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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**

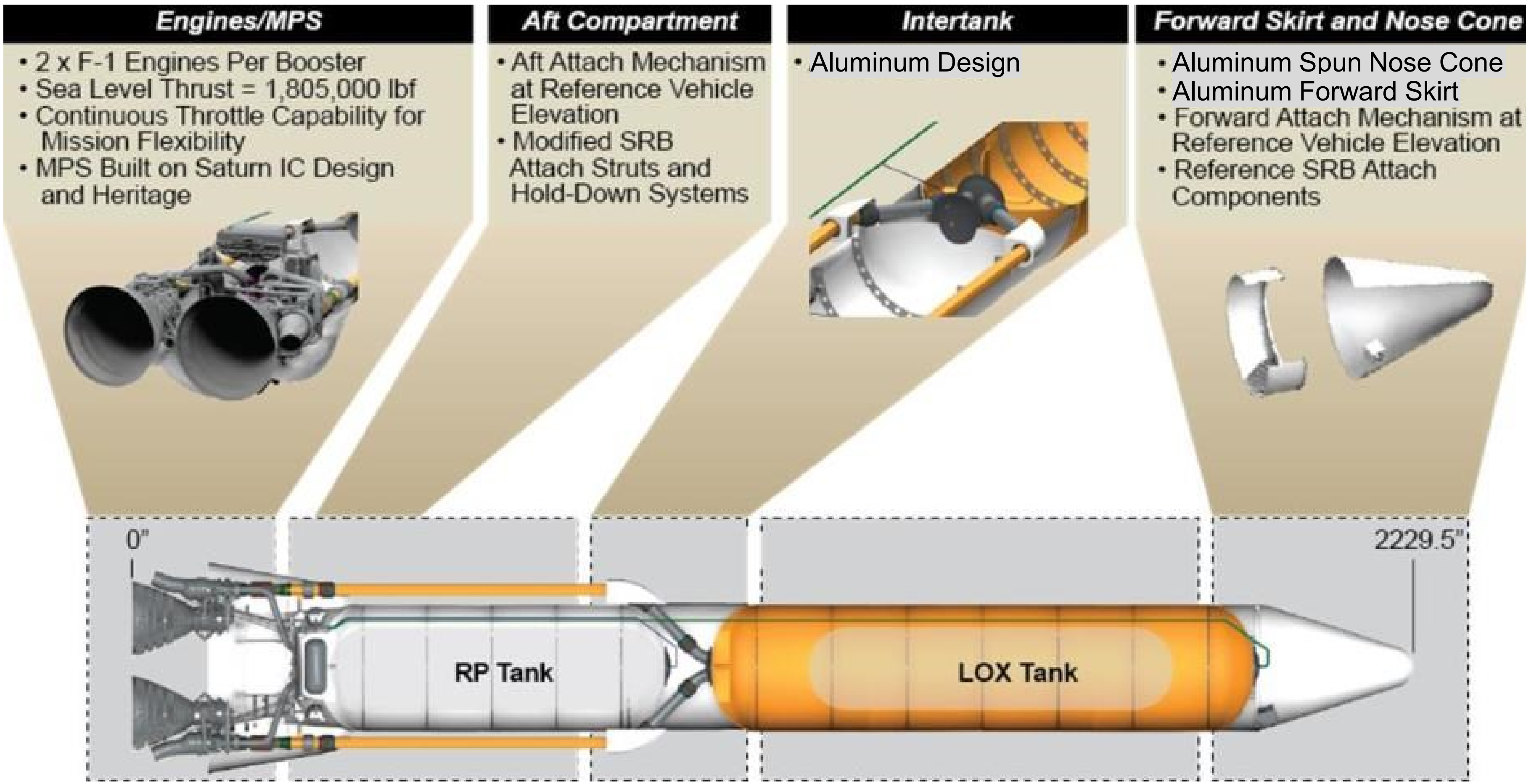
ABEDRR Awards

- **In October 2012 and February 2013, NASA awarded four contracts to improve the affordability, reliability, and performance of an Advanced Booster for the SLS:**
  - ATK to demo innovations for advanced solid-fueled booster: composite case, propellant, nozzle, and avionics
  - NGC for design and mfg for composite propellant tanks
  - Aerojet Rocketdyne to improve the technical maturation of LOX/RP oxidizer-rich staged-combustion cycle engine
  - Dynetics, Inc. (with Aerojet Rocketdyne):
    - 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

Scope of This Presentation

- **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**

Original Dynetics Booster Configuration



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Dynetics Risk Reduction Task Summary

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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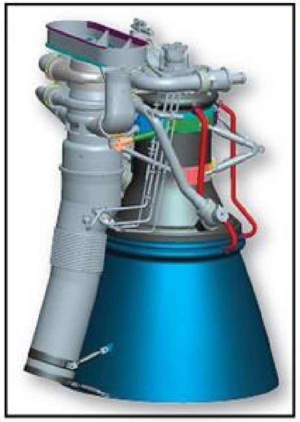

