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2020 Program Excellence Awards

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Nominee's Signature

Date: 6/26/2020

Nominee's Name (please print): RASA FULLER

Title (please print): Director of Development Program Management

Company (please print): Honeywell

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AVIATION WEEK NETWORK

2020 Program Excellence Awards

NOMINATION FORM

Name of Program: Additive Manufacturing for Space

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☐ Customer Approved

- Date: N/A
- Contact (name/title/organization/phone): N/A

☐ Supplier Approved (if named in this nomination form)

- Date: N/A
- Contact (name/title/organization/phone): N/A

CATEGORY ENTERED

Refer to definitions in the document "2020 Program Excellence Directons." You must choose one category that most accurately reflects the work described in this application**. The Evaluation Team reserves the right to move this program to a different category if your program better fits a different category.**

Check one

☒ Special Projects
☐ OEM/Prime Contractor Systems Design and Development
☐ OEM/Prime Contractor Production
☐ OEM/Prime Contractor Sustainment
☐ Supplier System Design and Development
☐ Supplier System Production
☐ Supplier System Sustainment

Abstract

In 2017, company leadership at Moog leveraged the preceding five years of research and AM (additive manufacturing) prototyping at the company in creating the Additive Manufacturing Center (Figure 1). The project set clear objectives of providing an additive production capability with repeatable processes to build trust in laser powder bed fusion (LPBF) additive manufacturing, while providing employees with a safe, challenging and rewarding work experience. The project team executed at a high level by conceiving of the factory as a "lean solution" for AM projects from powder to part. It provided opportunities for the AM team to grow, learn, and innovate with the best AM training. The team laid down metrics that included audit completion, environmental health and safety (EHS) actions and a record of the number of formal AM training sessions. This all-sided approach to AM capabilities created the conditions for an early success: the Ace Gen 2 fuel injector.

Figure 1 Moog AMC

Purpose

Moog set out to establish a modern additive manufacturing center geared to the development and production of next-generation, AM-enabled systems for its aerospace, defense, and industrial customers. The purpose of this program was to design, build, and maintain a best-in-class additive manufacturing facility to service internal and external customers. The Additive Manufacturing Center (AMC) has business systems that are easy to use, efficient, and robust, with the necessary controls to verify powder quality at the start of each build and to understand and prove the quality of metal in the end use hardware. The AMC came to provide opportunities for engineering education in additive manufacturing through hands-on use of the technology, while maintaining a working environment with health and safety objectives in the forefront. Finding creative solutions to difficult technical problems faced by Moog customers remains the overriding objective of Moog's AMC.

Acronyms used in this submission
AM – additive manufacturing
CAMS - Complex Assembly Manufacturing System, a system of Moog-developed software to contain work instructions
DfAM – design for additive manufacturing
EHS- environmental health and safety
LPBF – laser powder bed fusion, a type of additive manufacturing performed at Moog

MBS – Moog Business System, an internally created and maintained software solution for enterprise resource planning
TipQA- Third-part quality assurance tracking software used at Moog

Executive summary (15 points)

Moog's customers expect high-value solutions to complex motion-control problems. The company pioneered valve technology innovations from the time of its founding by Bill Moog in 1951. Today, customers demand increased performance that meets or beats the cost of current offerings, which poses significant design and planning challenges. To enable the type of engineering breakthroughs demanded in the marketplace, Moog invested heavily in additive manufacturing beginning in 2012. Initially, it created a research center at company headquarters with two Renishaw AM250 LPBF devices. The establishment of the AMC in 2017 in a remodeled 14,000-ft2 facility, which today contains 11 LPBF machines with dedicated post-processing equipment, marked a serious step change in investment and company effort.

Moog believes the investment to be entirely appropriate as industry as a whole has been going through enormous changes, and providers of motion control equipment must take advantage of the best tools and technologies available, including those like AM whose technological underpinning is still in development.

The implementation of a new technology is rarely seamless, particularly in the aerospace industry where the integrity and dependability of parts are questions of life and death. The adoption of additive manufacturing at Moog necessarily encountered significant hurdles whose dimensions included volatility, uncertainty, complexity, and ambiguity.

The experimental nature of all parts that have proceeded through the design for additive manufacturing (DfAM) process lends a high degree of **volatility** to the establishment of an AM center. The intricate and unconventional geometries that the best AM parts include allow dramatic performance gains but also create new potential points of failure and require the creation of new methods to verify part integrity. The Moog team has developed a number of innovative workflows to inspect and qualify parts for use in aerospace applications. Teamwork includes early discussions between AMC engineers and designers with engineers and designers involved in programs and system platforms. Working together and drawing on lessons of previous projects, these teams are often able to avoid problems in the building, inspection, and qualification of end use hardware. A key goal is always to avoid failures late in the project lifecycle where they would pose the greatest schedule and cost risk.

LPBF production machines remain in their relative infancy, despite important technical advances in speed and process control by original equipment makers (OEMs) and, as a result, device repeatability remains below the level expected of machines traditionally used to make metal hardware such as lathes and mills. The lack of repeatability is a key driver of **uncertainty** for additive manufacturing generally and LPBF specifically. In addressing uncertainty in AM, Moog has formed key collaborations with the engineering and maintenance departments at AM OEMs. By working together, Moog and OEM engineers are able to test machine parameters and use statistical analysis to improve performance and characterize the resulting metal quality. Moog

technicians also perform maintenance and repair work on the OEM machines, mitigating expenses and reducing dependence on OEM visits.

