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# The Use of Additive Manufacturing for Fabrication of Multi-Function Small Satellite Structures

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**ABSTRACT**

The use of small satellites in constellations is limited only by the growing functionality of smallsats themselves. Additive manufacturing provides exciting new design opportunities for development of multifunction CubeSat structures that integrate such functions as propulsion and thermal control into the satellite structures themselves. Manufacturing of these complex multifunction structures is now possible in lightweight, high strength, materials such as titanium by using existing electron beam melting additive manufacturing processes. However, the use of today's additive manufacturing capabilities is often cost-prohibitive for small companies due to the large capital investments required. To alleviate this impediment the U.S. Department of Energy has established a Manufacturing Demonstration Facility (MDF) at their Oak Ridge National Laboratory (ORNL) in Tennessee that provides industry access to a broad range of energy-efficient additive manufacturing equipment for collaborative use by both small and large organizations. This paper presents a notional CubeSat multifunction design that integrates the propulsion system into a three-unit CubeSat structure. The full-scale structure has been designed and fabricated at the ORNL MDF. The use of additive manufacturing for spacecraft fabrication is opening up many new possibilities in design and fabrication capabilities for what had previously been impossible structures to fabricate.

## 1.0 MISSION NEEDS

Flying multiple spacecraft in formation has long been a dream of space scientists. The ability to fly many spacecraft in controlled formations is directly linked to the ability to maintain spacecraft spacing and the ability to synthesize new missions over multiple platforms simultaneously. Development of the technologies needed for satellite constellations has been hampered in the past by the cost of individual spacecraft and the cost to launch. Because of the inherent risk of developing and testing formation flight in space, the space industry has been unwilling to pursue multiple satellite formations due to the potential for failure and the resultant loss of expensive space assets. What is needed for the development of spacecraft constellations and the associated technologies is a satellite class that is affordable to fabricate, is relatively inexpensive to launch, and has the capacity to test new technologies without an overwhelming cost penalty for failure. Small satellites fulfill this need because of their size and ability to be launched as secondary payloads. In the early days of the United States (U.S.) space program, many smaller satellites were launched to test new technologies and failure was an expected part of the development process. As our space industry has matured, we are much less willing to risk expensive space missions to test out new technologies. Without space testing and the resulting space heritage, new space technologies will not be adopted by operational spacecraft designers. Small satellites, and in particular the small CubeSat class of satellites, offer the potential for in-space testing of spacecraft formation flying technologies and they offer this with an inherent capability to accept risk. Small satellites are a much needed class of test satellites because they can afford to fail. It is only through failure and the inherent learning that accompanies well instrumented testing that new technologies will be introduced to the space community. This can directly support constellation and formation spacecraft applications such as remote earth observation, satellite repair monitoring and up-close satellite inspection.

Small satellites will require an increasing level of systems integration and integral systems design to enable the more complex sensor and propulsion-based mission capabilities needed for formation applications. CubeSats in particular are very limited in their mass and volume, even in the two unit (2U) and three unit (3U) configurations. One aspect of spacecraft design that has not been fully exploited is the development of multifunction structures that can integrate a variety of functions into the spacecraft structure itself thereby reducing system complexity and potentially releasing additional mass and volume to the spacecraft design for the integration of other spacecraft systems. Multifunction structures have been pursued by government and industry research organizations in the past but positive results have been limited by manufacturing concerns and the inability to test a sufficient number of multifunction structures in space.

The introduction of additive manufacturing to the small satellite community has opened up exciting new opportunities for the design and rapid, low-cost fabrication of multifunction structures. Additive manufacturing (AM) has significant promise to serve as a key advancement that will allow groundbreaking space missions to be developed, fabricated and successfully executed. Because of the revolutionary capabilities of additive manufacturing in three-dimensional structures, new unheard of designs can be developed and fabricated in monolithic structures. No longer are the designers constrained by the rule 'it must be designed so it can be fabricated'. The new generation of designers is just beginning to realize the expanded potential of AM coupled with computer-aided design (CAD) to revolutionize design and system integration tasks. This paper addresses the development and fabrication of a multifunction 3-unit (3U) CubeSat structure from titanium using electron beam melting (EBM) from titanium powder on the Arcam additive manufacturing equipment located at the Oak Ridge National Laboratory's (ORNL) Manufacturing Demonstration Facility (MDF). Although the design adheres to the overall CubeSat specifications, it is intended only as a demonstration of potential capabilities for small satellite multifunction structure fabrication. The small satellite community will need to expand the application of AM capabilities in the near term to evolve operational small satellite designs that capitalize on the innovative fabrication capabilities of AM. ORNL's MDF exists to assist industry, both small and large, in developing new, energy efficient manufacturing technologies, as described more fully in a later section of this paper.

