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CubeSat Advanced Technology Propulsion System Concept

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ABSTRACT

One of the many challenges when it comes to small satellites is low cost, especially when it comes to propulsion. At Aerojet Rocketdyne a CubeSat propulsion system was developed utilizing the advantages of the additive manufacturing process. This design reduces the part count by 50%, eliminates all 22 final assembly welds and reduces the projected recurring propulsion system cost by 75%. Starting with the CubeSat envelope of 1000 cubic centimeters, a typical satellite hydrazine mono propellant propulsion system was created for a baseline comparison. The goal of the advanced technology low cost propulsion system was to minimize part count by taking maximum advantage of additive manufacturing. This innovative concept combines 22 parts into two additive manufactured parts; literally, a “plug and play” final assembly approach. The propulsion system components (i.e., thrusters, valves, regulator, isolation valves, service valves, burst disks, etc.) are all installed into the two additive manufactured parts at final assembly. At Aerojet Rocketdyne, design guidelines were developed for the Direct Metal Laser Sintering (DMLS) process. These guidelines (i.e., part accuracy, overhangs, cavity features, floor features, wall features, minimum feature size, wall thickness, etc.) were used when designing the CubeSat DMLS parts. The parts initially were rapid prototyped with a multi-color 3D printer. The parts were then fabricated with both Inconel 625 and Titanium 6-4 using the Concept Laser M2 machine. Material test specimens form the same machine used to make the CubeSat parts were fabricated and tested for material properties (i.e., ultimate, yield, ductility, etc.). After fabrication the parts went through powder removal, clean, stress relief, wire Electric Discharge Machining (EDM) from the build plate and a Hot Isostatic Pressing (HIP) heat treat process. To verify that the parts met all the dimensional requirements, a white light inspection was performed and compared to the original Computer Aided Design (CAD) model. The final step was post machining operations on all the sealing surfaces and threaded interfaces. Due to the continuing improvement in additive manufacturing capability, low cost satellite propulsion systems are now possible.

DESIGN

When the primary goal of any product is low cost, the focus for design is to reduce part count and manufacturing operations. This means combining as many features into as few parts as practical. The additive manufacturing process is an attractive option to the designer as a means of accomplishing this goal. At Aerojet Rocketdyne, design guidelines were developed for the Direct Metal Laser Sintering (DMLS) process. These guidelines (i.e., part accuracy, overhangs, cavity features, floor features, wall features, minimum feature size, wall thickness, etc.) were used when designing the CubeSat DMLS parts. Although quite a bit less restrictive than wholly conventional alternatives, additive manufacturing still does not leave the designer free to create unlimited geometries. The design must consider build direction, minimum wall size, minimum feature size, powder removal from closed volumes, and subsequent subtractive manufacturing (conventional machining) operations.

Build direction is a very important consideration when designing for additive manufacturing. One of the biggest weaknesses of additive manufacturing is unsupported features. During the buildup, everything starts on a build plate. Features that are unsupported, or are supported by un-sintered powder, are not very robust. The results could be from a very poor surface finish, to outright failure of the feature. However, an unsupported feature in one build direction would be the top of a feature if the part was built in the opposite direction. Another option is the addition of features that would transition over to the unsupported feature. As a last resort, another option that can be traded is the addition of a lattice structure that would be machined off in the post additive manufacturing processing. This lattice structure does not have to be part of the design CAD model, but can be added in the machine control software as the part is prepared for the additive manufacturing run.

For closed volumes integrated into the additive manufactured part, whether they are for fluid passages, fluid tank, or lightening, cleanout ports need to be provided. Ideally there should be at least two, each one located at the extreme ends of the volume away from each other. This gives the option of flowing some medium through the volume to ensure no un-sintered powder remains. If this volume is to be used as a fluid tank, provision should be provided at the cleanout ports for plugging or the installation of a valve.

Any part interfaces that require higher precision, or smoother surface finishes, than that provided by the additive manufacturing process, will have to be "cleaned up" with subtractive manufacturing processes (conventional machining). Enough parent material will have to be added to insure good cleanup. Provisions for tool access will have to be maintained.

