FY 2017 Additive Manufacturing

Report to Congress

December 2017

Office of the Under Secretary of Defense
for Acquisition, Technology, and Logistics

Contents

1.0 Executive Summary

This report is being provided to the House and Senate Armed Services Committees and the House and Senate Appropriations Committees.

Each of the Military Services (MILSVCs) and Components have ongoing investments in Additive Manufacturing (AM). While extensive, this report is not an inclusive list of all Department of Defense (DoD) activity in AM, but describes many examples that show the wide range of technical challenges being addressed.

Joint activity in AM is progressing from relatively "grass roots" collaborations to higher-level coordinated activity. In 2016, 20 representatives from the Air Force, Army, Defense Logistics Agency (DLA), and Department of the Navy (DON) collaborated to develop a Joint DoD AM Roadmap. This process was facilitated and hosted by the Manufacturing USA Institute America Makes.[1] A high degree of overlap was identified among the objectives of the four organizations, and this finding strengthened the justification for more joint collaboration in pursuing DoD objectives for AM, in particular on qualification and certification. The final report of the roadmap offered recommendations that will be addressed by the Joint Additive Manufacturing Steering Group (JAMSG) and Joint Additive Manufacturing Working Group (JAMWG), which were formed in July 2017. Working together, these groups will:

- Develop a DoD AM vision;
- Disseminate information on DoD AM efforts throughout the MILSVCs and Components;
- Provide recommendations for joint AM investment strategy;
- Identify and share AM best practices; and
- Encourage joint approaches to accelerate AM qualification and certification.

Qualification and certification of AM processes and components have been and continue to be a challenging but high-level priority for DoD. Before the potential of AM can be realized within DoD, qualification and certification procedures for targeted components must be developed and demonstrated. The AM Quality Pyramid discussed in this report (section 5.0) identifies a foundation of information assurance and management, followed by qualification of raw materials, calibration of machines, standards, the building of a data body of knowledge, and feedback control in build-planning and build-modeling. Only with this structure underneath can a quality AM component be produced. The complexity of AM processes, coupled with the sheer variety of materials and applications being explored within DoD, make advancing the qualification and certification of AM difficult. In the Joint DoD AM Roadmap, nine of its integrated objectives are related to qualification and certification, which demonstrates the breadth of the task of qualification and certification for AM.[2] The recently formed JAMSG (and the associated JAMWG) are tasked, in part, to "encourage joint approaches to accelerate AM qualification and certification." The JAMSG will oversee several ongoing efforts include

[1] See section 4.1 of this report for more on the Joint DoD AM Roadmap

[2] Department of Defense Additive Manufacturing Roadmap Final Report, released 30 November 2016.

developing and evaluating advanced tools and pedigreed data that are critical to decision making for rapid qualification and certification of components.

2.0 Legislative Requirement

This report satisfies the requirements outlined in Senate Report 114-255, page 95, which accompanies, S. 2943, the National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2017, requiring the Secretary of Defense to submit a report on efforts to foster AM adoption and learning. Requirements of the report include, but are not limited to:

1. Details from each of the MILSVCs regarding their current AM efforts to include FY 2016 and FY 2017 planned and completed demonstrations and prototyping efforts.
2. Details regarding joint-development projects and efficiencies achieved through intra-Service collaboration.
3. Details regarding AM qualification and certification efforts for materials, processes, and components.
4. A recommendation regarding the expanded use of Working Capital Funded pilot programs, potential changes to public-private partnerships within the defense industrial base, or any other potential changes in law that could enable DoD to better demonstrate and execute AM end use fabrication.

3.0 Current AM Efforts within the Department of Defense

The first request in the NDAA for FY 2017 for this report was for "Details from each of the military services regarding their current AM efforts to include FY 2016 and FY 2017 planned and completed demonstrations and prototyping efforts."

While each of the MILSVCs are engaged in their own AM efforts, there is joint interest within DoD to improve readiness, reduce cost, and ensure agility across the MILSVCs and agencies. Current AM efforts within DoD apply the many benefits of AM to three joint areas: maintenance and sustainment, deployed and expeditionary missions, and new part/system acquisition.[3]

DoD is already demonstrating cross-cutting impacts of implementing AM across the Department. Each Service focuses their efforts differently, and investments are complementary. Overarching trends in AM at DoD include considerable work on the following topics as related to AM:

- Materials: Qualification, standards, and availability
- Processes: Validation, qualification, standards, configuration control, and repeatability
- Components: Validation, qualification, and integration into supply chains

[3] More on these three areas is discussed in section 3.3 of this report.

- Skillset development: Research and development (R&D), design engineering, and operations including part selection, reverse engineering, and design for AM (DfAM)
- Data: Collection, management, dissemination of data on materials, processes, and components
- Security: Technical data packages (TDPs), cybersecurity, protection of the digital thread, and intellectual property (IP)
- Cost and feasibility: business cases and profitability

Longer-term implementation programs, like AM, require thoughtful consideration of the supply chain network and business systems that will need to change to accommodate the new materials, processes, and designs. There are a number of non-governmental working groups that share information on a regular basis, but also a number of working groups within the MILSVCs. With the recently formed JAMSG and JAMWG, there are now joint-Service formal groups meeting as well. Supporting these exchanges is critical to the continued growth of joint AM activities.

Examples of each of the MILSVCs' planned and completed AM demonstrations and prototyping efforts are described in the following sections.

3.1 Army

The Department of the Army manages AM efforts through the Assistant Secretary of the Army for Acquisition, Logistics, and Technology in coordination with Headquarters, Department of the Army Deputy Chief of Staff for Logistics (HQDA G-4). The following focus areas are ongoing to support the Army's AM efforts:

- Science and Technology (S&T) Efforts (Basic and Applied Research, Advanced Technology Development)
- Army Manufacturing Technology Efforts incorporating AM
- Logistics and maintenance policies/procedures
- Supply Chain Incorporation of AM
- Qualification of Parts
- Army Strategic Planning for AM

The Army's overall planned use of AM is to augment the current supply chain. AM provides options for the Army to develop solutions congruent with other manufacturing methods to maximize operational efficiency and effectiveness. For some applications, AM provides unprecedented sourcing flexibility, enabling sustainment of the Joint Force, customized specification, and/or shorter lead times compared to traditional manufacturing methods. The Army also expects AM to enhance modernization processes by providing end users with means to influence system designs and performance. The Army intends to leverage efforts conducted by other MILSVCs and industry to reduce risk.

A strategic-level working group has been established to develop a long-range strategy for Army AM. The group includes membership from key stakeholders within the Deputy Assistant Secretary of the Army for Acquisition Policy, the Deputy Assistant Secretary of the Army for

Research and Technology (DASA(R&T)), and HQDA G-4. HQDA G-4 oversees logistics policies and procedures for maintenance and equipment readiness and is developing an Army interim AM policy with the purpose of leveraging statutes, regulations, and standard business practices to mitigate risk and drive efficiencies while continuing to innovate AM in the near term. An accompanying Army AM Implementation Plan will drive provide the workforce with AM support, including training, data and design management, and reach-back for technical support.

DASA(R&T) is investing in budget activities (BA) 1, 2, 3, and 7 funding areas that include AM related efforts. Army technologists lead in many military-unique AM research areas. AM technology insertions and operational constructs will enable the Army to:

- augment existing organic and external supply chains to increase agility and resilience
- reduce sustainment costs and reduce the impact of obsolescence and diminishing sources
- consider rapid innovation and delivery of critical-need components at or near the point of need

AM technology insertion supports efforts to address strategic and tactical challenges for various applications across the Army enterprise, from R&D through sustainment.

- The Army is developing an Army Additive Manufacturing Technology Roadmap in cooperation with the America Makes Manufacturing Institute. The Roadmap is structured to emphasize two primary categories: 1) Maintenance and Sustainment, and 2) New Part/System Production. These categories enable AM support for expeditionary operations at the point of need and provides reach-back capabilities to support the organic industrial base.

Army's AM efforts are supported by the Army Materiel Command through its Research Development and Engineering Command; the Engineer Research and Development Center, and the Medical Research and Materiel Command. Representatives of these organizations have formed an AM Community of Practice that meets periodically to coordinate their efforts.

3.1.1 Expeditionary Fabrication

3.1.1.1 Rapid Fabrication via AM on the Battlefield (R-FAB)

The Army is developing an expeditionary R-FAB system to produce critical supplies, parts, tools, and packaging at the point of need for Brigade Support Battalions, Sustainment Supply Activities, and other special mission activities. R-FAB Generation ("Gen") 1.0 was demonstrated at the Army Warfighting Assessment (AWA-17.1) in October 2016, Gen 1.5 was being used on Pacific Pathways 17-3 from August – September 2017, and Gen 2.0 will be demonstrated at Joint Warfighting Assessment (JWA-18) in May 2018. Gen 3.0 will be submitted at JWA-19 and will increase capabilities by incorporating printing energetic materials along with the current thermoplastic materials.

3.1.1.2 Automated Additive Construction for Expeditionary Structures Basing (FY 2015-2017)

The Army printed a three-dimensional 512 square-foot concrete structure in less than 24 hours. The three-year Army R&D effort called the "Automated Construction of Expeditionary Structures" (ACES) uses an AM process to "print" semi-permanent structures. ACES will allow the Army to print on-demand and in the field buildings and other required infrastructure, such as barriers, culverts, and obstacles on location and potentially reduce building materials shipped by half and reduce construction manpower requirements by 62 percent when compared to expedient plywood construction. The Army is teamed with the National Aeronautics and Space Administration (NASA) to make ACES technology more mobile, including extraterrestrial infrastructure and with Caterpillar Inc. to explore commercialization of ACES technology, focused on disaster relief operations and conventional construction applications. In August 2017, Marines also participated in the testing and demonstration of the capability to build obstacles.

3.1.2 Army Manufacturing Technology (ManTech) Efforts

3.1.2.1 Direct Digital Manufacturing for Helicopter Engines

The objective of this ManTech project is to improve the manufacturing capabilities and affordability of production components using Direct Digital Manufacturing (DDM). The AM technology enables the defense industrial base to supplement traditional component fabrication and performance limitations for both legacy and future critical gas turbine engine components. The Inlet Swirl Frame of the T700 turbine engine was selected to be produced for the UH-60 Blackhawk and the AH-64 Apache. Additively manufacturing this part will result in elimination of 926 manufacturing steps, consolidation by reducing 147 parts to 25 parts with an overall cost reduction. This program is slated to transition to the UH-60 and AH-64 platforms for the Improved Turbine Engine Program (ITEP). DDM enables an operational flexibility which is reconfigurable to reduce logistical requirements and compress the supply chain.

3.1.2.2 AM Used to Restore/Reclaim/Reutilize High Value Aviation Assets

The Army currently holds over $220 million of non-conforming high-value helicopter components in the Storage Analysis Failure Evaluation and Reclamation (SAFR) warehouse at Corpus Christi Army Depot (CCAD). Long replacement acquisition lead times negatively impact operation and sustainment costs and operational readiness. The objective of this ManTech project is to develop advanced AM technologies capable of repairing high value aviation assets that cannot be currently repaired or reclaimed using traditional processes. This project's specific goal is to establish validated repair procedures. Using the blown powder AM processes, these parts can be repaired/recovered for less than new part cost. The first of three selected part repairs, the T700 Compressor Discharge Piston (CDP) Seal, has undergone successful additive repair and turbine engine testing. This project's results will transition to the UH-60 and AH-64 platforms.