## 2.0 MULTIFUNCTION STRUCTURES

Multifunction structures and devices for spacecraft applications are not a new idea. Lockheed Martin developed a concept in 1999 to embed passive electronic components within composite materials to maximize the ratio of the volume of the electronic parts to the overall packaging volume. The design was intended to provide nearly an order of magnitude reduction in the mass and volume of the packaged electronics.[1]

In 2001 the Jet Propulsion Laboratories (JPL) developed a concept for multifunction structure solar panels. Their objective was to develop a modular continuous solar power harvesting and storage system with at least a 20% decrease in mass per kilowatt. Their concept was made possible by the combination of ultra-long life solid-state Lithium batteries, thin film thermoelectric devices, and integrated power management.[2]

Multifunction spacecraft structures (MFSs) offer the potential for significant mass and volume savings in addition to reduced overall complexity and shorter system assembly times. To fully achieve the advantages of multifunction structures, they must be designed from the start as integrated entities. It has been estimated that the introduction of multifunction structures could reduce the volume and mass of a spacecraft by approximately 80% and 90%, respectively, and decrease the assembly and rework labor by up to 50%.[3]

Overall, we are left with a promising approach for spacecraft optimization but with limited space-proven results and insufficient research activity in new multifunction spacecraft structure approaches. Often a technology concept meets a hurdle when there is not enough technology to enable efficient implementation of the concepts. In the case of multifunction structures, AM may well be the enabling technology that will allow the spacecraft industry to introduce operational multifunction spacecraft structures, beginning with small satellites.

In a 2007 article by S. Guglielmo on Multifunctional Structure Technologies for Satellite Applications he pointed out that despite the potential advantages of multifunctional structures, "The main issue that has hindered the development and wider utilization of MFSs in current satellites is the fact that, to fully exploit the potential offered by MFSs, an integrated design of the spacecraft must be carried out. The spacecraft subsystems cannot be designed and built independently, as commonly happens, but from the start the subsystems must be designed in an integrated manner."[4]

## 3.0 ADDITIVE MANUFACTURING

In the dual-week November 1&8 2010 issue of *Aviation Week and Space Technology* magazine Graham Warwick published an article entitled 'Adding Value' that presented the concept 'Additive manufacturing could bring much-needed affordability to aerospace products'. He went on to point out that 'Additive manufacturing (AM) appears almost perfectly suited to aerospace, allowing lighter parts to be produced for lower cost, in less time, but with mechanical performance equal to conventional forged or wrought components. And while larger forgings can have lead times of a year because of tooling, additive manufacturing eliminates that constraint and buys more time for design optimization.'[5]

AM typically has much less waste than traditional 'subtractive' machining methods. For many subtractive machining processes, particularly for high strength materials such as titanium, 90% or more of the original billet is machined away leaving only 10% of the material as the final product. In aerospace terminology, this results in a 10 to 1 buy-to-fly ratio. Needless to say there is a lot of waste in time, energy and materials to make parts by traditional subtractive machining methods. AM, in contrast, uses nearly all of the basic material to form the parts resulting in virtually no waste and a buy-to-fly ratio approaching one. In the powder-based approaches, the additive machining waste material is returned to the hopper and reused.

Another very important aspect of additive manufacturing is its close coupling with CAD. CAD models are fed to the AM equipment where they are manipulated using specialized machine-specific software. Once the fabrication is complete, the result is near-net-shape final products. The real breakthrough is that design approaches that could not be used for subtractive manufacturing (such as embedded complex passages and reinforcing struts and embedded mesh) are now possible with AM. Designers of the past were constrained by the edict 'design it so that it can be manufactured' (by traditional machining equipment). Designers of the future will not have these constraints and will be bounded only by their imaginations and creativity.