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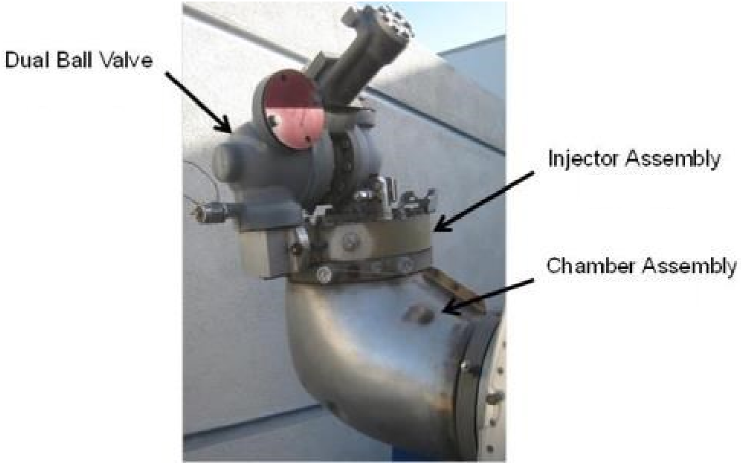
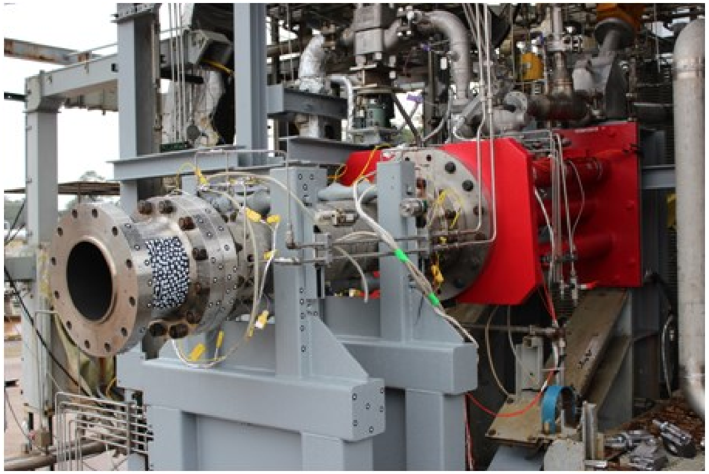
A


Heritage F-1 Gas Generator (GG) Testing

- **A GG test program was used to demonstrate continuous throttling, which offers SLS mission trajectory flexibility**
- **To enable early testing, existing GG and GG valve assets from heritage F-1 flight engines were used**
- **Primary test objectives were:**
  - To verify performance and stability characteristics for the GG at heritage F-1A conditions
  - To verify performance and stability at throttled set points
  - To determine the thermal characteristics of the GG



F-1 gas generator mounted at MSFC Test Stand 116



Heritage F-1 Gas Generator Testing (cont'd)

- **In February and March 2013, 10 tests were completed**
  - Seven were 20-second steady state tests at various chamber pressure and mixture ratio variations
  - One was a 35-second mainstage test
  - One was a 55-second, long duration mainstage test
- **Performance on all tests was nominal, and all test objectives were satisfied**
  - The test series verified the GG was stable at all throttle operating points from 63% to 100% power levels (1.3Mlbf to 1.8Mlbf)
  - A full duration qualification test was completed
  - The thermal performance of the GG was characterized
  - All performance data was consistent with heritage operations

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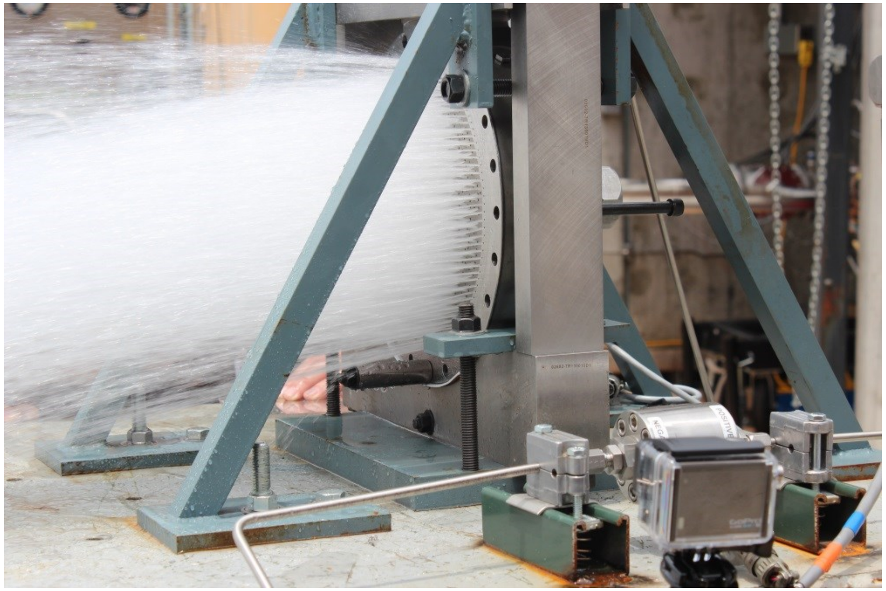
Heritage F-1 Gas Generator Testing (cont'd)