The stochastic nature of these early generation AM machines also complicates analysis and the creation of business cases for AM projects. If machine reliability is problematic, how is machine time to be costed and priced? If it requires greater or lesser operator intervention, what are the financial ramifications? If, despite these challenges, it is capable of producing parts with dramatically improved performance or weight (or both), how is that value to be captured and shared? How do any of these issues look from the customer's perspective? These are critical elements of uncertainty that have been addressed at Moog via collaborations with our traditional-manufacturing based cost engineering experts and managers of strategy and finance. There are as of yet no complete answers, but a methodological look at these issues allows us to consider the business case today and at several points in the near- and not-too-distant-future. Every business case is inherently forward-looking and dynamic. To this normal practice of case evaluation, AM adds dimensions specific to its technological maturation.

Curved flow paths and monolithic structures are two hallmark features of additive parts that testify to their **complexity**. Geometries that would be impossible to achieve via conventional techniques like milling are done today with AM (see example in Figure 2). The "design space" as a set of conceptual possibilities restricted by manufacturing techniques has been widened by additive, opening the door to new and imaginative solutions to existing engineering problems. Not everything that can be imagined, however, can be manufactured, even with the use of additive manufacturing. Experience ("Tribal knowledge") has shown the AM designers what is likely to succeed and what is likely to fail in LBPF. The crux of the complexity challenge lies not only with the idea creation, but also in bringing this guidance to a broader company community of designers and engineers, beyond those who work with AM machines and design every day. Moog has taken an approach that moves from introductory sessions of AM opportunities to selection of candidate parts and assemblies to more intensive collaboration between business unit engineers and AMC staff. Moog has made creative use of media to advertise its capabilities and successes so that AM is seen less as "cutting-edge" and more as another tool that can be deployed to solve particular customer problems. It finds a place to supply quick emails, newsletters, photos, slide shows, and videos to inform its workforce of AM applications within Moog, and on Moog solutions in addition to industry's applications and advancement.

Figure 2 AM Monolithic CubeSat

A final set of hurdles pertain to challenges of **ambiguity**. In additive manufacturing, these involve standards still in the process of development. Several standards-making bodies are at work on standards for AM materials and processes. In addition, governmental organizations (e.g., NASA) and private companies have created their own standards for AM. Many of these organizations refer to emerging industry-standards even if they are only in draft form. Moog has felt that the best approach to this challenging environment is to collaborate with both customers and standards-making bodies in the development of these methodologies. Moog participates in the ASTM F42 and SAE AMS AM committees and is regularly invited to present at the FAA and EASA annual events.

Moog's investment in additive manufacturing and its collaborative approach to addressing the hurdles of broad AM adoption and acceptance demonstrate the depths of its commitment to the exploration of the technology.

The case of the Ace Gen 2 thruster demonstrates the customer value provided by the AMC. Here Moog took its investment in the facility and its staff to deliver a solution that offered improved thrust, better thermal properties, with less weight by improving fuel flow through AM-enabled geometry optimized for improved fluid dynamics (see Figure 3 for illustration of the DfAM process).

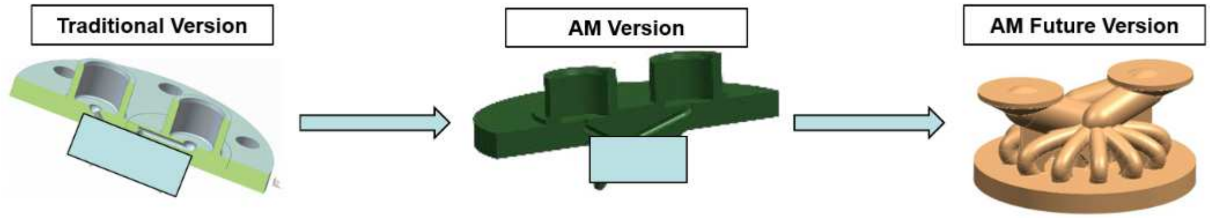


Figure 3 Conventional Design vs AM

The establishment of the AMC brought added value to Moog by helping the company explore new ways of solving existing engineering problems, particularly with in-space propulsion solutions like Ace Gen 2. It has allowed the company to get to solutions more quickly by printing visual aids and quick iteration prototypes. It has tied the company to industry-wide initiatives that bring together experts in additive manufacturing, digital twin creation, and new materials. It has also reinforced the belief that Moog applies innovative solutions to solve our customers' most difficult problems.

Moog engineers were able to produce the Ace Gen 2 thruster in 6 months, a dramatic cut from the typical 15 month period that is characteristic of this type of device when made conventionally in the past. When a second "emergency" set of parts were required Moog technicians printed and finished the new set of injectors in 2 weeks, a schedule turnaround that would have been considered impossible without the AMC.

The completion of the Ace Gen 2 project marked a milestone in Moog's AM journey. The outcome is a part that performs better, weighs less, and can get to market in half the time as its traditionally manufactured predecessors. This provides not only a new manufacturing method but also a new product solution, and this brings value to the company, its customers, and society as a whole.