## 4.0 THE ORNL MULTIFUNCTION CUBESAT STRUCTURE

The objective of this effort was to design and fabricate a notional CubeSat multifunction structure from titanium using the AM research and development capabilities at ORNL to highlight the resources available at ORNL for industry collaborative development in this rapidly expanding area of manufacturing technology. The design is not intended for flight but complies with the CubeSat standards and includes integral propulsion and cooling systems in the structure itself. Use of SolidWorks CAD software enabled Dr. Lonnie Love of ORNL to develop an integrated design with novel features such as rectangular pressure tank for cold gas or monopropellant, propulsion system 'plumbing' and nozzles integrated into the structure and sensor cooling tubes integrated into the structure. SolidWorks was used to design the rectangular pressure tank to a burst pressure of 3000 psi by thickening the walls in the areas of potentially highest stress as shown in Figure 1. The color-coding shows the various stress levels with red being the highest and blue the lowest. Note that the thickened areas show relatively low stress levels.

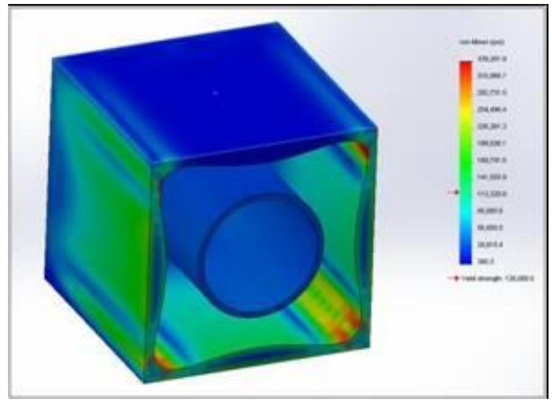

**Figure 1: CAD Model of Propellant Tank**

A CAD layout of the CubeSat structure in transparent and solid form is shown in Figures 2a and 2b with a notional sensor placed at the end opposite the propulsion nozzles. There is a tunnel designed in the center of the pressure tank to allow wiring to pass through. The demonstration version of the ORNL multifunction CubeSat structure will be fabricated in titanium (Ti6Al4V, a Titanium, Aluminum, Vanadium alloy) using the EBM process on the ARCAM technology equipment housed in ORNL's MDF. The Arcam Titanium Ti6Al4V (Grade 5) powder has a particle size between 45 and 100 microns. This limit on the minimum particle size ensures safe handling of the powder. Yield strength of the final EBM titanium material is 950 MPa (~138 kpsi) and the Rockwell scale hardness is 33 HRC (as compared with theTi64 wrought properties of 36 HRC).[6]

Additional design effort will be conducted to integrate passive cooling channels in the periphery of the structure surrounding the notional sensor. A passive cooling approach developed at ORNL by Dr. Lonnie Love, uses a magnetocaloric pump-to-pump ferrofluids using only external thermal and magnetic fields.[7] Ferrofluids are oil-based liquids that are loaded with nanometer-sized ferrous particles. As the fluid is exposed to an increasing thermal gradient and heats up, it loses its attraction to the magnetic field and is displaced by cooler fluid.

Using a ferrofluid in conjunction with the significant temperature extremes that exist in a space environment offers real potential for application of the magnetocaloric pump concept. For this notional CubeSat multifunction structure, cooling tubes will be incorporated as part of the monolithic titanium structure.

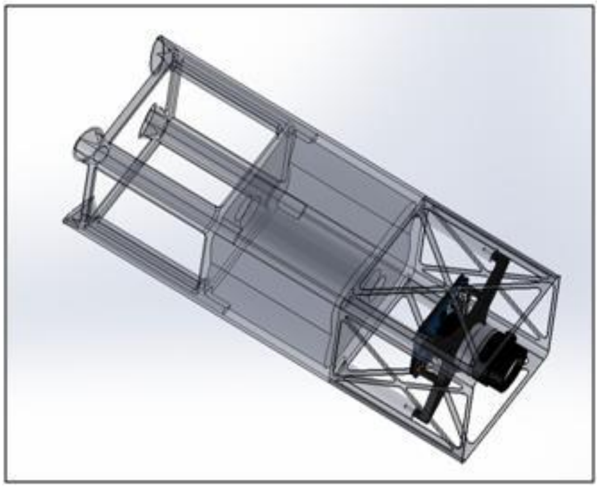

**Figure 2a: Transparent 3U CubeSat Structure**

The prototype CubeSat multifunction structure will first be built with polymer using Stratasys AM equipment. This will provide an opportunity to better understand the structure before building a titanium version using the Arcam machine.