Additive Manufacturing of a F-1B GG Injector

- As a cost reduction opportunity, AR also fabricated a full-scale GG injector using a modern, low-cost, additive manufacturing technique called sintered laser melting (SLM)
- Proof testing and inspections were completed and passed
- In June 2014, NASA MSFC successfully conducted water flow testing of the injector to characterize the fuel and oxidizer flow passage resistances and visualize the flows
- Due to scheduling issues, hotfire testing of the SLM GG injector was delayed until September 2015



F-1B SLM GG injector flow calibration test

Testing an Additively Manufactured Injector

- **Hotfire testing of the F-1B SLM GG injector was completed in the same MSFC test stand as the original heritage injector**
- **The main objective of the testing was to determine the combustion and stability characteristics and thermal performance of the injector manufactured with the SLM process**
- **All tests were successful and matched the heritage injector test results very well**
- **This test provided an opportunity for a one-on-one comparison of a part built with traditional manufacturing to a part built with a new process that the aerospace industry is investigating**

F-1B SLM GG injector hotfire test at NASA MSFC

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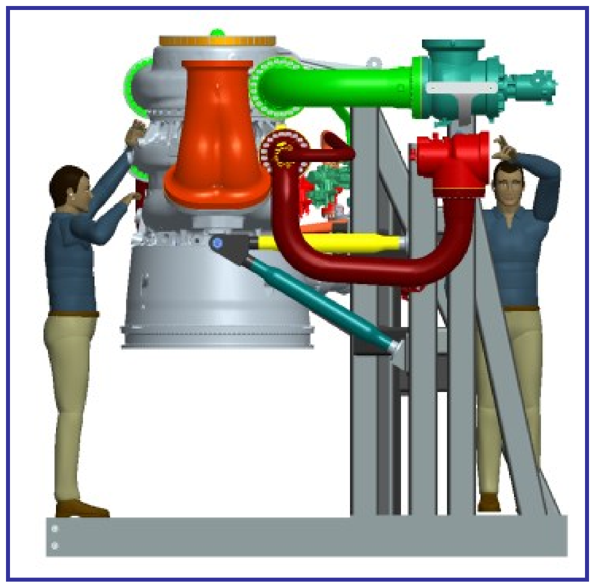
F-1B Risk Reduction – Previously Discussed

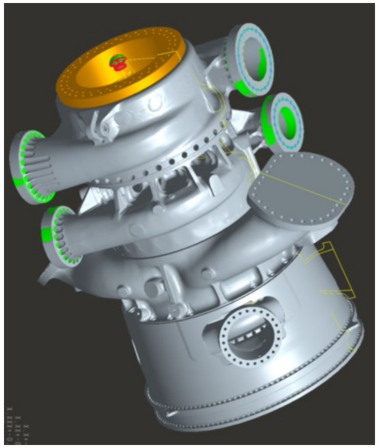
- This presentation will briefly discuss these activities, but they have been covered in detail in a previous paper/presentation

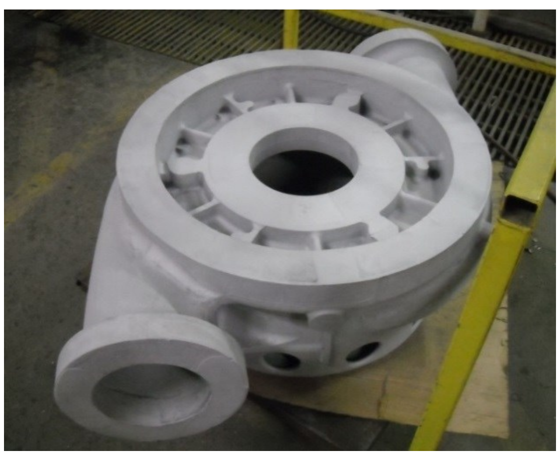
Structured light scanning the Mk-10A fuel inlet



Powerpack Assembly mounted on test skid

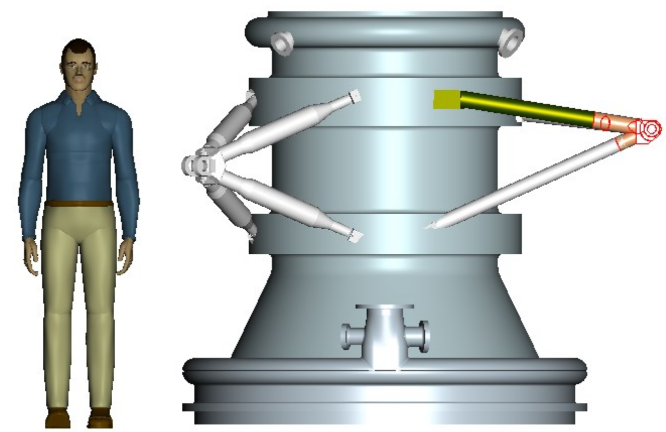
3-D Pro/Engineer turbopump assembly model created from scanned images





Successful F-1B LOX volute sand casting

F-1B Main Combustion Chamber



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 GG hot-fire test series, proving throttling capability
  - Completed a SLM 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