Value creation (10 points)

Value for Moog

The AMC provided value to the Company beyond the financial benefit; the Ace Gen 2 AM injector program is a showcase example. It became a pathfinder for many AM applications to follow, making each new AM qualification less resource-intensive. It enabled agile business practices, allowing products to be quickly created or adjusted based on market demands. Due to the technical difficulty, it strengthened the innovative culture promoted within the company. The program provided an additional path to educate a diverse group of engineers on how best to migrate the business to the incorporation of an Industry 4.0 mindset. The injectors were not the only project to bring these benefits to Moog, but they built upon previous work and made possible the building of subsequent challenging parts.

Value to customer

Having the AM capability provides customer value. Again, using the Ace Gen 2 program as an example, we can see a reduction of timing and cost, resulting in an increase in value. By implementing additive manufacturing, with its reduction of needed processes, the program was able to rescue potential time lost (4-6 weeks versus the 12-15 month lead-time that the hardware historically took to manufacture conventionally). By consolidating parts from eleven to one, AM was able to provide a reduction in cost by eliminating the expensive brazing process previously needed (see Figure 4). Within one-half inch, a thruster could have a surface temperature greater than 2500˚ F and another feature that needs to be maintained to less than 100˚ F. The additive configuration allows these temperatures to be accommodated where traditional manufacturing methods would not meet the expected package requirements.

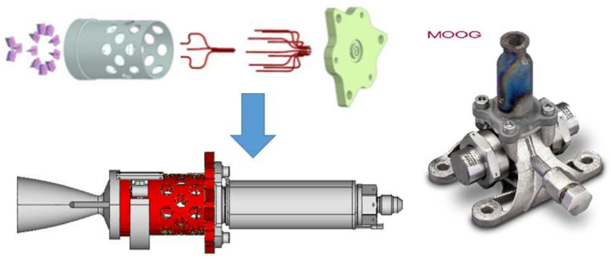


Figure 4 Part Count Reduction

Value to team members

This program provided an immense amount of value to the team by forcing them to use out of the box thinking to solve problems such as creating parallel paths in the implementation of a new unproven technology without sacrificing program schedule. Implementing agile program management such as rolling wave methods was required to accommodate a short delivery schedule, lack of complete requirements at program kick off, and facilitate development of an ever-changing design. It allowed for a cross-functional group to provide input at creation as well as throughout the program, providing insight into not only of what one individual does on her own, but a broader perspective on how her actions affect co-workers, and vice versa.

Value to society

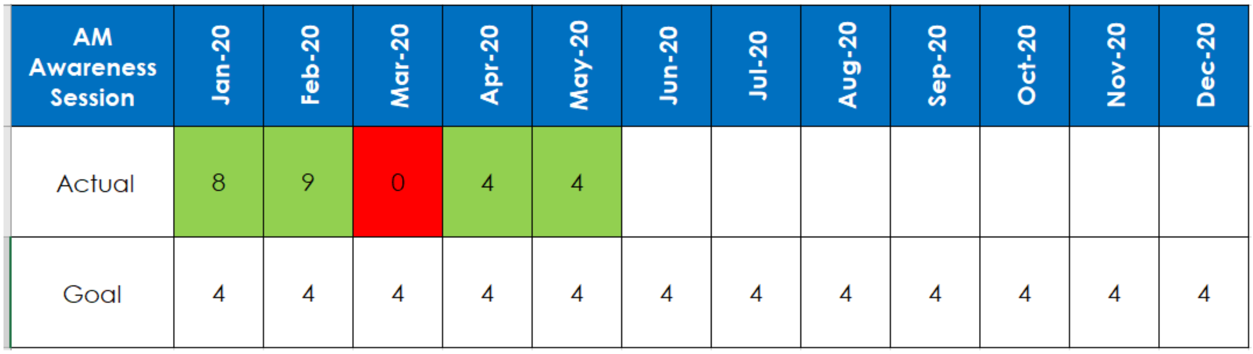
Society in general will see direct and indirect benefits from this program. A direct AM product benefit from performance gains may lead to the adoption of green fuels, reducing the need for hydrazine. This is a giant boon for the environment. By implementing AM technology the manufacturing process to build hardware consumes fewer resources, again another benefit for the environment. Additive manufacturing uses only the material needed, rather than cutting away large sections from billet to get a final part. The “buy-to-fly” material ratio is far better for additive than subtractive technologies, saving metal and energy. As a growing number of assemblies incorporate additive, there will be fewer separate parts ordered, shipped, and assembled. In addition to reducing stocking and handling costs, this consolidation will have ripple effects throughout the supply chain and reduce the overall use of freight of all types (land, sea, and air). Indirectly there is also a point-of-need, point-of-use benefit. The AMC allows for the first steps in a distributed manufacturing network that one day may allow the Armed Forces to manufacture critical components in theater, reducing its dependence on the “iron mountain” (the large, traditional supply chain), and improving US safety by raising our fleet readiness.

Predictive metrics drive action toward program excellence (10 points)

The Additive Manufacturing Center tracks a range of key performance indicators (KPIs) to provide timely and easily understood insight into the work area’s effectiveness. From the family of KPIs, two in particular drive action towards program excellence.

