From Design to Reality: Additive Manufacturing for Spaceflight

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ABSTRACT

In 2017, APL's Jovian Energetic Electrons (JoEE) spectrometer team finalized its innovative design for the instrument, slated for the European Space Agency's JUpiter ICy moons Explorer (JUICE)—the first mission to orbit an icy moon. However, the curved collimator design pushed the limits on traditional manufacturing techniques, and the most viable method, additive manufacturing, faced significant hurdles for acceptance. Engineers, scientists, and machinists from across the Johns Hopkins University Applied Physics Laboratory (APL) brought their expertise together to address challenges ranging from unexpected machine behavior to unreliable inspection methods to ultimately qualify and launch. By testing and refining metal additive techniques and collaborating internally and with external partners, they were able to achieve the complex geometries required for the collimator and successfully develop, qualify, and launch the flight collimator—APL's first additively manufactured flight component—in just 2 years.

INTRODUCTION

Additive Manufacturing

The last decade has seen an explosive growth in the development and adoption of additive manufacturing technologies, more commonly known as AM or 3-D printing, with global market share rising from $500 million in 2010 to over $5 billion in 2020.[1] This growth represents a shift away from niche or hobby-level equipment toward adoption of large-scale industrial printers by the auto, aerospace, and medical industries. AM technologies now cover seven categories of equipment with at least 27 distinct processes capable of printing everything from organ surrogates to complex metal lattices.[2] However, despite AM's game-changing impact, the road to implementation has been uneven, particularly for high-criticality components in aerospace and defense applications. Building flight components requires not only demonstrating that the technology could work but also successfully integrating it into the broader system of trusted manufacturing. This article, a companion to another recent article on this same topic,[3] describes how APL drew on its vast breadth of expertise to go from a ban on using AM components in space missions to delivering an AM flight collimator for the European Space Agency's (ESA's) JUpiter ICy moons Explorer (JUICE) mission[4] in under 2 years.

JoEE Collimator

The Jovian Energetic Electrons (JoEE) spectrometer (Figure 1) is a part of the Particle Environment Package – High (PEP-Hi) onboard JUICE, the first mission to go into orbit around an icy moon. Around 2017 the JoEE design team searched for a solution to accurately align electrons and ions at the aperture. The instrument, designed to measure electrons in the Jovian environment including its icy moons, Ganymede, Europa, and Callisto, requires particle collimation resolving the arrival direction to characterize the angular distributions of electrons that are critical to understand how the intense Jovian electron radiation belts are generated. Working within tight size, weight, and field-of-view requirements, the team had come up with an innovative circular geometry that would provide a 270°-wide field of view while aligning the sensors to the device's magnetic fields. There was another challenge—the design called for the collimator to be bent in an arc.

Traditional collimators are formed by etching and stacking thin plates of metal to build up a "banded" block containing the appropriate holes. APL had previously flown these collimators on multiple missions, and simply bending the bands was not expected to cause a problem. This collimator design, however, was no simple structure. The design was composed of 4,662 half-millimeter holes aimed in different directions in a complex honeycomb arrangement with walls the width of a human hair. While building this design was technically feasible, the mechanical design team identified significant hurdles that made it impractical. When the sheet metal was bent in a circle, the thin walls would stretch and bend, requiring custom design tools to compensate for different deformations in each layer. The small wall thickness made each layer incredibly sensitive to misalignment or bending during stack-up, and engineers feared that launch vibration might damage the fragile structure.

Faced with a manufacturing challenge, the design team turned to APL's mechanical fabrication experts to explore potential alternatives to the banded approach. When the possibility of AM was raised, the JoEE team was initially skeptical. Metal AM had only been a capability at the Lab for a few years, and the wall thickness of the JoEE design pushed the resolution and design limits of the powder bed fusion printer. The AM team, however, had demonstrated a viable proof-of-concept component for Parker Solar Probe (although it was never flown) and thin-walled components for an internal research and development initiative, so the team approved an exploratory trial.

A week later the team met to review preliminary prints made of titanium. The AM team presented two builds, one printed using the original design and another modified for manufacturability. While reviewing the initial design, the AM team realized it had several features that were not well suited for AM. Like all manufacturing methods, AM processes each have unique strengths and weaknesses that make them an ideal choice for certain geometries but not for others. By leveraging their prior experience building similar geometries, the AM team was able to make several changes to optimize the design for AM. On review, the results were clear: the optimized blocks significantly outperformed the originals. Although the alternative design would necessitate going back to the drawing board, the results were promising enough to warrant further exploration.