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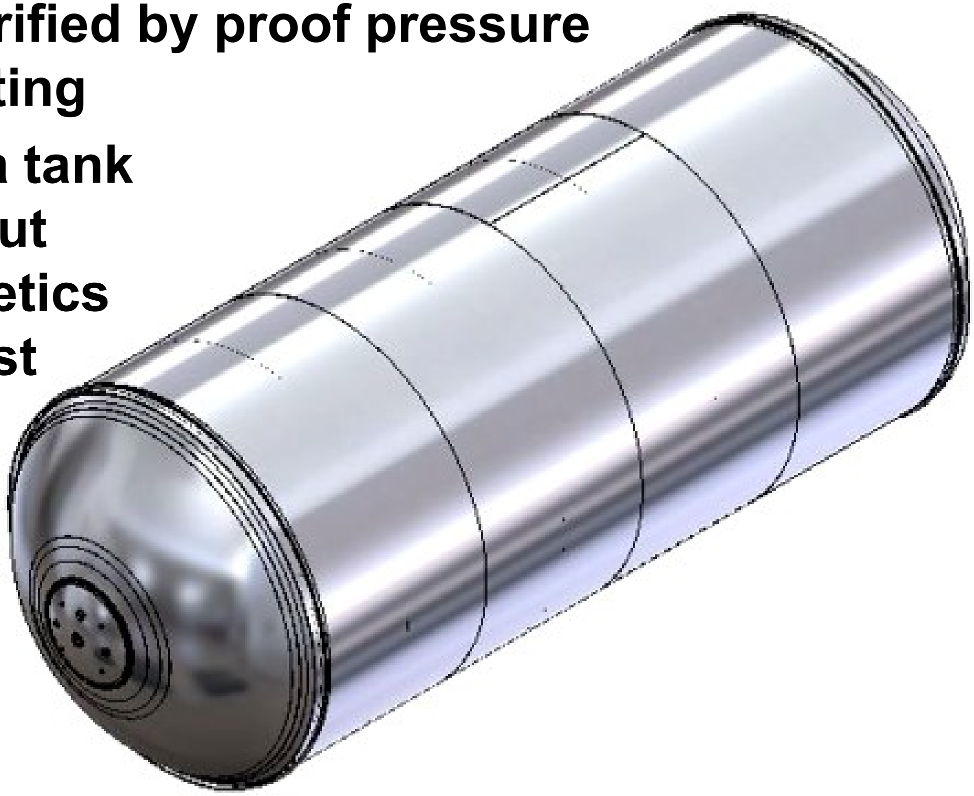
Structures Risk Reduction – Cryotank Build

- Structures risk reduction task planned to validate the designs, materials, equipment, and processes to produce robust and affordable structures
- Ultimately, the task planned to create a full-scale cryotank assembly that would be 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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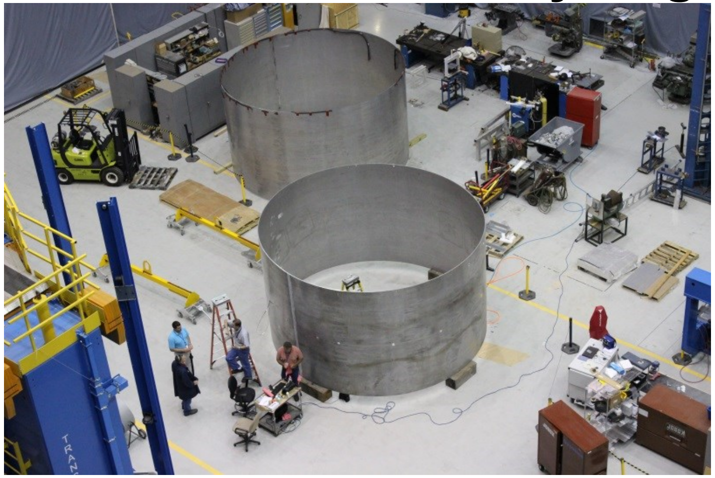
Structures Risk Reduction – Design and Analysis

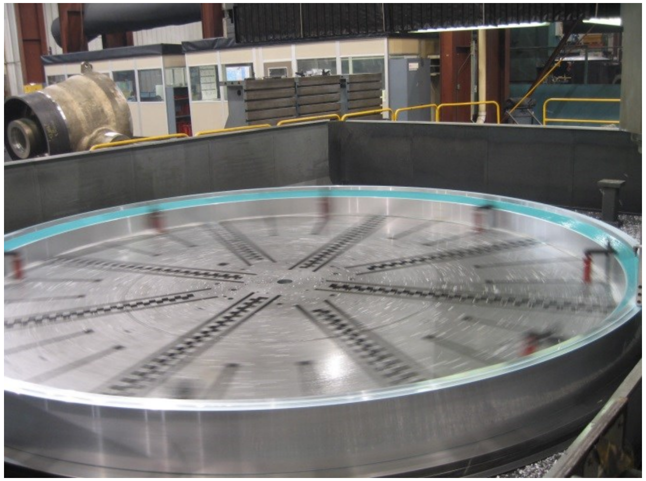
- Performed initial structural analysis and verified that the RP-1 tank, intertank, and LOX tank designs had positive margin for stress and buckling
- Performed detailed coupled loads analysis, including simulations for vehicle rollout, pre-launch, liftoff, and ascent phases (transonic, max Q-alpha, max Q, max thrust, and max acceleration), to generate the design loads
- Generated max shear and moment loads and Peq loads, interface loads, vehicle support post loads, and stay loads
- Generated fatigue and fracture stress spectra
- Working with NASA Langley, used the latest experimental data to update shell buckling knockdown factors
- Performed thermal analysis of the tanks and intertank
- Determined appropriate proof pressure levels for planned tank testing