3.1.2.3 Weight Reduction of Large Ground Vehicle Components

The Army will demonstrate the use of AM and Advanced Topology Optimization tools to reduce the weight of large vehicle components. The effort will focus on optimizing a road wheel for Ground Combat Vehicles, which is expected to reduce 30 percent of the component weight. AM provides the ability to produce optimized designs that are either impossible or too expensive to produce with traditional manufacturing methods. The Army is partnering with its organic base, which has manufacturing capabilities to produce prototype and production road wheels. The optimized road wheel will undergo full testing to validate the design.

3.1.3 AM for Parts and Repairs

3.1.3.1 Optimized Process for Repairs

The Army is developing an optimized process for repairs, build up, and coatings for components utilizing a Direct Energy Deposition technology. Part of this project will update MIL-STD 3049 (Materials Deposition, DDM: Direct Deposition of Metal for Remanufacture, Restoration, and Recoating) created in an Army laboratory. The project results will include: process parameters for a minimum of 10 alloys, material characterization of deposition on coupons and complete material testing and evaluation, expanded material laboratory services, and prototype capabilities.

3.1.3.2 Repair of Abrams Tank Suspension Army

The Army in coordination with Anniston Army Depot completed repair of the Abrams Tank Suspension Arm in March 2016, and expects a 6,000-mile road test to be completed by the end of 2017. Approval is expected from the Program Manager of Main Battle Tanks Systems (MBTS) no later than 2018. Production repair process of the suspension arm will commence after approval.

3.1.3.3 Spray Repair Technology

The Army is demonstrating applications of cold spray (CS) technology. In the Bushmaster application, a Tungsten-Tantalum tube was produced by the CS Process and successfully and explosively clad into the inside diameter of a Bushmaster, forming a high temperature/wear resistant coating. The CS tube was produced at less than half the cost of a conventional extruded tube and reduces long lead times. The CS process is also capable of producing tubes comprised of materials that cannot be produced by conventional techniques. This work is a collaborative effort between the Army and industry.

Another CS application is rotorcraft sustainment. The purpose of this research effort was to develop a CS process to repair magnesium aerospace components for Army rotorcraft. This application has the potential of saving millions of dollars in sustainment costs. The pay-off would enable the reclamation of high cost ($800,000/part) transmission parts for service. The SAFR warehouse at CCAD had over $220 million of parts removed from service because of excess corrosion and/or wear, of which a significant portion could be reclaimed by the CS process. Annual savings are expected to exceed $100 million based upon a trade study by Sikorsky Aircraft Corporation.

Army developed a high wear, conductive CS coating for the Navy electromagnetic (EM) Gun Rail Program that has recently been applied to full-scale small caliber rails and survived 30 shots at full muzzle velocity without any evidence of erosion or other damage. This achievement represents a major breakthrough for advancing the Navy EM Gun toward implementation. The CS Team leveraged powder synthesis and process optimization research from the former Army

EM Gun Program to develop a means of utilizing the AM capability of CS technology and applying it to the unique rail configuration through a materials-by-design approach.

3.1.3.4 T700 Compressor Case Remanufacture for Use with "Ruggedized" Blisk

All in-service Army T700 engines will transition to ruggedized compressor stage 1 blisks for up to two times longer engine time-on-wing. The Army's new blisk requires a compressor case for maintaining containment. The older replacement part exceeds $17,000 each. This project will use CS technology to remanufacture fielded T700 compressor cases to provide proper ballistic containment properties as defined by Aviation Engineering Directorate by depositing a thin layer of Titanium 64 alloy material to the compressor case. Remanufacturing avoids approximately 92 percent of costs and logistics of the new-make compressor cases.

3.1.4 AM Materials and Process Development

3.1.4.1 Basic and Applied Research for AM

The Army's Center for Agile Materials Manufacturing Science (CAMMS) leads research focused on discovery, innovation, and maturation of materials and manufacturing science to permit agile, adaptive, mobile processing for highly flexible expeditionary manufacturing capabilities to quickly produce tailored parts and components. CAMMS is configured to support material and process maturation and transition to stakeholders. Through CAMMS, the Army is conducting basic research in the synthesis and development of material systems and multi-scale material modeling, as well as applied research in the optimization of AM processes and process-to-microstructure modeling. Together, these basic and applied research areas allow for 100 percent verifiable feedstock pedigree for AM-compatible polymers, metals, ceramics, and printed electronics, and manufacturing reliability through in-situ characterization and verification.

Additive Manufacturing enables new manufacturing capabilities through the development of high performance feedstock materials (polymers, metals, ceramics), physics-based process models, and in situ process monitoring that can be integrated with process models to enable real-time control and manipulation of materials structure and properties. This research aims to push the limits of AM (e.g., resolution, designer feedstocks, and process controls) to produce lightweight materials for protection and maneuverability that cannot be produced through traditional manufacturing methods.

3.1.4.2 Research in New Polymer Technologies for AM

The Army is developing and advancing capabilities to rapidly design, produce, and deploy novel polymer-based technologies to include abilities to repair, produce spares, and even develop new components under forward operating conditions using stereolithography, selective laser sintering, and fusion deposition modeling AM techniques. Developments focus on materials with high strength, high toughness, and ballistic resistance for Army operational environments via revolutionary advancements in capabilities based on breakthroughs in polyimides, polybenzoxazines, dicyclopentadienes, polyureas, and polycarbonates while novel hybrids with (meth) acrylates and epoxies enable rapid manufacture.

3.1.4.3 Topology Optimization for Missile Structures
This effort develops the design and analysis tools that allow the efficient optimization of missile structures for weight and cost reduction. The optimization of structures for structural, thermal, and dynamic properties is accommodated by AM processes. Currently, this optimization process is under development. The Army is working with industry such as the Department of Energy's Sandia National Labs and other Government entities to improve the optimization process through demonstration on missile structures and components.

3.1.4.3 Printable Materials with Embedded Electronics
The Army is using AM for Printable Materials with Embedded Electronics within missile S&T programs. Printing both general passive electronics and radio frequency (RF) structures offers new ways to support Aviation and Missile Research.

3.1.4.5 Advanced Materials for AM
The Army conducts synthesis of novel AM specific materials that can be adapted for use in powder fed AM processes enabling transition to DoD structural applications. In addition, Army provides for the development, advancement, and implementation of state-of-the-art intelligent AM processing, machine learning, sophisticated automation and controls, and advanced inspection techniques that satisfy performance and affordability goals, supporting the production of aircraft, munitions, and ground vehicle systems assuring reliability and repeatability of AM systems and final product.

3.1.5 AM Training Related Efforts

3.1.5.1 Field Level Maintenance
PEO Combat Support and Combat Service Support, in conjunction with Combined Arms Support Command, will be conducting a Limited User Experiment (LUE) at the tactical level in conjunction with the fielding of the Metal Working and Machining Shop Set (MWMSS). The focus of the LUE will be Soldiers printing polymer parts at Field Level maintenance. Soldiers will either use those parts on non-mechanical items or for prototyping utilizing the equipment in the MWMSS. The data gathered from the LUE will identify ease of use, quality of components made, repeatability, dependability, reliability, and types of polymers used.

3.1.5.2 AM Coursework Development
The Army has developed internal AM courses to support training and leadership development. Curricula are offered at various levels dedicated to training Soldiers, Special Operators, and Program Managers. Additionally, a Rapid Fabrication (R-FAB) training program that emphasizes expeditionary AM is offered.

3.1.6 Medical AM

3.1.6.1 US Army Medical Materiel Development Activity Prototype Development
US Army Medical Materiel Development Activity (USAMMDA) utilizes 3D printing Technology in the development of medical materiel. Fused Deposition Modeling (FDM) is the AM technology that USAMMDA uses to rapidly prototype field medical materiel and Army laboratory testing apparatus. In an effort to minimize the logistical footprint down range,

USAMMDA is participating in a collaborative effort to investigate feasibility of leveraging the versatility of 3D printing technology in the repair or replacement of equipment/parts. The technology has reduced the concept-product development process and has a resulted in quicker fielding of equipment.

3.2 Navy

As defined in the DON AM Implementation Plan, AM provides two overarching benefits to the Navy and Marine Corps: increased readiness/sustainment and enhanced warfighting capabilities:

Increased Readiness/Sustainment. DON has used AM for over twenty years to produce indirect items (tooling, fixtures, molds, prototypes, etc.) that make production processes more cost effective and efficient; these applications need to continue to be expanded and exploited. As AM evolves to be used for the production of end-use components, there is significant potential for AM to resolve obsolescence and long lead time issues. The eventual production of components "on demand" and close to the point of need will support a robust, scalable supply chain and allow a new era of supply chain independence.

Enhanced Warfighting Capabilities. AM eliminates traditional design constraints, creating a new design space that allows for previously unobtainable design characteristics. Multi-component assemblies can be consolidated into a single item, lattice-like structures will yield lighter and stronger parts, advanced materials enable multi-functionality, miniaturized sensors can be embedded into a structure – all resulting in more effective and more lethal platforms. AM also allows for widespread customization, enabling tailored solutions that are specific to each mission or even each Warfighter.

The enterprise wide challenges to AM adoption can be consolidated into five broad categories:

1) *Expeditionary and Operational Manufacturing*
2) *Qualification/Certification*
3) *Digital Thread*
4) *Workforce Development*
5) *Business Processes*

DON has numerous additive manufacturing projects underway to address these challenges across multiple System Commands and projects range from operationalization to S&T. S&T investments for design and performance tools, exploration into new functionality, AM for rapid tooling, AM repair, new AM alloys and process improvements are enabling enhanced Warfighter capabilities while operationalization of polymer AM technologies are helping increase readiness today. It is important to note that DON is actively coordinating efforts within the Navy and Marine Corps and with the other MILSVCs, Government agencies, manufacturing institutes, academia, and industry. Engagement with the industrial base is especially important as DON works to enable scalable, distributed manufacturing throughout the enterprise. The following are examples of coordinated DON AM initiatives.

3.2.1 Expeditionary and Operational AM

The Navy and Marine Corps are operationalizing AM technology in order to realize readiness and warfighting benefits today. Efforts are underway attempting to address the considerations necessary to ensure reliable production in any operational environment. The following projects highlight examples of successes in DON operationalization of AM.

3.2.1.1 3D Printed Unmanned Aircraft System

The Marine Corps partnered with MITRE, a Federally Funded Research and Development Center (FFRDC), to field the "Nibbler", a Group I, 3D Printed unmanned aerial system (UAS). The current Squad-level fielded UASs have more endurance than the Nibbler, but pose a higher risk to the user in combat by exposing them to fire and provide no ability to repair or customize the drones at the user level. Furthermore, it costs $230,000 - $250,000 for conventional UAS system package (three UASs, controller, and other required equipment) versus $3,000 for a Nibbler (one UAS, kit, and controller included). As Nibblers are fielded, Marines are trained not only to operate the Nibblers but print and assemble them, as well, so that the full breadth of mass customization enabled by 3D printing can be employed by Marines at the point of use.

3.2.1.2 H-1 Helmet Visor Clip

The H-1 Helmet visor clip is a highly consumable item with a significant demand signal, long lead time (approximately 9 months), and a per unit cost of $300. Due to the long lead time, H-1 program office officials worked with the U.S. Navy Air Warfare Center (NAVAIR) AM IPT to develop an alternative equivalent for this item that can be made on-demand using a desktop level 3-D printer. The team produced a working prototype for review by the team within 72 hours, and created an approved solution that can be utilized in the fleet within 7 days of the initial prototype. At a per unit cost of approximately $0.75, the clip is the first AM part in the Navy supply system approved for fleet operations. The initial batch of 100 of the clips was manufactured and delivered in 10 days to the squadrons who needed them for flight operations.

