**Research & Engineering Framework**

1. Qualification and Certification Approaches
	1. Risk based qualification and certification approach
		1. Define and establish comprehensive, tailorable additive manufacturing quality and certification procedures to achieve DoD-wide consistency, and synchronization with industry while mitigating safety and performance risks.
		2. Qualification procedures will be appropriate to component risk assessment.
	2. Acceptability/Verification Procedures and Practices
		1. Define and establish procedures to assure each component meets form, fit and function requirements. This will include things such as coordinate measuring machine (CMM) inspection and non-destructive testing and inspection. The criteria for these tests and inspections should depend on the current and future technical capability of AM to control geometric tolerances and material properties.
	3. Qualification by similarity (equivalency) and reciprocity for qual/cert
		1. DoD identified common qualification (specifications/standards) “metrics” = the acceptable “tolerance” levels for key parameters to enable equivalency or reciprocity.
		2. Establish DoD-wide panel to identify the common “metrics” and routinely refine as processes and materials evolve
			1. Leverage “Common” “metrics” (Topic 2)
			2. Limit Service specific “metrics”
			3. Limit product specific “metrics”
		3. Establish interface/body of knowledge to share information (beyond JAMMEX to the engineering data, meta-data behind the designs for qual/cert)
	4. Quality and certification procedures shall address variances in critical factors to assure repeatability and reproducibility.
		1. Repeatability (same machine, parameters, materials, etc. and the ability to do it over and over again and what is the variability)
		2. Reproducibility (same machine, parameters, different materials, operators, etc. and the ability to do make quality parts and what is the variability)
2. Common Procedures: Where AM techniques will produce satisfactory products, DoD applications of AM should meet service/COCOM needs by improving on legacy components.

Lifecycle Considerations: Each proposed application of AM must:

* + 1. Address provenance, quality, physical properties as well as the safe handling, use and recapture of unused material which leads to possible recycle.
		2. Use Integrated computational materials engineering to ensure that the new material has the desired characteristics
		3. Comply with established standards such as safety, environmental and OSHA issues.
		4. Enable the collection of in situ data recorded for every layer of the build process to ensure quality and repeatability leading to proper substantiation of the completed part.
		5. Employ modeling and simulation in accordance with proper requirements to validate data for design
		6. Employ specifications, standardized parameters and post processing that make possible repeatable production of quality assets.
	1. Engineering and Design
		1. Determine the suitability for AM to produce the desired item
			1. Size and aspect ratio of the desired item vs. minimums and maximums
			2. Minimums incl. minimum hole sizes
			3. Features, scale, other factors that cannot be produced by AM or when it is cost prohibitive
			4. Determine whether AM is uniquely suited to produce the desired item, e.g. lattices, curved channels, optimized topologies
			5. What is the appropriate AM for the use case (temporary vs. permanent)
			6. Further reading:
		2. Determine the need AM is intended to meet, e.g. reduced cost, reduced resupply times, identify the value of AM
			1. Enhanced performance
			2. Reduction in assembled parts
			3. Precise replication
			4. Tooling
		3. Create validated digital twin (standard AM technical data packages)
			1. Modeling and Simulation for design and performance-based structures
			2. Use of AI/Machine Learning
	2. Materials:
		1. Material Lifecycle - Need to consider provenance, quality, physical properties as well as the safe handling, use and recapture of unused material which leads to possible recycle. (Material lifecycle = raw, in process, final product, reuse)
		2. Provenance (Pedigree) - Will have a design of experiments for physical and chemical testing (coupons, etc.) as part of material qualification. This can include expanded data collection methodology for in-situ and post-build that will be used to identify the key process variables for process control. Part of certifying and down-selecting materials.
		3. Quality and Process Control: Does the material meeting the specifications per the chemical/Physical Property Testing. Is the material in compliance with process parameters (e.g. flowability), and does it meet consolidated material specifications.
		4. Safe Handling: Storage for quality control as well as managing safety, health, environment considerations for control gases, raw powders (NFPA 484 spec) and materials need to be defined.
		5. Methodology of Reuse: Need to define reuse strategy – how the left over material is handled after every build (automated, manual, homogenized, virgin – no reuse, number of recycle).
		6. Improving Material Qualification Processes: Integrated computational materials engineering, including machine learning and artificial intelligence, are encouraged for use in guiding the design of experiments for physical testing to reduce cost and labor of qualification. The use of ICME as a qualification tool without physical testing is encouraged and continued advancement is needed.
		7. Benefit analysis - risk and cost benefit analysis for the use of ICME needs to be completed.
	3. Process:
		1. Process Provenance (Pedigree): Need to have a process control specification with standardized parameters for build and post processing strategy to achieve repeatable quality. Need a strategy for build specimens and surrogates, impacts testing plan and to verify post-processing strategy. Need to understand the impact of process variables that may effect bulk material properties in post-processing after the build. (Orientation, scan strategy, handling of as-built surfaces, heat treatment, distortion compensation, etc.)
		2. In-situ monitoring process control: A system will (will is a goal) be in place enabling the collection of critical (key process variables) in situ data recorded for every layer of the build process to ensure quality and repeatability leading to proper substantiation of the completed part.
			1. Collecting all information for every layer produces an unmanageable amount of data, need to realistic. A key activity will be identifying process parameters that impact quality and performance. A step in the process set up must be the establishment of the key process parameters. Also need to have data management practices in place to access and use the relevant information.
			2. The goal of using in-situ process monitoring is to minimize the post-build inspections which can be costly, so ultimately reducing cost and ensuring quality.
		3. Modeling and Simulation: Perform modeling and simulation of the process needs to be integrated to incorporate how the different process steps effect one another (e.g. recoater interference, distortion compensation) in accordance with proper requirements to validate data for design.
	4. Final Part Testing

