UPDATE ON RISK REDUCTION ACTIVITIES FOR A LIQUID ADVANCED BOOSTER FOR NASA'S SPACE LAUNCH SYSTEM

Andrew M. Crocker
Dynetics, Inc., USA, andy.crocker@dynetics.com

The stated goals of NASA's Research Announcement for the Space Launch System (SLS) 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 and enable competition by mitigating targeted Advanced Booster risks to enhance SLS affordability. Dynetics, Inc. and Aerojet Rocketdyne (AR) formed a team to offer a wide-ranging set of risk reduction activities and full-scale, system-level demonstrations that support NASA's ABEDRR goals.

During the ABEDRR effort, the Dynetics Team has modified flight-proven Apollo-Saturn F-1 engine components and subsystems to improve affordability and reliability (e.g., reduce parts counts, touch labor, or use lower cost manufacturing processes and materials). The team has built hardware to validate production costs and completed tests to demonstrate it can meet performance requirements. State-of-the-art manufacturing and processing techniques have been applied to the heritage F-1, resulting in a low recurring cost engine while retaining the benefits of Apollo-era experience. NASA test facilities have been used to perform low-cost risk-reduction engine testing.

In early 2014, NASA and the Dynetics Team agreed to move additional large liquid oxygen/kerosene engine work under Dynetics' ABEDRR contract. Also led by AR, the objectives of this work are to demonstrate combustion stability and measure performance of a 500,000 lbf class Oxidizer-Rich Staged Combustion (ORSC) cycle main injector. A trade study was completed to investigate the feasibility, cost effectiveness, and technical maturity of a domestically-produced engine that could potentially both replace the RD-180 on Atlas V and satisfy NASA SLS payload-to-orbit requirements via an advanced booster application. Engine physical dimensions and performance parameters resulting from this study provide the system level requirements for the ORSC risk reduction test article. The test article is scheduled to complete fabrication and assembly soon and continue testing through late 2019.

Dynetics has also designed, developed, and built innovative tank and structure assemblies using friction stir welding to leverage recent NASA investments in manufacturing tools, facilities, and processes, significantly reducing development and recurring costs. The full-scale cryotank assembly was used to verify the structural design and prove affordable processes. Dynetics performed hydrostatic and cryothermal proof tests on the assembly to verify the assembly meets performance requirements.

This paper will discuss the ABEDRR engine task and structures task achievements to date and the remaining effort through the end of the contract.

I. INTRODUCTION

NASA'S Human Exploration and Operations Mission Directorate's Advanced Development Office at Marshall Space Flight Center (MSFC) released the SLS ABEDRR NASA Research Announcement (NRA) on February 9, 2012. The intent was to "1) Reduce risks leading to an affordable Advanced Booster that meets the evolved capabilities of SLS; and 2) Enable competition by mitigating targeted Advanced Booster risks to enhance SLS affordability."

To establish a basis for a program of risk reduction activities, the Dynetics Team developed a booster design that could take advantage of the flight-proven Apollo-Saturn F-1. The wealth of operational experience associated with the legacy F-1 engine allowed the focus of the effort to be on affordability rather than technical feasibility. They bring unique lessons to the Advanced Booster cost and performance trades.

The F-1 offers safety and reliability features demonstrated on 13 Saturn V flights of 65 engines with no failures. As a liquid engine, the F-1 can be acceptance tested to screen for defects prior to integration and, with the vehicle restrained, can be run on the pad to demonstrate pre-launch readiness. If an engine does shut down, the booster can maintain controllability by shutting an engine down on the opposite booster, allowing either mission completion or safe crew escape, depending upon the timing of the shutdown.

The high thrust of a two-engine, F-1-based booster design would deliver significant performance margin beyond NASA's 130 mT (287 klbm) Low Earth Orbit (LEO) payload requirement. The performance margin inherent to the proposed two-engine, F-1-based booster enables a robust approach to structural design. To reduce costs compared to traditional vehicle structures, low-cost aluminum alloy could be used for tanks and skirts using low-cost, self-reacting friction stir welding (FSW). The friction stir welded 5.5 m (18 ft) diameter structure leverages over $90M in recent NASA investments in tank manufacturing tools, facilities, and processes, significantly reducing development and recurring costs. The performance margin also allows a forward thrust takeout approach that avoids costly changes to the SLS Core and minimizes ground infrastructure changes. Using NASA's vehicle assumptions for the SLS Block 2, the proposed booster delivers 150 mT (331 klbm), providing a 20 mT (44 klbm) margin, even with a conservative, affordability-focused booster (Fig. 1).

II. BOOSTER CONCEPT DESCRIPTION

The original proposed booster features a robust structural design paired with two F-1B engines (Fig. 2). This combination of a simple, robust, and manufacturable structure with reliable, high-thrust engines provides confidence that NASA's affordability, reliability, and payload-to-orbit requirements can be met. Fig. 2 details design features of the booster concept central to this proposed affordable and reliable solution.[1]

Dynetics selected a 5.5 m (18 ft) diameter booster with F-1 engines to provide excess payload to orbit capability while staying within the vehicle dimensional requirements and mechanical interfaces required by NASA. The booster baseline design also reflects an effort to emphasize commonality in interfaces and loads between the SLS Core Stage and the Advanced Booster configuration. This booster concept uses a similar holddown and Core attach structure while also yielding an acceleration and dynamic pressure profile within NASA's requirements.

To minimize structural and attach impacts to the Core stage, Space Shuttle historical booster loads were assumed with the application of a conservative load factor. This was a conservative assumption because many of the load contributors inherent to solid rocket boosters, such as thrust rise, thrust rate mismatch at liftoff, thrust oscillation, and thrust mismatch at separation, are eliminated or mitigated by liquid engine boosters.

Although the focus of the booster design was the Block 2 SLS configuration, the performance of the booster concept for the Block 1A SLS configuration (i.e., prior to incorporation of the Upper Stage) was also assessed. For the Block 1A version of the booster, a derated F-1B engine was baselined to provide increased reliability by operating at reduced chamber pressure and thrust while building flight heritage for the F-1B in preparation for Block 2. The SLS Block 1A configuration with the proposed Advanced Booster provides payload capability from 103 mT (227 klbm)—with the F-1 derated to 85%—to 120 mT (265 klbm)—with the F-1 at 100% power. Fig. 3 shows both Advanced Booster options.

In early 2014, NASA and the Dynetics team agreed to move additional large liquid oxygen/kerosene engine work that had originally been its own ABEDRR prime contract to AR to become a subcontract under Dynetics. Led by AR, this work is focused on an Oxidizer-Rich Staged Combustion (ORSC) cycle engine that can apply to both NASA's Advanced Booster and other launch vehicle applications. This effort will demonstrate combustion stability and performance of a full-scale ORSC cycle main injector and chamber.