Additive manufacturing can reduce or eliminate the need for tooling. However, if it is desired, tooling features and/or interfaces can be easily added to facilitate any post additive manufacturing processing. Understanding the material properties specific to the material (i.e., Inconel 625, Titanium 6-4, etc.) and the machine (i.e., laser, electron beam, etc.) is essential. The material properties (i.e., ultimate, yield, ductility, etc.) can be different then wrought material properties pre and post heat treatment.

At Aerojet Rocketdyne additive manufacturing was applied to two different CubeSat design concepts. The first design concept is built around a piston tank and the second design concept is built around a spherical tank. The piston tank design concept included additive manufactured piston tank, thrust chamber/nozzles, standoffs, and brackets. The spherical tank design took an aggressive approach to additive manufacturing by minimizing part count. This spherical propellant tank design reduces the part count by 50%, eliminates all 22 final assembly welds and reduces the projected recurring propulsion system cost by 75%. Figure 1 shows the two different design concepts. Both design concepts are hydrazine propellant systems with gas pressurization systems as shown in Figure 2.

The piston tank concept uses Nitrogen as a blowdown system and the spherical tank concept uses Helium as a pressure regulated system. Both use mono propellant catalyst bed thrusters. The delta velocity performance capability of each system is shown in Figure 3 as a function of payload mass.