PATH TO A VIABLE PROTOTYPE

Although AM had been demonstrated, the mechanical fabrication team investigated several manufacturing processes in parallel to mitigate risk to the program. The first approach was to modify the design for traditional machining. Merely drilling each hole was a challenge; the specified measurements, 0.5 mm (0.019 in.) wide and more than 12 mm (0.472 in) deep, exceed the standard 10:1 length-to-diameter restriction on drilling. High-aspect-ratio holes require custom tooling, and the

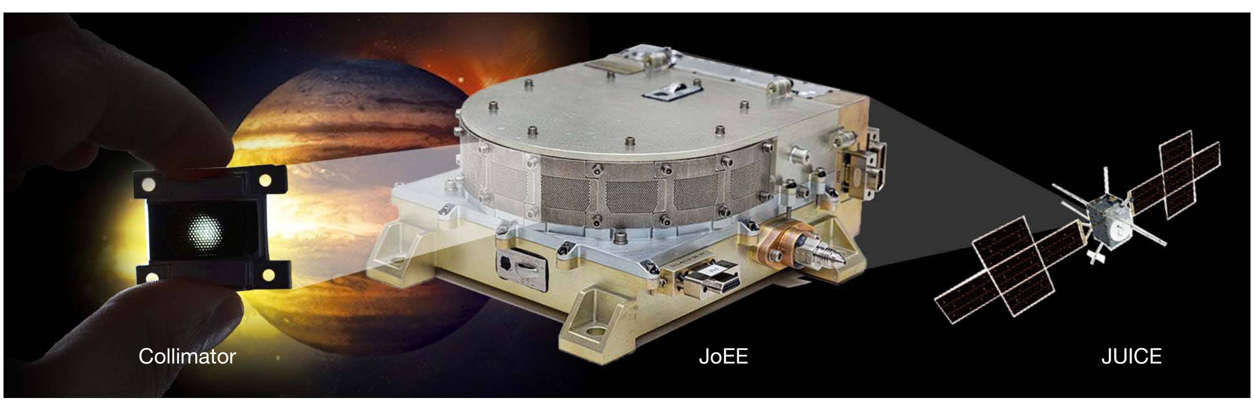

Figure 1. The JoEE spectrometer, part of the PEP-Hi instrument. The spectrometer (center) has strict requirements on collimation of electrons to measure their angular distributions in the harsh Jovian radiation environment onboard JUICE (right). APL solved that challenge by using AM to fabricate robust and precise collimators (left).

increased depth strained the drill bit and machine. With only 100 µm of material between each hole, the slightest wobble or skip in the drill bit would cause it to rip through the thin layer and ruin the entire assembly. Successfully building the collimator would require perfectly drilling 4,662 half-millimeter holes without a single mistake.

Despite these obstacles, the machinists were able to find the right mix of tooling and settings to begin prototyping. In each attempt, the first few hundred holes drilled perfectly before the drill bit broke and ripped through nearby walls. The machinists persisted, progressively reducing the number of holes drilled before changing the drill bit until they were replacing the bit after drilling every 20 holes. Despite their best efforts, they could not finish an entire block without failure. The failure point of each drill varied, making it impossible to predict lifetime, thus resulting in unexpected early failures. Because of the holes' small sizes and large drilling depth, any small defect in the drill led to failure. Worse yet, analysis showed that the smooth surfaces of the drilled holes caused significant internal reflection, degrading the efficiency of the collimator even further. Even if the design were possible to manufacture, it would not be affordable.

Investigation into the banded approach similarly revealed challenges. Thin strips of sheet metal, only 100 µm thick, bent and stretched in unforeseen ways. Design tools were ill equipped to predict the distortion, and designers would have had to make significant investments in custom simulation tools to even start the process. Designing the correct pattern would require costly experimental iteration and would depend on external vendors with long lead times. Even if the design could be realized, the vibration characteristics of the stacked and curved thin walls were difficult to simulate and would require further iterative testing to validate.