First, adoption of additive at Moog has required persistent outreach to a community of thousands of designers, engineers, program experts, project leaders, supervisors, and executive management. Outreach takes many forms from the impromptu conversation to a formal 3-day course that explores AM in considerable technical detail and has participants get their hands dirty with their own parts and the AM machines in the lab space.

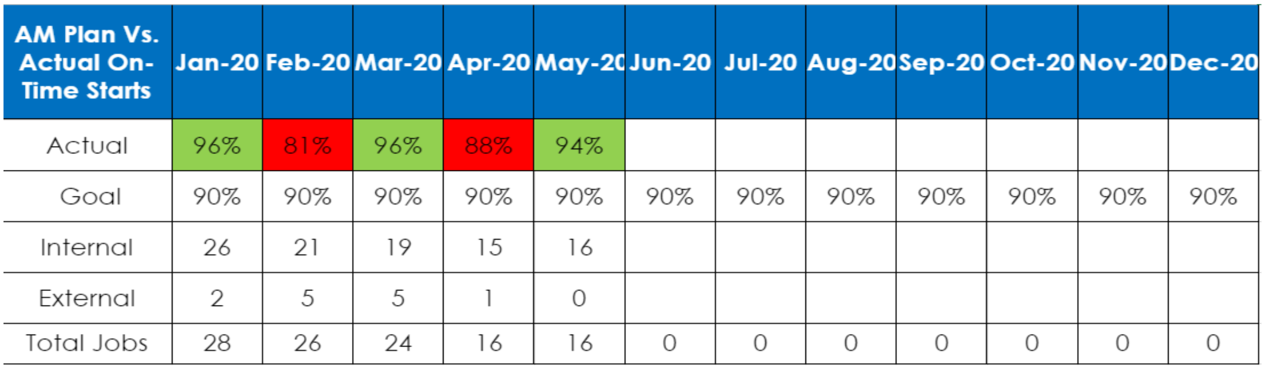
Total outreach activities



AM Awareness Session	Jan-20	Feb-20	Mar-20	Apr-20	May-20	Jun-20	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20
Actual	8	9	0	4	4							
Goal	4	4	4	4	4	4	4	4	4	4	4	4

In assessing overall performance and tracking the impact of improvement projects, the AMC uses the percentage of builds started on time as a second KPI. The table below indicates performance over recent months. In those months where performance dips below the 90% target, specific discussions are held within the team and improvement efforts are initiated. These efforts are discussed during a monthly review.

On time starts



AM Plan Vs. Actual On-Time Starts	Jan-20	Feb-20	Mar-20	Apr-20	May-20	Jun-20	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20
Actual	96%	81%	96%	88%	94%							
Goal	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Internal	26	21	19	15	16							
External	2	5	5	1	0							
Total Jobs	28	26	24	16	16	0	0	0	0	0	0	0

DEALING WITH PROGRAM CHALLENGES: VOLATILITY, UNCERTAINTY, COMPLEXITY, AMBIGUITY (25 Points)

Overall VUCA (10 points) with examples (15 points)

The use of a novel technology (Additive Manufacturing) involves challenges in each of the VUCA focus areas. Moog's Additive Manufacturing Center (AMC) brings together a group of experts with a diverse array of experience. This cross-functional team was tasked with the elaboration of policies to address the dynamic VUCA-related hurdles. To consider each:

Volatility –Unique geometry that enables unique solutions can also create unique problems that are often not discovered until after the planned milestone dates.

The experimental nature of new additive-enabled designs brings with it the risk of build failure. Despite pre-build risk assessment and engineering review, parts can fail at one of several stages. Most often, a part may fail during build, usually at a particular feature in the geometry. This, however, is not the most problematic for timing volatility. Parts may fail after heat treatment, during machining, or during inspection. Methods to inspect the key features of the part may prove inadequate with trapped powder or micro-fractures (refer to Figure 5), a result that may not occur for weeks following the actual printing of the part. For example, a computed tomography (CT) scan of the part's interior may provide insufficient resolution. A plan for coordinated machine measurement (CMM) may not be able to reach the key elements of critical features and require new probes and programming, or a new inspection approach altogether, such as blue light scanning. Possibly even a new design. The further along the production workflow, the greater the impact on both cost and schedule, creating a strong measure of volatility with both.

Cost and timing **volatility** is addressed by bringing together the program experts from the business unit with AMC engineers and managers at the earliest possible stage. Changing a program plan is done with the least headache when done early. To this end, company habits or practices force this discipline. First, on a weekly basis, the entire team gathers for 60-90 minutes to discuss all new actual and potential additive business. This engineering review will often include guest presenters from the home business unit for the project in question. Secondly, there is a much shorter daily review of all of the work going through the AMC, more commonly referred to as a stand up meeting. This too involves the whole team and brings to the forefront any problems that have arisen in production over the preceding day. The exchange of ideas at this meeting, and agile approach to gaining visibility to the ever changing landscape in additive helps troubleshoot problems and creates a repository of experience in solving particular AM problems. The key lessons are distilled in the company AM design manual as well as operating instructions to communicate lessons learned to future designers and teams in a proactive fashion. These practices have proven critical to anticipating potential cost and timing volatility, halting a process early if signs point to failure, and quickly correcting course.