3.2.1.3 3D Printed TS-10 Purge Kit Handle

In January 2017, Marine Corps Systems Command (MCSC) approved Combat Logistics Regiment (CLR) 25's request to 3D Print the TS-10 Purge Kit handle. With minimal training and an inexpensive consumer grade 3D printer, Marines were able to reverse engineer and design replacement handles for seven purge kits, which resulted in a cost avoidance of $5,677. In the same month, the 3rd Expeditionary Sustainment Command from the Army visited CLR-25's AM lab where it was identified that the Army utilizes the same Purge Kit and has been experiencing the same failure. CLR-25 has coordinated with them, shared the approved files for them to use.

3.2.1.4 T-45 Oxygen Mask Valve

In April 2017, concerns over Physiological Episodes affecting pilots caused a significant reduction in types of training events able to be performed by T-45 Goshawk crews. While working through a permanent fix to the problem, the NAVAIR AM/DT IPT worked with multiple Program Offices to rapidly iterate and agree on a 2-part AM produced oxygen mask valve assembly that attaches to the pilot's mask. The valve allows aircrew to breathe pressurized cabin air up to a 15,000-foot altitude. It is designed to seal shut quickly and allow safe use of the liquid oxygen system during an emergency. Due to the urgent need, a distributed manufacturing approach across six sites was used to deliver an initial production run of 300 units in 10 days;

and a follow-on production run of 500 units in 5 weeks. This use of AM allowed T-45 aircrew to resume training and provides a key demonstration of the power of distributed AM to meet urgent Fleet requirements. This project validated the ability of AM to accelerate both the design cycle and the production of urgent items.

3.2.1.5 3D Printed Duct Assemblies

The air conditioning duct assembly, P/N 2600692, NSN 2540-01-585-1451, for the Marine Corps' Amphibious Assault Vehicle (AAV) was originally made using stamping and forming dies and is not available through the supply system until mid-2018. The non-availability of the duct assembly was preventing the Marine Corps' Depot in Albany, Georgia from completing AAVs for return to the Fleet Marine Forces. Employing the CAD models for the part, Marine Corps AM experts designed form blocks and created accurate flat patterns for the duct assembly. By using AM forms, the Marine Corps was able to fabricate the duct assemblies and return a number of AAVs back to the operational Marine forces in 2017 vice 2018.

3.2.1.6 3D Printed Wrenches

Due to complications with new 81mm mortar tubes, there was an immediate need for a long lead time high-torque wrench for Marines in the U.S. Central Command (CENTCOM) Area of Responsibility (AOR) engaged in combat. Using their deployed 3D design and printing capabilities, the unit designed their own interim solution, then reached back to MCSC engineers for an improved design that met the manufacturer's spec for 150 ft/lbs of torque. The printed wrenches were able to provide the unit with maintenance capability while the conventional supply system was working to fulfill the requirement. The cost of the printed wrench was approximately $2 in material compared to $61 for a conventionally manufactured wrench.

3.2.1.7 Concrete Additive Manufacturing

USMC has partnered with the Army Corps of Engineers to evaluate 3D concrete printing in 2018. Work will focus on increasing the speed, precision and strength of printing structures using concrete and other hybrid materials for printing in distributed operations to include humanitarian and disaster events.

3.2.1.8 Afloat Additive Manufacturing

AM has been deployed in afloat settings onboard USS TRUMAN, USS KEARSARGE, and several other platforms. These demonstrations have validated the feasibility to print in afloat environments and have been crucial to identifying shipboard applications that AM can address. Current afloat initiatives are underway to deploy additive manufacturing capabilities aboard a range of ships to quantify environmental and motion impacts to AM, identify shipboard integration requirements, and to expand the number of applications that can be addressed through afloat AM.

3.2.2 Qualification/Certification

The need to qualify and certify additively manufactured parts is a fundamental barrier to more extensive use of AM across platforms. With AM, the resultant properties of the part are determined by the material, the processing and the component geometry simultaneously, making qualification and certification very complex. The following DON efforts in Qualification and Certification are highlighted below:

3.2.2.1 Quality Made

Supported by related S&T investments, the Quality Made project will focus on providing the Navy with the ability to rapidly qualify material and processes for production of metallic AM components using modeling and simulation (M&S) tools and in-process sensors and controls. This Office of Naval Research effort will analyze both integrated computational materials engineering (ICME) approaches to predict and evaluate AM resultant material properties and evaluate closed loop feedback strategies to make processes more repeatable and reliable. The project will be foundational in developing confidence in metal AM processes and in the DON's incorporation of predictive materials modeling that will allow for more rapid qualification and certification of AM materials. The three-year project has been approved to begin in FY 2018 and is expected to include several DoD, academic and industry partners.

3.2.2.2 Flight Safety Critical Components

Qualifying and certifying AM parts for use in flight safety critical applications is a challenge given the strict manufacturing quality requirements for aerospace. In July 2016, DON performed a V-22 Osprey flight demonstration of a titanium safety critical assembly made via AM. This was the first time safety critical AM components were approved for use on Navy aircraft. The V-22 components have since been certified for full performance – having the same performance and life as the original stock items. DON will qualify and certify additional flight safety critical items in 2018 for the H-1 and CH-53 using different metal alloys. The AM standards and processes that are developed for flight critical items will be used to expand the use of AM for high need items to improve readiness. These efforts also provide foundational data to the Quality Made project support the development of model based qualification and certification to accelerate qualification and certification.

3.2.2.3 AM Technical Data Package (TDP)

DON established a working group that is developing the requirements for a standardized TDP for AM components. This effort includes identifying key elements required for AM and a standard layout needed to repeatedly produce items. This effort will also develop the guidelines for exchanging AM related technical data between Government and industry.

3.2.2.4 3D Printed Antennae for Signals Intelligence

An ongoing Space and Naval Warfare Systems Command (SPAWAR) Systems Center, Pacific R&D effort designed to 3D print antennae with the same characteristics of traditionally manufactured antenna assemblies. The goal is to increase readiness, improve sustainment, and enhanced warfighting capability at the point of need.
A second product, the Submarine Broadband Antennae, is also under development.

3.2.3 Digital Thread

As a digital manufacturing technology, AM requires managing vast amounts of digital data for effective implementation. This digital data is needed for a number of digital manufacturing processes, of which AM is a subset. The digital AM framework includes the IT architecture and infrastructure, tools, cybersecurity, digital data standards (including design), data acquisition, and management required to utilize AM across the Naval Enterprise. The following efforts on the AM digital thread are highlighted below:

3.2.3.1 Expeditionary Maker 3D Model and Collaboration Portal

USMC has successfully deployed an online collaboration portal for its Marine Maker movement. This interim digital interface acts as an initial capability for Marines to share ideas, problems, and successes. Current efforts are underway between USMC, SPAWAR, Naval Facilities Engineering Command, and Naval Postgraduate School to deliver a long term, cloud based, 3D model repository and collaboration portal. This portal will be capable of delivering a scalable, repeatable, affordable, and secure digital AM management tool, to the DON expeditionary enterprise.

3.2.3.2 EXMAN Mobile Test-bed

The Expeditionary Manufacturing Mobile Test Bed (EXMAN) has been deployed by SPAWAR to the 1st Maintenance Battalion, 1st Marine Expeditionary Force, at Camp Pendleton as part of the strategy to mature the Smart Manufacturing Grid in the context of real world requirements. The first unit, EXMAN TB-100, is a prototype mobile facility designed to support the continuous experimentation of advanced manufacturing tactics, techniques, and procedures under actual operational or combat conditions.

3.2.3.3 Digital Thread Development Environment

The "Digital Thread" for AM is the digital process from design through manufacturing and contracting married with the digital design and manufacturing data. To develop the "Digital Thread" framework for AM, a digital lab has been setup by NAVAIR intended to standardize the "Digital Thread" for AM and define the interchange of digital data between Government and industry. The initial capabilities enable the interchange of digital design data (e.g., Computer Aided Design) and consider how standard Product Lifecycle Management tools utilized by industry can be used for AM. The Digital Thread Development Environment will serve as both a testbed for digital interchange between Government organizations and industry partners, and as a working environment for prototyping next generation digital manufacturing technologies.

3.2.4 Workforce development

Training the DON workforce in AM encompasses all development, deployment, and utilization of AM education, training, and certification programs and opportunities to ensure that the DON workforce (both civilian and military) can safely and effectively use AM, leveraging these technologies along with digital design capabilities, to the fullest capacity. These efforts for FY 2016-2017 include:

3.2.4.1 Mobile Manufacturing Training

USMC has deployed a mobile training lab to travel to Marine Makers around the country to teach programing, welding, soldering, 3D printing and its application to the modern battlefield. These skills help Marine learn what is in the realm of the possible with current, low end, high effect technology

3.2.4.2 Old Dominion University Fleet Maker Training

The Office of Naval Research with Old Dominion University is providing laboratory-based educational workshops for active duty Sailors and Marines to highlight digital design and manufacturing. These workshops include 3D design, scanning, reverse engineering, and AM fabrication. Training classes will continue through 2019.

3.2.4.3 Fabrication Laboratory (FAB LABs) and Maker Space Deployments

FAB LABs and maker spaces have been deployed to sites throughout the Navy and Marine Corps in order to train the Marines, Sailors, and civilians in advanced manufacturing capabilities. Many of the examples from the Expeditionary and Operational section above are a direct result of the deployment of FAB LABs maker spaces to the fleet.

3.2.5 Business Processes

The understanding of necessary business models (contracting language, intellectual property considerations, liability concerns, etc.) to support AM is rapidly evolving as the technology is more widely adopted and employed. DON must posture itself to ensure these considerations are addressed in business and acquisition policy in order to ensure the rapid adoption of AM. The following describe DON AM efforts related to business processes:

3.2.5.1 Participation in DOD Business Model Wargame

DON informed and actively participated in the Office of the Secretary of Defense (OSD) and America Makes sponsored business model wargames. These were crucial efforts that brought DoD Agencies and industry together to discuss new business models that enable more rapid implementation of AM, encourage a strong industrial base, and are fair to Government customers. Discussions included business practices regarding intellectual property, data rights, and contracting issues specific to AM, risks to the industrial base, legal concerns, and liability.

3.2.5.2 Business and Acquisition Policy

In order to fully recognize the logistical benefits of AM as the technology matures, our supply chains and acquisition activities need defined processes to acquire AM produced items and services. To that end, cost analysis tools are under development to better capture the cost components of AM and accurately report on their Return on Investment, not just from a production standpoint, but across a system's life cycle. DON is developing new business models and processes, in concert with the other MILSVCs, that incorporate contracting, legal, and acquisition concerns. This guidance will be formalized in a comprehensive AM Contracting Guide that provides boilerplate language for implementation of multiple business models that have been developed for AM sustainment, early acquisition, and new capability development. In addition, DON has identified capability gaps in Logistics IT systems and will be working with DLA on updates to DON and DoD supply chain policy for the effective management of AM produced items.

3.3 Air Force

AM or 3D printing is an important game-changing technology for the United States Air Force (USAF).[4] It can improve asset velocity to the USAF supply chain network, resolve diminishing manufacturing supply issues, and improve mission readiness and availability. The USAF is taking a deliberate approach to implementing AM by focusing on the power of the enterprise to

[4] Information provided for this report by representatives of the Air Force Life Cycle Management Center.

improve readiness, reduce cost, and ensure agility and flexibility for the Warfighter. The vision is to print on demand, anytime, anywhere, any machine. In order to achieve this vision, USAF is laying a strong foundation focusing on nine key challenge areas: material standards and availability, part selection, skillset development, configuration control, reproducibility, cyber security, part validation and qualification, process validation and qualification, and reverse engineering.