The AM team was facing its own challenges in printing a prototype. The first test pieces were titanium, a material not dense enough to fully stop the highly energetic electrons in Jupiter's orbit. Of the available AM materials, only 316L stainless steel had both the density and nonmagnetic performance necessary for the final component. However, after the switch to 316L, the previously clean thin-walled structures fused into a nearly solid mass of partially sintered powder.

It took hours of reloading prints, discussing with the equipment manufacturer, and poring over the machines computer code to reveal a small detail hidden in the depths of the equipment's laser processing parameters. Although the same geometry files were used for both materials, the settings for titanium included one laser pass to generate the 100-µm-thick walls, while the stainless settings included three. The rules that governed and generated the laser pathing for the machine had complex interactions that led to emergent behavior as various parameters shifted and changed (Figure 2). Solving the problem required exploring how each of the parameters interacted to trigger the correct settings. By experimentally iterating the inputs, the team was not only able to fix the challenge, but they also figured out how to tune the wall thickness of the resulting build. With these new principles in mind, the team successfully printed the core design in stainless steel.

INTEGRATING WITH THE SYSTEM

The collimator is just one component in a complex, incredibly sensitive instrument designed to probe Jupiter's magnetic field. The high-energy electrons it was

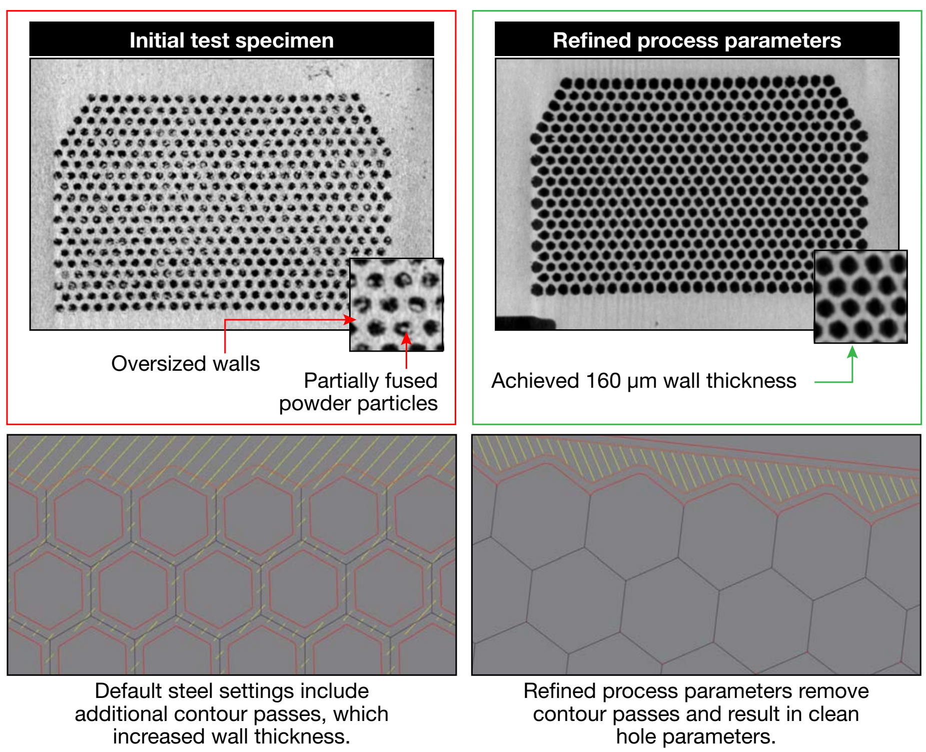

Figure 2. Steel settings and resulting prototypes. Left, default steel settings (bottom) included two contour laser passes in addition to an infill operation, which resulted in oversized walls and a large number of blockages. Right, by tuning the input parameters (bottom), the team limited the walls to a single laser pass, resulting in thin walls and no blockages.