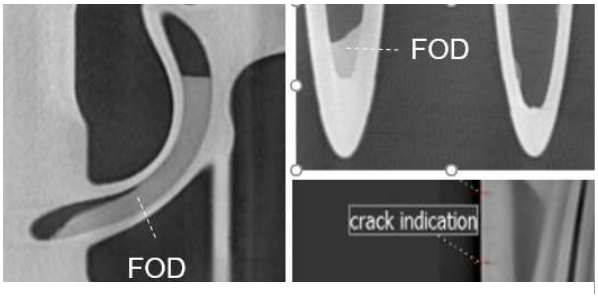


Figure 5 CT Imaging showing Hardware Failure

A key example of **uncertainty** is the repeatability of the additive machines themselves. The tremendous dependence of the AM metal material properties on the machine parameters (both those intended for adjustment and those set by the OEM) creates potential for significant process drift. Furthermore, operational control of the machinery is not at a closed-loop state; the machine is not capable of self-monitoring and self-correction. Instead, a dedicated team of designers, engineers, and technicians in the AMC continuously monitor process variables, particularly as the part is built one layer at a time. Some sections of the part geometry will prove more susceptible to process risk. In the most unfavorable outcome, process drift will result in build stoppages and uncompleted parts that must be scrapped and new parts regrown with modified settings derived from the failure investigation. As the Fishbone diagram below shows (refer to Figure 6), there are multitudes of inputs that can affect the end AM product. An experienced additive team is able to reduce the frequency of such failures, anticipate problems, and propose alternate courses.

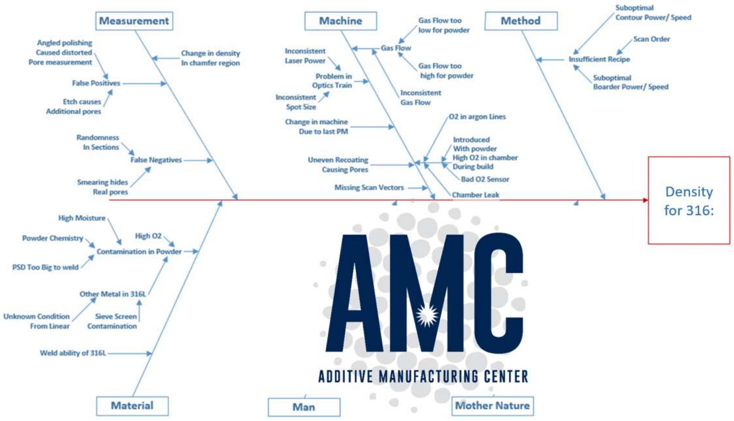


Figure 6 Example of an AM Fishbone for problem root cause analysis

Moog has taken a two-fold approach to the **uncertainty** that comes with having newly developed machinery from the OEMs. First, the company partnered with the three OEMs that provide its laser powder bed fusion (LPBF) machines to train Moog staff not only in the proper operation of the devices, but in basic and advanced repairs. As seen in the above Fishbone diagram (Refer to Figure 6) Moog operators, engineers and maintenance staff have collaborated on both preventive and restorative maintenance on all the devices and built up a body of knowledge regarding key indicators of emerging mechanical and electrical problems, as well as software, design and post processing that could affect end product. Using root cause analysis, Moog is able to identify the actual fault in a workflow with a multitude of input processes. These processes are monitored daily and are addressed in the daily standup meeting, allowing the team to adjust in an agile manner if needed as the manufacturing environment changes (see example in Figure 7). Secondly, Moog has devoted extensive time, money, and effort to optimize the user-adjustable machine parameters to yield optimal properties and reduce porosity and cracking risks. A series of blog posts by Moog senior engineer George Baggs explains the statistical methodology for these designed experiments. These two approaches, taken together, have resulted in performance that mitigates the uncertainty arising from the OEM equipment at its current TRL/MRL.

Figure 7 Daily stand up meeting

Complexity arises in multiple portions of an AM project. First, the generation of a business case for the development of an AM solution involves not simply immediate financial assessments but longer-term, arguably strategic issues. In many cases, a less expensive subtractive alternative can work to meet minimum requirements. However, additive solutions, like the injector, bring additional value, including a reduction in parts count, total process time, points of potential failure, and supply chain risk. Determining the appropriate financial value to assign to these benefits requires both engineering and business judgment and experience. In the case of the Ace Gen 2 thruster, a relatively high value was placed on the ability of the additive lab to get a part into the hands of design engineering in half the time it would have taken to procure a conventional part. Likewise, the economics of part count reduction was particularly valuable, though this area of costing is very new with no overarching consensus on how its full value can be ascertained.

Design **complexity** is almost a given with additive solutions; in fact, the more complex a part, the more advantageous it becomes to manufacture via AM. Curved flow passages, allowing for more efficient fuel delivery, are a part of the injector and many other AM applications for space. A whole series of AM-specific design rules are brought to bear to create an additive part. The design rules allow the part to grow to completion without trial-and-error. There are rules for edges, flat surfaces, build angles, and many other features that must be obeyed, though some of these may conflict with part-specific objectives. Taken as a whole these rules, which sometimes contradict local feature optimization in a part, foster a significant degree of complexity in the design geometry.