The Air Force Life Cycle Management Center (AFLCMC) Product Support Engineering (EZP) has been appointed as the USAF lead for AM implementation. The AFLCMC is working in close collaboration with the Air Force Research Laboratory (AFRL), the Air Force Sustainment Center and the Air Force Nuclear Weapons Center to aggressively address the challenges of AM through an enterprise approach to implementation. The following sections describe highlights of Air Force AM efforts.

3.3.1 Air Force AM Innovation Centers

The first USAF AM Innovation Center has been established and is operational near Wright Patterson Air Force Base, Ohio, in collaboration with University of Dayton Research Institute. Additional Innovation Centers are being established at the three Air Logistics Complexes (ALCs). As the USAF brings on-board new AM machines and post processing equipment, facility, safety, and hazard risk assessment standards are being developed for each type of equipment. Policies are in place to standardize various AM equipment and tool purchases across the USAF to ensure configuration control is maintained and communication improved.
In support of those policies, standard facility guides and installation procedures have been developed and are being used as part of planning for future USAF AM Innovation Centers.

3.3.2 Standard Procedures and Configuration Control Processes

The USAF is also developing standard procedures and configuration control processes for all aspects of the Air Force AM Strategic Implementation Plan (AMSIP). Strong configuration control principles will ensure the current design and build state is known, good, trusted, repeatable, and meets the design intent. Configuration control across all aspects of design, print, and qualification is critical to ensuring correct and repeatable performance is achieved. Standardized maintenance procedures, material handling, storage procedures, and quality control procedures are being developed. Configuration control standards will enhance system reliability and repeatability through more rapid detection and correction of improper configuration that could negatively impact component design and build properties. For example, machine-to-machine variations will be minimized through strict configuration control and quality practices. Standardized post-processing requirements have been evaluated and down-selected. A standard facility equipment installation checklist has been established. Material specification sheets are under development, numerous parts have been printed and qualified, an engineering design rules guidebook is being established and training courses provided.

3.3.3 Materials Properties Database

Selecting the right AM material and process is a key foundational requirement for successful AM implementation and will directly affect the expected return on investment. Whether the AM product is for a prototype, first article testing, component repair, or an end-use production part, understanding the application is the first step. There are hundreds of materials and numerous process methods to consider. The right material choice for the application and post heat treatment (based upon part geometry and function) are critical to ensure desired mechanical properties can be achieved. The USAF approach for developing AM material standards that produce optimum material properties is based upon a realization that successful AM is a marriage between the material, the type of AM machine, machine settings, post processing steps, and sometimes redesigning parts for AM. To that end, USAF is currently developing an enterprise material properties database based on the AM machine, optimized process parameters and the powder characteristics (i.e., Particle size distribution, powder shape, and flow characteristics). All critical factors are being identified, captured and incorporated into an AM design rule guidebook to reduce duplication and ensure the engineering/design community leverages best practices and lessons learned.

3.3.4 AM Metal Part Prototyping

Over the past year, USAF has been working on optimizing build parameters, characterizing AM material properties, reducing print time, and validating repeatability for stainless steel and titanium parts and expanding into aluminum and nickel components. The following are a few of the successes achieved using metal AM technology:

- Three stainless steel parts (lug, hinge, and hook) have been designed, optimized for AM, printed, tested and installed on the MQ-9 Reaper Trailer.
- One stainless steel engine bracket has been designed, optimized, printed, tested, and installed on the TF33 engine stand.
- Stainless steel Y and T shaped conduit junction boxes have been designed, optimized, printed, and are being tested for the B-2 smart bomb rack.
- Stainless steel C-5 Galaxy aft cargo door handle has been designed, optimized, printed, and is currently being tested.
- Titanium C-5 Galaxy aft door bellcrank has been design, optimized, printed, and is currently being tested.
- Printed Memphis Bell Flying Fortress (B-17) lock lever knob and ball turret end cap parts for USAF museum restoration.

3.3.5 Candidate AM Part Selection Process

As AM technologies have matured, it is now possible to match the technology to broader applications. Part screening and selection are important foundational processes that must occur for each potential application. Part selection analysis includes technical complexity, part size, material, component application, economic considerations, lead time, and risk. The opportunity for cost effective readiness is important and the USAF is using a value chain approach that takes into consideration both economic and readiness criteria to ensure the correct applications are being pursued. The USAF is developing a standardized, systematic approach to selecting parts, materials, and processes for AM across the USAF enterprise. USAF is using a crawl, walk, run approach to down-select initial parts based on risk. Until the infrastructure exists to utilize better selection tools, the USAF has taken a deliberate approach to minimize risk while leveraging opportunities to learn and advance the technology through a strong foundation.

3.3.6 Workforce Development

The aerospace community will need to invest in the skills of the people who design, build, and use AM technology across the aerospace industry. The majority of today's engineers have been trained using conventional engineering methods that only consider subtractive manufacturing design principles. Changing that paradigm will take time and deliberate steps, addressing the current work force as well as the engineer of tomorrow. AM designers will need to be creative and innovative to utilize a new design methodology, taking full advantage of this technology.

The USAF is developing internal training focused on the specific tools, applications, processes, and equipment down-selected for use across the enterprise. The target audience of the skillset development plan includes both new and experienced engineers, designers, operators, supply chain and maintenance communities. The AMSIP includes leveraging partners across other MILSVCs, academia, and industry to ensure new engineers and/or technicians entering the USAF have the necessary AM foundational skills. Focus areas for this specialized training include fundamentals of AM designs, economic considerations, design strategies for AM, quality control, safety operations, equipment maintenance practices for equipment, AM materials selection, and hands on design and print projects for AM components.

This approach will allow the USAF to effectively standardize skillsets, tools, design principles, configuration control, quality control and validation procedures, while building a centralized library of qualified, validated designs. Close collaboration and innovation with the other MILSVCs, academia, and industry are key components of the AMSIP that will help shape the future aerospace workforce.

3.3.7 Air Force Research Laboratory Projects (Overview)

Within the USAF and industry, AM technology continues to evolve and expand. The AFRL leads in areas where there is a specific military need and where the USAF is primarily responsible. AFRL invests in AM research for applications including hypersonics, munitions, energetics, survivable electronics, conformal and structural antennae, and printable wearables for airmen. AFRL/RX is investing approximately $140 million on over 100 active projects with industry providing about $45 million in cost share. FY 2017 funding is about $49 million.

3.3.8 Program Management of America Makes

Air Force Research Laboratory serves as the Government Program Management side of the public-private partnership with America Makes, the National Additive Manufacturing Innovation Institute, which was the first-established of the 14 Manufacturing USA institutes. America Makes is a consortium of over 180 industry and academic members forming the ecosystem for U.S. AM research, equipment, production, and workforce training. As of early 2017, America Makes had a research portfolio of 66 projects with almost $100 million combined public and private investment. Government agencies (primarily within DoD) have gone to America Makes for fourteen agency-directed R&D and workforce training projects so far. America Makes facilitated the creation of the first DoD-wide Joint AM R&D roadmap, which creates a shared understanding of AM R&D priorities. In addition, America Makes is collaborating with American National Standards Institute (ANSI) to operate the Additive Manufacturing Standards Collaborative, which has already identified AM standards that need to be written and is facilitating collaboration among all major U.S. Standards Development Organizations to write the standards.

3.3.9 Maturation of Advanced Manufacturing for Low Cost Sustainment (MAMLS)

The average age of aircraft in the Air Force inventory is 27 years. With legacy aircraft, the Air Force faces challenges such as out-of-production spares and the need to replace parts for decades into the future. The objective of this project is to develop AM processes that improve the efficiency of the factory or Air Logistics Center for rapid part replacement for legacy and other aircraft. It specifically targets on-demand replacement of critically damaged or life-limited components for which the production volume makes it uneconomical to use conventional supply chains. The project benefits will be to reduce the cost and time to produce replacement components for aircraft in the sustainment centers and to demonstrate rapidly-fabricated tools (assembly aids, jigs, fixtures, processing aids) for use on the Air Logistics Center shop floor.

The project is proving that AM has the materials and processes in place to create nominal structural and functional performance properties for four different, complex, direct part demonstrations – a bell crank, a fuel-oil cooler, composite sandwich panels, and structural repair panels – with breadth to cover a family of each type of part, leading to a path for qualification.

The team is not only demonstrating the advanced manufacturing technologies for sustainment operations but is also providing focused workforce training to enable transition at an organic level at the ALC's and flight lines while also developing training and workforce education curriculum to support the AFRL and AFLCMC at enterprise levels.

3.3.10 AM Laser Powder Feed

There is a need for a reliable and robust AM repair method for military aircraft related components manufactured from Ti-6Al-4V. Depending on the component, conventional repair methods may not always have been capable or reliable. Therefore, interest in Laser Powder Directed Energy Deposition (LPDED) to solve this problem has grown. However, it is a maturing technology, lacking specifications, best practices, procedures, and process controls. The goal of this project was to help facilitate the adoption of AM for "flight-worthy" repairs by restoring the Ti-6Al-4V component function without compromising structural integrity. The benefit would be to enable DoD part repairs for numerous applications, with significant lead time reductions and cost savings.

The project initiated the development of an LPDED repair methodology to the point that it can be cost-effective and consistently applied to a wide range of highly reliable applications in a certifiable, approval-based fashion. This was achieved by coordinating a collaborative integration of available, past and ongoing, LPDED development efforts into a centralized Directed Energy Database. This project has relied upon, and promoted, ongoing collaboration with DoD branch repair Depots, Original Equipment Manufacturers, supply chain, and technical societies in order to identify "best practices" for comparable repair methods currently in use and approved for military aircraft engine applications. The project also relied upon collaboration with other DoD-funded projects such as America Makes and relevant Small Business Innovation Research (SBIR). This leads progress towards identifying and satisfying airworthiness qualification requirements and data for LPFDED repairs of DoD components.

3.3.11: F-15 Pylon Rib Qualification and Certification

In 2003, nearly 15 years ago, USAF fully qualified the first metallic additive manufacturing structural part. The part was the F-15 Pylon Rib and was qualified for the life of the aircraft as a one-to-one replacement based on a corrosion fatigue problem with the original component. The additive manufacturing process used to fabricate the replacement part was the Laser Additive Manufacturing process which is categorized as a metallic Directed Energy Deposition process. The replacement component solved a lead time issue that could not be addressed by the conventional manufacturing supply base. Approximately a dozen parts were produced prior to the conventional process becoming available, and those parts are still flying today with no reported field issues.

3.3.12 Printed Tooling for Aerospace Castings

An AFRL led partnership with America Makes has demonstrated how additive manufacturing can decrease casting lead times through processes such as 3D sand printing for casting tooling. An AF C-130 reserve unit required lead time reduction for an aluminum casting required for an aerial spray system. The current component was fabricated used multiple cast parts welded together. A single replacement part was reverse engineered from the existing platform, and a 3D model created. The casting process was computer simulated, a sand mold was printed, and the aluminum part subsequently cast. Lead time was reduced from over 10 weeks to less than 4 weeks with cost and performance benefits currently being validated. In addition, future parts will be cheaper and faster to fabricate due to elimination of non-recurring costs. Similar advancements are being made for investment casting through a process called Quickcast, which directly produces the core versus the mold. A demonstration heads up display mount was cast using the investment casting process. Work continues to qualify these processes for air worthiness.

3.4 DLA

The investment strategy for the DLA R&D ManTech AM Program seeks to solve procurement issues related to the sustainment of legacy repair parts. With the collaboration of the MILSVCs, industry and academia, DLA is:

- Identifying the proper parts for AM conversion,
- Assisting the MILSVCs in the qualification process of AM procured items,
- Leveraging DLA information technology assets for the exchange of AM technical data, and eventually,
- Integrating the qualified AM parts into DLA supply chains.