\*Final part testing (needs to be covered, currently part of the Acceptability aspect of the Q/C section a in our doc).

* 1. Reverse and Re-Engineering

(AM is just a tool for this – how much do we want to include in this guidebook vs. other place – what to include on this topic needs a lot of consideration):

* + 1. Data rights: Need to know the data rights for doing reverse engineering (Mike Acosta has some good starting guidelines on this that should be included) – what is the legal ability to do it? Breakout (re-engineering) vs. reverse engineering.
		2. Data availability: Access to parts is critical to ensure a successful reverse engineering project. Access to available OEM data, drawings and specifications is highest priority, access to DOD information (reliability and failure) is critical. Required data is not always available to assure form, fit, function.
		3. Data generation: Is it a good AM part candidate? Need to go through that evaluation and generate the TDP.
		4. Approval: Then need to develop a technical data package appropriate for the risk categorization and use case (temporary part) and follow qualification/certification procedures just like a new part.
		5. Access to Tech Orders/DMWR/TGI leads to injection of reliability improvements
		6. Is the part conforming to begin with that you are starting with? How to make sure you get the original specifications beyond the geometry (load, tolerances, etc.)?
		7. Training: Sufficient training is needed to support all aspects of reverse engineering skills - scanning, creating models, design enhancements, etc. (key skills are pretty well defined in the AM Body of Knowledge link to them here)
		8. Part tracking: In the supply systems need to consider part numbering, tracking, etc. if there are changes to form, fit, function *(connect to the FCC work for FLISS).* Need to connect that feedback on part failures and the ability to locally manufacture to inform logistics.



Recommend a graphic to describe the Q/C process. This is from MSFC-STD-3716 NASA Guide for Process – Something like this in the Guidebook.