Structures Risk Reduction – Barrel and Y-Ring Mfg

- Fabrication activities started with a mill run of Al 2219 plate
- Plates delivered to Spincraft for spin-forming domes and to Major Tool and Machine for manufacturing tank barrels
- Unique single-sheet barrel rolling technique was developed for the robust tank structure and demonstrated on 7 barrels
- ATI Ladish started with large aluminum ingots and worked them into ring forgings—sent to Major Tool and Machine to be machined into y-rings



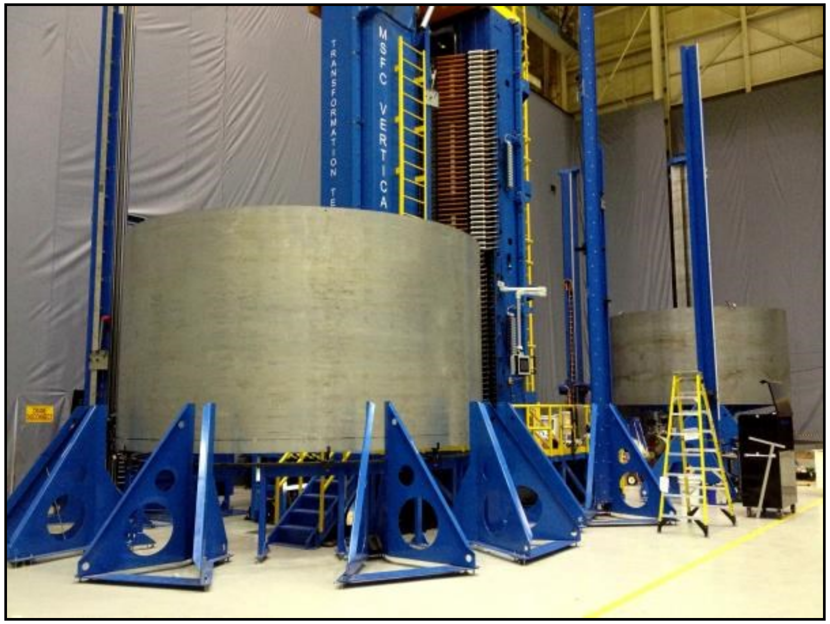
Dynetics tank barrels at NASA MSFC Building 4755



Dynetics y-ring in machining

Structures Risk Reduction – Tank Barrel Welding

- **Developed a tank build plan to weld the barrels using NASA MSFC Friction Stir Welding (FSW) tools**
- **Developed conventional FSW parameters—implemented on longitudinal barrel welds on the Vertical Weld Tool**
- **All barrels passed Phased Array Ultrasonic Testing (PAUT) and dye penetrant testing**



Dynetics barrels on MSFC FSW tools, Vertical Weld Tool (near) and Vertical Trim Tool (far)