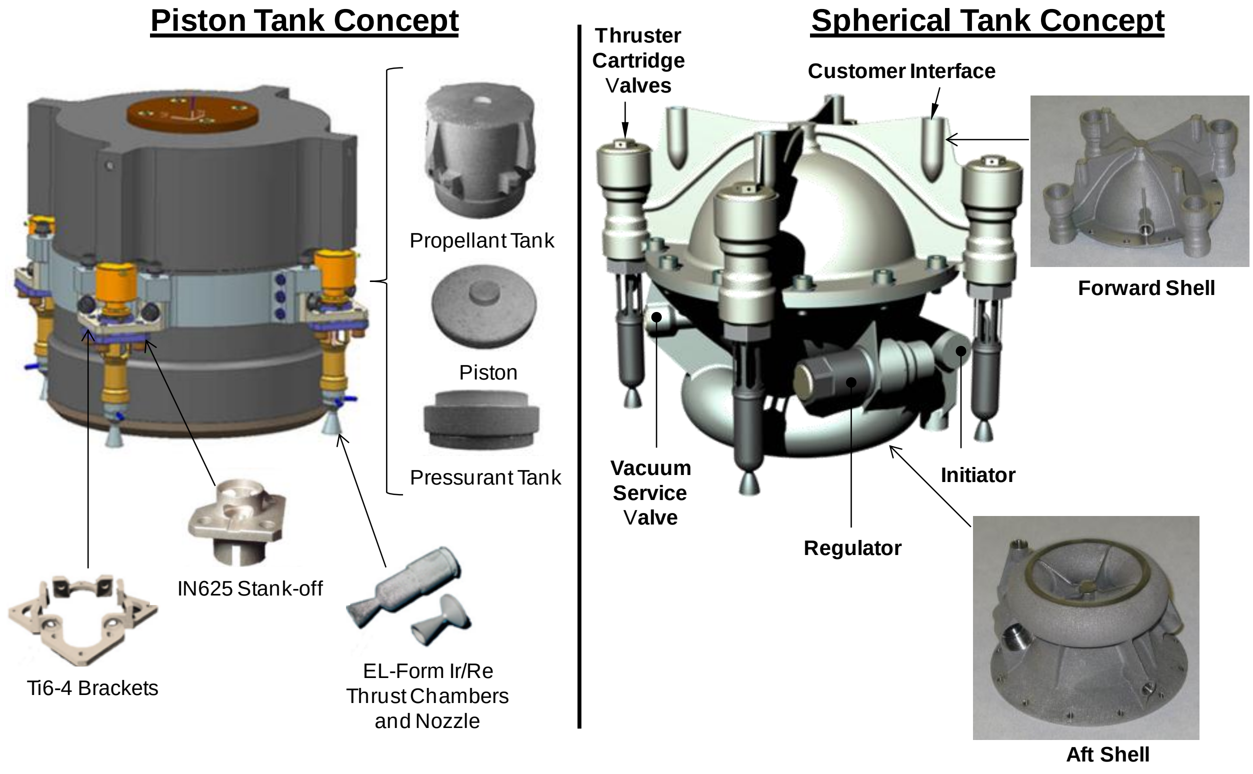
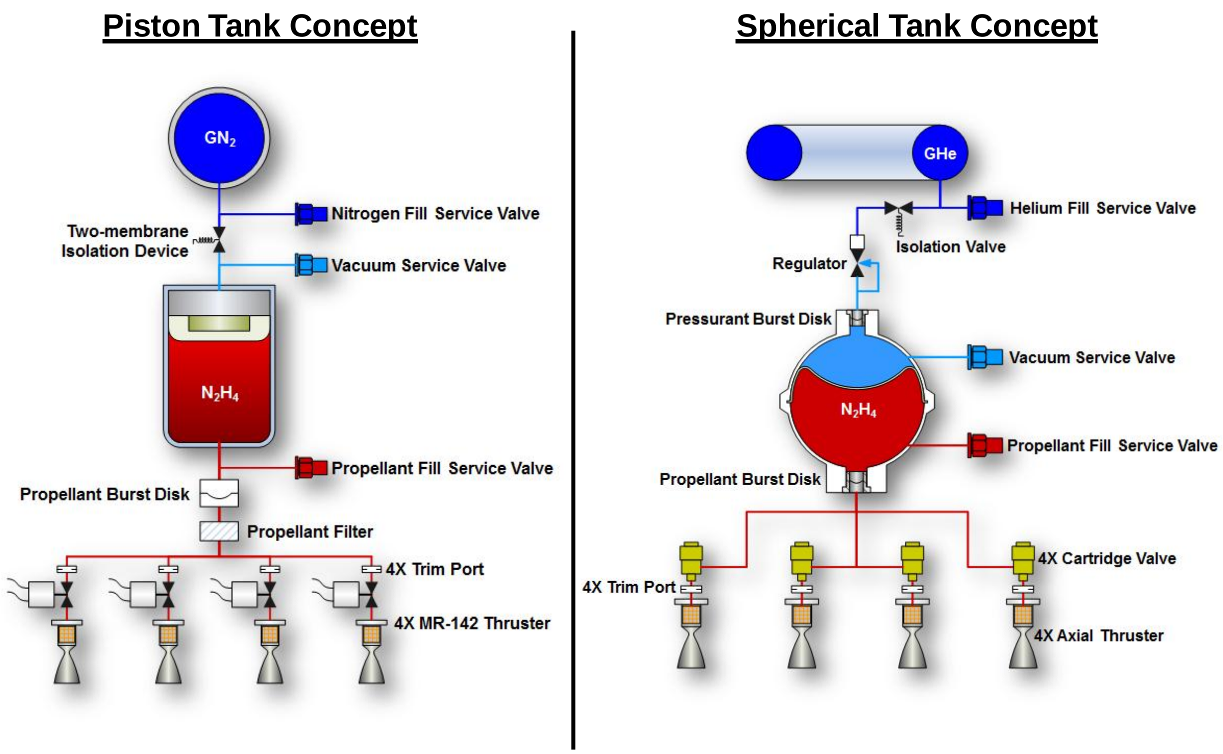


Figure 1: Propulsion Systems Top Assemblies



Piston Tank Concept

Spherical Tank Concept

Figure 2: Propulsion System Schematics

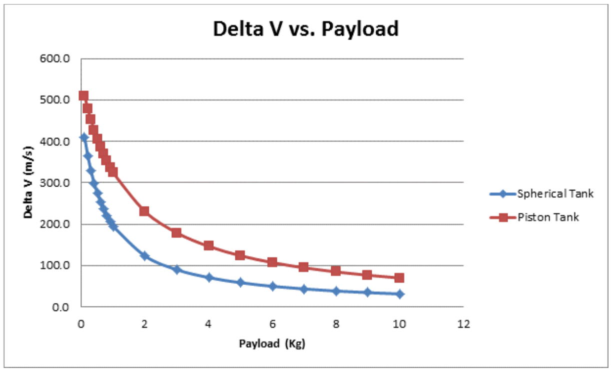


Figure 3: Spherical and Piston Tank Concept Performance Summary

FABRICATION AND POST PROCESSING

This section is focused on the fabrication and post processing spherical tank concept. There are two main fabrication methods that can be used for additive manufacturing, Electron Beam (EB) and Laser. Each manufacturing method has advantages and disadvantages depending on the material and geometry. As an example, the EB machines have the ability to have a pre-heated build plate that can result in less residual stress in the parts after fabrication. Since Aerojet Rocketdyne has in-house capability with the Concept Laser M2 machine (shown in Figure 4) that has a build volume of 9.8 inches x 9.8 inches x 11.0 inches height, it was decided to start with Inconel 625.