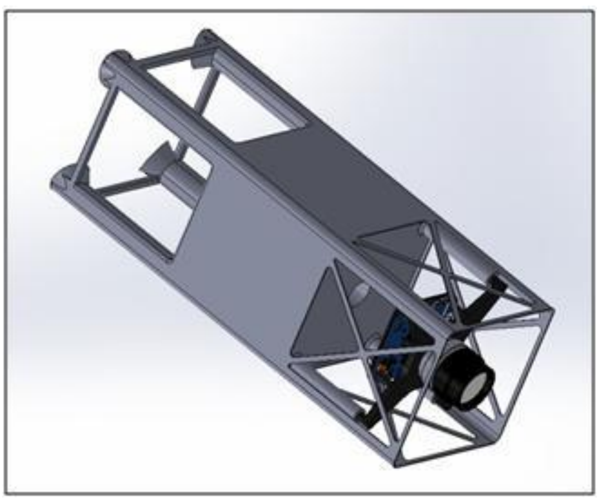

**Figure 2b: Solid 3U CubeSat Structure**

## 5.0 ARCAM AB MODEL A2

The Arcam AM equipment uses high power EBM, a process developed by Arcam, to melt powders site specifically. Net-shape components are directly manufactured from computer models. ORNL is working with Arcam to develop and implement in situ process monitoring and closed-loop control to expand the technology for additional materials and to increase the processing speed and quality assurance. Figure 3 shows the placement of the Arcam A2 equipment in the MDF.

**Figure 3: ORNL's MDF Additive Manufacturing Equipment, showing Arcam A2**

The standard Arcam A2 has two interchangeable build tanks for maximum flexibility, one for tall builds and one for wide build. The tall build tank has a build envelope of 200×200×350 mm. The wide build tank has a build envelope of 300×200 mm.[8] The manufacturing sequence for Titanium EBM using the Arcam equipment is shown in the sequence of images in Figure 4. Image 'A' shows a complex jet engine turbine blade with internal cooling ducts. In image 'B' the design is captured by a CAD program and separated into the two-dimensional 'slices' that will be built up by the EBM a thin layer of titanium powder. In image 'C' the powder hoppers are filled with the titanium powder and slid back into the chamber. The EBM occurs in a vacuum environment ($1\times10^{-4}$ mBar) to preclude oxidation of the titanium at the high operating temperatures during the buildup of each layer. Not shown are the powder dispersal, the pre-heating and the melting sequences for each layer. A thin layer (approximately 50μm or more depending on the design) of titanium is spread over the entire working area by a mechanical rake. Preheating is done over the entire working surface of the powder by continuously scanning a defocused electron beam over the powder surface. After preheating, the electron beam melts the areas specified by the CAD model using