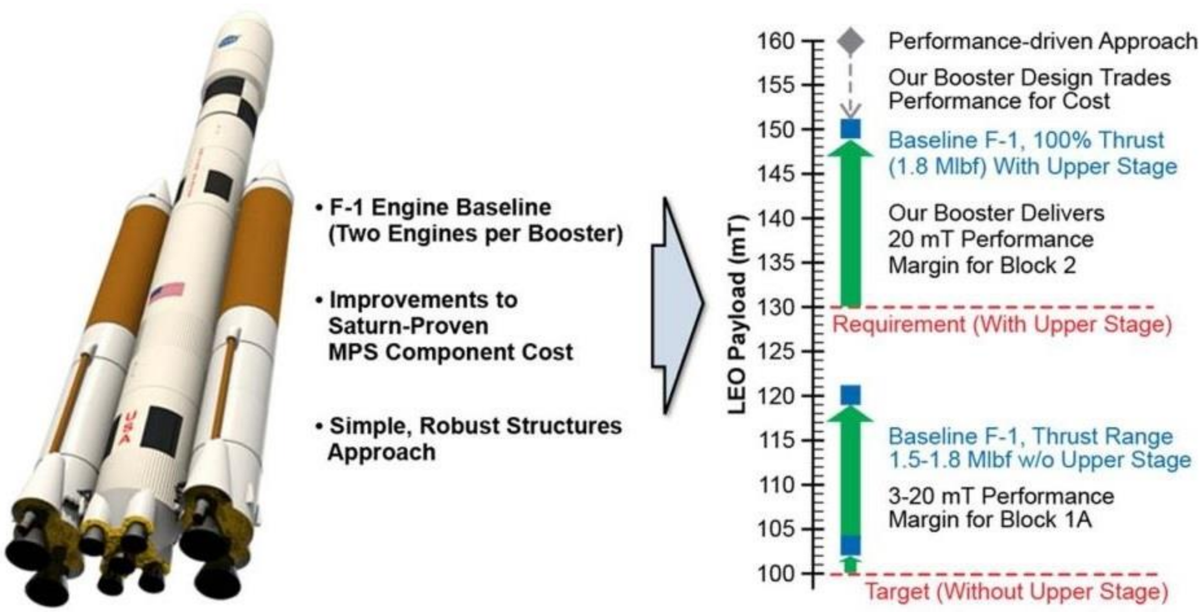


Fig. 1. The booster design exceeds performance requirements 20 mT over the 130 mT requirement.

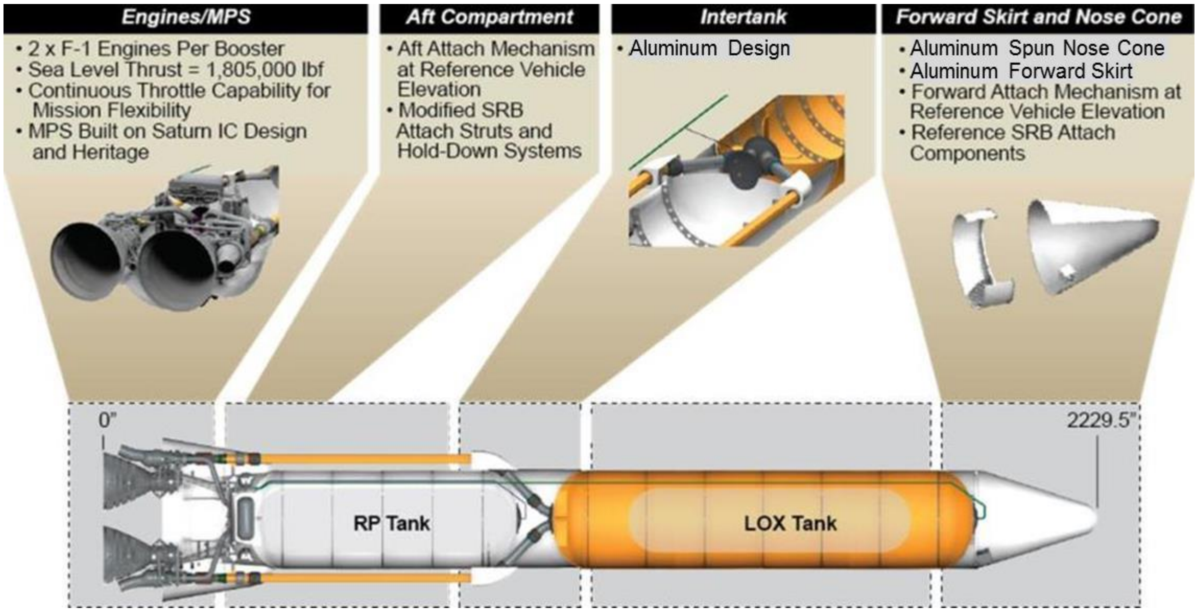


Fig. 2. Overview of the original Dynetics booster configuration.

III. RISK REDUCTION PROGRAM

Fig. 4 outlines a series of full-scale manufacturing and performance demonstrations focused on reducing risks associated with meeting aggressive affordability targets. In the F-1B engine task, the team modifies proven Apollo-Saturn components and subsystems to improve affordability and reliability (e.g., reduce parts counts, touch labor, or use lower cost manufacturing processes and materials).

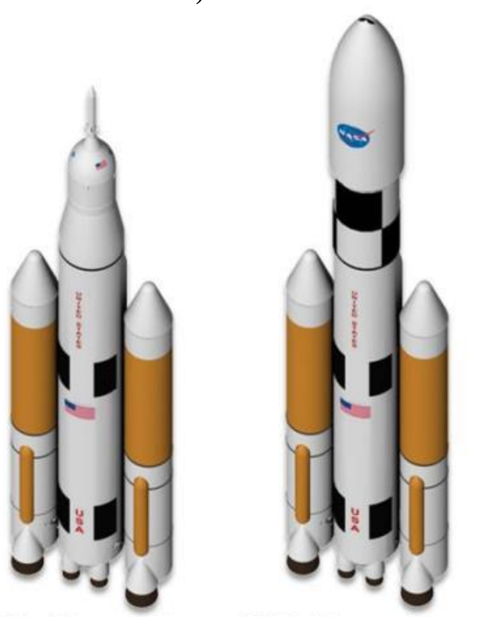


Fig. 3. Dynetics' Advanced Booster solution provides payload margin for both SLS configurations.

The team then builds hardware to validate production costs and tests to demonstrate it can meet performance requirements. State-of-the-art manufacturing and processing techniques will be applied to the heritage F-1, resulting in a low recurring cost engine, while retaining the benefits of Apollo-era experience. NASA test facilities will be used to perform a full-scale powerpack hotfire for low-cost risk-reduction engine testing.

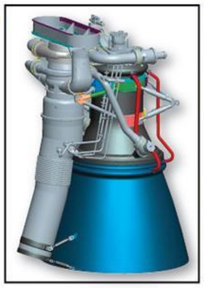
The structures task validates our innovative approach to achieve a low-cost booster structure. Dynetics builds a full-scale cryotank assembly to verify the structural design and prove affordable processes. Then we perform proof and cryothermal cycle tests on the assembly to verify the assembly meets performance requirements.