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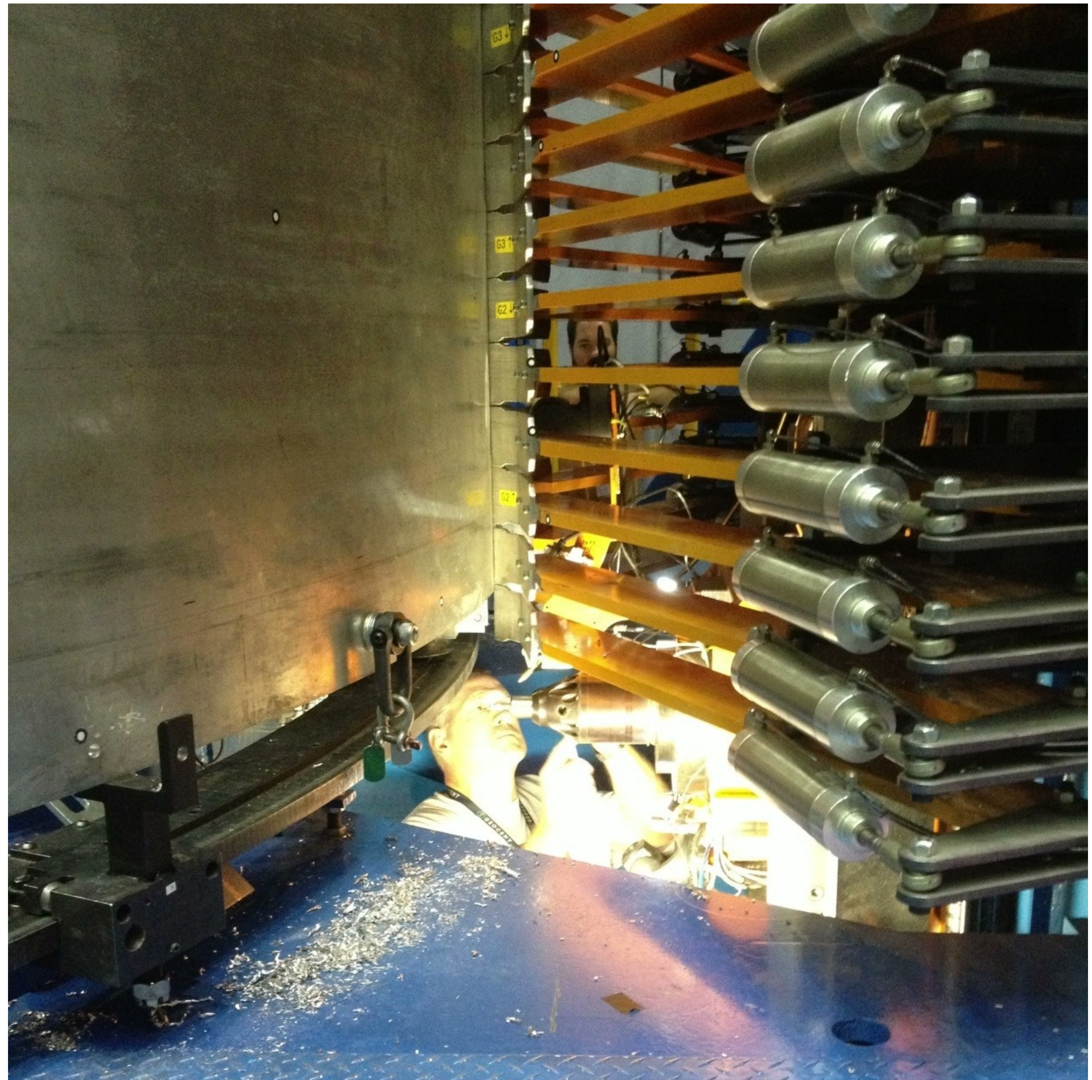
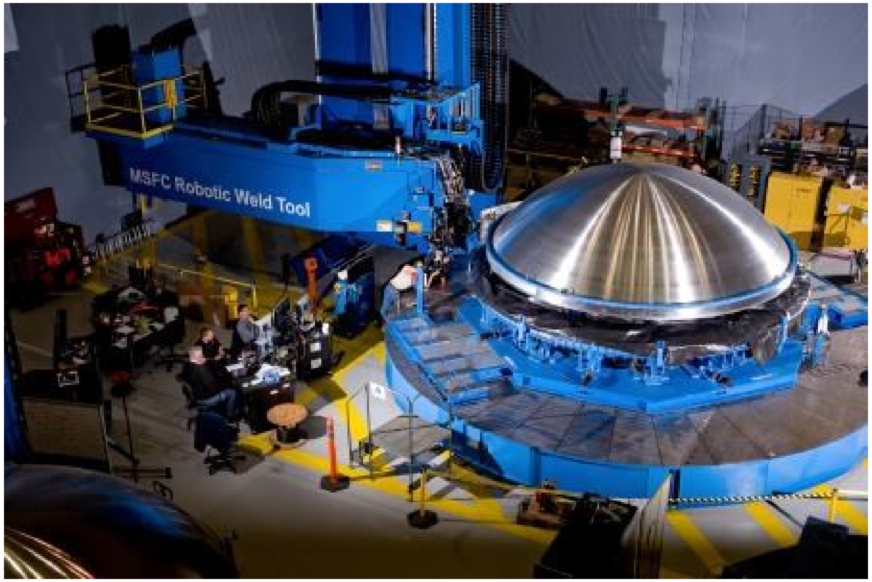
Structures Risk Reduction – Barrel Welding (cont'd)