Before the parts are fabricated the Computer-Aided Design (CAD) models are reviewed to make sure good design practices were followed, ports are available for power removal, and additional material is added between the parts and build plate for removing the parts from the build plate (i.e., wire EDM). If required, additional lattice structure is added to the CAD model for additional structural support during the build process and later removed. The Inconel 625 parts were very successful the first time through, due to following good design guidelines described in the previous section, quality of powder material, and laser fabrication parameters. Once the build process was completed, the parts were removed from the additive manufacture machine and any internal powder was removed. The build process can take approximately a day per one inch of part height. If temporary lattice structure is required, it can be removed from the parts using a deburring process. While still on the build plate (see Figure 5) the parts go through an annealing heat treat for removal of residual stresses. The parts are now removed from the build plate by wire EDM or an alternate process. Depending on the material and

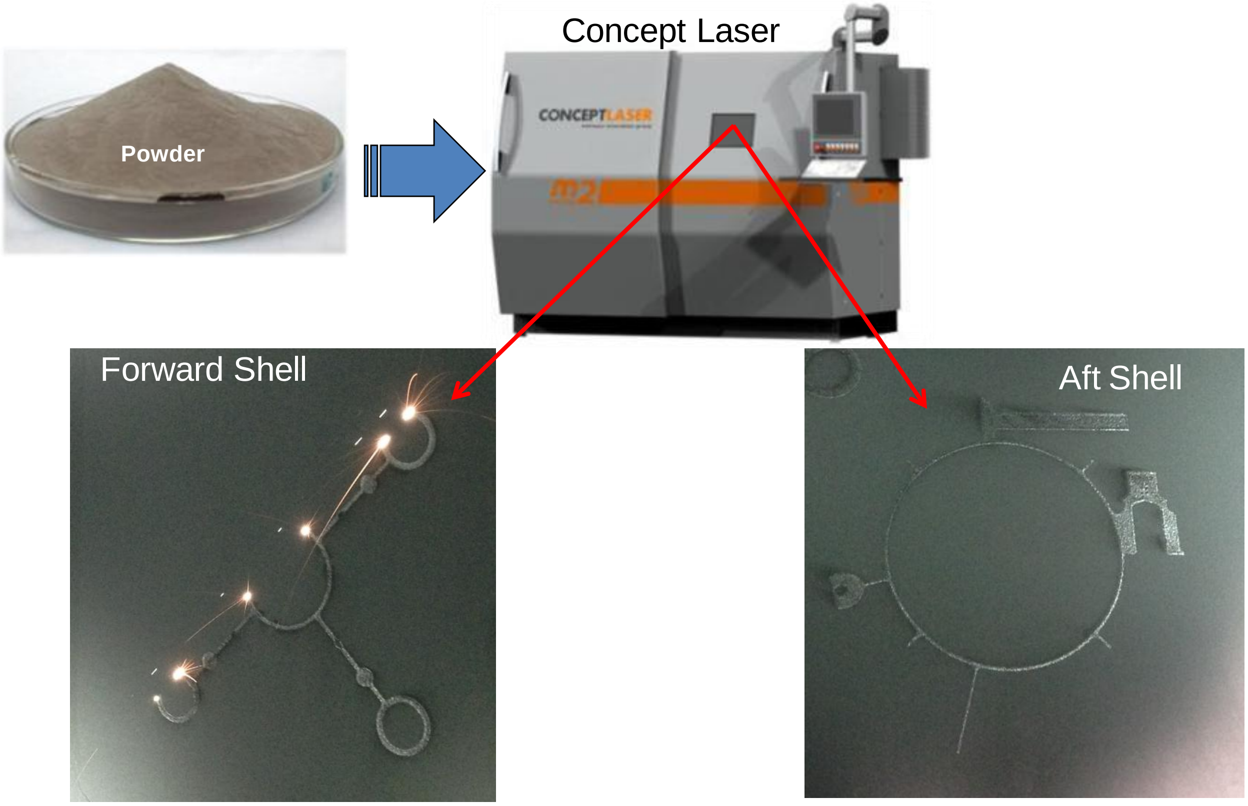


Figure 4: Spherical Tank Concept in AM Machine

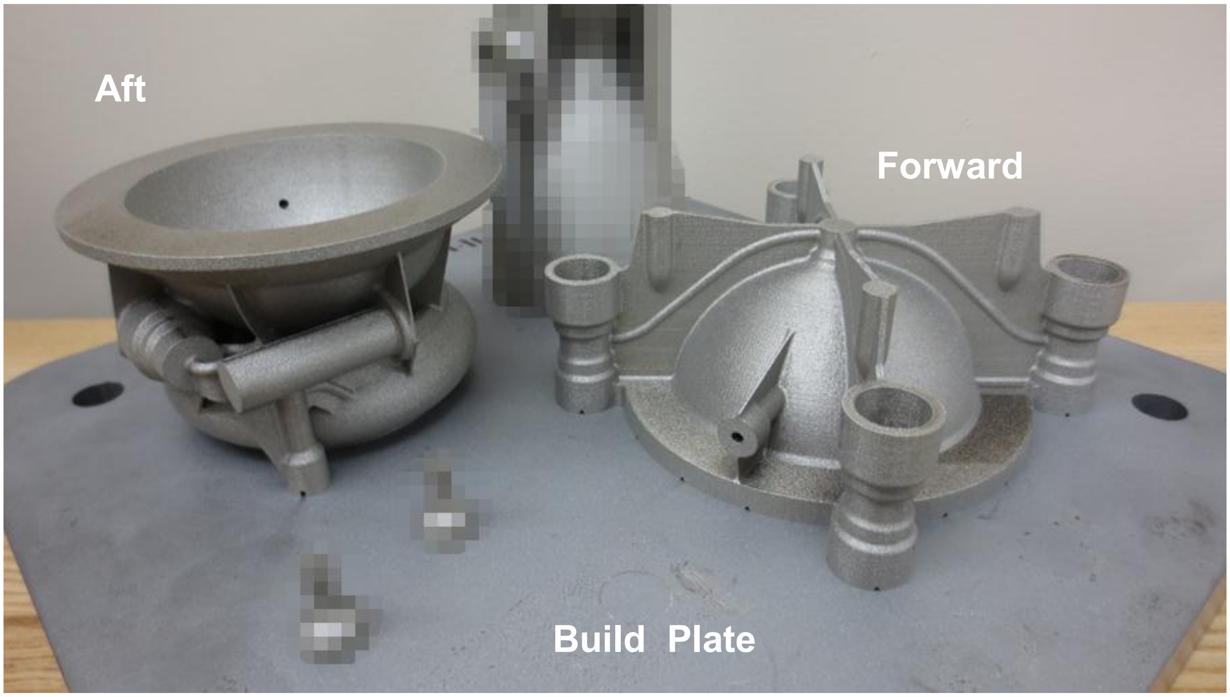


Figure 5: Spherical Tank Concept on Build Plate

material properties, the parts may require an additional Hot Isostatic Pressure (HIP) heat treat for improved properties and/or reduced porosity. Due to the complex geometries the additive manufacturing capability can create, inspecting the parts can be a challenge. Structured light inspection was used to inspect the Cubesat propulsion system parts. Structured light inspection is a 3D scanning technique of the actual parts that can be compared to the 3D CAD models for dimensional compliance. This is a great technique for inspecting the external surfaces of complex parts. Figure 6 shows the parts being inspected by the structured light machine and the dimensional variations relative to the original CAD models. The final step is the post machining, if required, for all threaded interfaces and sealing surfaces prior to a fine clean process (see Figure 7).