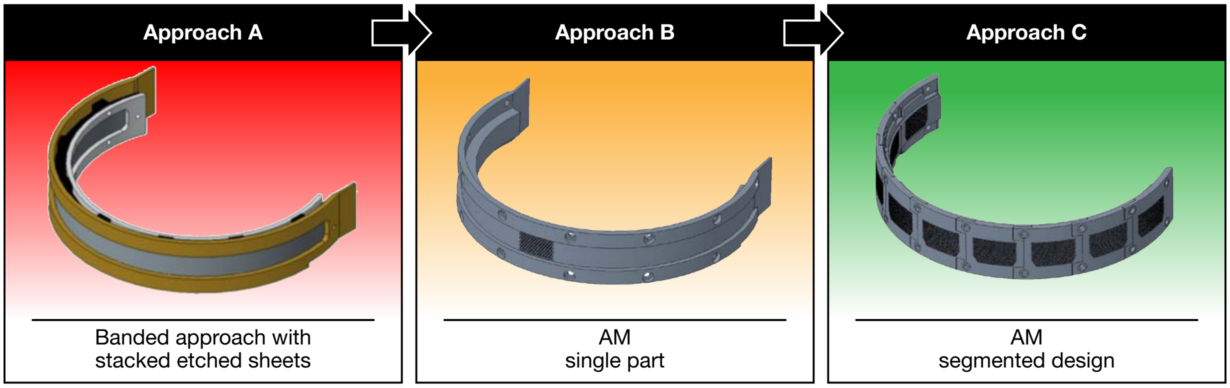

Figure 3. Approaches to collimator manufacturing. While the ultimate shape of the collimator remained the same, APL's scientists, engineers, and machinists had to rapidly iterate to find a design that could be readily manufactured.

designed to detect could flit through the tiniest of gaps, and every misaligned hole degraded performance. For the instrument to work as designed, each of the 4,662 holes had to converge on a point only half a millimeter across when bolted to the assembly. This posed a problem: while powder bed fusion AM is capable of precisely creating complex structures, the surfaces created are rough. At the edge of the sample, unmelted powder leaves a bumpy surface reminiscent of sandpaper. For the collimator holes, this rough surface was a benefit, as it minimized electrons from reflecting within each tube. When it came to assembly, however, the rough surface left gaps and created poor alignment. Achieving the appropriate surfaces would require post-machining, which posed its own problems. The critical feature, the hole pattern, was too small to index, and the surface roughness made indexing the machining tools a challenge.

APL's machinists, AM engineers, designers, inspectors, and structural engineers began to rapidly iterate, centered not on the AM or design team but instead on the experimental machinists who would shape the component into its final shape. The first design was unbuildable; the radii of the complex, curved, interlocking steps were too tight to be properly machined. The machinists quickly turned around prototypes and relied on APL's inspection team to set design limitations. The design team then iterated with the structural engineers to create a new design that could pass structural launch loads (Figure 3). Every change had to be validated against assembly-level models to ensure that the vibration of launch would not shake the instrument to pieces.

Machining a blank of steel to the dimensions necessary was hard but possible, but machining an AM blank while ensuring the holes aligned posed a seemingly insurmountable challenge. It was only by revisiting the AM process with the final machining steps in mind that the team found a solution. Instead of shaping the AM component to be as close as possible to the final shape, they went the opposite direction and overbuilt. By centering the hole pattern in a symmetrical block, they took advantage of the fact that the top surface was smooth enough to index and the shrinkage during the process was uniform. With this approach, the team was able to use an alternative visual inspection tool to precisely determine the center point of the final blank, allowing the machinists to fit their models to the center of the hole pattern and to electrical discharge machine (EDM) a near-net-shape blank, providing flat precision surfaces for final five-axis machining.

INSPECTION AND VALIDATION

With a manufacturing process in place, the team's next challenge was inspection. The visual inspection tool used for machining was only sufficient to locate the holes; it could not be used to check the alignment in the final assembly. The team turned to x-ray computed tomography (XRCT), an x-ray technique used to generate internal 3-D models. Although APL had built up a wide range of software techniques to rapidly scan the components for structural integrity and internal flaws, the collimator's complex hole geometry once again proved intractable. The XRCT software did not have the tools necessary to interrogate it in the ways the design team needed. Traditional measurement tools were optimized around traditional parallel collimators (Figure 4) and failed to handle the various angles of the new design. Without these tools, the design team had no way to quantifiably check the alignment of the final holes, the number of blockages within the tubes, or the integrity of the walls.