* 1. Environmental, Health, Safety and Sustainability Considerations:
		1. Additive Manufacturing Sites are required to develop controls to ensure all AM processes and machines conform to all applicable EHS&S policies, regulations, and requirements.
		2. AM EHS&S plans need to address the following areas:
		3. Engineering Controls to mitigate employee exposure.
		4. Address management of metallic particles for fire and explosion control
		5. Monitor work areas atmospheric conditions to ensure uncontaminated and breathable air

New Topic: Physical Infrastructure Management (may not fit in R&E or SS but needs to be captured)

* + Incorporation/Transition of new AM technologies as the industry evolves, tech refresh as well as ruggedized equipment
	+ Life cycle management of AM machines/equipment (depots, forward deployed – logistics benefits/impacts, etc.)
1. Configuration and Change Control
	1. Program Managers, Logistics, Supply, Engineering personnel must follow established configuration management and change control processes when developing, building, testing and integrating AM parts within a weapon system or component. (Reference existing procedures – e.g. airworthiness)
	2. AM technical data packages must be uploaded to the authoritative source of data within the relevant organization and these need to connected through DoD wide approved system, JAMMEX.
	3. Critical application item or critical safety items will be class 1 Engineering Change Proposal (ECP) when moving from traditional manufacturing to AM.
	4. Update configuration change control board procedures based on new technologies and information.
2. Parts Management
	1. Identify AM parts, account and track AM parts in the supply system in particular for temporary part use and management procedures (reference Army and USMC temp use procedures)
	2. Subassembly level AM part creation management (sub existing tracking level, needs new part code)
	3. AM parts need to be easily identified in the Federal Cataloging system. (connect to the FCC work)
	4. Apply the highest level of traceablity (e.g. lot control of the part or serialization of the part vs. not) to the lowest level of criticality when it is not cost prohibitive.
		1. Tracked at the detail level by some industry in the material specification - would not be identified at the assembly level detail that a component is AM.
	5. Consider direct part serialization and part markings whenever feasible and for temporary part use and management. (An area for R&D – how to create new code for each part without having to change the build file and affect print quality and doesn’t need post-processing that would impact the serial number).
	6. Identify AM part candidates based on technical, cost, lead time, readiness drivers and performance considerations. A part management aspect to address obsolescence. *(may fit elsewhere but important – see below section on economic & affordability considerations)*
3. Anti-Counterfeit Technology Protection (AM Tech Protection Consortium to provide input)
* Use AM for anti-counterfeit practices to embed capability to ensure part pedigree that is not cost prohibitive.
1. Standards and Specifications
	1. Use of Common S&S
		1. Leadership will support the practice of exchanging information for the benefit of the AM community. Leadership will lead the collaboration efforts and information sharing across the AM landscape. Leadership will leverage existing industry AM expertise and existing AM capabilities.
	2. Development of Common Standards and Specification
		1. Leadership will encourage SME participation in the development of Non-Gov Standards Organizations and support the development of using Common Standards as a priority. Standardization documents, to the greatest extent possible should utilized widely accepted best industry practices to minimize conflicting requirements. Prior to creating a unique Additive Manufacturing standard or specification, market research must be completed to ensure an existing Non-Government standard/specification or Defense document cannot be used.
		2. In accordance with DoD Manual 4120.24, Defense Standardization Program (DSP) Procedures, DoD Additive Manufacturing personnel are encouraged to participate as liaison representatives to Non-Government Standards technical committees to promote standards that meet DoD needs.
		3. The main criteria for adoption of an NGS are whether it meets the user’s needs and if it will be used in direct procurement, as a reference in another document, or as a design or reference guide. While it is not mandatory for an NGS to be adopted to be used, adoption is strongly encouraged to provide for document visibility and identify a DoD technical focal point.
2. Basic and Applied Research Considerations

The overall R&D investment strategy needs to address basic through applied research activities, to achieve improvements in cost and performance of weapon systems and platforms. Fundamental research may be beyond the scope of individual programs that would be funded by the Services, however, the business case development for AM to support funding and adequate resourcing must be evaluated for each program and component to identify gaps for continued R&D investment strategy. Fundamental R&D of materials is needed from both Government and Industry for classes of materials used in AM to identify the critical process and microstructural properties to optimize properties. R&D must also identify critical data with the necessary data infrastructure to facilitate interoperability within DoD and industry of validated trusted data and data rights management. Investment efforts to develop the tools to model and produce new and improved materials will address Mission Readiness, weapons system performance improvements, while reducing overall acquisition and sustainment costs.