To enable these lines of efforts, DLA has established service agreements with NAVAIR, U.S. Naval Sea Systems Command (NAVSEA), U.S. Army Research, Development and Engineering Command (RDECOM), Department of Energy and the U.S. Marine Corps Systems Command. Underway is a service agreement with U.S. Air Force Materiel Command. The DLA R&D ManTech office is engaging these groups, with projects to develop AM cultural champions, to prioritize efforts, and to maintain strategic alignment.

DLA will continue to engage in projects with industry to accelerate AM parts procurement. These projects will address qualification of the AM vendor network, digital traceability of the

AM technical data, management of AM technical data rights, and technical data provisioning. Additionally, DLA has reached out to industry with a request for information to initiate the baseline of the cost of producing AM technical data, building models, delivering first article tests and a full production of AM parts. The results will help gauge the readiness of the current vendor base and will assist in the development of contractual language for future procurements.

3.4.1 Prototype Selection Tool

As part of the effort to identify the suitable AM part candidates, DLA R&D contracted for the development of a prototype selection tool capable of sorting through the technical and business attributes of over a million legacy parts. The tool identifies availability of 2-D technical data in DLA repositories, material specifications, criticality, and business attributes such as backorders and lead-times.

3.4.2 Common Framework for AM Part Production

DLA is collaborating with NAVSEA to develop a common framework for AM part production. This project will enable future AM technical data to be produced rapidly by correlating material and geometric characteristics to a combination of processing parameters and base geometric features.

3.4.3 Demonstration of Building Legacy Parts

In a collaborative effort between DLA and NAVAIR, six legacy hard-to-source parts were selected, using the AM part candidate selection prototype tool, and put under contract with industry to convert the legacy 2-D dimensional data into 3-D technical data and eventually build the models using AM. The six finished AM parts are undergoing NAVAIR qualification and required certification of the materials and processes before DLA can use them to address a Warfighter sustainment need.

3.4.4 Demonstration for Acceleration of Casting Mold Production

A project with RDECOM to demonstrate the use of in-theatre desert sand for casting molds. The project will provide a proof of concept for reducing long lead-time for components. DLA is also taking advantage of the SBIR program to fund initiatives that will develop areas that can accelerate the technical and manufacturing readiness level of AM such as: in-situ inspection, AM powders for high-performing parts, 3D printing of molds for cast parts, prosthetics, and ceramic AM molds.

3.5 Missile Defense Agency

MDA is participating in AM primarily through SBIR initiatives to manufacture components that are lighter and cheaper, eventually seeking lower cost interceptors.[5] MDA leverages the SBIR program to demonstrate and prototype parts. MDA released one 2016 SBIR topic, "Additive Manufacturing for Affordable Missile Defense," within its Manufacturing Technology research area. MDA awarded six Phase 1 SBIR contracts for projects to develop processes for manufacturing and qualifying noncritical parts for missile defense applications, including missiles, kill vehicles, sensors, and radars. These projects will deliver prototypes with

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[5] Information provided for this report by representatives of Missile Defense Agency.

mechanical properties that meet or exceed requirements using representative metals and part specifications.

Through upcoming SBIR solicitations, MDA is seeking innovative processes to print a 3D package around a bare semiconductor die to reduce counterfeiting, as well as AM methods for shielding individual microelectronics from radiation.

Additionally, MDA is in early discussions with several major prime contractors to explore the implementation of AM for some products.

3.6 Examples of AM Capabilities in Action for DoD Today

Not all DoD work is R&D focused on advancing AM capabilities. Also important is the Department's work to apply today's AM capabilities to address today's needs. This work serves to demonstrate the potential value of AM to wider audiences, which will accelerate the adoption of AM throughout DoD. The following sections describe examples of DoD putting today's AM capabilities into action.

3.6.1 Air Force Application Demonstrations

In 2003, USAF fully qualified the first metallic additive manufacturing structural part. The part was the F-15 Pylon Rib and was qualified for the life of the aircraft as a one-to-one replacement based on a corrosion fatigue problem with the original component. The additive manufacturing process used to fabricate the replacement part was the Laser Additive Manufacturing process which is categorized as a metallic Directed Energy Deposition process. The replacement component solved a lead time issue that could not be addressed by the conventional manufacturing supply base. Approximately a dozen parts were produced prior to the conventional process becoming available, and those parts are still flying today with no reported field issues.

There are many opportunities where AM can and is being successfully implemented today within USAF. Hundreds of polymer parts, tools, and fixtures have been designed, printed, and are currently being used across USAF. For example, Sheppard Air Force Base, Texas, printed KC-135 Brake Assemblies from AM polymer for a training application, realizing a cost avoidance of $31,000 per assembly; Tinker ALC, Oklahoma, designed and printed tooling for a radar range fixture reducing flow days by 20 days and achieving a cost avoidance of $9,000; Warner Robins ALC designed and printed Multi-Functional Color Display System Panels saving 364 flow days across the entire effort and $1,138 per panel.

3.6.2 Printed Tooling for Aerospace Castings

An AFRL led partnership with America Makes has demonstrated how additive manufacturing can decrease casting lead times through processes such as 3D sand printing for casting tooling. An AF C-130 reserve unit required lead time reduction for an aluminum casting required for an aerial spray system. The current component was fabricated used multiple cast parts welded together. A single replacement part was reverse engineered from the existing platform, and a 3D model created. The casting process was computer simulated, a sand mold was printed, and the aluminum part subsequently cast. Lead time was reduced from over 10 weeks to less than 4 weeks with cost and performance benefits currently being validated. In addition, future parts will be cheaper and faster to fabricate due to elimination of non-recurring costs. Similar advancements are being made for investment casting through a process called Quickcast which directly produces the core versus the mold. A demonstration heads up display mount was cast using the investment casting process. Work continues to qualify these processes for air worthiness.

3.6.3 Qualification of Air Cooling Duct

An AFRL led partnership with America Makes resulted in team member Boeing conducting a case study to develop and then qualify an additively manufactured air cooling duct for the C-17. The current duct is repeatedly damaged in the cockpit primarily from foot loading and recent solicitations for replacement parts received a "no-bid" status. A FDM approach was developed using Ultem 9085 material and an improved design. The additive manufacturing qualification was achieved by Boeing through the C-17 Chief Engineer.

3.6.4 DON 3D Print-a-Thon

In March 2017, twenty naval organizations, including scientists and engineers from across the Naval Research and Development Establishment (NR&DE), maintenance operations, and Marines and Sailors from multiple commands presented over 40 items produced through the use of AM technology. In addition to demonstrating how AM enhances warfighting capabilities and increases readiness, the event offered a forum for subject matter experts to share lessons learned and develop future collaboration opportunities. Senior leadership from across the Navy, Marine Corps, and Office of Secretary of Defense attended the event.

3.6.5 3D Printed Unmanned Aircraft System

In order to fulfill the Commandant of the Marine Corp's requirement for a squad level Intelligence Surveillance and Reconnaissance (ISR) UAS, the Marine Corps' Next Generation Logistics (NexLog) team partnered with MITRE, a FFRDC, to field the "Nibbler", a Group I, 3D Printed UAS. The current Squad-level fielded UASs have more endurance than the Nibbler, but pose a higher risk to the user in combat by exposing them to fire and provide no ability to repair or customize the drones at the user level. Furthermore, it costs $230,000 – $250,000 for conventional UAS system package (three UASs, controller, and other required equipment) versus $3,000 for a Nibbler (one UAS, kit, and controller included). The Nibbler can be launched from cover, is more capable than its counterparts in urban or wooded environments, and all structural parts can be made on a desktop 3D printer. Additionally, because the Nibbler was developed by an FFRDC, the Marine Corps owns the data rights, allowing Marines to customize the Nibbler to unique mission requirements that may be encountered on the battlefield. Finally, as Nibblers are fielded, Marines are trained not only to operate the Nibblers but print and assemble them, as well, so that the full breadth of mass customization enabled by 3D printing can be employed by Marines at the point of use.

3.6.6 3D Printed TS-10 Purge Kit Handle

In January 2017, MCSC approved Combat Logistics Regiment (CLR) 25's request to 3D Print the TS-10 Purge Kit handle. With minimal training and an inexpensive consumer grade 3d printer, Marines were able to reverse engineer and design replacement handles for seven purge kits which resulted in a cost avoidance of $5,677. In the same month, the 3rd Expeditionary Sustainment Command from the Army visited CLR-25's AM lab where it was identified that the Army utilizes the same Purge Kit and has been experiencing the same failure. CLR-25 has coordinated with them, shared the approved files for them to use.

3.6.7 Threat Ordnance Training Aids

The Marine Corps has produced IED and threat ordnance Training Aids using 3D Printing. The Marine Corps has produced around 80 sub-munition training aids for our courses. Italian VS50s, U.S. M42s, and U.S. Hydras. These are around $100 each for a factory-made inert training aid, which are produced internally for $0.60 each. Total savings of $7,952 in the first few months of printing.

3.6.8 3D Printed Wrenches

Due to complications with new 81mm mortar tubes, there was an immediate need for a long lead time high-torque wrench for Marines in the CENTCOM AOR engaged in combat. Using their deployed 3D design and printing capabilities, the unit designed their own interim solution, then reached back to MCSC engineers for an improved design that met the manufacturer's spec for 150 foot-pounds. The printed wrenches were able to provide the unit with maintenance capability while the conventional supply system was working to fulfill the requirement. The cost of the printed wrench was approximately $2 in material compared to $61 for a conventionally manufactured wrench.

3.6.9 3D Printed Duct Assemblies

The air conditioning duct assembly, P/N 2600692, NSN 2540-01-585-1451, for the Marine Corps' AAV was originally made using stamping and forming dies and is not available through the supply system until mid-2018. The non-availability of the duct assembly was preventing the Marine Corps' Depot in Albany, Georgia from completing AAVs for return to the Fleet Marine Forces. Employing the CAD models for the part, Marine Corps AM experts designed form blocks to make the two parts with multiple radiuses and created accurate flat patterns for the other three rolled parts that make up the majority of the duct assembly. By making the form blocks, the Marine Corps was able to fabricate the duct assemblies in house for installation in vehicles, and return a number of AAVs back to the operational Marine forces in 2017 vice 2018.

3.6.10 Marine Corps System Command Prototype Demonstrations

In FY 2016, MCSC supported Additive Manufacturing Demonstrations at the 2016 Sea, Air, and Space Exposition and the 2016 Marine Corps Modern Day Marine exposition. In both cases, MCSC demonstrated AM fabricated prototypes that had the potential to improve system readiness for several Marine Corps programs. In 2017, the Headquarters Marine Corps (Integration and Logistics) (HQMC(I&L)) along with MCSC, hosted the 2017 Naval Additive Manufacturing Technical Interchange (NAMTI), which included poster demonstrations of several Navy / Marine Corps AM initiatives. Since the release of MARADMIN 489/16, MCSC has coordinated the development and fabrication of over 20 AM prototypes designed and printed by individual Marines. MCSC has established a process whereby working prototypes can be AM fabricated by Marine personnel, both within the Continental United Stated (CONUS) and Outside the Continental United States (OCONUS), and evaluated by the appropriate program office as a temporary solution to improve system readiness or as a potential permanent replacement.