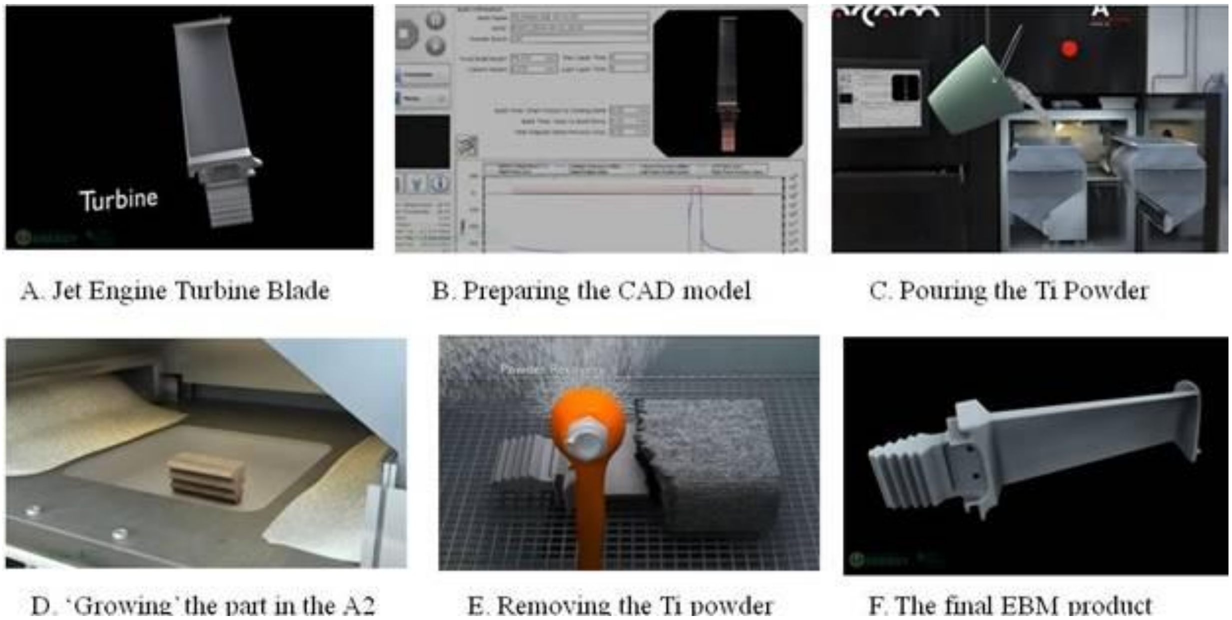


**Figure 4: ARCAM Build Sequence**

a focused electron beam (up to 3500W with a spot size of 0.2 to 1.0 mm continuously variable). After a layer is complete, the stage elevator is lowered and a subsequent layer is deposited. Image 'D' shows the bottom of the part 'sinking' into the powder bed as each successive layer is completed. In this image the powder that would be surrounding the solid part is removed for visualization. As shown in image 'E', once the build is complete, the 'brick' containing the part and sintered powder is removed from the build chamber and taken to a pressure blasting chamber where the titanium powder is blasted away and recovered, leaving the finished part as shown in image 'F'. Interfaces can be final finished as necessary using traditional machining. Although the Arcam equipment is presented as a 'CAD to metal' capability, according to an ORNL Arcam operations expert, Dr. Ryan Dehoff, there is still a certain amount of art and training required to achieve designs and products from the Arcam EBM process that will enable powder removal and to remove the powder. This does not negate the considerable design freedom that is enabled by the 'CAD to metal' process.

Additive manufacturing can be a very cost-effective manufacturing method, compared with conventional subtractive manufacturing. A significant difference is due to the amount of waste material, described in aerospace terms as 'buy-to-fly'; the ratio of raw material to the amount of material in the final product. For example, using EBM with the Arcam equipment instead of traditional subtractive manufacturing for a titanium (Ti64Al-4-V) Bleed Air Leak Detect (BALD) bracket used in the hot side of the engine on Lockheed Martin's Joint Strike Fighter reduces the buy-to-fly ratio from 33:1 to 1:1. A recent case study on the comparative manufacturing of the BALD bracket provided more than a 50% cost reduction for the overall manufacturing process (fabrication, hot isostatic pressing, final machining).[9]

## 6.0 ORNL'S MDF

ORNL's MDF, shown in Figure 5, offers distinctive world-leading capabilities in manufacturing and materials research technologies and characterization facilities that leverage previous and on-going government investments. The MDF enables research and development from concept to prototype in an open or secure environment for reducing risks and costs, accelerating innovation, optimizing energy efficiency, protecting intellectual property and maximizing investments. Dr. Craig Blue is the Director of ORNL's MDF. In a recent article Dr. Blue stated "Our main purpose is to help companies by allowing them to come here and test processes and components that will be part of a larger system." He added, "We have all the facilities under one roof to function as a beta test site—and basically serve as an extension of companies' own research capabilities."[10]


**Figure 5: ORNL MDF**

The fact that ORNL's MDF exists as a national resource to assist industry in developing new manufacturing technologies is not well known. Jeff DeGrange, Vice President of Direct Digital Manufacturing at Stratasys stated "The level of awareness within the aerospace engineering community about ORNL's mission and what it is doing to drive advanced manufacturing technologies has been low. In the case of additive manufacturing, they don't understand the current state of the technology and how it can be applied to their function, which Oak Ridge is very good at doing." He draws an analogy with information technology. "Turn back the clock when computers were in their infancy," DeGrange says. "How many people were able to appreciate how computers could be tailored to business and manufacturing functions? ORNL has all the personnel and tools needed to help aerospace companies figure that out and put such applied research on a fast track."[11]

ORNL's MDF gives industries access to unique research facilities and reduces their risk for adopting cutting-edge manufacturing technologies. The MDF offers a collaborative, shared infrastructure to facilitate the development and use of energy-efficient, rapid, flexible manufacturing technologies and promotes rapid technology dissemination, ensuring that new technologies and design methodologies are developed in the United States and high-tech enterprises have the infrastructure to flourish here. Such critical advances in manufacturing technologies will provide the basis for high-quality jobs for Americans and sustain U.S. competitiveness in the 21st century. The MDF provides physical and virtual tools from design to evaluation for rapidly introducing new technologies and optimizing essential manufacturing processes. These technologies can reduce energy intensity, lower carbon emissions, create lower-cost production pathways, and enhance the competitiveness of U.S. advanced manufacturing industries.