R&D focus areas identified include advancing an understanding of process variability and characterization, for example, how to account for printing in the field vs a controlled laboratory, R&D for new materials and improved existing materials – designed for AM specifically, to drive lower costs and improve outcomes, and material characterization, including geometric and mechanical properties is essential to advancing AM technology. Part to part process variability needs to be addressed and further understood to increase the reliability and decrease the cost of parts produced. Critical variables and statistical boundaries need to be determined to ensure repeatability and permitted allowances in variability. This also includes developing reliable process models to reduce the volume of testing and traditional design of experiments for each application. Additional areas of pursuit include:

\*Addressing the digital thread and cyber security requirements to have reliable and trusted databases to allow data to be utilized for Artificial Intelligence (AI) and the development of new materials, and to support the lifecycle of fielded products. Allowing sharing of data across the DoD and industrial base to avoid duplication of efforts. (chemistry, post processing, machine settings)

\*In-situ process monitoring to identify critical flaws and voids, and addresses topological design, surface finish and mechanical properties, to optimize cost versus performance. Also addresses thermal profile and phase changes that address microstructure generation.

*\*Material characterization – geometric and mechanical properties.* In-situ process monitoring, and process control are required to resolve several technical challenges that need to be identified and corrected in Additive Manufacturing. This includes detection of voids and critical flaws in the build and classification of the material microstructure to determine mechanical properties through thermal profile analysis and phase change analysis. At the macrostructure level process monitoring and control can be used to address topological design and surface finish. Through the use of in situ process monitoring and control it is possibility to simultaneously improve performance and reduce costs.

*\*R&D for new materials and improved existing materials – designed for AM specifically, to drive lower costs and improve outcomes.* Significant investment in new materials for use in new product development and for use in maintenance and sustainment is required. The thermal effects on the materials that results from the layer by layer building process of Additive Manufacturing (AM) need to be addressed. This requires: 1.) the development of new tools and processes to model and simulate the development of new materials or improve the performance of existing materials. (e.g. achieve wrought mechanical properties) 2.) Addressing issues such as thermal stress and thermal tear in key AM materials. 3.) Utilization of in situ process control to achieve microstructure for optimal mechanical and physical properties. 4.) Creation of new classes of materials (e.g. metal matrix composites, nanomaterials, metamaterials, multifunctional materials) that results in improvements in mechanical or physical properties.

The result of these new and improved materials will result in savings in the cost to produce, maintain and operate future systems and provide the warfighter with a competitive advantage.

*\*R&D to identify critical data with the necessary data infrastructure to facilitate interoperability within DoD and industry of validated trusted data and data rights management*.

Use of the digital thread and cyber security is required to have reliable and trusted databases to develop new materials through modeling and simulation, artificial intelligence (AI) and machine learning and support the lifecycle of legacy systems. The intent is to share information and data across the DoD and industrial base to avoid duplication of effort in the develop of new material chemistries, Additive Manufacturing processing parameters and post-processing of produced components. The interoperable efficiencies that result from this will result in significant cost savings.

*\*R&D for new materials and improved existing materials – designed for AM specifically, to drive lower costs and improve outcomes*

Significant investment in new materials for use in new product development and for use in maintenance and sustainment is required. The thermal effects on the materials that results from the layer by layer building process of Additive Manufacturing (AM) need to be addressed. This requires: 1.) the development of new tools and processes to model and simulate the development of new materials or improve the performance of existing materials. (e.g. achieve wrought mechanical properties) 2.) Addressing issues such as thermal stress and thermal tear in key AM materials. 3.) Utilization of in situ process control to achieve microstructure for optimal mechanical and physical properties. 4.) Creation of new classes of materials (e.g. metal matrix composites, nanomaterials, metamaterials, multifunctional materials) that results in improvements in mechanical or physical properties.