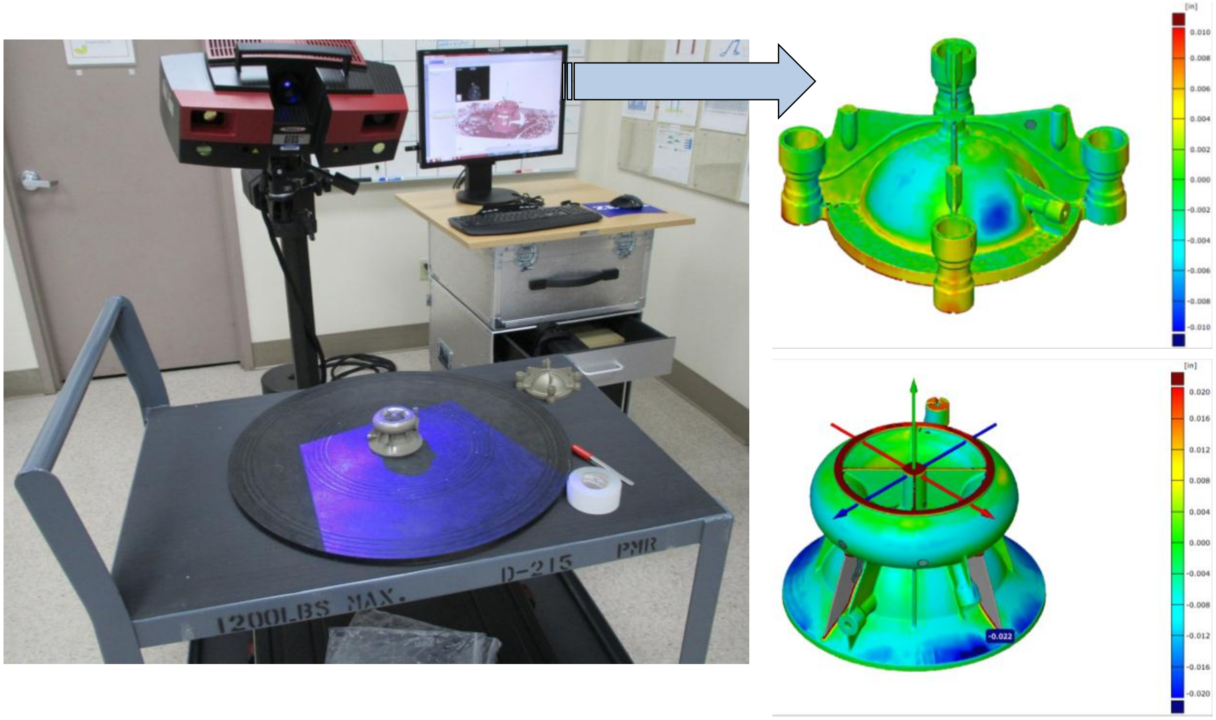


Figure 6: Spherical Tank Concept Structured Light Inspection

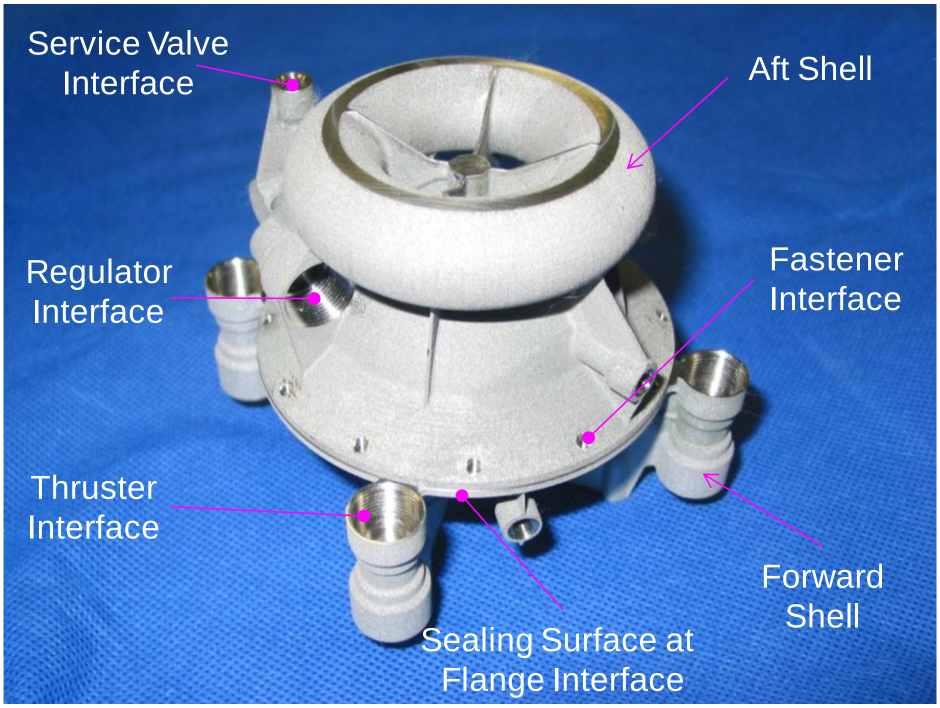


Figure 7: Spherical Tank Concept Post Machined

TEST

The spherical tank concept is in the initial planning phase for proof, leak, and hot fire testing. The piston tank design concept has completed a series of testing. Under contract with NASA, Aerojet Rocketdyne is currently developing the MPS-120 hydrazine propulsion system to provide high total impulse for CubeSat missions. In May 2014, a series of expulsion tests were conducted with the additively manufactured propellant tank, piston and pressurant tank integrated together and tested at the system level. The propellant tank was filled with water and the piston was driven via the gaseous nitrogen pressurized pressurant tank until it reached the fully expelled state. The test produced very high expulsion efficiency for many consecutive fill and drain cycles. This test demonstrated that the piston tank performed reliably over the entirety of its operational range of pressures going as far as to demonstrate the piston's ability to expel propellant at far below normal operating pressures. Figure 8 shows the expulsion test setup with some tooling attached.

A preliminary test of the MPS-120 isolation system was conducted on a representative aluminum part. Testing of the final titanium version is planned for June 2014. The first hotfire testing of the MPS-120 is planned for fall 2014.

Figure 8: MPS-120 Piston tank system subassembly, with tooling attached for expulsion test purposes

Under contract with Plasma Processes and NASA, Aerojet Rocketdyne is developing the MR-143 CubeSat scale rocket engine, shown in Figure 9, to provide a green propellant option for high total impulse CubeSat propulsion. By shortening the additively manufactured MPS-120 propellant tank exit ports, the MR-143 engine can be integrated to convert the MPS-120 hydrazine system into the MPS-130 AF-M315E system. The MPS-130 uses AF-M315E HAN-based monopropellant, a lower toxicity and greater than 50% density-Isp alternative to traditional hydrazine, enabling both a green solution as well as higher performance. In