III.A. F-1 Engine Risk Reduction

Proposing critical demonstrations for ABEDRR, the Dynetics Team determined that using the F-1B engine for an Advanced Booster could enable a sustainable SLS architecture that delivers 150 mT (331 klbm) of payload, has traceable man-rated reliability/safety, has an affordable development and production price, and could fly by 2021. The engine approach would meld the best of F-1, F-1A, modern components, and lessons learned.

AR, as the engine task lead, planned to use existing engine components updated with new parts to establish performance, throttling, and transient characteristics. The team planned to demonstrate improved F-1B design and manufacturing processes to significantly reduce development time and cost and production cost.

A couple of years into the program, NASA's funding for ABEDRR became constrained, and it decided to deemphasize the F-1B effort. The following sections describe the work completed.



	Engineering Demonstrations and Risk Reduction Tasks	Benefit of Proposed Effort/Status at Start of DDT&E
A	**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

Fig. 4. Risk reduction demonstrations summary.

III.A.1. Gas Generator Build and Hot Fire Test

A Gas Generator (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.

The GG, valve, and instrumentation were integrated into NASA Marshall Space Flight Center (MSFC) Test Facility 116 (Fig. 5, Fig. 6). 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, and to determine the thermal characteristics of the GG. Secondary test objectives were to demonstrate TEA/TEB start transient characteristics, demonstrate GG capability to perform a full duration qualification test, and determine sooting characteristics of the GG hardware over multiple tests.

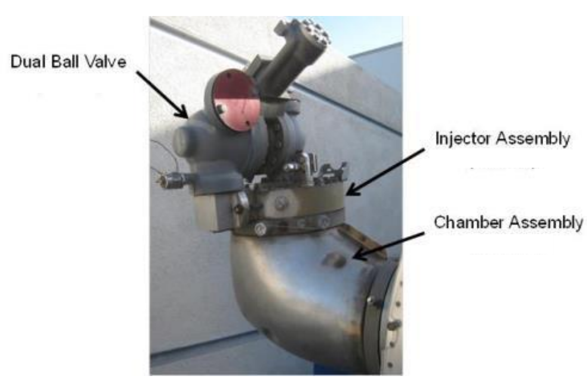


Fig. 5. F-1 gas generator test article hardware.

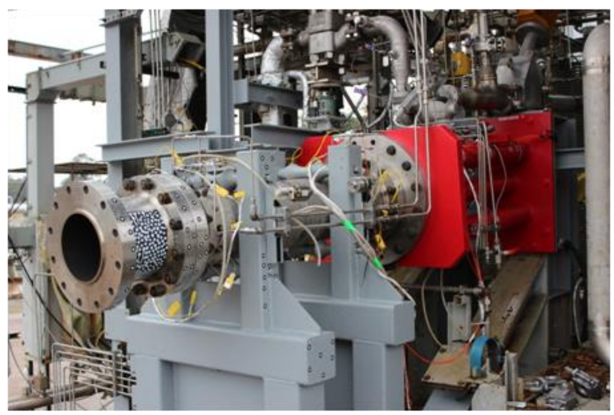


Fig. 6. F-1 gas generator mounted at NASA Marshall Space Flight Center Test Stand 116.

In February and March 2013, 10 tests were completed (Fig. 7). 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. The GG accumulated 235 seconds of hotfire time.

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. In summary, the risk to throttling operation was successfully reduced in preparation for subsequent Powerpack Assembly (PPA) testing.

Fig. 7. F-1 gas generator hotfire test.

As a cost reduction opportunity, AR fabricated a full-scale GG injector using a modern, low-cost, additive manufacturing technique called selective laser melting (SLM). This process has the potential to reduce production costs by reducing part count and simplifying the joining processing.

The SLM GG injector assembly was successfully completed. The injector core was fabricated using SLM techniques, saving months of machining time. Due to current SLM machine size limitations, the fuel manifold was fabricated separately. The manifold and inlet were welded to the core, and final machining/processing was completed. Proof testing and inspections were completed and passed. The injector assembly was delivered to NASA MSFC. In early June 2014, MSFC successfully conducted water flow testing of the injector to characterize the fuel and oxidizer flow passage resistances and visualize the flows (Fig. 8).

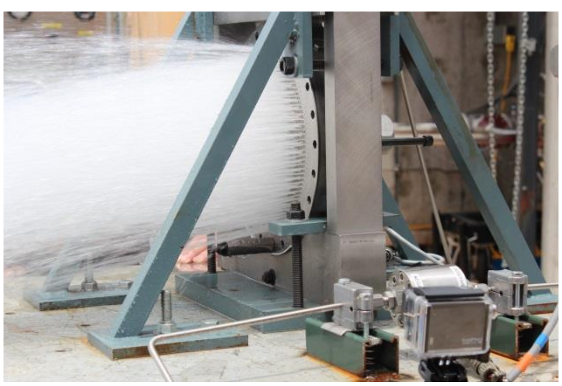


Fig. 8. F-1B SLM GG injector flow calibration test.

Due to scheduling issues, hotfire testing of the SLM GG injector was delayed, but it was completed in September 2015 in the same NASA MSFC test stand as the original heritage injector testing. 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 using a low conductivity metal. The test configuration included the F-1B SLM injector, the heritage F-1 bipropellant valve, the heritage F-1 combustor body, and a custom exhaust duct/nozzle sized for F-1B conditions. All tests were successful and matched the heritage injector test results very well (Fig. 9).

Fig. 9. F-1B SLM GG injector hotfire test at MSFC.

The SLM GG test provided an opportunity for a one-on-one comparison of a part built with traditional manufacturing for the Apollo F-1 engine to a part built with a new manufacturing process that the aerospace industry is investigating. The F-1B GG testing (and other tests with 3-D printed parts) helps NASA and the aerospace industry gather data on this new manufacturing process. The 3-D-printed F-1B GG adds more data to help NASA and industry reduce the risks associated with using 3-D printing to make parts for future engines.

III.A.2. Mk-10A Turbopump Risk Reduction

This paper will briefly discuss these activities, but they have been covered in detail in a previous paper[2].

The F-1B engine approach takes full advantage of the lessons learned and improvements developed over more than 60 F-1 R&D turbopumps, which led to the final F-1A Mk-10A turbopump configuration. These improvements enabled the engine to throttle while incorporating numerous producibility and design simplifications to reduce recurring costs and improve design reliability.

One task objective was to overhaul an AR-owned Mk-10A turbopump to demonstrate the ability to revise past designs and integrate new parts. First, AR disassembled the hardware. Next, AR used state-of-the-art reverse engineering technology to provide an “as-built” heritage hardware product definition for comparison against an existing Mk-10A engineering drawing database. Using the reverse-engineered model data, AR performed key analyses in preparation for PPA testing: turbine aerodynamic analysis, axial thrust analysis, rotordynamics analysis, updates of heritage rotor balance procedures, instrumentation planning, and bearing and dynamic seal design.

Another task was to manufacture a new LOX volute using modern casting techniques. This was done successfully, even demonstrating improvements over AR's recent J-2X LOX volute casting development. The first stage turbine blade was another casting effort. It yielded turbine blades capable of development hotfire testing. Finally, AR planned a task to develop a low-cost cast turbine manifold employing the configuration of the Mk-10A. The team designed and analyzed the turbine manifold through Critical Design Review. Then the team fabricated the cast turbine manifold parts and verified the feasibility of the approach.