The result of these new and improved materials will result in savings in the cost to produce, maintain and operate future systems and provide the warfighter with a competitive advantage.

Finally, the business case to transition *AM* R&D into fielded systems and improvements must be developed *to ensure continued interest in an AM R&D investment strategy.* The overall utilization and thus investment strategy for Additive Manufacturing (AM) in the DoD is beyond the scope of an individual program or technology application that is traditionally funded by the Services or industry. Investment in AM will have broad applications in Mission Readiness (Ao) of legacy systems and offer performance improvements in new weapons systems while lowering the total cost of ownership over the entire lifecycle.

1. References for all Q/C and SS section
* ANSI/AMSCRoadmap https://www.ansi.org/standards\_activities/standards\_boards\_panels/amsc/America-Makes-and-ANSI-AMSC-Overview
* AIA best practice document https://www.aia-aerospace.org/wp-content/uploads/2020/02/AIA-Additive-Manufacturing-Best-Practices-Report-Final-Feb2020.pdf
* Nasa tech standard for L-PBF https://standards.nasa.gov/standard/msfc/msfc-std-3716
* http://everyspec.com/MIL-HDBK/MIL-HDBK-0099-0199/MIL-HDBK-115C\_54170/
* https://www.astm.org/Standards/additive-manufacturing-technology-standards.html
1. Economic and Affordability Considerations

(NOTE: This is from Fred Herman and requires integration into the document, there are many places this kind of information can go – and need to integrate with the metrics team work they were also doing cost estimating)

Success in the use of AM for sustainment and maintenance requires the achievement of Mission Readiness at an affordable Total Cost of Ownership (TCO). This includes the cost of building support infrastructure, manufacturing, logistics and operations associated with the use of AM to produce sustainment and maintenance components.

3.1 Support Infrastructure Costs

In order to identify, analyze and approve the use of AM on sustainment and maintenance components, an information management infrastructure needs to be established that generates and shares the required information and data. The backbone of the infrastructure is the digital thread. The digital thread will be used to link together the artifacts created from identifying the component for AM, creation of the TDP and the ESA that approve the use of AM.

Digital Thread and Information Technology (IT): Digital thread and its associated effort digital twin are broad DOD efforts to lower life cycle costs in all aspects of a system’s life.[[1]](#footnote-1) Because the effort in digital thread is relatively new and the need to create and share technical information is required, initial AM sustainment and maintenance parts may have to bear some of the effort to create their own digital thread. This will require the identification, planning, resourcing, acquiring facilities, hardware, software, documentation, manpower, and personnel necessary for planning and management of computer hardware and software systems.

In addition, the services will need to identify, plan, resource, and implement management actions to develop and acquire information;

* to operate, maintain, and train on the equipment to maximize its effectiveness and availability;
* effectively catalog and acquire spare/repair parts, support equipment, and all classes of supply;
* to define the configuration baseline of the system (hardware and software) to effectively support the Warfighter with the best capability at the time it is needed.

Component Identification and TDP Creation: The process to identify a component for AM and build the subsequent TDP is a manually intensive effort because it requires a detailed understanding of AM capabilities along with the specific life cycle requirements which are unique to every component. These efforts would result in a onetime sunk cost.

In addition, there will be a significant amount of capital infrastructure that will be required. In order for AM to be implemented DLA and the services must do the following:

Maintenance Planning: Identify, plan, resource, and implement maintenance concepts and requirements to ensure the best possible equipment/capability is available when the Warfighter needs it at the lowest possible life cycle cost.

Manpower and Personnel: Identify, plan, resource, and acquire personnel, civilian, and military, with the grades and skills required:

* to operate equipment, to complete the missions, to effectively fight or support the fight, and to win our Nation’s wars;
* to effectively support the Soldier and to ensure the best capability is available for the Warfighter when needed.