Dynetics barrel on the Vertical Weld Tool

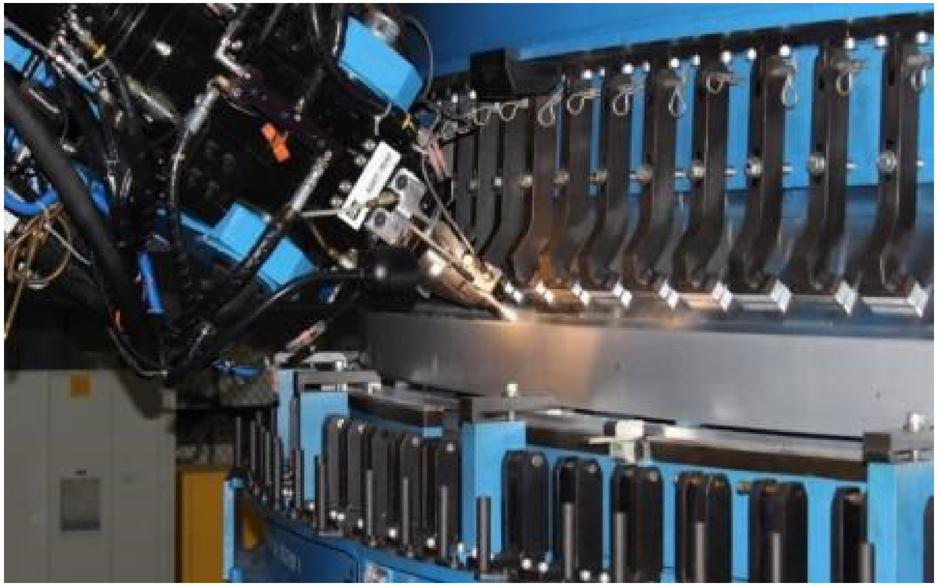


Structures Risk Reduction – Dome to Y-Ring Welding

- Developed weld schedule for self-reacting FSW
- Completed circumferential welding of two domes to y-rings on MSFC's Robotic Weld Tool
- Passed PAUT and dye penetrant testing



Tank dome on the MSFC Robotic Weld Tool



MSFC RWT welding Dynetics dome to y-ring

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Structures Risk Reduction – Dome to Barrel Welding

- Developed weld schedule for self-reacting FSW for circumferentially welding tank barrels to the dome/y-ring assemblies and the barrels to other barrels on MSFC's Vertical Assembly Tool
- Mechanical modifications were made to the tool to accommodate the size and weight of Dynetics' structure
- Test welds were completed; all passed PAUT inspection, tensile testing results good
- Next step to complete final circumferential welds

NASA MSFC's Vertical Assembly Tool

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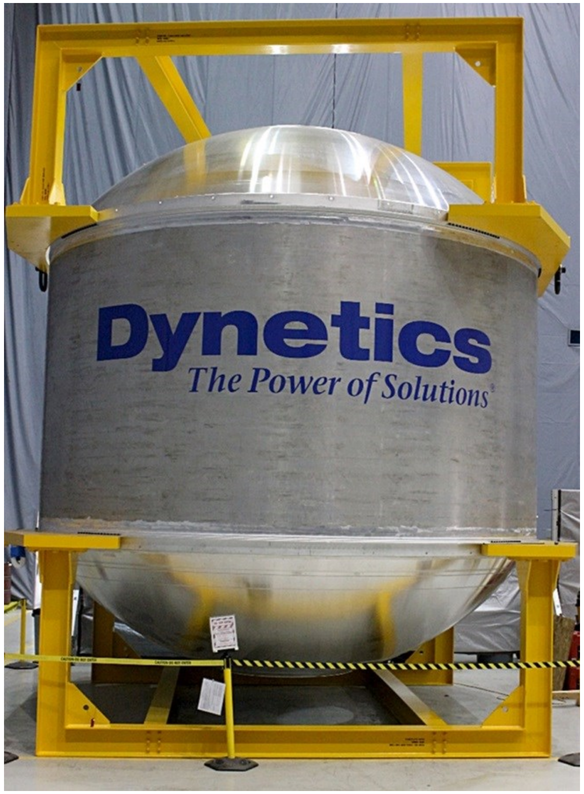
Structures Risk Reduction – Final Tank Welding

- **Circumferential welding started with the aft end of the tank**
  - Hawthorne clamps used to hold the y-ring and barrel together for welding
- **PAUT inspection completed**
  - One defect found in overlap region of weld
  - Created a defect panel with a similar sized indication, tensile tested, resulted in a weld strength higher than the design allowable
- **Forward end welded with same approach**
- **PAUT inspection completed**
  - Tiny indications found at notches for Hawthorne clamps
  - Indications measured, sum of all was much smaller than aft end weld indication
- **All welds deemed acceptable**



Finished Tank

Structures Risk Reduction – Test Article Integration

- Tank, test stand, and supporting hardware moved from MSFC fab facilities to test site in Iuka, MS
- Once in Iuka, tank integrated to test stand to form the test article
- Strain gauges installed on test article
- After strain gauge installation, test article transported to test pad
- Once mounted to test pad, modified lifting fixture with decking installed

Integrating the tank and test stand in Iuka, MS

Placing the integrated test article on the test pad

Structures Risk Reduction – Testing Introduction

- **Dynetics performed series of proof and thermal cycle tests**
- **Demonstrates that designs, materials, manufacturing processes, and inspection methods for building pressurized cryotanks are ready for DDT&E**

- **Testing conducted per a NASA-approved test matrix**
- **Test pass/fail criteria were defined in a Tank Test Plan**
- **Procedures generated to define the steps for each test**

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Structures Risk Reduction – Hydrostatic Proof Testing

Test 1 – Hydrostatic Proof Test

- Test article was 100% filled with water
- Pressurized with GN_2 to 10 psig $\pm$ 2 psi to verify strain gauges operational
- Tank pressurized to specified hold points, held for 3 mins each
- Pressurized to target pressure, held for 5 mins

- All strain, temperature, and pressure sensors operational
- Visual leak checks performed throughout the test
- Test was a success; strains observed were in ranges expected

- Following tank drain, sump seals replaced with cryogenically-rated Chrysler O-ring seals; tank reassembled per cryogenic configurations defined in Test Plan