III.A.3. Assemble and Hot-Fire Test F-1 Powerpack

This paper will briefly discuss these activities, but they have been covered in detail in a previous paper[2].

Powerpack Assembly (PPA) hotfire tests are a logical progression of increased technical risk reduction by coupling several critical components. PPA tests achieve realistic interactions between components that simulate tank head engine start, steady state, throttle, and cut-off environments. The PPA includes the GG, GG valves, Mk-10A turbopump, and heritage F-1 main propellant ducts and valves. Successful PPA testing reduces DDT&E schedule and cost risks by identifying and addressing technical challenges early.

AR had planned PPA testing late in the program, following successful GG and turbopump task completion. However, NASA's funding for ABEDRR became constrained, and PPA testing was removed from the plan. Prior to task stoppage:

- AR was ready to assemble and deliver two existing GG valves to enable the PPA to throttle.
- NASA MSFC had available engine main propellant valves that had been inspected deemed acceptable for PPA testing.
- A test skid was being designed to achieve engine-like environments during hot-fire tests.
- The PPA test article and facility design were taken to a preliminary design maturity level.

If the F-1B engine were selected for development, a key goal would be to complete PPA hot-fire testing at the start of DDT&E, with the Mk-10A turbopump rebuilt with new cast LOX volute, first stage turbine blades, and turbine manifold and an SLM GG injector and refurbished GG valves and main propellant valves. The effort described above made this possible.

III.A.4. Thrust Chamber Assembly Development

This paper will briefly discuss these activities, but they have been covered in detail in a previous paper[2].

The heritage F-1 engine Thrust Chamber Assembly (TCA) used many "hand-crafted" components, including a tube wall TCA, nozzle extension, and a wrap-around turbine exhaust manifold that exhausted into the nozzle. The objectives of the risk reduction task were to reduce fabrication risks through design, analysis, and demonstration of fabrication processes and to demonstrate low-cost fabrication technologies. The team planned to conduct detailed design, structural, thermal, and performance analyses and to fabricate and assemble an F-1B Main Combustion Chamber (MCC).

As discussed above, NASA's funding for ABEDRR became constrained early, and these constraints impacted the TCA task plan. Before task stoppage, all major MCC components were drawn and ready for fabrication, long-lead items ready for procurement, and all major tooling was ready for fabrication. Only final assembly drawings and minor tooling drawings remained.

AR had developed a process for making the MCC liner from a single ingot. A low-cost braze alloy was ready for use. Long lead plating tooling, liner machine tooling, and handling fixtures were ready for fabrication.

For the MCC jacket, component forgings were ready for procurement, all components and joining processes were ready for fabrication, and the final machining and jacket plating processes were ready.

Structural analysis indicated that the HIP cycle would result in acceptable bonding of the liner to jacket. The HIP assembly process cycle was defined and ready for manufacture.

The overall program objective was to reduce F-1B engine development risks leading to an affordable Advanced Booster. Despite funding challenges, the effort met this objective.

The team demonstrated F-1B engine and component understanding and readiness. It completed a gas generator hot-fire test series, proving throttling capability. It disassembled and reverse engineered an existing Mk-10A turbopump. It demonstrated long-term affordability through full-scale demonstrations of an additively manufactured GG injector and a cast LOX volute, turbine blades, and turbine manifold. Both the SLM process and the sand casting knowledge are transferrable to other parts of the F-1B engine. It prepared main propellant valves for test. It integrated engine loads and design, developed transient operational models, and designed interfaces with the facility for Powerpack testing. Finally, the team developed a new MCC design focused on dramatic cost reductions.

III.B. Structures Risk Reduction

Traditional launch vehicle structures designs are driven by mass considerations that result in custom parts and minimal commonality. Dynetics capitalizes on the performance margin provided by the F-1 engine to select an innovative, robust design, significantly lower cost than typical lightweight and complex launch vehicles. Robust design is coupled with state-of-the-art Friction Stir Welding (FSW) tooling and facilities at NASA to drive down life cycle cost.

The structures risk reduction task was planned to validate the designs, materials, equipment, and processes to produce robust and affordable structures. From design and analysis through production and testing, each key risk is systematically addressed and mitigated. Ultimately, the task planned to create a full-scale cryotank assembly (Fig. 10) that would be verified by proof pressure and cryothermal cycle testing.

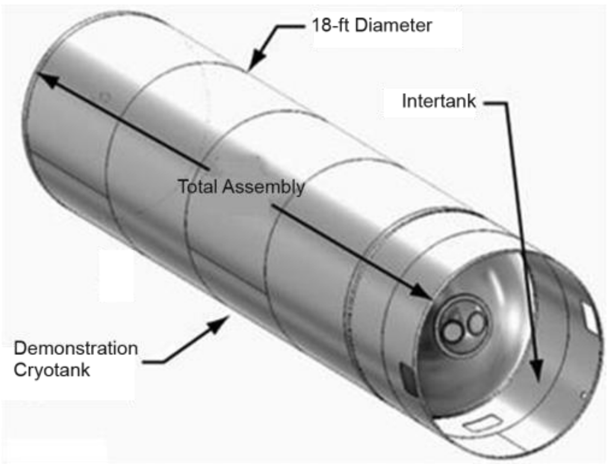


Fig. 10. Dynetics planned to demonstrate cost-effective manufacturing processes with a full-scale test article.

III.B.1. Build and Integrate Demonstration Cryotank

The structures task started with design and analysis activities. Dynetics performed initial structural analysis on the Advanced Booster skins and verified that the RP-1 tank, intertank, and LOX tank designs had positive margin for stress and buckling.

The team performed a detailed Advanced Booster 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. The team generated max shear and moment loads and P-equivalent loads, along with interface loads, vehicle support post loads, and stay loads. The team also generated fatigue and fracture stress spectra for Advanced Booster life assessments.

Working with NASA Langley Research Center, the team used the latest experimental data to update shell buckling knockdown factors.

Dynetics also performed thermal analysis of the tanks and intertank, in particular to determine steady-state temperature gradients in the structural components during ground testing.

Using these analyses, Dynetics determined the appropriate proof pressure levels for the planned tank testing. The team also made the final tweaks to the designs to complete the final structural component drawings.

The fabrication activities started with a mill run of aluminum plate. The plates were delivered to Spincraft for spin-forming domes and to Major Tool and Machine for manufacturing tank and intertank barrels.

A unique single-sheet barrel rolling technique was developed for the robust tank structure and demonstrated on seven barrels (Fig. 11). These barrels were trucked to NASA MSFC for welding.

Fig. 11. Dynetics tank barrels at NASA MSFC Building 4755.

ATI Ladish started with large aluminum ingots and worked them into ring forgings. The forgings were sent to Major Tool and Machine to be machined into y-rings (Fig. 12).

