ORNL/TM-2024/3376

Utility of Big Area Additive Manufacturing for Part Production for Low-Head Hydropower

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January 2024

CRADA FINAL REPORT
NFE-21-08560

Approved for Public Release
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OAK RIDGE National Laboratory

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Manufacturing Science Division

ADVANCED PATHING SOLUTIONS FOR LARGE FORMAT POLYMER PRINTING

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January 2024

Prepared by
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UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACKNOWLEDGEMENTS

This project under CRADA NFE-21-08560 was conducted as a CRADA project within the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) sponsored by the US Department of Energy Advanced Manufacturing Office (CPS Agreement Number 24761). Opportunities for user projects under the MDF Technical Collaboration Program are listed in the announcement "Manufacturing Demonstration Facility Technology Collaborations for US Manufacturers in Advanced Manufacturing and Materials Technologies" posted at http://web.ornl.gov/sci/manufacturing/docs/FBO-ORNL-MDF-2013-2.pdf. The goal of Technical Collaboration Program is to engage industry partners to participate in short-term, projects within the Manufacturing Demonstration Facility (MDF) to assess applicability and of new energy efficient manufacturing technologies. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

ABSTRACT

ORNL worked with Cadens, LLC to explore the use of additive manufacturing (AM) for the production of low-cost parts for low-head hydropower systems. Cadens develops design optimization software that leverages the flexible, low-cost, high-strength benefits of AM and composite materials, and operates a micro-hydro lab to test AM components in controlled environments. Until now Cadens' tests have been limited in size to components that they can cost-effectively manufacture using local commercial systems. This project provided an opportunity for Cadens to scale up their modular AM hydropower parts using the capabilities of Big Area Additive Manufacturing (BAAM). This project was a success and resulted in the design and fabrication of several end use parts of a hydropower system using a Big Area Additive Manufacturing (BAAM) system. The fabricated parts include draft tube, thimble, runner housing mold, PVC end fitting and two PVC pipe supports. The components have been in use for more than three years without a 3D printed component failing.

1. UTILITY OF BIG AREA ADDITIVE MANUFACTURING FOR PART PRODUCTION FOR LOW-HEAD HYDROPOWER

This technical collaboration project (MDF-TC-2020-206) began on July 18, 2018, and concluded in December 2023. The collaboration partner Cadens LLC is a small business. The results included printing various large format additively manufactured components and installing them with over a year of continuous operation at a micro-hydro facility in Wisconsin.

1.1 BACKGROUND

Cadens is developing technology to enable power generation at low-head locations. Their intended products are additive manufactured micro-to-small hydropower S-turbine systems, with an intake, guide vanes, turbine runner, shaft, curved conveyance including intake and diffuser, and an off-the-shelf generator situated out of the flow path for simplicity in maintenance, assembly, and installation. The systems are modular in that several sub-components are manufactured and assembled together to make the final machine – a powertrain plus conveyance as an integrated system (PPC).

Cadens target market is small, low-head hydropower plants. There are currently over 1,700 small hydropower plants in the country providing low-carbon, reliable electricity. A resource assessment conducted by ORNL indicated an additional 29 GW of new small hydropower technical potential is present at over 10,000 sites (Kao et al., 2014). However, the Department of Energy modeled deployment of this potential and predicted 0 GW will be developed by 2050 unless the industry can radically reduce costs. DOE suggested exploring the use of new materials and manufacturing methods as one cost reduction pathway (DOE, 2016). ORNL has also suggested using standardization and modularity as strategies to make small low-head hydropower development affordable (Witt et al., 2017). Cadens modular design coupled with Cadens optimization software and AM components enables a first of its kind validation of small modular hydropower systems. By producing semi-custom modular systems that can deploy with high efficiency across many different sites with few changes to design and manufacturing processes, Cadens believes the system can be a low-cost, high efficiency solution for the hydropower industry.

What is not well understood is the durability and overall performance of PPC as an integrated system made with BAAM methods/materials and assembled AM components operated continuously under normal and off-design conditions in a field demonstration. The PPC project test plan will evaluate durability of AM

PPC and the wear to components under continuous operation and overall performance in off-design conditions vs. normal operating conditions. The DOE MDF at ORNL is uniquely positioned to assist Cadens by rapidly pushing the envelope in large scale AM.

