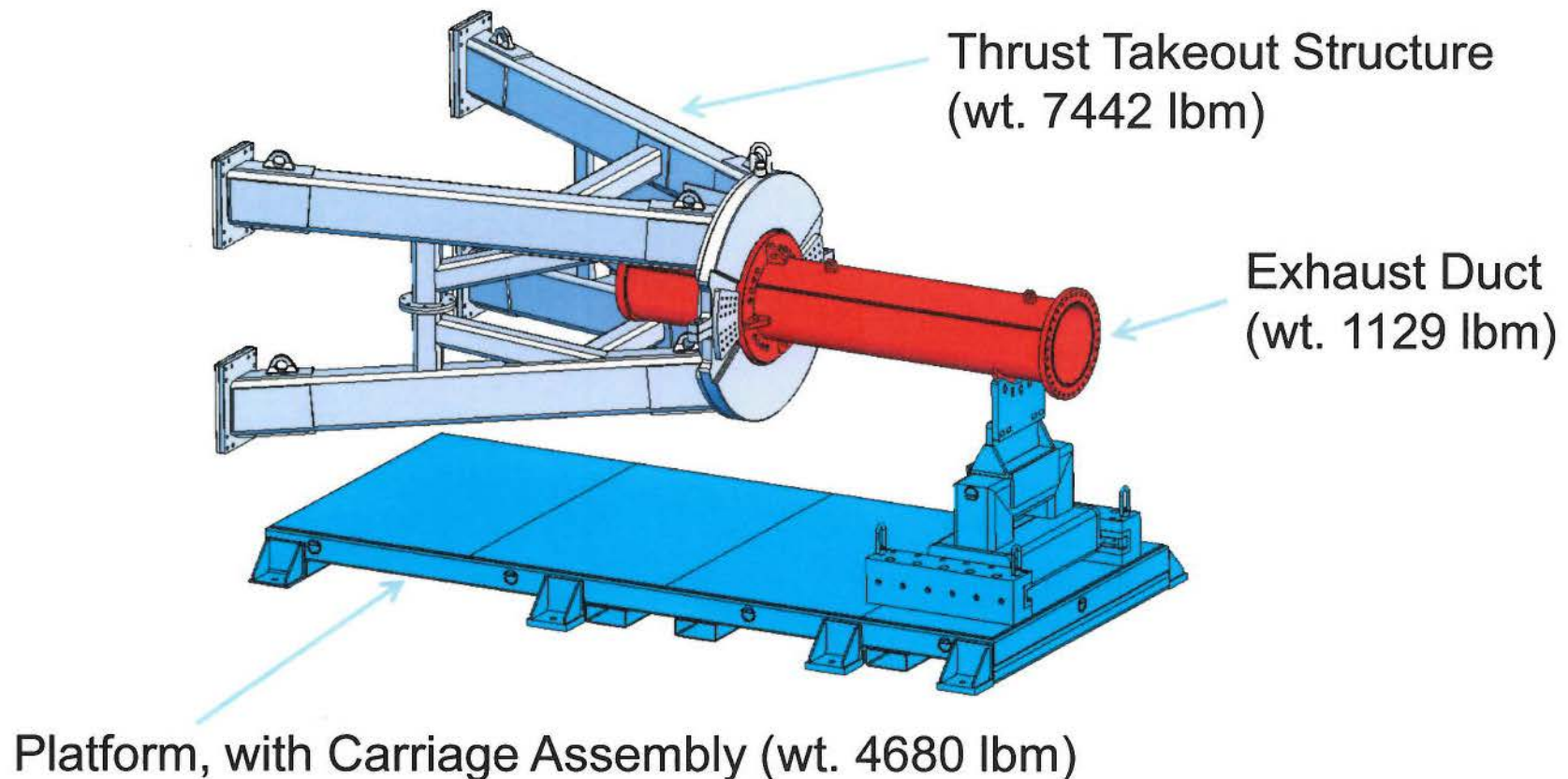
Testing at NASA Stennis Space Center Stand E1





Test Skid Assembly Design Status

- Completed Conceptual Design Review in Oct 2015
- Completed Preliminary Design Review in Dec 2015
- Completed Detailed Design Review in Feb 2016





Test Skid Assembly Build Status

- **Thrust Takeout Structure**
 - Final welding complete; post-weld inspection complete
 - Thrust takeout plates in machining
 - Stress relief after welding
 - Then final machining and painting
- **Exhaust duct**
 - Final welding complete; post-weld inspection complete
 - Moved to large gantry mill for post-weld machining
 - Then proof testing and final processing
- **Carriage assembly**
 - Final weld complete; post-weld machining complete; inspection complete
 - Next step: painting
- **Platform**
 - Welding in work; will finish sometime next week
 - Next steps: NDT → paint
- **Build completion expected end of October**



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Test Skid Assembly Build Progress Thrust Takeout Structure (Post-Weld)





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Test Skid Assembly Build Progress (cont'd) Exhaust Duct (Post-Weld)





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Test Skid Assembly Build Progress (cont'd) Carriage Assembly (Post-Weld)





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