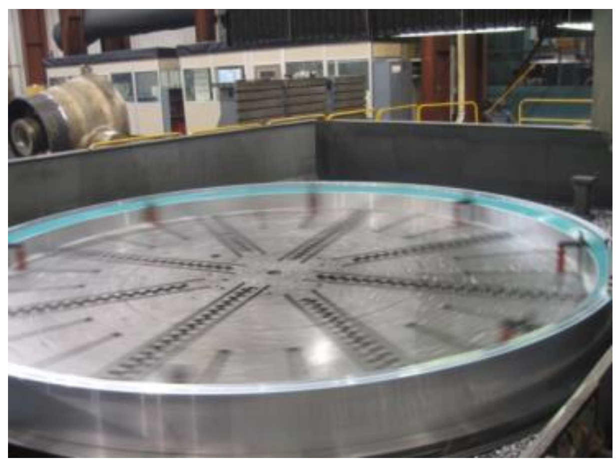


Fig. 12. Dynetics y-ring in machining.

Dynetics developed a tank build plan to weld the barrels using NASA MSFC FSW tools. Weld schedules were developed on a MSFC Production Development System (PDS). First, the team developed conventional FSW parameters. These were successfully implemented on longitudinal barrel welds on the Vertical Weld Tool (Fig. 13, Fig. 14). All barrels passed Phased Array Ultrasonic Testing (PAUT) and dye penetrant testing. The original plan for start to finish time on welding operations and trimming barrel to length operations was 17 working days; Dynetics was able to complete the operations in 6 working days.

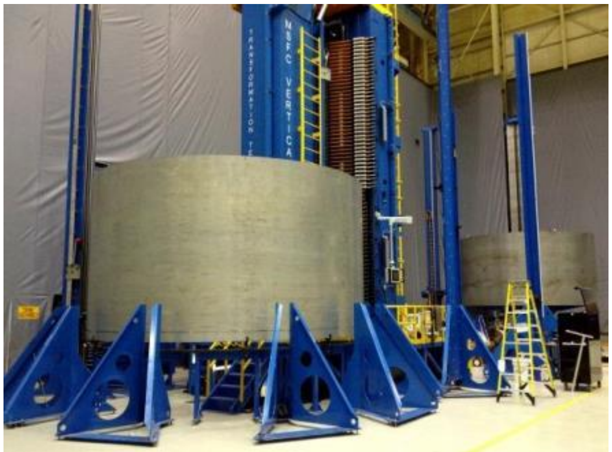


Fig. 13. Dynetics barrels on MSFC FSW tools, Vertical Weld Tool (near) and Vertical Trim Tool (far).

Fig. 14. Dynetics barrel on the Vertical Weld Tool.

Following the longitudinal welding, the weld schedule for self-reacting FSW was developed on the PDS and transferred to MSFC's Robotic Weld Tool for circumferential welding of the two domes to the y-rings (Fig. 15). Dome to y-ring welds were completed, passing PAUT and dye penetrant testing (Fig. 16).

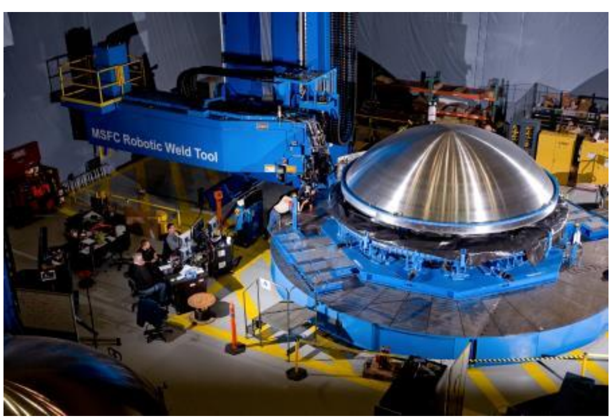


Fig. 15. Tank dome on the MSFC Robotic Weld Tool.

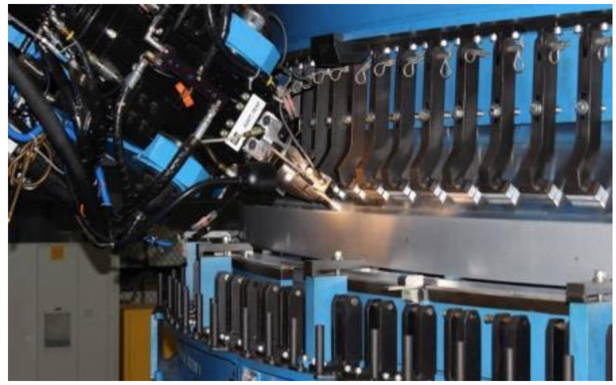


Fig. 16. MSFC RWT welding Dynetics dome to y-ring.

Next, a weld schedule was developed for self-reacting FSW for circumferentially welding the tank barrels to the dome/y-ring assemblies and the barrels to other barrels on MSFC's Vertical Assembly Tool (VAT) (Fig. 17). Mechanical modifications were made to the tool to accommodate the size and weight of Dynetics' structure. The tool was checked out to verify that circumferential welding of the thick barrels could be accomplished.

Test welds were completed on test panels on the VAT, and all welds passed PAUT inspection and tensile testing results came back good.

Fig. 17. NASA MSFC's Vertical Assembly Tool.

Whereas the original plan was to build a tank with four barrel sections, NASA negotiated with Dynetics to reduce schedule and cost by building a tank with a single cylindrical barrel. Circumferential welding would still be demonstrated, and testing could still be completed.

Circumferential welding started with the aft end of the tank. Hawthorne clamps were used to hold the y-ring and barrel together for welding. This worked well, and there were no broken pin tools during the welding process.

After the first weld (aft end) was completed, PAUT inspection was completed. The joint had no rejectable defects in the vast majority of the weld. There was one defect found in the overlap region of the final weld where the final weld pass crossed over the original start up point. The material in this area is more ductile than parent metal due to the fact it has been processed once already. Dynetics chose to create a defect panel with a similar sized indication in it and have it tensile tested to evaluate the strength of the joint in that area. The results of the tensile testing of the defect panel resulted in a weld strength higher than the design allowable. So the weld was deemed acceptable.

The forward end weld was then conducted using the same approach as the aft end but with a much smaller weld overlap area (Fig. 18). PAUT inspection followed, and tiny indications were found at the points of the notches cut for the Hawthorne clamps. These indications were measured, and the sum of all the indications was much smaller than the indication that was identified on the aft end of the tank. So, due to the previous defect panel testing, the weld was deemed acceptable.

With all FSW and PAUT completed, the finished tank was removed from the VAT, attached to a transport fixture, and moved to the assembly area for final inspection (Fig. 19).

The self-reacting FSW process on both ends of the tank required plugs to be welded in place. The procedure was identical to that for the dome assemblies. Final procedures also included flushing the inside of the tank to remove debris and installation of the sump seals, the sump covers, and all fasteners. Fig. 20 shows the tank after completion.