1.2 TECHNICAL RESULTS

1.2.1 First Iteration

1.2.1.1 System Design

The first task of the project was to design and prepare all of the components for manufacturing. The list of components to be printed included intake adapter (B), draft tube (I), turbine housing (F) (discussed in section 1.2.1.3), turbine (F&G), and various fittings (D&E). The rest of the flow conveyance components, such as the conveyance tube that directs water into the turbine housing, don't require customization and can be implemented with off the shelf components such as PVC pipe. Figure 1 shows a model of the full system with components in black representing those that need to be additively manufactured.

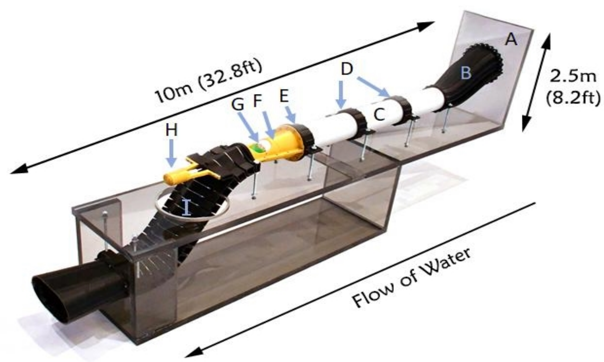

Figure 1: Scale model of the full hydropower system.

The intake adapter (B in Figure 1) is used to adapt the incoming flow of water from the dam wall (A) to the conveyance tubing (C). This piece needs to be customized to mate with the specific sizing of the dam and the turbine housing, which are determined by the flow and head of the dam. The adapter lowers the centerline, or flow line, of the water to increase the head before water enters the turbine. The forces on this component can be high, so the adapter was designed with small channels around the circumference where thread rods could be inserted to provide additional strength. These threaded rods are tightened with nuts on each end to help compress the component and improve the layer-to-layer bond strength. The adapter, just 58in long, can be printed upright in BAAM and thus doesn't require use of supports. The thimble adapter design can be seen in Figure 2.

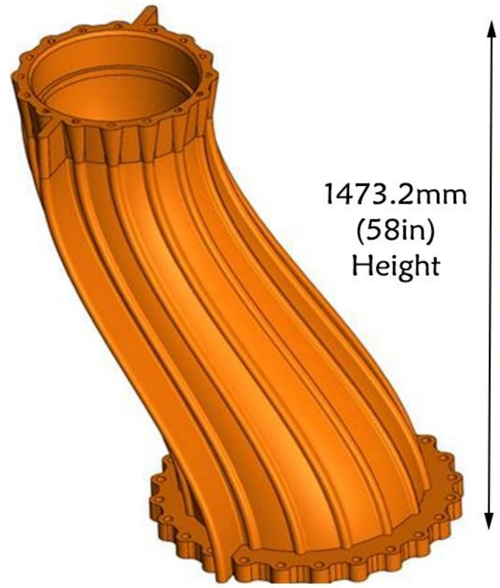

Figure 2: Design of the intake adapter.

The draft tube serves as the outlet of the turbine housing. The inlet of the draft tube must be custom fit for the turbine housing, and the outlet and routing of the conveyance was custom designed based on the floorplan of the Rome Mill site. This meant a 53-degree angle to properly fit to the turbine and convey the water out the floor of the mill. The draft tube was too large, and too complex of a geometry, to be designed for printing on end like the intake adapter. Laying the draft tube down on its side would require support on the inside to maintain the round interior geometry, so it was decided to print the draft tube in two halves, like a clam shell. This design still required support on the outside to maintain the exterior curvature but saved on print time and material by eliminating the interior support material. Figure 3 shows the design of the draft tube.

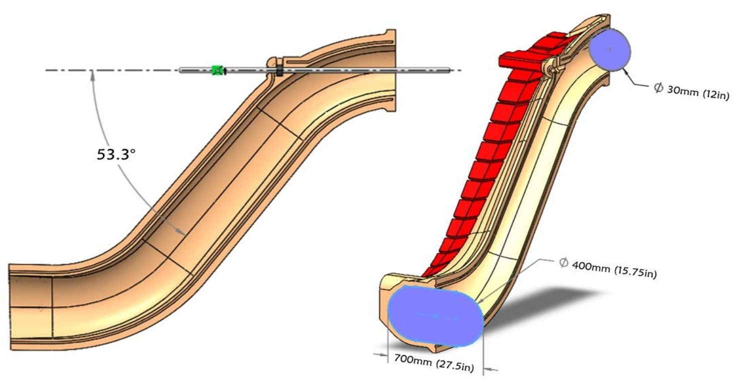

Figure 3: Design of the draft tube showing conveyance angle (left) as well as inlet and outlet dimensions (right).