Facilities: Identify, plan, resource, and acquire facilities to enable training, maintenance, and storage to maximize effectiveness of system operation and the logistic support system at the lowest life cycle cost. Identify and prepare plans for the acquisition of facilities to enable responsive support for the Warfighter.

Training and Training Support: Plan, resource, and implement a cohesive integrated strategy to train military and civilian personnel to maximize the effectiveness of the doctrine, manpower and personnel to operate and maintain the equipment throughout the life cycle.

Packaging, Handling, Storage, and Transportation (PHST): Identify, plan, resource, and acquire packaging/preservation, handling, storage, and transportation requirements to maximize availability and usability of the materiel to include support items whenever they are needed for training or the mission.

3.2 Manufacturing Costs

The key for DOD to obtain the lowest Total Cost of Ownership possible through AM is to ensure that AM is affordable by the organizations that will use it in production. In this case, that is predominately Tier 3 OEMs[[2]](#footnote-2) and the maintenance and logistic organizations of the services. Affordability[[3]](#footnote-3) can be broken down in to two areas:

AM Product System Purchase Cost: Current production AM systems can cost upwards of $500K for a polymer based system[[4]](#footnote-4) and over $1M for a metal based system.[[5]](#footnote-5) Typically, this is too much for a Tier 3 OEM to afford especially when an initial low utilization rate will reduce the return on investment. To address this, multiple companies have introduced hybrid powder fed AM systems with three and five axis CNC machining systems as a way to improve utilization rates and speed up overall manufacturing time. However, because some of these systems start at $2M they may not be affordable for Tier 3 OEMs or widespread use in DOD logistics infrastructure.

Re-occurring costs: One of the drawbacks to AM is that it has high reoccurring costs compared to conventional manufacturing.[[6]](#footnote-6) Processes such as selective laser sintering require special powders that are often five to ten times the cost of the base material.[[7]](#footnote-7) Also, these processes are laser based[[8]](#footnote-8) and will require significantly more power than conventional manufacturing processes need to achieve similar results.



Figure 6: Optomec LENS AM- CNC hybrid manufacturing system

The key to widespread adoption of AM production systems by the Tier 3 is the technical development of a low cost AM manufacturing system that minimizes procurement and operational costs.



Figure 7: Per unit production cost of AM (3D Printing) vs Conventional Production base on number of components built and complexity of design

3.3 Logistics Costs

AM based production has the ability to lower logistics costs. This is based on the fact that AM can generally produce components in a faster time than conventional manufacturing and allow for true “just in time” production runs which result in the following:

Procurement Costs: Because AM results in production rate independent per unit manufacturing costs, the expectation is that there will be cost reduction compared to conventional manufacturing of sustainment and maintenance components, because they are typically small volume production runs.

Reduced Inventory Carry Costs: By reducing the time it takes to replenish the stock on Mission Readiness critical components the DLA and services can reduce the amount of inventory needed on hand in order to ensure a constant supply. This will in turn reduce the warehousing requirements and associated carrying costs.

 Smaller Logistical Footprint: The use of AM in forward deployed locations or at sea will significantly lower the logistical requirement in terms of both volume and weight of materials that must be deployed. Instead of bringing high value finished replacement components to the theater, lower cost and more transportable raw materials can be shipped instead.[[9]](#footnote-9),[[10]](#footnote-10),[[11]](#footnote-11)

 In order to achieve this, the services must implement the following:

Supply Support: Identify, plan, resource, and implement management actions to acquire repair parts, spares, and all classes of supply to ensure the best equipment/capability is available to support the Warfighter or maintainer when it is needed at the lowest possible life-cycle cost.

Support Equipment: Identify, plan, resource, and implement management actions to acquire and support the equipment (mobile or fixed) required to sustain the operation and maintenance of the system to ensure that the system is available to the Warfighter when it is needed at the lowest life-cycle cost.

3.4 Operational Costs

 This includes costs that are associated with the impact of using AM to perform maintenance and sustainment by the services. The main factors to consider are the cost associated with operation costs and downtime of the systems in need of replacement components and the affect that has on Mission Readiness.