3.6.11 H-1 Helmet Visor Clip

The H-1 Helmet visor clip is a highly consumable item with a significant demand signal, long lead time (approximately 9 months), and a per unit cost of $300. Due to the long lead time, H-1 program office officials worked with the NAVAIR AM IPT to develop an alternative equivalent for this item that can be made on-demand using a desktop level 3-D printer. The team produced a working prototype for review by the team within 72 hours, and created an approved solution that can be utilized in the fleet within 7 days of the initial prototype. At a per unit cost of approximately $0.75, the clip is the first AM part in the Navy supply system approved for fleet operations. The initial batch of 100 of the clips was manufactured and delivered in 10 days to the squadrons who needed them for flight operations.

3.6.12 T-45 Oxygen Mask Valve

In April 2017, concerns over Physiological Episodes affecting pilots caused a significant reduction in types of training events able to be performed by T-45 Goshawk crews. While working through a permanent fix to the problem, the NAVAIR AM IPT worked with the Program Office to rapidly iterate and agree on a 2-part AM produced a Valve that attaches to the pilot's mask. The valve allows them to breathe cabin air up to a 15,000-foot altitude. It is designed to seal shut quickly and allow safe use of the emergency oxygen system as appropriate. Due to the urgent need, a distributed manufacturing solution was demonstrated resulting in an initial production run of 300 units delivered in 10 days, with a follow-on run of 500 units delivered in 5 weeks. This use of AM resulted in an increased training envelope for the T-45, a demonstration of the ability of distributed manufacturing to meet urgent requirements, and a validation of utilizing AM as a means to accelerate both design and production of an end component.

4.0 Joint Development Projects

The second request in the NDAA for FY 2017 for this report was for "Details regarding joint-development projects and efficiencies achieved through intra-service collaboration." The following sections provide examples of joint AM activities.

4.1 DoD AM Roadmap

A highly significant joint project in AM recently was the development of a DoD AM Roadmap, which culminated in a final report released in November 2016. The DoD AM Roadmap and associated final report were co-authored by 20 representatives from numerous Air Force, Army, DON, and DLA organizations, with process facilitation and other assistance contributed by experts from America Makes and Deloitte Consulting.[6]

The effort began by conducting eight workshops (two each for Air Force, Army, DON, and DLA) to develop independent roadmaps that were customized to each Service and agency.

[6] Department of Defense Additive Manufacturing Roadmap Final Report, released 30 November 2016.

They conducted a 9th workshop that used the 4 independent roadmaps as input to develop a joint DoD AM roadmap.

Perhaps the most important finding was how much overlap there was among the AM objectives of the four organizations. Of the 29 integrated objectives initially identified, 20 were aligned with all four MILSVCs /agencies; 26 were aligned among three or more; 28 were aligned with at least 2. Although some overlap was expected at the outset, this high degree of overlap strengthened the justification for more joint collaboration in pursuing DoD objectives for AM. The high degree of overlap encouraged the team to further analyze the 29 integrated objectives, and as a result, they consolidated them into 19 integrated objectives identified in the published version of the roadmap. Table 1 is adapted from the public-release version of the Consolidated DoD AM Technology Roadmap. The published roadmap goes a level deeper than what is shown in the table by showing detailed technology elements to develop.

Focus Area	Integrated Objective	Impact Statement
Design	Enable robust, integrated and intelligent design tools	Streamline design process, reduce cycle time, and higher performance products
	Enable design for AM	Increase capability rapidly delivered to Warfighter
	Improve reverse engineering capabilities	Push AM forward, enabling increased self-sufficiency of units and innovation by users in the field
	Develop design for function (application-based design) guidelines	Apply AM to meet specific weapons systems requirements
Material	Define standard AM materials requirements	Enhance predictability of resulting part performance using an interoperable framework for AM at DoD
	Establish vendor qualification and encourage expansion of material sources	Increase the range of materials available to designers, enhancing part performance
	Develop AM materials	Establish priorities for AM material development activities necessary to meet DoD requirements
	Create defined and accessible pedigreed datasets and schemas	Establish authoritative data sets for simulation and reference
	Establish a DoD-wide materials and process AM data repository	Establish a single repository of material, process, and performance data. Speed up research, enable quality
	Develop model-based approaches to accelerate materials qualification and certification	Guarantee quality of AM parts
Process	Develop non-destructive evaluation and process control	Enhance the sensing capability of machines, gather data to ensure quality
	Establish stable and robust AM processes	Enable broader application of AM through process stability and equipment ruggedization
	Develop open architecture equipment	Ensure transferability and interoperability through specifications and standards
	Modify existing or develop new process capabilities	Modify or develop processes to increase the applicability of AM in a variety of situations
Value Chain	Build cost models and decision tools	Understand when, where, and how to apply AM
	Develop qualification and certification methods for parts and systems	Guarantee quality of parts and interface with existing/new DoD policies
	Establish cyber infrastructure and cyber security	Enable secure information technology infrastructure for end-to-end connectivity of the manufacturing process
	Establish physical AM infrastructure	Install AM machines across the DoD enterprise
	Business practices – intellectual property, data rights, and contracting issues specific to AM	Establish agreed-upon business practices to ensure seamless integration of AM into the existing supply chain

Table 1: Public-Released DoD Consolidated AM Technology Roadmap (Adapted for this Report)

The authors of the DoD AM Roadmap offered the following recommendations. (These recommendations are now being addressed by forming the Joint AM Steering Group and Joint AM Working Group, discussed in another section of this report.)

1. *Further Refinement and Development – Create a coordinated DoD-wide plan for advancing AM capabilities*
   The development of a detailed, tactical DoD-wide AM coordination plan is beneficial for speeding the advancement of AM capabilities. The plan should focus on concrete and coordinated actions to achieve the integrated objectives set forth within the DoD roadmap. To achieve this critical next step, a strong recommendation is for the development of a Lead Integrator and supporting team to champion and lead this effort. Having this role assigned and resourced will help maintain momentum and focus. The supporting team must involve all stakeholders – R&D, engineering, test, logistics, quality assurance, inventory management, maintenance and sustainment, and operating/end users. To enable this coordination, a DoD-wide and DoD-only information sharing mechanism is recommended, such as a Community of Practice/Community of Interest. The sharing mechanism developed should build upon best practices developed within existing groups.

2. *Initial Execution – Begin the execution of the DoD-wide coordination plan for developing AM capabilities*
   The MILSVCs and DLA are currently conducting many activities which are contributing to delivering specific objectives outlined within the joint DoD AM roadmap. This information should be captured and disseminated to other DoD stakeholders for greater awareness. Integrated objectives may be prioritized based on impact to DoD and resources needed to achieve the objective. Prioritized initiatives may then be defined in more detail with appropriate partners and resources. Commitment is required to achieve the technology objectives.

3. *Continuous Improvement – Sustain the development of AM capabilities across the DoD and refine the DoD AM roadmap as AM technology matures*
   The authors of the DoD AM Roadmap recommend that the Lead Integrator periodically coordinate revisions to the DoD AM roadmap to reflect changing priorities, maturing technology, and through gathering the most recent input from all stakeholders. Progress towards achieving the key national defense objectives should be documented, including progress towards achieving the desired impact on capability/readiness and reduced cost using AM.

4.2 Formation of the JAMSG and JAMWG

An action memo was signed on July 6, 2017, by James A. MacStravic (Performing the Duties of the Under Secretary of Defense for Acquisition, Technology, and Logistics) to establish a joint leadership structure for the DoD AM community. In response, the Office of the Deputy

Assistant Secretary of Defense for Manufacturing and Industrial Base Policy (ODASD(MIBP)) is chartering and leading the JAMSG and the JAMWG.

The JAMSG is composed of ODASD(MIBP) leadership, other relevant OSD leadership, Senior Executive Service-level leaders from all the MILSVCs, and relevant DoD Components, Joint Staff, and a senior-level representative from the Industrial Base Council. Each organization represented on the JAMSG will appoint one or more members to the JAMWG. JAMWG members will be DoD program-level personnel who are more directly involved in AM plans and programs on a day-to-day basis. The greater DoD AM Community will be kept informed on a regular basis, and included on an ad-hoc basis when appropriate projects, programs, or initiatives require a more extensive list of individuals working with AM across the DoD.

The JAMSG, with the support of the JAMWG, is directed to:

- Provide this report to Congress;
- Develop a DoD AM vision
- Disseminate information on DoD AM efforts throughout the MILSVCs and Components;
- Provide recommendations for joint AM investment strategy;
- Identify and share AM best practices; and
- Encourage joint approaches to accelerate AM qualification and certification.

The JAMSG and JAMWG convened their first formal meetings in September 2017.

4.3 Three Cross-Cutting DoD Application Spaces for AM

In retrospect, the high degree of overlap among the objectives identified in the DoD AM Roadmap should not have been surprising. The DoD AM Roadmap Final Report observed that there are three primary application spaces for AM, and that all of these application spaces cut across Service/Agency boundaries.[7] The application spaces are maintenance and sustainment, deployed and expeditionary, and new part / system acquisition.

- Maintenance and Sustainment
  - Manufacture of parts typically produced using conventional manufacturing
  - AM repair of conventionally manufactured parts
  - Manufacturing aides for support to conventional manufacturing
  - Prototyping for rapid innovation and reverse engineering
- Deployed and Expeditionary
  - Manufacturing of parts typically produced using conventional manufacturing
  - AM repair of conventionally manufactured parts
  - Prototyping for rapid innovation and reverse engineering
- New Part/System Acquisition
  - New parts/systems designed for AM and manufactured using AM

[7] Department of Defense Additive Manufacturing Roadmap Final Report, released 30 November 2016.

- Manufacturing aides for support to conventional manufacturing
- Prototyping for rapid part/system development

The following sections provide the description of each application space given in the DoD AM Roadmap Final Report.

4.3.1 Maintenance and Sustainment

The Maintenance and Sustainment application space encompasses locations such as logistics centers, depots, and CONUS operating bases. AM has been widely used in the Department's maintenance and sustainment enterprise for over 15 years. The driver for adopting AM within the DoD maintenance and sustainment environment is primarily for producing acceptable parts on demand to ensure DoD platforms are functional and mission-ready; obtaining those items that have demand but also have chronic supply issues with traditional manufacturing; and hard-to-source and long production lead-time parts.

4.3.2 Deployed and Expeditionary

The Deployed and Expeditionary application space encompasses locations such as aircraft carriers, submarines, battlefields, OCONUS operating bases, and other unique environments.

Drivers to utilize AM technology within a Deployed and Expeditionary environment are for *rapid manufacturing of parts* typically produced using conventional manufacturing. Motivations for adoption of AM stem from further increased difficulty with obtaining parts critical to complete a mission. Opportunities for AM in this application space are for shortening the logistics tail and producing mission critical parts at the point of need.

Unique needs for this application space include ease of DfAM and reverse engineering procedures for less-experienced users and remote operation for design and engineering support (reach back). Other unique challenges include equipment ruggedization, resiliency, mobility, ease of calibration, and maintenance.

4.3.3 New Part/System Acquisition

The New Part/System Acquisition application space refers to the adoption of AM into new acquisition platforms, where the part/system is designed for AM and manufactured using AM. Other applications of AM to this environment are manufacturing aides to support conventional manufacturing, and AM prototypes used for rapid design iteration and form/fit tests.

For New Part/System Acquisition, the drivers for adoption are the expected benefits of AM over traditionally manufactured parts/systems. Army, DON, and Air Force are all very interested in applying AM for enhanced capabilities within New Part/System Acquisition. Typically, these drivers include an enhanced performance or capability not able to be affordably produced using conventional manufacturing processes, such as enabling complex geometry, mass customization, or rapid manufacturing solving a production lead time issue causing an acquisition schedule slip.