The turbine housing is discussed in section 1.2.1.3 including the design and manufacturing. The turbine is discussed in section 1.2.1.2 which covers the simulation and modeling needed for the design. Manufacturing of the turbine is covered in section 1.2.1.4. Lastly, the various pipe fittings and alignment components (D&E in Figure 1) were simple design that could easily be modified for the 3D printing bead geometry on BAAM and then manufactured.

1.2.1.2 Turbine Simulation

Turbine design is essential for maximizing power output and system efficiency. With additive manufacturing, complex geometries can be easily manufactured. Also, one 3D printer can quickly manufacture several different turbine designs for testing. To determine the geometries to be printed and tested, Cadens used the Turbine Builder software. This software was used to create rotor and stator designs that could be printed with a medium format 3D printer, the 3D Platform Workbench 400 Series. A sample simulation can be seen in Figure 4.

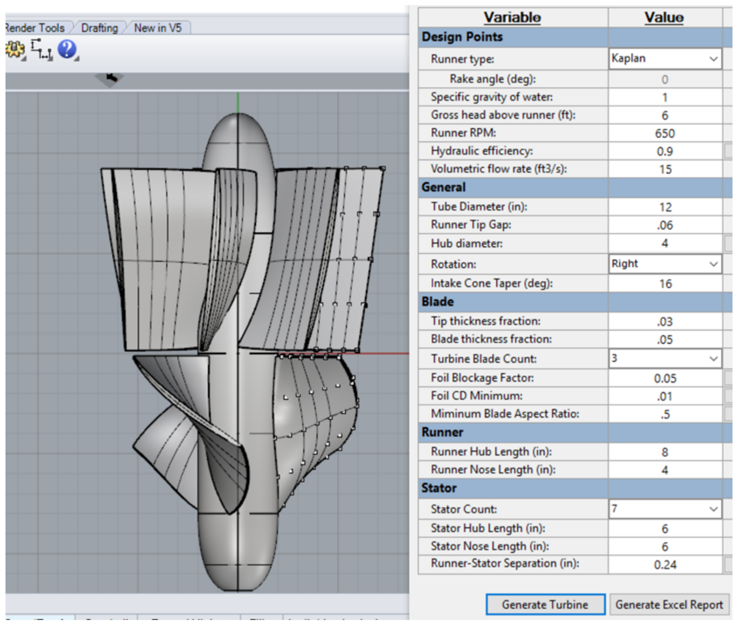

Figure 4: An example simulation from Turbine Builder.

1.2.1.3 Turbine Housing

Once the final turbine design was completed, the team could begin designing the turbine housing that would surround the rotor and stator. For maximum efficiency, the fitment between the turbine itself and its housing needs very high tolerances. This is to ensure that all water flowing through the system must go across the turbine with no water leaking around the outside.

To fit the turbine inside, and to allow for easy access for maintenance, the turbine housing needs to be made in at least two pieces that can be disassembled. Due to the overall size, to be 3D printed, the housing would need to be manufactured using BAAM which would require low resolution printing. This housing could be printed and then machined to the tolerances, but that would be a slow and expensive process that would have to occur twice, once for each half of the housing.

Rather than print with a low resolution, the team decided to use the BAAM process to make a mold for the housing. This housing could be quickly printed at low resolution using BAAM, then machined to the tolerances. Finally, a fiberglass can be laid up on the mold to make the turbine housing. Repeating the process twice gives both halves of the housing that can then be bolted together. Figure 5 shows the lay up process and a completed piece made on the mold.

Figure 5: Fiberglass lay up for the turbine housing (left) and a completed fiberglass component (right).

1.2.1.4 Manufacturing

After all components were designed, primarily by Cadens, the final files were passed off to the team at MDF for printing. On BAAM, the chosen material was Carbon Fiber reinforced ABS (acrylonitrile butadiene styrene) thermoplastic, with 20% chopper carbon fiber measured by weight. This material is easy to print with, low cost at about $6/lb, and provides sufficient mechanical properties for the components of the project. The printed bead geometry was approximately 0.34" wide by 0.15" tall. The intake adapter was printed first and took 14 hours with a weight of 323 pounds (Figure 6).

Figure 6: The printed intake adapter. Visible are the channels for inserting thread metal rods around the circumference.