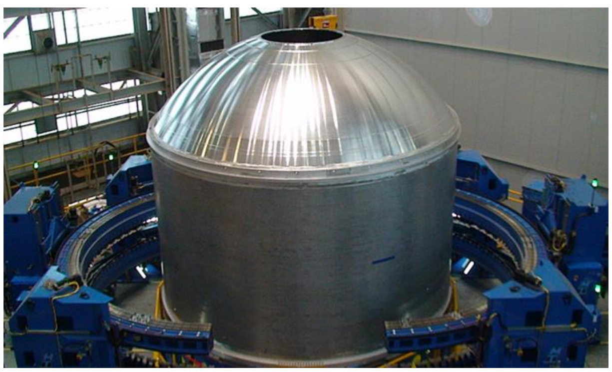


Fig. 18. Forward weld completed on tank in VAT.

Fig. 19. Completed tank removal From VAT using forward lifting fixture.

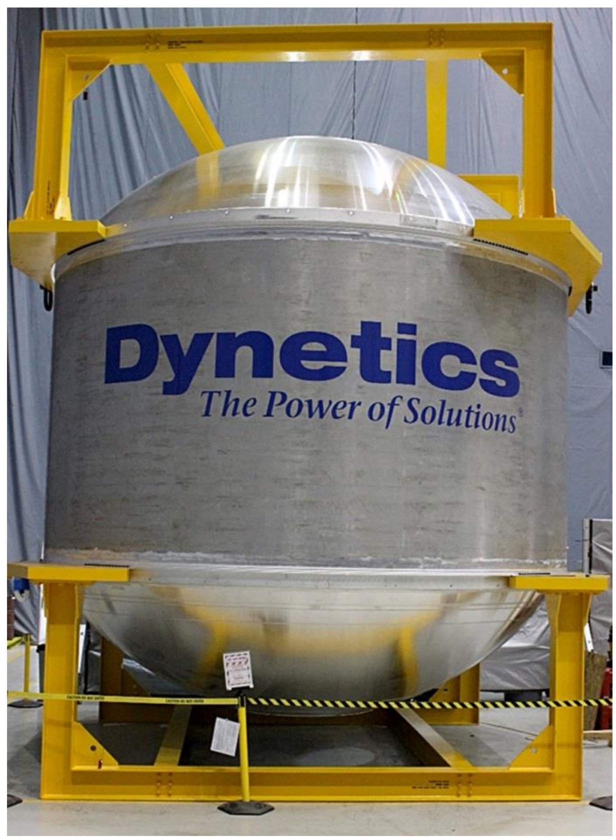


Fig. 20. Finished Dynetics tank.

Prior to testing, the tank, test stand, and supporting hardware were moved from the fabrication facilities at MSFC to Dynetics’ test site in Iuka, Mississippi. The hardware was first moved across Redstone Arsenal to the MSFC dock on the Tennessee River (Fig. 21). There, the hardware was loaded onto a barge (Fig. 22). The top lifting fixture was removed from the tank, and the tank covered for transit.

Fig. 21. Moving the completed tank across MSFC to the river.

Fig. 22. Placing the tank and fixtures on the barge for transport.

Once in Iuka, the cover was removed, and the lifting fixture was re-attached to the tank. The tank, test stand, and supporting hardware were then craned off of the barge and transported to a support building adjacent to the test site. There, the bottom lifting fixture was removed from the tank, and the tank was integrated to the test stand to form the test article (Fig. 23).

Fig. 23. Integrating the tank and test stand in Iuka, MS.

While in the support building, the first set of strain gauges was installed on the test article. During the strain gauge installation, access decking, railing, and a support structure were fabricated onto the removed lifting fixture. After strain gauge installation, the test article was craned onto a transportation platform and transported from the support building to the test pad (Fig. 24). Once mounted to the test pad, the existing lifting fixture was removed, and the modified lifting fixture was installed (Fig. 25, Fig. 26).

Fig. 24. Transporting the integrated test article to the test facility.

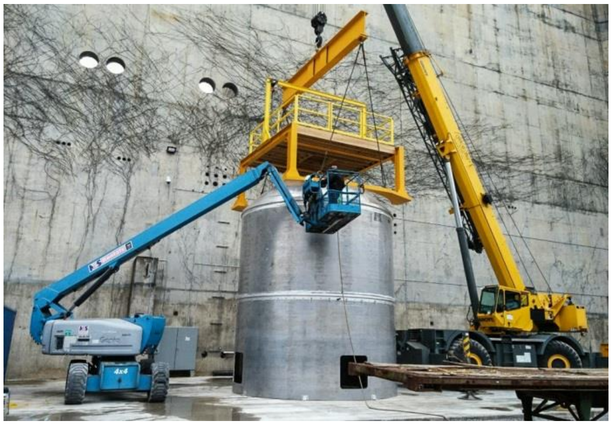


Fig. 25. Placing the integrated test article on the test pad.

Fig. 26. Integrated test article on the test pad.

III.B.2. Cryotank Proof and Thermal Cycle Test

Dynetics performed a series of proof pressure and thermal cycle tests to demonstrate that the designs, materials, manufacturing processes, and inspection methods for building pressurized cryotanks are ready for DDT&E. Testing was conducted per a NASA-approved test matrix. The test pass/fail criteria were defined in a Tank Test Plan. Procedures were generated to define the steps for each test.

For Test 1, the hydrostatic proof test, the test article was 100% filled with water (determined by water flowing from the vent valve on top of the tank. The vent was then closed, and the test article was pressurized with GN_2 to 10 psig ± 2 psi to verify the strain gauges were operational. Then the tank was pressurized to the specified hold points prior to reaching the target pressure. Each pressure was held for 3 minutes, and the target pressure was held for 5 minutes. Following the proof, the vent valve was opened, and pressure was relieved. Then the tank was drained. All strain, temperature, and pressure sensors were operational during the test. Visual leak checks were performed throughout the test using pan/tilt/zoom (PTZ) cameras. Overall, the test was a success, and the strains observed were in the range expected.

Following the tank drain, the sump flanges were removed to replace the Buna-N O-ring seals with cryogenically-rated Chrysler O-ring seals and to confirm no water was present in the sump main seals. The tank was reassembled per the cryogenic configurations defined in the Test Plan.

Prior to the LN_2 transfer and control test, the test article was purged using 3,200 ft^3 of GN_2 to remove moisture from the system. A blanket positive blanket pressure was applied to the tank to prevent moisture buildup.

The purpose of the LN_2 transfer and control test was to serve as a trial run to ensure operations between the test team and the LN_2 vendor went smoothly. It also provided the opportunity to test the LN_2 fill, vent, and drain systems.

For the LN2 transfer and control test, the team filled the tank with up to 6,000 gallons of LN_2. The tank bottom dome was filled with LN_2 up to the aft y-ring. Following fill, tank valves were used to control boil-off and pressurization. Maximum pressure inside the tank reached less than 7 psig. Temperature compensating thermocouples were used for this test. Strain, temperature, and pressure were measured during the test. Visual leak checks were performed using PTZ cameras.

Prior to the LN_2 thermal proof test, the access ports on the tank stand were sealed off using insulation to reduce in convective heat transfer. The team also added a LN_2 sprinkler to chill the test stand faster to reduce the temperature delta between the test stand and tank y-ring interface. It was anticipated that the sealed ports and LN2 sprinkler system would decrease total LN2 fill duration (Fig. 27).