To address this **complexity** in both design and cost, a three-stage process involving education, distribution of detailed design guidance, and intensive engineering collaboration were used. The process began with introductory presentations to hundreds of Moog designers and engineers, at about a dozen each time, over a period of several years. The majority of the presentations were approximately an hour and offered a survey of additive technologies, industry cases, and Moog's own work. A critical supporting portion of this introductory work was the presentation of the Moog AM design guide which summarized both generally accepted design principles with lessons derived from company-specific projects. This guide served as the starting point for multiple AM applications at Moog. Finally, projects that had been initiated on the basis of the introductory awareness sessions enhanced through individual study of the design guide were brought to formal commencement with the bringing together of designers from the business units with engineers from the AMC. Business unit engineers brought the specific engineering problems to solve along with developing familiarity with additive technologies. The AMC staff contributed its particular expertise with many different additive projects. At an initial stage, projects were discussed during weekly AMC engineering calls with the business unit designers and engineers as guests. Then a dedicated project team would be created with one engineer and one designer from the AMC assigned to work a given project. Collaboration become more detailed as the timeline unfolded. And, in a direct result of this early collaboration, costs that would have been incurred due to failed builds, difficult to machine components, trapped powder, and inspection problems were avoided.

Ambiguity arises out of the limited industry specifications available to help govern this technology. Adding to the confusion, multiple customers have created their own specifications that sometimes conflict with one another. This general lack of industry standards is compounded by unclear material properties and associated design allowables. The start of a project is accompanied by considerable deliberation over achievable tolerances, required feature dimensions, drawing requirements, inspection methods, and overall acceptance criteria. Every project intends to avoid moving the goalposts after it has already started, but this remains a risk in AM. There are several industry initiatives to elaborate standards for AM materials, processes, and products and overall US-wide efforts to coordinate the varied standards initiatives, but during the period in which the injector was being manufactured, for example, such standards were still in development. Amid this changing landscape, the project team had to decide which standards would apply and justify their selection.

When considering what specs the project team needed to call out on their drawing there was much discussion of how best to do this. What the designer should point to for design allowables, was just one of the many questions that surfaced when deciding to move forward with this hardware and manufacturing process. Members of the team who happened to be on industry bodies creating specifications (SAE and ASTM, for example) began to weigh in. Compliance matrices were created against developmental documents like the NASA Marshall AM spec. Internal Moog specifications were also created to address work process and part cleanliness. By participating in industry standards creation as well as generating internal specs, Moog increased the internal trust level in the manufacturing process and mitigated the **ambiguity** problem. Furthermore, the Ace Gen 2 thruster project prompted Moog to create a statistically-significant number of mechanical property coupons in Ti64 (Tensile AM Build and microstructural analyisis can be seen in Figures 8 and 9) so as to be able to mimic the metals characterization at the "S-level" of the Metallic Materials Property Development and Standardization (MMPDS) handbook. While MMPDS does not have a released process to incorportate AM materials in its handbook, development efforts are underway to add one. In the meantime, Moog engineers created a process that was essentially akin to the one used to characterize metals formed by traditional manufacturing methods. Moog's generation of "S-basis-like" like data was also an important route to reducing ambiguity in the Ace Gen project, as well as all of Moog's work with the Ti64 alloy.

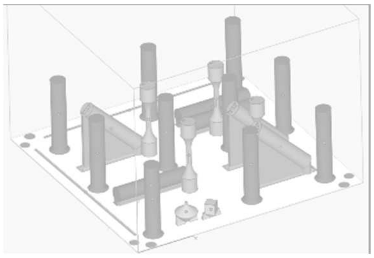


Figure 8 Tensile Bars

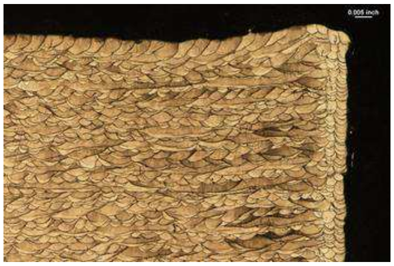


Figure 9 Microstructure Analysis

ORGANIZATIONAL BEST PRACTICES AND TEAM LEADERSHIP (40 points)

Innovative program execution practices (15 points)

The finished AM part is only the last chapter in a much longer story. The result, after all, is simply the embodiment of a process that entailed the work of many people. The Moog culture places a premium on the collaborative work that enables the creation of remarkable products like the thruster. In order for collective work to be effective, particularly in new technologies like additive manufacturing where work practices are necessarily a bit more fluid and must have more "give," structure is needed. This framework has to be flexible enough to allow for experimenting with the new AM tools and be able to adapt to the unanticipated, but also solid enough that a project can be managed in an orderly fashion.

Moog has been particularly successful at tailoring its pre-existing, internally developed work planning and information system (the Moog Business System, MBS) to the needs of the new additive processes. By creating AM-specific processes in place of the traditional business processes—from raw material demand of different types and grades of powder, to production work processes, to shipment planning—Moog has been able to integrate AM components into larger products, assemblies, and ways of doing business. This approach has largely made the use of AM seamless to the rest of the organization outside of the additive center. The benefits of this integration show themselves at every step of the process, from planning to build to verification.