After the intake adapter, the two halves of the draft tube were printed (Figure 7). Each half took approximately 9.5 hours and weighed 350lbs. Due to the thicker geometry with larger cross-sectional area, the draft tube was able to be printed faster than the thimble. The thimble took longer time because of the slower printing process to ensure sufficient cooling time for the thin cross-sectional area of the walls.

Figure 7: One half of the printed draft tube. In this photo, the draft tube is upside down from the print orientation. The open rectangles seen in the photo are the support structures.

The last components to be printed were the actual turbine components. Various geometries were modeled and simulated via Turbine Builder, then manufactured. For smaller, higher resolution components, the Stratasys Fortus 900 system was used with Ultem 9085 material. For the larger components, such as the stator, the 3D Platform Workbench 400 Series was used with PETG material. Figure 8 shows one iteration of design and manufacturing a turbine.

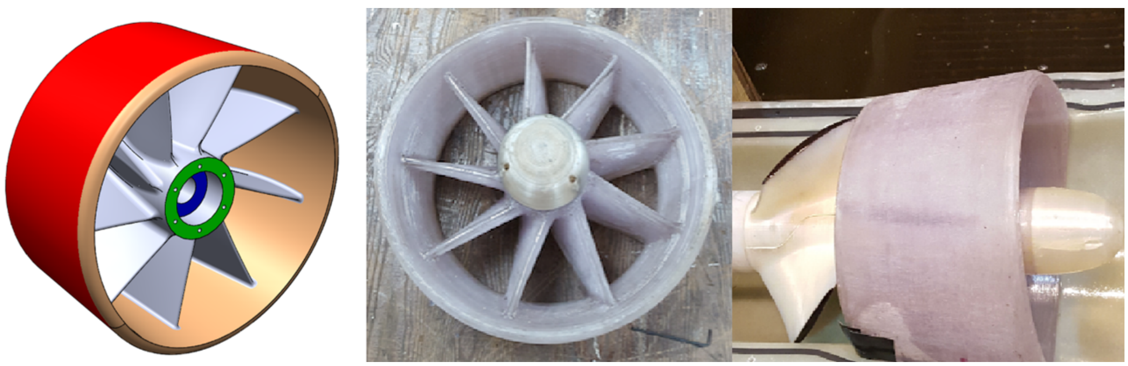

Figure 8: A modeled stator (left), the as printed stator (center), and the assembled turbine (right) with Ultem components shown in tan.

1.2.1.5 Post-Processing

The as printed surface finish of the BAAM components is not very smooth, with ridges from the layers every 0.15” of Z-height. This can create a rough surface for the water to flow across. There are also intermittent issues where components are not completely watertight and could leak. To clean up all the BAAM components in preparation for assembly, mounting, and water flow, tools such as a belt sander and router were used to smooth the outer surface. Once cleaned up, Max Bond Thixotropic epoxy was used to fill voids and create a smooth exterior surface. The mating surface of the draft tube can be seen in Figure 9, showing how it was prepared for mounting to the turbine housing.

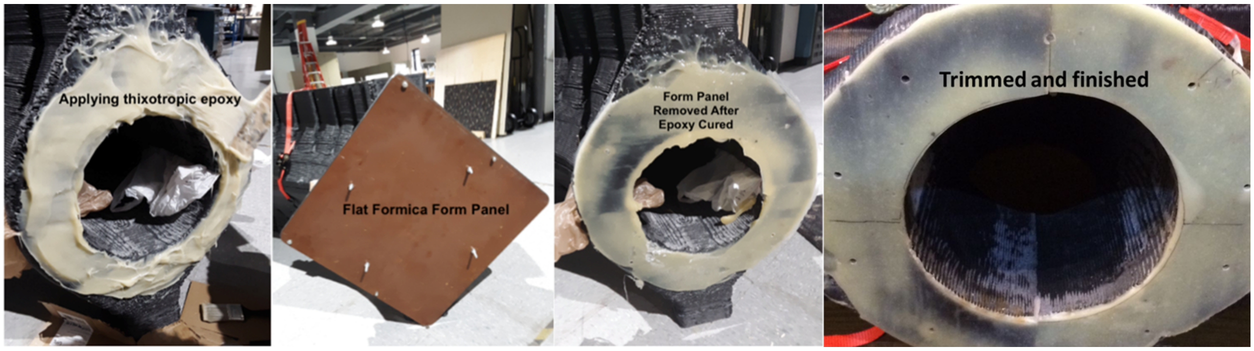

Figure 9: Preparing the draft tube to mount to the turbine housing.