ORNL's unique advanced-manufacturing technology capabilities focus on several broad, cross-cutting technology areas:

- Additive Manufacturing: a broad range of state-of-the-art direct manufacturing technologies for metal and polymer material systems, including electron beam melting, ultrasonic, extrusion, and laser deposition. Current additive manufacturing equipment includes multiple versions of the latest equipment from Arcam, POM and Stratasys.

- Additional cross-cutting technology capabilities include: carbon fiber composites; roll-to-roll processing; lightweight metals processing; magnetic field processing; low temperature materials synthesis; and extensive characterization capabilities including neutron beam imaging.

ORNL is seeking industry partners for short-term, collaborative projects within the MDF to assess applicability and of new energy-efficient technologies available to the U.S. manufacturing industry. ORNL has issued a Collaborative Technology Assessment to provide industry access to ORNL's experienced staff and unique equipment and capabilities to demonstrate proof-of-principle for advanced concepts in manufacturing and materials as needed to warrant further development and deployment in the U.S. manufacturing industries.

The full announcement can be found at: http://www.ornl.gov/sci/manufacturing/mdf_user_program.shtml

## 7.0 SUMMARY

AM offers exciting potential to revolutionize the fabrication of complex structures for aerospace applications. With the design and flexibility afforded by AM, new design processes can be implemented, such as multifunction structures, that were not feasible or economic using traditional machining methods. The small satellite community is a logical 'first adopter' of AM due to their reputation for innovation and progressive design/testing of space hardware. Testing and qualification of these new manufacturing capabilities in space can best be accomplished by a class of satellites, i.e. small satellites, that can afford to take risks and demonstrate the feasibility of new space technologies. The ORNL MDF offers a unique national resource for U.S. companies and organizations to try out new manufacturing and materials technologies before making the large capital investments associated with production. The benefit to the country is the introduction of new energy savings manufacturing methods.

## 8.0 ABOUT THE AUTHORS

Brian Horais is a former DARPA Program Manager with a focus on spacecraft and advanced materials. He has been a frequent contributor to and presenter at the Small Satellite Conference and has co-chaired a number of small satellite remote sensing conferences with the International Society of Optical Engineering (SPIE). Mr. Horais received an M.B.A from the University of New Haven in 1986, an M.S. in Aeronautical Engineering from the Naval Postgraduate School in 1972 and a B.S. in Aerospace Engineering from the U.S. Naval Academy in 1971. He is co-author of two patents and has published more than 20 papers and journals. Mr. Horais currently provides technical consulting support to the Oak Ridge National Laboratory's Manufacturing Demonstration Facility.

Dr. Lonnie Love is a senior research scientist in the Oak Ridge National Laboratory's Automation, Robotics, and Manufacturing group. His work at ORNL and in the local community runs the gamut from robotics to prosthetics to science education. Dr. Love earned his Ph.D. in Mechanical Engineering from Georgia Institute of Technology in 1995. His M.S. and B.S. are from Old Dominion University in 1990 and 1988, respectively. Dr. Love has been on the research staff at Oak Ridge National Laboratory since 1995, conducting research in human amplification, ship motion compensation, learning control, telerobotics, micro-assembly and smart and adaptive fluidic systems. He presently holds one patent and has an additional patent pending.

Dr. Ryan Dehoff graduated from The Ohio State University with a Ph.D. in Materials Science and Engineering in 2008. Dr. Dehoff worked on process development of laser engineered net shaping pertaining to Nb-Si based alloys in conjunction with the mechanical behavior, micro-structural characterization, and high temperature oxidation performance of these materials. During a brief post-doctoral position at The Ohio State University, he worked on micro-structural characterization of aluminum alloys fabricated by ultrasonic additive manufacturing. Currently, as a research staff member at the Oak Ridge National Laboratory he is working in the area of direct manufacturing of components utilizing various techniques including electron beam melting, laser metal deposition, and ultrasonic additive manufacturing.

## 9.0 ACKNOWLEDGEMENTS

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