Fig. 27. Chilling the test stand with liquid nitrogen.

For the LN_2 thermal proof test, during the first 20% of the fill operations (Fig. 28), it was noticed that there was an increased pressure on the fill line upstream of the isolation valve. Fill operations were halted. After investigation, it was determined that the poppet of the LN_2 fill isolation valve was stuck half open. To correct this and prevent further interruptions, the vent for the control valve was blocked to provide full flow through the control valve body allowing the isolation valve to be completely open.


Fig. 28. LN2 tankers connected to LN_2 fill system.

As the tank approached 40% full of LN_2, the above-mentioned control valve vent blockage failed, resulting in the LN_2 fill isolation valve failing shut. This resulted in a pressure spike that popped the fill line relief valves. Fill operations were again halted. The fill isolation valve was manually opened for the remaining duration of the test. The total fill operation took approximately 12 hours (Fig. 29).

Once the tank was approximately 95% full, all tank valves were closed, and the tank was pressurized with GHe. The target pressure was held for 5 minutes. Temperature compensating thermocouples were used for this test. Strain, temperature, and pressure were measured during the test. Visual leak checks were performed throughout the test. There was no yielding of the tank during this test, and the test was successful.


Fig. 29. Integrated test article is chilled down with liquid nitrogen (shows boiloff at top of tank).

For Test 4, the hydrostatic proof and burst test, the test article was 100% filled with water, as determined by water being seen flowing from the vent valve on top of the tank. The vent was then closed, and the tank was hydrostatically pressurized using a water pump. Pressure hold points were held for at least three minutes, then pressurization continued until failure of the test article. The failure location was along a machining non-conformance on the top dome. Progression of the burst can be seen in Fig. 30 through 33. The increase of pressure versus time is shown in Fig. 34.

Fig. 30. Moment of burst (note fluid escaping through crack in top dome).

Fig. 31. Moments after tank burst.

Fig. 32. Several seconds after tank burst.

Fig. 33. Several seconds after tank burst.

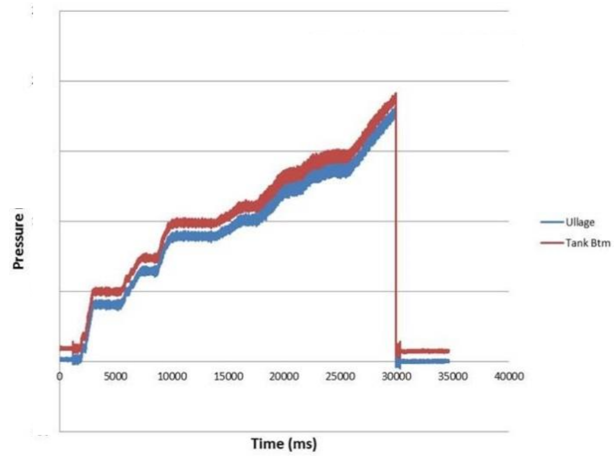


Fig. 34. Pressure vs. time for final proof and burst test.

Following the failure, the pump was turned off, and the vent and drain valves on the top and bottom of the tank were opened and the tank allowed to drain completely. Temperature compensating thermocouples were not used for this test. Strain, temperature, and pressure were measured during the test. Visual leak checks were performed remotely throughout the test. All the data looked good during this test until the burst event occurred. During the event, some of the strain gauges de-bonded or disconnected. It is likely that this was due to the burst event, the shock of the tank and fixture landing on the ground, or the lifting fixture damaging the wires feeding the data acquisition system.

The proof and burst test results verified the structural design and manufacture of an affordable booster concept for the SLS.

III.C. Oxidizer-Rich Staged Combustion Cycle (ORSC) Engine Risk Reduction

The purpose of this risk reduction activity is to demonstrate combustion stability and measure performance of a 500,000 lbf thrust class main injector. To meet these objectives, the effort is focused on the design, analysis, fabrication, and test of a full scale ORSC main injector, Thrust Chamber Assembly (TCA), and supporting hardware.

As stated above, NASA and the Dynetics Team agreed to move work focused on an ORSC cycle engine under Dynetics' ABEDRR prime contract. Although it was originally contracted for demonstrations related to NASA's Advanced Booster, the technologies also apply to other launch vehicle applications, such as a domestic replacement for the Russian-based RD-180 rocket engine on the Atlas V launch vehicle.

Through the original Aerojet prime contract, NASA partnered with the US Air Force to investigate the feasibility, cost effectiveness, and technical maturity of a domestically-produced engine that could replace the RD-180 and also potentially satisfy NASA SLS payload requirements for an advanced booster. The resulting engine performance parameters were used as design requirements for the ABEDRR risk reduction activity. As of the writing of this paper, the following activities have been accomplished on the ORSC risk reduction task.

The main injector and TCA have completed design and analysis, conducted several AR and NASA/USAF customer design reviews—including Critical Design Reviews (CDRs) of both major components, and have completed many fabrication risk reduction activities. All injector and TCA drawings are complete and released, and nearly every piece part is on contract to be fabricated.

For the injector, major components have been manufactured, and major assembly has been completed. Remaining items include material coatings (e.g., thermal barriers) and small component fabrication for parts to be attached to the injector in the final stages of assembly.

The chamber is a heat sink with several locations down the length for injection of boundary layer cooling fluid. The chamber has completed major manufacturing operations and is in the final assembly phases.

The integrating components—components that direct the hot gas flow from the customer-provided preburners to the injector and TCA—have completed and released all drawings, and all components are on order for manufacturing. Several major components have already finished fabrication and are in storage at AR's NASA Stennis Space Center (SSC) location. Others are still in work and will be completed over the next few months.

Due to the extremely high pressures and temperatures of the oxygen-rich flow coming from the preburners, many components are manufactured from a high strength, burn-resistant alloy. The ABEDRR test program will mark the first hotfire test of components of this alloy. ABEDRR has been working through various methods of manufacturing with this alloy—casting, several additive manufacturing approaches, etc.—which has taken additional time but will lay the foundation for future efforts using this material.

The test skid assembly supports the test article and provides the structural interface to the test facility. Over the last year, the team has finalized the design and analysis of the test skid assembly, completing a Detailed Design Review (DDR), and has completed manufacture, assembly, and testing of all hardware. A Hardware Acceptance Review (HAR) was held at SSC to verify that the assembly and all associated hardware met their requirements. Fig. 35 shows the main thrust takeout structure and the exhaust duct (for use when testing the preburners only). Fig. 36 shows the test skid, and Fig. 37 shows a closer view of the carriage assembly; these will be used to support the exhaust duct and TCA when they are mounted to the thrust structure in the test stand.

The SSC test facility design and analysis to handle single preburner, dual preburner, and then integrated testing with two preburners, main injector, and TCA has been completed. Multiple design reviews were conducted to cover each major stand upgrade, addition, or modification to Test Stand E1, Cell 1. An example is the addition of an overhead bridge crane structure being built over/around the cell (Fig. 38). Also, analytical integration activities have been ongoing—generation and detailed review of Interface Control Drawings (ICDs), for example—to ensure that all interfaces will match and that build-up of the stand will efficient.