1.2.1.6 Testing

After full assembly at the Rome Mill, the canal gate upstream of the turbine was opened to start water flow through the system. This initial waterflow was useful for finding any additional leaks in the AM components or joining features. Leaks were quickly resolved with epoxy, and actual testing of the turbine could begin with the help of a prony brake attached to the shaft of the generator to help develop a power curve with the help of a tachometer to measure rotation speed and a crane scale to determine torque in foot-pounds. The output shaft was also connected to a generator via a 5-1 pulley to generate power during the continuous turbine operation. During testing, the available head fluctuated between 7.1ft and 7.85ft based on the water level which created an average flowrate of 13ft^3/s. The best performing turbine design performed at 750RPM and generated 115lbs of torque. This resulted in 8.21hp or 6.24kW of output power.

1.2.2 Second Iteration

Learning from the design and manufacturing lessons of the first design, a second iteration was created to improve the process and streamline efficiency.

1.2.2.1 System Design

The new system design was developed by Cadens, and the work with ORNL focused entirely on the flow conveyance components that could be printed with BAAM. This involved a new thimble adapter, modeled for the center thimble of the Rome Mill (flow simulations for this can be seen in Figure 10), a new PVC reducer coupling, a power elbow, new draft tube, and five support feet.

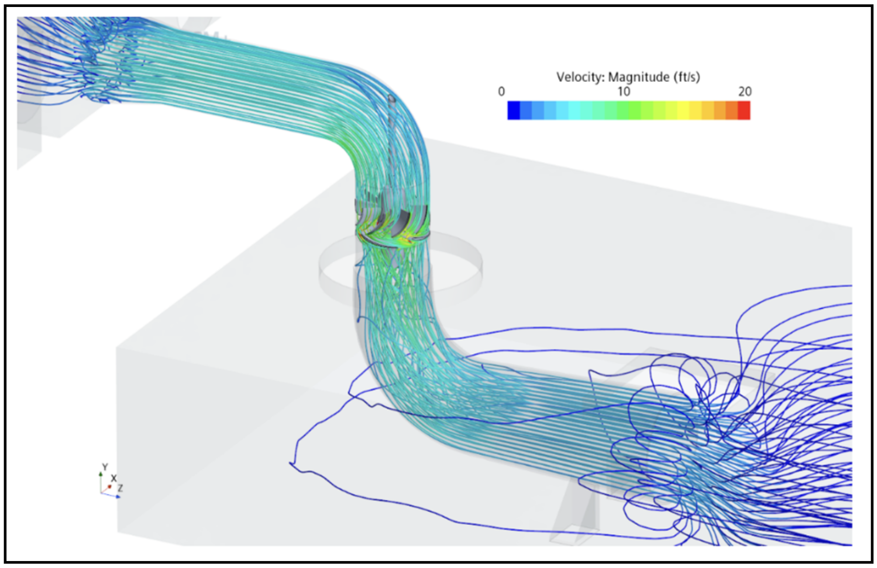

Figure 10: Flow simulation for the center thimble at the Rome Mill.

The original design had the turbine housing in-line with the flow conveyance tubing. This new design places the power generation components below the power elbow, which directs the flow down into the turbine helping to increase velocity of the water. This new design can be seen in Figure 11.

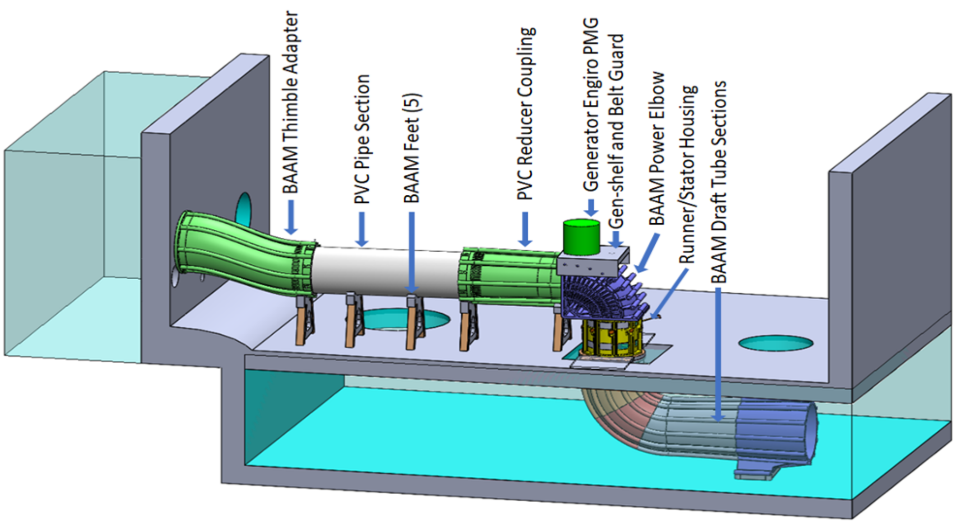

Figure 11: CAD model of the new system design.