A complicating factor in planning is the low-volume, high-mix factor. No two additive build plates are the same and, for the moment, there are significant machine-to-machine variations. For this reason, there is some amount of customization in every build. Customizing might solve several problems, only to create new ones. Moog's adapted AM workflow guarantees that customizations for one product are repeated on the next build. In this workflow, tracking of customizations is done through another program called Complex Assembly Manufacturing System (CAMS). CAMS integrates with MBS and is the location where operations sheets that contain the detailed work instructions are created. For any changes or updates, a new revision is created. They include: operation numbers (which provide the sequence of steps), work center where the task is performed (with AM machines given a special group code), standard setup and run hours per piece, and specific instructions for performing the operation. All of the routing information is extracted from CAMS and loaded into MBS.

Through this use of MBS and CAMS, the required operations are known and executed at the correct points in the workflow. The job- and machine-specific processes that have been developed are all captured in detailed work instructions and linked to the job. A job at any stage in the process can be picked up, and its previous processes established by an examination of the operations number and data collection in MBS.

The completion of all manufacturing steps moves the part into the inspection and verification portion of the workflow. Moog's AMC employs blue light technology, CT scans, and density coupons analysis. Used in concert, these processes qualify the hardware. The record of all the output processes is compiled, and any needed deviation reports and approvals are collected and assembled in a third-party quality management software program, TipQA, also previously integrated with MBS.

The creative solution adopted at Moog was to make use of all the legacy software—MBS, CAMS, and TipQA—and adapt it for use with additive manufacturing. The most difficult elements of the AM incorporation lie in processes used in AM but not elsewhere, in particular, the use of powder feedstock with its capability for re-use and the potential to run multiple parts on a given build plate (of the same or different part number). These challenges were solved via continued development of each system (MBS, CAMS, and TipQA)

Knowledge transfer and staff development processes (15 points)

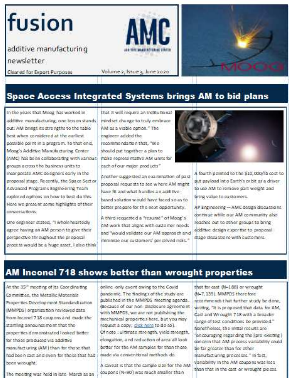
A large problem when implementing a new technology like Additive Manufacturing in a large aerospace company is not so much a resistance to change from the engineers' standpoint, but the fact that the industry as a whole is built on systems based on flight heritage. This flight heritage criteria in and of itself is resistant to change. Although having flight heritage is a lower risk and conservative approach to critical applications, it does present several hurdles that block innovative solutions, and slows progress. To help overcome these hurdles, but insure these technologies are implemented responsibly, Moog has introduced a robust training program that allows technology experts to transfer knowledge to Moog engineers throughout the company. These changes do not take place overnight but require steady and constant education.

Training comes in many forms. When trying to train an experienced workforce that is already expert in its perspective field, many things need to be considered. How does one suggest that a designer change the way that he has designed for the past 30 years? In most cases when one implements a new innovative technology this will force change, and in the short term most of the heavy lifting is done by the designers and engineers. So standard training courses are not enough to convince the design community the value of AM. Steady and constant education must be employed. This at times can be difficult, but repeated training sessions covering different aspects of the subject are needed so that the material is not redundant. This helps to keep these ideas fresh and the engineers engaged.

Those who attended introductory sessions were able to extend their knowledge with a 3.5 day course that delved into much greater detail and offered hands on experience with the machines and the overall additive project workflow from powder manufacture to finished part inspection and qualification.

After the AM training has taken place, the engineers and designers are encouraged to keep an open mind as they approach new applications. As the daily demands and tasks begin to pile up the designers have a high likelihood to slip back into old design habits and pick up the tools used in the past that have delivered successful results. It is easy to forget an AM technology solution. Some individuals are more successful at identifying different applications and uses for the technology. So getting the insight of these early adopters out to the rest of the design community is paramount.

One of the most effective ways to communicate these new designs or applications across the business is a simple newsletter (see ***fusion***, Moog's AM newsletter, Figure 10). Is should feature short articles to be reviewed quickly by designers, while also providing insight on the projects and applications where AM has worked and give recognition to projects that have implemented the technology. A newsletter in and of itself is nothing unique or innovative. The audience should include the entire company to encourage an atmosphere that invites everyone to weigh in from Program Mangers to Supply chain specialist on possible AM applications. This is easily tracked by the uptick in inquiries about the next AM training session from employees outside the design engineers.



fusion

additive manufacturing
newsletter

Cleared for Export Purposes

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Space Access Integrated Systems brings AM to bid plans

In the years that Moog has worked in additive manufacturing, one lesson stands out: AM brings its strengths to the table best when considered at the earliest possible point in a program. To that end, Moog's Additive Manufacturing Center (AMC) has been collaborating with various groups across the business units to incorporate AMC designers early in the proposal stage. Recently, the Space Sector Advanced Programs Engineering Team explored options on how to best do this. Here we present some highlights of their conversations.

One engineer stated, "I wholeheartedly agree having an AM person to give their perspective throughout the proposal process would be a huge asset, I also think that it will require an institutional mindset change to truly embrace AM as a viable option." The engineer added the recommendation that, "We should put together a plan to make representative AM units for each of our major products"

Another suggested an examination of past proposal requests to see where AM might have fit and what hurdles an additive based solution would have faced so as to better prepare for the next opportunity.