High thrust, LOX/kerosene rocket engine test facilities are rare, so the capabilities at SSC's "E" test complex are in high demand. The 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. There are limited SSC personnel and physical resources available for testing at E1. Therefore, the pace of test progress will depend, at least in part, on the pace and duration of adjacent test programs. Previous test plans have been stretched out to accommodate SSC's expected resource availabilities.

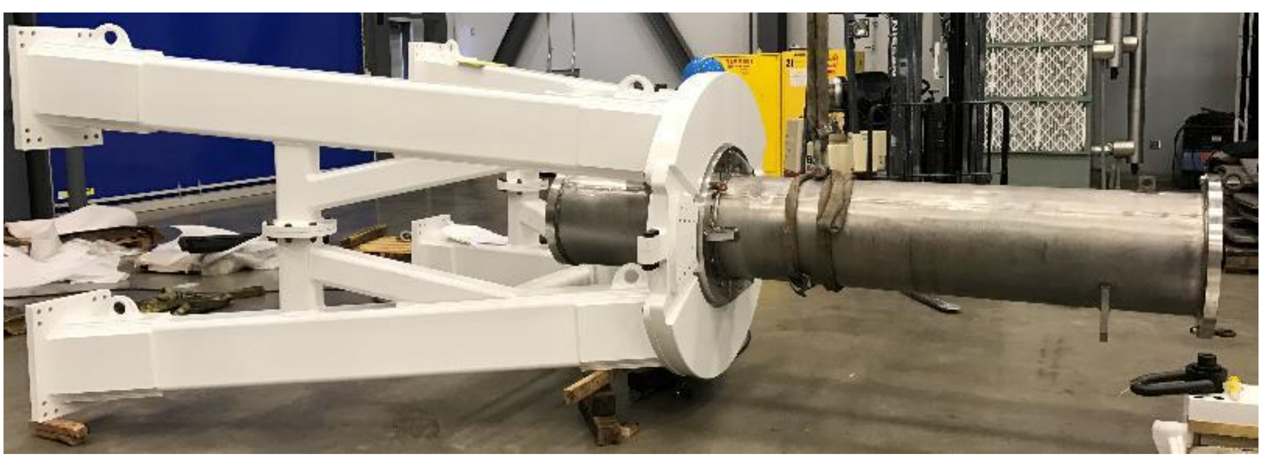


Fig. 35. ABEDRR thrust takeout structure and exhaust duct at Dynetics facility after final assembly and checkout.

Fig. 36. Test skid, ready for delivery to NASA SSC.

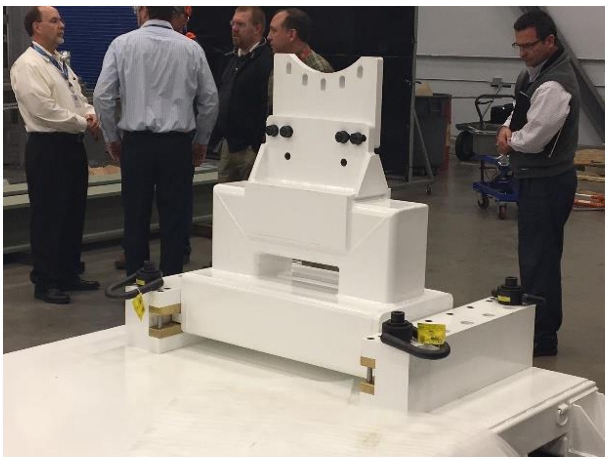


Fig. 37. Carriage assembly, mounted on test skid and ready for delivery to NASA SSC.

Testing by the other engine program in E1, cell 1 is expected to be completed by Fall 2017. Upon release of the stand, NASA will complete its physical additions and modifications to the stand, which are expected to be finished by the end of 2017. At that point, ABEDRR has the responsibility to physically install the test skid assembly and the integrating components to the stand.

When the test skid assembly (including the exhaust duct) and integrating components are installed, the first customer-provided preburner will be integrated, in early 2018. Single preburner testing will be conducted through mid-2018. Then SSC and ABEDRR will reconfigure for testing the second preburner, which will continue through late 2018. Then both preburners will be mounted at once, and dual preburner testing will be conducted through early 2019. Finally, the exhaust duct will be removed, and the integrating components will be configured to accommodate the injector and TCA. The team will conduct testing to demonstrate combustion stability and measure performance. ABEDRR testing is planned to continue through the end of 2019.

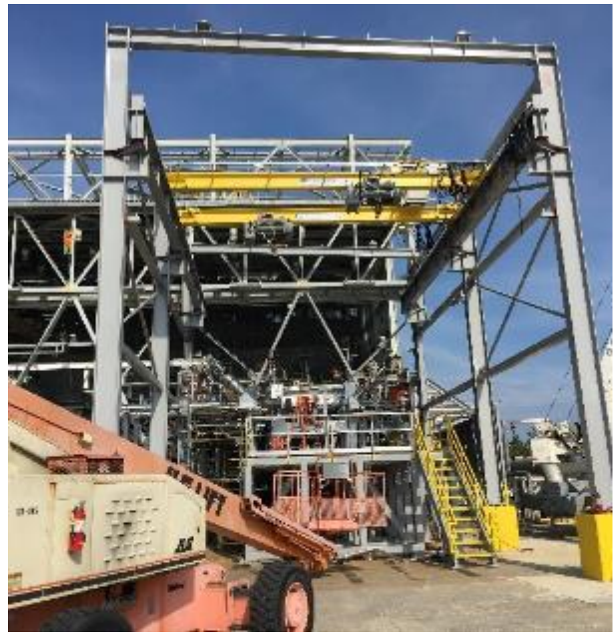


Fig. 38. Overhead bride crane structure being built at SSC Test Stand E1, Cell 1 for use with integrated testing.

IV. SUMMARY

For NASA's SLS ABEDRR procurement, Dynetics and AR formed a team to perform a series of full-scale risk mitigation hardware tasks for an advanced booster approach to meet the evolved capabilities of the SLS. During the ABEDRR effort, the Dynetics Team 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 an ORSC cycle engine, which may provide the affordability and performance required for both a NASA Advanced Booster and other launch vehicle applications. Finally, Dynetics has designed innovative tank and structure assemblies and manufactured them using friction stir welding to leverage recent NASA investments in manufacturing tools, facilities, and processes. Dynetics successfully conducted tank proof and burst testing, demonstrating the viability of the affordable structural design and build processes.

V. REFERENCES

1. IAC-12-D2.8.10x16320: "Enabling an Affordable, Advanced Liquid Booster for NASA's Space Launch System," Crocker, A., et al., 63rd International Astronautical Congress, Naples, Italy, 1-5 October 2012.
2. AIAA Paper 2014-3476: "Update on Risk Reduction Activities for an F-1-based Advanced Booster for NASA's Space Launch System," Crocker, A., et al., 2014 Joint Propulsion Conference, Cleveland, OH, 28-30 July 2014.