 Mission Readiness: The cost of downtime and the impact of Mission Readiness for the military services can be difficult to quantify. But there is no question that downtime affects the operational capability and readiness of the military units when a system is no longer available due to a shortage of spare parts. The possibility that AM can produce components in a “right time and right place manner” will have a positive outcome on the Mission Readiness of the services and to the Warfighter.

Operational Costs: The use of AM can not adversely impact the operation of the component in question and thus induce further cost due to operational limits[[12]](#footnote-12) or life cycle and/or life span reduction[[13]](#footnote-13). However, one area were AM might be able to reduce operational costs is the repair of wear items in lieu of replacement.[[14]](#footnote-14)

3.5 Factors Influencing Cost Considerations

 The current and future cost of AM manufacturing is primarily driven by technical factors. Development of AM technologies and techniques to increase material deposition rate, improve material performance, quality and lower manufacturing costs will have the biggest impact in reducing the overall Total Cost of Ownership of AM produced parts.

In order for AM to become affordable and reduce the lifecycle cost to provide maximum Mission Readiness to the warfighter AM must resolve two critical challenges with respect to materials and processes. The first is the improvement and adoption of current materials systems currently used in legacy systems for use in AM processing and the development of new materials for use in AM that provide new capabilities in future systems. Second, is the development of in situ process control and process monitor to ensure pervasive quality assurance of AM components to reduce the risk of adoption and barriers to qualification.

Another framework to consider…

* Platform/machine
	+ Polymer
	+ Metal
	+ Ceramic
	+ etc
* Process
	+ Photopolymerization.
	+ Material jetting.
	+ Binder jetting.
	+ Material extrusion.
	+ Powder Bed Fusion.
	+ Sheet Lamination.
	+ Direct Energy Deposition
	+ (Cold Spray?) etc
* Material
	+ Powder
	+ Ink
	+ Resin
	+ etc
* Environmental/Operational/Facility
* Personnel
* Product
	+ In situ
	+ Destructive
	+ Non-destructive
1. From conceptual design to end of life including sustainment and maintenance. [↑](#footnote-ref-1)
2. Small business sized machine shops. [↑](#footnote-ref-2)
3. Affordability is a relative term and depends on the specific organization involved. [↑](#footnote-ref-3)
4. Such as Fused Deposition Modeling (FDM) or polymer jet printing. [↑](#footnote-ref-4)
5. Such as selective laser sintering, electron beam additive manufacturing or Laser Engineered Net Shape (LENS). [↑](#footnote-ref-5)
6. AM reduces other non-reoccurring cost such as tooling and can result in a net overall cost savings. [↑](#footnote-ref-6)
7. Gas atomized Titanium 6-4 powders cost between $150 to $300 per pound, where the equivalent grade welding wire is between $30 to $50 per pound. [↑](#footnote-ref-7)
8. Lasers are between 10% to 20% efficient in converting input power to output laser energy. [↑](#footnote-ref-8)
9. NASA has already demonstrated this by sending a “makerbot” printer to the International Space Station to print miscellaneous parts. Some technical work remains to ensure that AM production can occur in a more rugged and hostile environment such as on a ship at sea or forward base. [↑](#footnote-ref-9)
10. Requires use of an ESA approved TDP that specifies design, materials and processing requirements [↑](#footnote-ref-10)
11. Additional systems to perform post processing heat treat will likely be required [↑](#footnote-ref-11)
12. Weight growth due the use of AM on an aircraft parts could reduce aircraft range or increase fuel consumption for a given mission. [↑](#footnote-ref-12)
13. Increase in maintenance cycles due to reduction in fatigue life. [↑](#footnote-ref-13)
14. Developed by Pratt & Whitney in the 1970’s, Metal additive manufacturing got its start as a laser cladding process to repair jet engine turbine blades. [↑](#footnote-ref-14)