A third requested a "resumé" of Moog's AM work that aligns with customer needs and "would validate our AM approach and minimize our customers' perceived risks."

A fourth pointed to the $10,000/lb cost to put payload into Earth's orbit as a driver to use AM to remove part weight and bring value to customers.

AP Engineering – AMC design discussions continue while our AM community also reaches out to other groups to bring additive design expertise to proposal stage discussions with customers.

AM Inconel 718 shows better than wrought properties

At the 35th meeting of its Coordinating Committee, the Metallic Materials Properties Development Standardization (MMPDS) organization reviewed data from Inconel 718 coupons and made the startling announcement that the properties demonstrated looked better for those produced via additive manufacturing (AM) than for those that had been cast and even for those that had been wrought.

The meeting was held in late March as an online only event owing to the Covid pandemic. The findings of the study are published in the MMPDS meeting agenda. (Because of our non disclosure agreement with MMPDS, we are not publishing the mechanical properties here, but you may request a copy; click here to do so).

Of note: ultimate strength, yield strength, elongation, and reduction of area all look better for the AM samples for than those made via conventional methods do.

A caveat is that the sample size for the AM coupons (N=90) was much smaller than that for cast (N=188) or wrought (N=7,139). MMPDS therefore recommends that further study be done, writing, "It is proposed that data for AM, Cast and Wrought 718 with a broader range of test conditions be provided." Nonetheless, the initial results are "encouraging regarding the [pre existing] concern that AM process variability could be far greater than for other manufacturing processes." In fact, variability in the AM coupons was less than that in the cast or wrought pieces.

Figure 10: AM newsletter

Perhaps the most valuable tool for knowledge transfer is the DfAM (Design for Additive Manufacturing) process. In the early stages, there is little AM expertise outside of the AM center staff, and there is absolutely no substitute for hands on experience. DfAM allows the AM designers to work with the applications engineers to develop an AM solution. This usually will take place over a course of a few weeks with a lot of back and forth discussions; it is a very iterative process. DfAM also involves everyone on the team from quality to manufacturing to program management. The entire landscape of manufacturing has changed, and provides a unique problem for the program manager to solve. However if DfAM is performed correctly, the process is streamlined and many of the problems that might have occurred later in the process and potentially created delays are addressed early and the AM process is much more efficient than that of even conventional methods.

Unique practices used to engage customers (10 points)

When integrating a new technology into a platform or product, a level of reassurance must be provided to the customer that the product will perform as well or better than previous models. Additive manufacturing can solve problems that the customer does not know that she has. Past manufacturing experiences have provided her with certain outcomes that have included data points that at one time were correct. In certain cases, however, those data points may no longer be valid. So finding unique ways such as "Lunch and Learns", parallel paths, and proof of concept exercises to engage customers is critical to getting buy-in on all levels of a program.

Lunch and Learns are an easy way to address a larger group at a customer site. When one holds these events for customers at a program level it helps to give an introductory understanding of the technology and its possible applications. Lunch and Learns are especially good when using components on current programs that are creating a headache or causing difficulties as examples of candidates for DfAM. Talking through some of these applications helps to provide insight on applications as well as possible drawbacks of implementing AM. These Lunch and Learns also provide a forum where engineers can share ideas freely, an important practice if one is trying to understand the struggles of a program as well as reservations about new applications. Lunch and Learns can also follow a small DfAM activity that has introduced a portion of AM design thinking. This type of event allows for understanding of both function and technical capability and tends to provide the best guidance for decisions about pursuing an additive solution to a particular problem.

As a rule, customers want to try new ideas and implement innovative technology into their program. It is typically easier to say no to the new idea and go back to a traditional method. No manager on a program likes to play firefighter most of the time. In the end, it comes down to de-risking the decision. This can be done by proposing a parallel path in which an AM part is designed and built alongside the traditional one. This choice allows the customer a safe and tried method to a successful completed program, but also allows them to investigate an innovative idea that may provide value to the program. Milestones along the AM component's qualification path can be set to monitor its progress. Based on the customer's comfort level, the AM component can begin to take the lead path if all objectives are met, and a final AM component is delivered. Alternatively, dual paths may be maintained and two solutions provided to the customer: the conventional one and an AM variant. This scenario allows the customer the ability to cut in the AM component or fall back on the conventional solution if needed.

Bringing the customer in early is critical to the success of the implementation of new technologies such as AM. In the end, customers are the ones that have to use the hardware and it is critical to gain their input and confidence. However, before the parallel paths and even the Lunch and Learns it usually starts with an idea. Moog engineers look at the problem the customer has and develop different ways that it can be solved. If one of those ways includes additive manufacturing then AM can be a great tool to do a quick proof of concept so that when conversations are being had about implementing a new product, a prototype part can be held in hand. This can be a critical step in the process of gaining customer buy-in. It is the old adage: "Seeing is believing." Once the idea is real, customers are able to visualize the possibilities. Additive allows the manufacturing capability to deliver these concepts with fewer up-front costs than are normally associated with prototyping.

Finding unique ways to engage customers such as Lunch and Learns, parallel paths, and proof of concepts is critical to getting "buy-in" on all levels of the program including all those on both sides of the supplier and customer relationship. Although the processes themselves may not be intrinsically new or unique, the application provides a stable conventional platform to build on with innovative technologies like additive manufacturing.