The problem demanded a custom solution, and one APL could not achieve alone, so the team worked with the software vendor to implement new capabilities. Checking the hole alignment required adding the capability to manually set the camera view in the digital reconstruction. Setting the camera view to the focal point of the CAD assembly enabled the use of APL tools to fit the scanned file and create an instrument

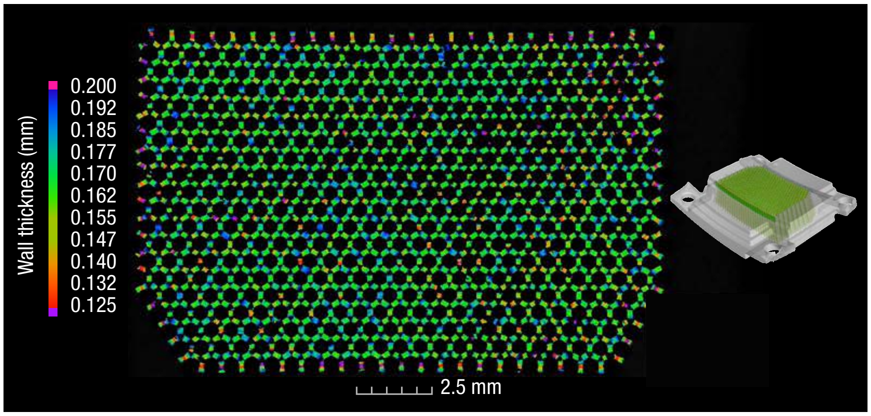

Figure 4. Challenges with validation. Traditional measurement tools in the XRCT software could generate simple wall thickness measurements of the collimator geometry but, because of the wide range of hole orientations, they could not be used to quantifiably check the alignment of the final holes, the number of blockages within the tubes, or the integrity of the walls.

simulation. By looking at the scans from the simulated "viewpoint" of the instrument, the team could check for occlusions, measure wall thickness, and even simulate the effect of wall breakages. The collaboration resulted in a software patch that permanently updated the vendor's software and is now a well-used functionality within it. The software fix did not solve all the APL team's problems, but with the ability to properly view and measure the component, the team was able to generate custom MATLAB and MIPAR image processing code to generate quantifiable results. The design team could now see not only exactly where the holes intersected but also the pattern from the electrons' point of view (Figure 5).

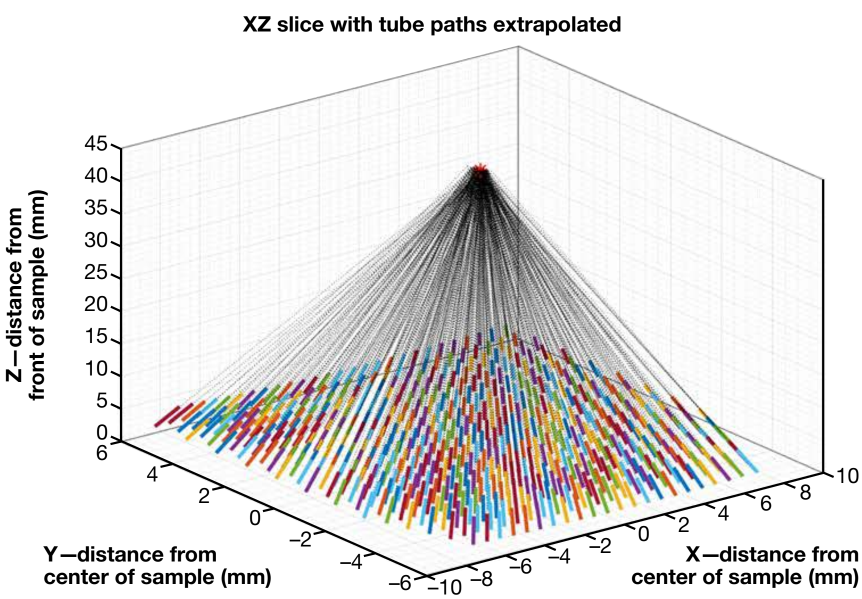

Figure 5. Validation solution. By combining the simulated viewpoint of the instrument with image analysis tools, the team was able to individually fit each hole pattern and calculate the focal point of the collimator pattern.

With inspection results in hand, the team began physical testing. The instrument requirements called for a minimum test load of 20 g of sine vibration, a benchmark that had to not only be met but exceeded. In addition to needing to prove that the holes were aligned when built, testing had to show that they would stay that way during the high-vibration loads of launch. The instrument's alignment during launch put the collimator directly above the fragile instruments it was designed to protect. If the slightest fragment of broken material or residual powder broke free, the fragment would accelerate back into the sensor body before ricocheting around the delicate innards. Proving that the instrument would survive required turning to experts in APL's vibration and cleaning labs.