As with any new technology, insertion risk is present with AM and must be managed in accordance to the application and requirements. Lower risk parts are generally pursued in the near term and in each MILSVCs individual plans. Near term opportunities for new parts produced using AM include components for remotely piloted aircraft, microsatellites, liquid rocket engines, munitions, and limited life platforms which may exhibit lower risk and less stringent safety requirements. As confidence is built for AM, longer term implementation opportunities are for full life, non-critical structural applications, embedded electronics/sensors, and even farther term for fracture-critical components.

4.4 America Makes – Convening MILSVCs/Components

America Makes, the National Additive Manufacturing Innovation Institute, was established as the first of fourteen Manufacturing USA institutes in 2012. America Makes seeks to "support the transformation of manufacturing in the United States through innovative, coordinated AM and 3D Printing Technology Development, Technology Transition, and Workforce and Educational Outreach."[8] America Makes has over 180 members from industry, academia, regional development organizations, as well as several Federal Government partners. America Makes involved industry, universities, and Government personnel to develop roadmaps for both technology development and education & workforce development. These roadmaps guide project investments.

America Makes receives guidance from all MILSVCs. DoD personnel sit on the Government Partners Advisory Council and the Executive Committee; assist in evaluating project proposals; serve as advisors to industry project teams and attend project reviews; participate in roadmapping; and serve on various America Makes working groups. America Makes is managed by the Air Force on behalf of OASD(MIBP).

America Makes has conducted 38 technology development projects funded by its initial startup resources provided by DoD. The projects combined about $30 million of Federal investment plus $31 million of private cost share. As of March 2017, America Makes had also initiated 21 agency-directed projects with total Federal funding of over $38 million sponsored by OSD, Joint Staff, Air Force, Army, SOCOM, and the Department of Commerce (NIST).

4.5 Additive Manufacturing Maintenance Operations (AMMO) Working Group

In Spring 2015, in recognition that a Department-level collaborative venue was necessary to drive unity of effort, the DoD Office of the Deputy Assistant Secretary of Defense (DASD) for Maintenance Policy and Programs (MPP) chartered the AMMO Working Group (WG) as a public-private resource in the development of a strategic and coordinated implementation plan for AM throughout DoD OSD's Maintenance Operations complex.[9] The WG is composed of members from the Army, Air Force, DON, DLA other Government agencies such as NIST, DOE, NASA, and industry. AMMO WG members are authoritative maintenance leaders, recognized AM leaders, and domain-level experts. Participation is voluntary.

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[8] America Makes Strategic Business and Marketing Plan, November 2015
[9] A representative of DASD MPP provided a description of the AMMO WG for this report.

4.5.1 AMMO WG Purpose

The AMMO WG purpose is to promote expansion, adoption, transition, and implementation of AM throughout the DoD maintenance complex in support of the DoD mission to maintain weapons systems readiness at best cost. DoD has implemented AM capabilities at defense depot and maintenance centers creating immediate production successes, readiness improvements, and cost/cycle time savings. The AMMO WG was created to develop an integrated DoD strategic vision and facilitate collaborative tactical implementation of AM technology in support of the Department's global weapon system maintenance enterprise.

4.5.2 Advancing the AM Business Model

Because AM business implications present challenges and barriers as real as the technical developmental hurdles, AMMO partnered with the America Makes Maintenance and Sustainment Advisory Group to identify the business implications and work collaboratively to address them. The objective was to ensure DoD and industry business communities are prepared to leverage AM as the technology continues its rapid development. As a means to pull the business community together, this group formed and executed the AM Business Model Wargames.

The first AM Business Model Wargame was conducted in May 2016. The purpose was to bring together participants from DoD and industry, and illuminate the required business transactions when DoD requires repair parts to be additively manufactured at a DoD depot or 3rd party location in support of an immediate readiness goal. Additionally, the wargame assessed gaps and challenges discovered during the simulation in order to begin developing the necessary environment to support the continued adoption of AM capabilities.

Upon completion of the simulation, participants recognized that the status-quo of the Government-industry ecosystem and existing business models needs to change in order to successfully implement AM on a broad scale. The following focus areas were identified for further study:

- AM Ecosystem – business model ideas that include acquiring intellectual property (IP) and technical data rights (TDP) are needed, and include Government industry partnering.
- Liability and Quality – Liability shift and brand reputation are key concerns.
- Security – IP/TDP protection and business risk.
- Cost and Profitability – Revenue stability, pricing models, and profitability are all threatened by uncertainty stemming from a non-traditional manufacturing process.

The second AM Business Model Wargame was conducted in May 2017 to address the business model aspects of AM for sustainment. The scenario was expanded to include the life cycle platform considerations to further develop the necessary business environment to support the continued adoption of AM capabilities. The scope included business practices regarding intellectual property, data rights and contracting issues specific to AM, risks to the industrial base, legal concerns and liability shift from industry to Government, and brand/reputation.

Some common threads identified by the teams included warranty, liability shift, and brand risk concerns as identified in Wargame I. In addition, the teams made recommendations to create technology refresh opportunities, revenue cost models, and an increased reliance on data and the security of that data. Despite these challenges, there was a general consensus that with the proper cost-benefit business models in place, AM has significant potential to increase flexibility within the supply chain and create opportunities to provide improved sustainment support to the Warfighter.

4.6 Joint Interest AM Projects

Several DoD organizations are engaged jointly with each other at the project level. The following sections describe a sample of joint AM projects across communities of interest. Now, with the formation of the JAMSG and JAMWG, more formalized areas of joint interest are taking shape. Many of these projects were first identified as areas of joint interest during the DoD AM Roadmapping workshop.

Critical areas of joint interest include standardizing TDPs and material standards for easier procurement processes. Other areas of joint interest include developing a common framework for understanding AM systems, and supporting communities and forums for regular information exchange between MILSVCs.

4.6.1 Standardizing Data and Materials for Acquisitions

The Air Force, Army, DON are working to standardize TDP requirements between all MILSVCs.[10] They are working to identify and standardize TDP requirements to ensure consistency in acquisition and repeatability of builds in the global AM supply network.

The MILSVCs, industry, and academia are working to address material standards.[11] Work is being done to ensure knowledge generated in this area is captured and incorporated to add speed to implementation. Standardized tools to help in the selection of the materials and equipment are being investigated for adoption across the enterprise. Qualified Products Lists (QPL) are being developed for ease of procurement and to ensure only qualified materials are purchased from qualified vendors.

4.6.2 Common Framework for Understanding AM Technology

In FY 2016, MCSC, HQMC(I&L), and NAVAIR (Patuxent River) coordinated on the development of a Marine Corps 3D Printer Guidebook. Developed by the NAVAIR AM Innovation group, this guidebook provides Marines with an introduction of AM and associated 3D printers, a critical first step in understanding the basics of AM technology. By coordinating with NAVAIR, Marine users of AM technology on ground systems utilize a common framework and have a common understanding as those operating with air systems.

4.6.3 Communities of Practice and Organized Technology Interchanges

The Air Force, Army, and DON each organize internal groups to share and discuss AM activities and projects. These groups have been self-organizing for years and are a rich resource for the

[10] Information provided for this report by representatives of Air Force Life Cycle Management Center, Product Support Engineering Division (AFLCMC/EZP).
[11] Information provided for this report by representatives of Air Force Life Cycle Management Center, Product Support Engineering Division (AFLCMC/EZP).

growing community, as it continues to formalize.

The Army AM Community of Practice regularly brings together representatives from at least eight different Army organizations to coordinate their efforts with AM. The Air Force LCMC/EZP meets regularly and brings together a group across the Air Force organizations. In addition to regular meetings, the DON hosts an annual NAMTI and includes hundreds of participants from the DOD, industry, and academia. The 4th annual NAMTI was held in August 2017 and participants shared ongoing work, discussed challenges, and identified short term needs regarding qualification and certification of AM processes and materials, digital manufacturing efforts and needs, workforce development, contracting and business process guidance, and expeditionary AM capabilities.

4.6.4 Airworthiness Qualification Process Development for Additively Manufactured Parts
This DLA-funded project is a joint effort from DLA, Army, and NAVAIR. The objective of this project is to exercise the Army's airworthiness qualification/acceptance process of an additively manufactured metal aviation component culminating in a limited airworthiness release (AWR) for a 50-hour flight demonstration. To exercise the AM qualification process, the UH-60-M bellcrank was chosen with careful consideration and input from the UH-60 program office. The bellcrank is a DLA-managed part with a lead time of 18 months. The bellcrank is currently a 7000 series aluminum forging and part of the mixer assembly on the UH-60. While additively manufacturing the bellcrank will not result in substantial cost savings versus the traditional process, AM will greatly reduce the lead time. This project will demonstrate the feasibility of printing a bellcrank or generic component that exceeds the requirements of the originally manufactured part. The larger goal is to move towards qualifying and flying metal aviation components in the Army as a means to improving component performance and Warfighter readiness.

The Army will leverage data to be provided by NAVAIR from their flight demo program for the V-22 Osprey's engine nacelle 3-D printed titanium link. By leveraging the NAVAIR data and using the same material, machine, parameters, and processes, the amount of coupon testing required for material characterization in this project is reduced by approximately 75 percent. The limited material testing is necessary to ensure equivalency to the NAVAIR produced AM data.

5.0 Qualification and Certification Efforts

The third request in the NDAA for FY 2017 for this report was for "Details regarding AM qualification and certification efforts for materials, processes, and components." Qualification and certification is an enormous and extremely complex task due to the nature of AM processes and the rapid pace of development.

The Department of the Navy AM Implementation Plan V2.0 notes that "qualification and certification are necessary to ensure that AM components will meet requirements of naval systems.[12] Qualification is the demonstrated capacity to consistently produce properties or performance. Certification is approval by an authorized representative that a part meets the

[12] Department of the Navy AM Implementation Plan V 2.0

characteristics required to perform satisfactorily in its intended application." Qualification requires placing controls on facilities, materials, equipment, processes, policies, and personnel as appropriate. For critical applications or those with severe service condition levels, statistically substantiated properties for material and process qualification must be demonstrated by testing them in the assembled condition at the subsystem or system level.

In the Joint DoD AM Roadmap, nine of its integrated objectives (itemized below) related to qualification and certification, which demonstrates how broad the task of qualification and certification for AM is.[13]

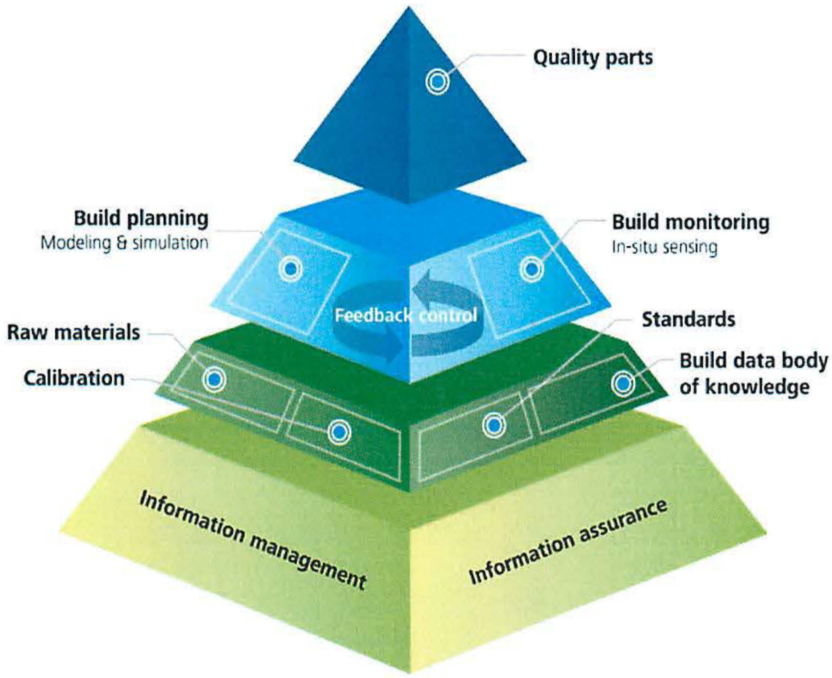
- DoD.D.1 – Enable robust, integrated and intelligent design tools
- DoD.M.1 – Define standard AM materials requirements
- DoD.M.2 – Establish vendor qualification and encourage the expansion of material sources
- DoD.M.4 – Create defined and accessible pedigreed datasets and schemas
- DoD.M.5 – Establish a DoD-wide materials and process AM data repository
- DoD.M.6 – Develop model-based approaches to accelerate materials qualification and certification
- DoD.P.1 – Develop Non-Destructive Evaluation and Process Control
- DoD.P.2 – Establish stable and robust AM processes
- DoD.V.2 – Develop qualification and certification methods for parts and systems

The recently formed JAMSG and JAMWG are tasked, in part, to "encourage joint approaches to accelerate AM qualification and certification." Because of the broad scale and critical importance of qualification and certification to AM, these groups are likely to prioritize it highly when considering areas for investment.