February 2014, the first MR-143 engine was tested at Aerojet Rocketdyne and demonstrated successful operation. The engine was almost entirely additively manufactured using Plasma Processes' EL-Forming process for the chamber, nozzle, and injector and the valve stand-off was 3D printed using Selective Laser Melting (SLM). The valve used in the test was the hydrazine valve planned for the MR-142 CubeSat scale hydrazine engine. While more work is required to fully develop and qualify the MR-143, the February test was an important first step in demonstrating CubeSat scale AF-M315E rocket engine technology.

Figure 9: MR-143 Engine

SUMMARY

In summary, Aerojet Rocketdyne has multiple low cost options for Cubesat propulsion systems. With the introduction of additive manufacturing with Titanium and super alloys (i.e., IN625, etc.), significant cost savings can be achieved. First time through success can be achieved as long as engineers follow the additive manufacturing design guidelines, design for both additive manufacturing and final design, and perform stress analysis based on additive manufacturing material properties. For the spherical tank design, the part count was reduced by 50% (22 parts was reduced to two additive manufactured parts), 22 final assembly welds were eliminated, and the projected recurring propulsion system cost was reduced by 75%. The reduction in part count, welds, and cost were determined by establishing a baseline Hydrazine mono propellant propulsion system first. This baseline system was based on conventional design, fabrication and assembly methods. The baseline system had a total of 40 drawings, 28 welds and an estimate for recurring cost.

The piston tank design is currently under contract with NASA and is planned to be hot fire tested at the system level later this year (2014).

References

1. Derek Schmuland, Christian Carpenter, Robert Masse, Jonathan Overly, "New Insights Into Additive Manufacturing Processes: Enabling Low-Cost, High-Impulse Propulsion Systems", *Proceedings of the 27th Annual AIAA/USU Conference on Small Satellites,* Paper No. SSC13-VII-4