The first step was to clean the instrument and check for residual material trapped in the rough internal walls. Before this step could be completed, the cleaning team had to learn both the AM process and the post-machining required to complete the component. The AM surfaces had the potential to trap both the 25- to 35-μm powder particles and the small 5- to 10-μm metallic flakes created when laser-vaporized metal resolidified. In addition, the electrical discharge machine operation exposed the component to water, which had the capability to partially "glue" the loose powder into the holes, while the machining operations immersed the component in coolants. The cleaning lab technicians used this information to work through several experiments, testing each method for residual powder using both their own particle counting methods and the new XRCT capabilities. The final result was a modified process that doubled the normal cleaning time.

After the component was certified to be particle free, it headed to the proof testing lab, informally known as the "shake and bake," for a final series of tests. The components needed to survive thermal cycling, pass an off-gassing test, and survive vibration testing. One of the key success criteria APL had negotiated with NASA

Marshall Space Flight Center was proof testing each collimator before it could be tested with the instrument assembly. APL had to definitively show that the component could survive launch before it could even get close to other flight components. To guarantee a clear success, the team set an ambitious goal of testing at 25 g in sine vibration for twice the demanded duration, a full 25% more than the basic flight requirements, which already included a massive safety factor. The equivalent for a person would be carrying ~4 tons (~3,628 kg) for several minutes. After each thermal cycling and vibration test, including random vibration and shock, the collimator was disassembled and sent back for cleaning and XRCT. The smallest deviation or evidence of loose fragments would be grounds for immediate failure. When the scans came back, the results were identical; the collimator met and exceeded every metric for performance.

UPDATING STANDARDS

Despite this success, a single sentence in APL's space flight design guidelines presented yet another challenge: "AM shall not be used for flight components." As a novel manufacturing process, AM had not yet been shown to have the demonstrated reliability necessary for spaceflight operations. APL's ability to create flight components is built on a foundation of rigorous adherence to both quality engineering and quality assurance. The team had proved the component met engineering requirements, but approval would depend on the team's ability to put together a quality framework robust enough to meet NASA's, ESA's, and APL's own exacting standards. The team turned to their partners at NASA Marshall who had released MSFC-STD-3716,[5] a baseline for AM components, just 1 year prior.

Putting this standard in place, however, was no trivial task; it was designed to be tailored to each application and interwoven into existing flight requirements. Following the roadmap developed by NASA required cooperation among many stakeholders, including NASA Marshall and APL AM team members; NASA, ESA, and APL program managers; and APL's quality assurance teams, chief scientists, and JoEE designers. Simply determining whether and how APL could meet the 110 individual requirements of the standard required several daylong meetings for which APL engineers traveled to meet with the Marshall team in Huntsville, Alabama.

The result was a plan to write over 30 documents, including part process plans, qualified metallurgical procedures, manufacturing plans, training requirements, and inspection plans. With the final design review looming, the team had less than 6 months to produce preliminary drafts. As the deadline approached, the core team worked with staff members across the Lab to write, implement, and validate each of the documents. By the time of the critical design review, the Lab had added multiple new quality documents, set up new training courses for APL technicians, validated new inspection methods, and implemented new data storage systems. The path for taking an AM component to spaceflight had been established.

THE PATH TO FLIGHT

Less than 2 years after APL's AM team printed its first test part, the JoEE team boxed the flight model. It was integrated with the rest of the JUICE spacecraft at the Airbus premises in Toulouse, France. JUICE launched April 14, 2023, on Ariane 5 from the European Spaceport in Kourou, French Guiana. The road to application was built not on one individual breakthrough but on the strengths of a hundred tiny solutions pioneered by experts across the Lab. Many of those innovations were breakthroughs in their own right, from the laser pathing methods now being used for other AM components to the XRCT software improvements now in use across industry. Others were simply well-engineered adaptations of existing methods, like the cleaning techniques and proof testing used to validate the final components. Many of the solutions were simply small critical moments of communication, from APL space executives helping the AM team find the right connection at NASA to scientists sitting down and learning from machinists. That these solutions were there to be found was made possible by APL's tight integration of manufacturing with research and development and systems engineering. As the pace, global scale, and diversity of innovative technologies continues to accelerate, APL maintains its manufacturing capabilities not just to produce components but as an important tool in its ability to create defining innovations.

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