5.1 DoD Perspective on Qualification and Certification

DoD acknowledges the significant challenges of qualifying and certifying AM components. An illustration of the process of qualifying AM components is described in the AM Quality Pyramid.[14] The AM Quality Pyramid identifies a foundation of information assurance and information management. Then comes the qualification of raw materials, calibration of machines, standards, and building a data body of knowledge. Next comes feedback control in build-planning and build-modeling. Only with this structure underneath can a quality component be produced.

[13] Department of Defense Additive Manufacturing Roadmap Final Report, released 30 November 2016.
[14] Wing, Gorham, Sniderman, "3D Opportunity for quality assurance and parts qualification," Nov.2015. https://dupress.com



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5.1.1 Rapid Qualification for AM Component Integrity

A critical step in the AM process is validating the part build integrity.[15] The Air Force is exploring and testing multiple avenues to validate part build integrity, repeatability and qualify parts for aerospace. Analyzing parts through melt pool analysis, predictive tools, Non-Destructive Inspections and destructive testing in a systematic manner that can be compared with existing data will allow for confident validation and qualification. The Air Force continues to build a multitude of parts and gain the knowledge and confidence of the AM process while employing in-process monitoring to confidently ensure integrity of the build and qualify parts faster. The Air Force, in close coordination with the other MILSVCs, will continue to leverage and participate in industry efforts to further enable this capability.

DLA considers AM qualification and certification by the MILSVCs as the most critical element that will enable integration of AM into DoD supply chains. DLA collaborates with the MILSVCs and leverages their advancements to incorporate the latest technical specifications needed for AM contracts to industry.

5.1.2 Rapid Qualification for Repair and Non-Traditional Approaches

The Department of the Navy AM Implementation Plan V 2.0 notes that qualification and certification needs to encompass repair procedures and development of rapid non-traditional approaches that will accelerate the qualification and certification process.[16]

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[15] Information provided for this report by representatives of Air Force Life Cycle Management Center, Product Support Engineering Division (AFLCMC/EZP).
[16] Department of the Navy AM Implementation Plan V 2.0

To realize AM's substantial capability, significant R&D and S&T is required to ensure affordable, reliable use of AM. Current technologies and approaches for qualification and certification are ill-suited for AM components, which are produced unit-by-unit in low volumes with limited confidence in material, processing history, and component geometry/tolerances. The end state of Navy efforts will be a framework to enable accelerated qualification/certification of components than is currently possible, thereby providing reasonable assurance those components will perform to meet their performance requirements. The Implementation Plan describes near term initiatives to start in FY 2017 and FY 2018.

5.1.3 Army Perspective on Qualification and Certification

In order to reach the goal of producing qualified and approved AM parts, design and production standards must be established. Qualification and quality control, along with acceptance testing and inspections must be established to ensure that all AM parts meet specification requirements for their intended application. This is in addition to system-level requirements. The Army intends to establish a parts, materials, and processes working group to address technical requirements in the same way that traditionally manufactured parts are addressed in accordance with applicable requirements.

5.2 Current Qualification and Certification Projects and Programs Led by DoD

There are multiple AM qualification and certification projects throughout DoD. Those projects described in the following sections serve as examples of how these efforts are informing AM challenges and opportunities. While these efforts often originate with a Service-specific AM challenge, the data and lessons learned will be shared throughout DoD.

The complexity of AM processes coupled with the sheer variety of materials and applications being explored within DoD make advancing the qualification and certification of AM difficult. However, these advancements are foundational to DoD realizing the benefits of AM and are therefore crucial investments. The Joint AM Steering Committee with the support of the Joint AM Working Group will continue to coordinate these and future investments to ensure resources are leveraged and that DoD will continue to adopt and deploy AM technologies.

Several efforts are developing and evaluating advanced tools and pedigreed data that are critical to decision making for rapid qualification and certification of components. AM incorporates multiple processes and materials used in a variety of applications; it is important to note that efforts highlighted below are often limited to specific processes and/or materials.

5.2.1 Rapid Qualification/Certification using Advanced Tools

The objective of this project is to address technical barriers to qualify and certify AM components, including new, replacement, and repaired/remanufactured parts. The particular areas to address are drawn from the Joint DoD AM Roadmap, and include design tools, standard material requirements, software models, process variability reduction, equipment certification and calibration, risk identification, and procedural methods. Expected deliverables will include: material and process data and allowables to accelerate the ability to certify AM produced parts;

predictive design tools to reduce time to generate parts with desired properties; and reduction of technical barriers to qualify AM materials, systems, and parts. The initial phase will be funded by the Defense-wide Manufacturing S&T Program, with expected cost share from the MILSVCs and industry

5.2.2 Qualification and Certification of Air Cooling Duct

An AFRL-led project with America Makes resulted in team member Boeing conducting a case study to develop and then qualify an additively manufactured air cooling duct for the C-17. The current duct is repeatedly damaged in the cockpit primarily from foot loading and recent solicitations for replacement parts received a "no-bid" status. A FDM approach was developed using Ultem 9085 material and an improved design. The additive manufacturing qualification was achieved by Boeing through the C-17 Chief Engineer. This is one demonstration project within the larger MAMLS program described in section 3.3.9 of this report.

5.2.3 Development of Qualification and Certification Processes for Families of Aerospace Components

An AFRL-led partnership with America Makes is developing processes to enable certification and qualification of additive manufacturing for multiple part families: bell cranks, oil coolers, hybrid sandwich structures (fairings etc.), and repair brackets (doublers). Each project team is composed of university, industry, and Government representatives all focused on developing the appropriate tech data packages that will lead to standardized qualification procedures for a series of part families. Qualification of additive manufacturing for individual components is extremely costly. The AF is pursuing a strategic plan to qualify multiple additive manufacturing processes for larger families of parts.

5.2.4 Quality Made

The need to qualify and certify metallic additively manufactured parts, including structural components, is a fundamental barrier to more extensive use of AM across platforms. With AM, the resultant properties of the part are determined by the material, the processing and the component geometry simultaneously, making qualification and certification much more complex. An investment in S&T is required to develop advanced tools and controls to ensure AM production of structural metallic components for use in naval platforms meets the repeatability and reliability of properties to prescribed acceptable levels in a cost-effective manner. Certified additively manufactured structural components for aircraft, ships, and ground vehicles could greatly benefit maintenance activities and the Naval supply chain.

The Quality Made project will focus on providing the Navy with the ability to rapidly qualify AM material and processes for production of metallic pats using M&S tools and in-process sensors and controls.

This Office of Naval Research effort will analyze both ICME approaches to predict and evaluate AM resultant material properties and evaluate closed loop feedback strategies to make processes more repeatable and reliable. The project will be foundational in developing confidence in metal AM processes and in the DON's incorporation of predictive materials modeling that will allow for more rapid qualification and certification of AM materials. The three-year project has been approved to begin in FY 2018 and is expected to include several DoD, academic and industry partners.

5.2.5 V-22 Osprey Component

Exercising AM components through current qualification/certification (Q/C) processes is important to identify Q/C challenges. In July 2016, the DON produced a V-22 Osprey flight critical titanium component utilizing AM that was installed and flown. This part has since been certified to full performance life of the original part and future demonstrations will optimize the component design. This is an example of how AM components can be used in critical applications and highlighted several qualification/certification challenges that inform the DON and DoD roadmapping activities.

5.3 Taking an Active Role in Developing AM Standards

Development of AM specifications and standards is foundational to rapid adoption and formalization of qualification and certification requirements. The DoD aims to leverage national and international Standard Development Organizations (SDOs) to the greatest extent possible in specification and standard development, as such, Service representatives participate and are members of many of the SDOs, such as the International Organization for Standardization Technical Committee on Additive Manufacturing (ISO/TC 261), the American Society for Testing and Materials committee F42 on Additive Manufacturing Technologies (ASTM 42), and the ANSI.

To coordinate specification and standard development, the Additive Manufacturing Standards Collaborative (AMSC) was formed, led by America Makes and the ANSI. This collaboration includes 260 individuals from over 150 public and private sector organizations. In February 2017, the AMSC developed and published the first iteration of the Standardization Roadmap for AM[17] to coordinate standards development work of the SDOs, identify existing standards and specifications, assess gaps, and make recommendations for where further standardization and certification work should be focused to address stakeholder needs. The Standardization Roadmap for AM has already been widely adopted by AM industry and other Government partners as the foundation for further standards work in AM. Phase 2 of the AMSC's work was kicked off on September 7, 2017.

6.0 Recommendations

The final request in the 2017 NDAA for this report was, "A recommendation regarding the expanded use of Working Capital Funded pilot programs, potential changes to public-private partnerships within the defense industrial base, or any other potential changes in law that could enable DoD to better demonstrate and execute AM end use fabrication." The following sections provide these recommendations.

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[17]The roadmap may be downloaded from this web site:
https://www.ansi.org/standards_activities/standards_boards_panels/amsc/amsc-roadmap.aspx?menuid=3

6.1 Working Capital Funded Pilot Programs

DoD AM would benefit from a working capital funded pilot program for DoD-centric AM training curriculum development and delivery. Although some AM training curriculum exists in the free market, it is neither readily available to nor targeted at key DoD personnel who are needed to implement AM. DoD organizations are faced with either paying for organization-specific curriculum, which is expensive and not very scalable to meet the broader DoD need, or using curriculum that is too generalized. For example, DoD field operations personnel need appropriate training not just in how to design and build parts, but also more DoD-specific in understanding that the parts they design (or download) may not have been rigorously tested to the standards of most military equipment. DoD field operations personnel need to understand the risks, risk mitigation options, and limitations of using such parts. Another DoD-specific audience is repair and maintenance personnel, who need training in how to reverse-engineer and build parts that are not available through normal channels. They also need training in how to use AM to repair or refurbish parts. DoD would benefit from having professionally developed and delivered DoD-specific curriculum that can be deployed as needed. The development and delivery could be made self-sustaining by charging customers for delivery of written curriculum or instructor-led training. Customer payments would replenish the working capital fund.

6.2 Potential Changes to Public-Private Partnerships within the Defense Industrial Base and Potential Changes in Law

At this time, DoD offers no recommendation on changes to public-private partnerships within the defense industrial base or changes in law. However, DoD is monitoring the development and integration of AM technologies, process, and capabilities into the defense industrial base and into DoD for any challenges that might be mitigated by changes within these two areas. The Department's goal is to use these Public-Private Partnerships to inculcate AM within the fabric of DoD and its supplier base, while continuing to grow these capabilities into the future.