Structures Risk Reduction – Cryothermal Testing

Test 2 – LN_2 Transfer and Control Test

Chilling test stand with LN_2

- Purpose was to serve as a trial run for test team operations and provide opportunity to test fill, vent, and drain
- Prior to test, test article was purged with GN_2 to remove/prevent moisture
- Filled tank with 6,000 gal of LN_2, bottom dome filled up to the aft y-ring
- After fill, controlled boil-off and pressurization
  - Max pressure reached less than 7 psig
- All measurements and visual results satisfactory
- Prior to next test, access ports on stand sealed with insulation
- Also added LN_2 sprinkler to chill stand faster to reduce the temperature delta between the stand and tank y-ring interface

Structures Risk Reduction – Cryothermal Testing (cont'd)

Test 3 – Cryothermal Cycle / Proof Test

- **Only issue was failure of LN_2 fill isolation valve**
  - Valve was manually opened to avoid problems
  - Total fill operation took approximately 12 hours
- **When tank approximately 95% full, all tank valves closed, and tank was pressurized with GHe**
  - Target pressure was held for 5 mins
- **Used temp-compensating thermocouples and low-temp strain gages**
- **Test was successful**
  - Reached target pressure
  - All measurements and visual results were satisfactory
  - No yielding of tank structure

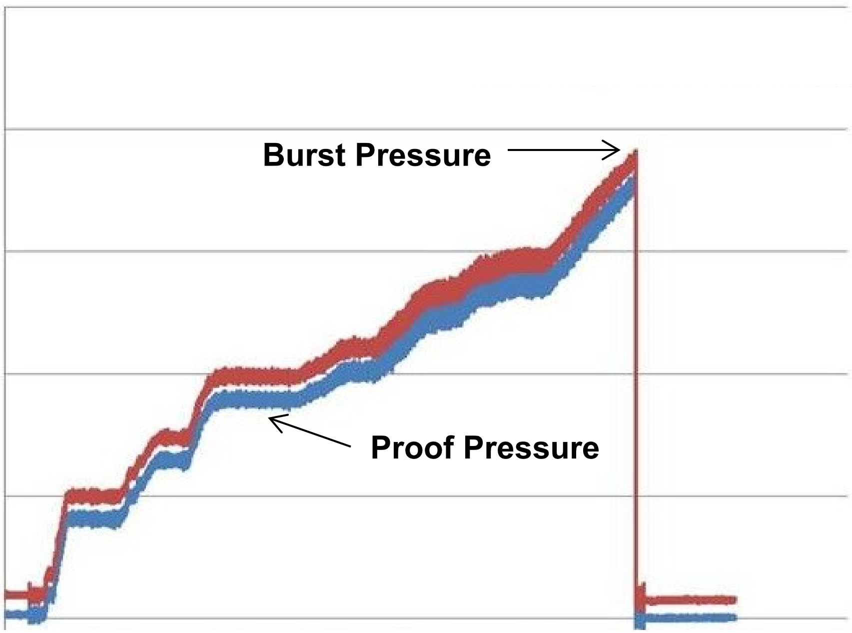
Integrated test article chilled with LN_2

Structures Risk Reduction – Hydrostatic Burst Testing

Test 4 – Hydrostatic Proof / Burst Test

- **Test article 100% filled with water**
- **Tank hydrostatically pressurized using a water pump**
- **Pressure points held for 3 mins each**
- **Failure location at machining non-conformance on the top dome**
- **Test was successful**
  - Met previous proof pressure
  - Burst pressure >2x proof
  - All measurements and visual results were satisfactory
- **Proof and burst test results verified structural design and manufacture of an affordable booster concept for the SLS**

ABEDRR Tank Pressure vs Time



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Structures Risk Reduction – Burst Testing (cont’d)

Moments after tank burst

Several seconds after tank burst

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ORSC Cycle Engine Risk Reduction

- **Effort focused on design, analysis, fab, and test of 500 klbf full-scale ORSC main injector, TCA, and supporting hardware**
- **Test article scheduled to complete critical design review in Fall 2015, begin testing in early 2017**
- **Following activities have been accomplished:**
  - **Main injector and TCA made design and analysis progress, incl several design reviews, and completed fab risk reduction activities**
  - **Integrating components completed CDR, begun long-lead fab**
  - **Requirements dev, prelim design for test skid**
  - **Design reviews, long-lead procurements for NASA SSC test facility**
- **In the coming months, the team will:**
  - **Complete injector and TCA design and analysis, proceed into fab**
  - **Complete fab of integrating components**
  - **Finalize design and build test skid, test facility**
  - **Conduct testing of injector and TCA to demo combustion stability**

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Summary

- AR has applied state-of-the-art manufacturing and processing techniques to the heritage F-1, resulting in many noteworthy accomplishments and reducing the risk for full-scale engine development
- AR has also made progress on technology demonstrations for ORSC cycle engine, which offers affordability and performance for both NASA and other launch vehicles
- Dynetics has designed innovative tank and structure assemblies; manufactured them using FSW to leverage NASA investments in tools, facilities, and processes; conducted proof and burst testing, demonstrating the viability of design and build processes