A scale model of the new system can be seen in Figure 12. The scale model was made with a desktop 3D printer, and meant to showcase the design for manufacturing details to be discussed in section 1.2.2.2.

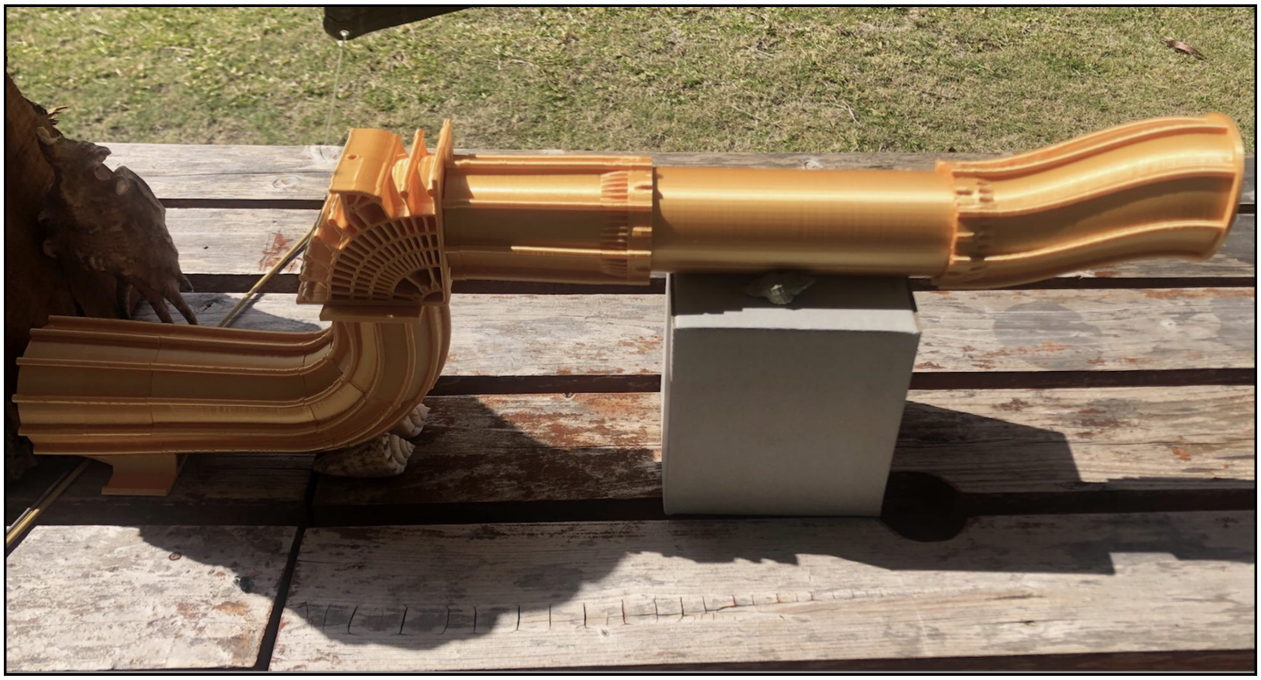

Figure 12: Scale model of the new flow conveyance design.

Components printed on BAAM in the first iteration were often too heavy, required too much post-processing, and occasionally had leaks. Raster infill was determined to be a primary culprit of some of these issues, due to how the raster pattern mates with the bounding contours. Also, because of the rapid printing and 180 turns of the raster pattern, overfill was common at the endpoints which increased the amount of sanding needed at joint. For the second iteration, the designs focused on new toolpathing strategies that involved only closed loop contours instead of raster fill. To enforce the desired closed-loop pathing, small cuts were strategically placed throughout the object to prevent surfaces from being connected and to force the toolpathing to take a non-traditional path. The raster pattern and the new pattern can be seen in Figure 13. The changes were applied to the reducer coupling, the draft tube, and the thimble adapter.

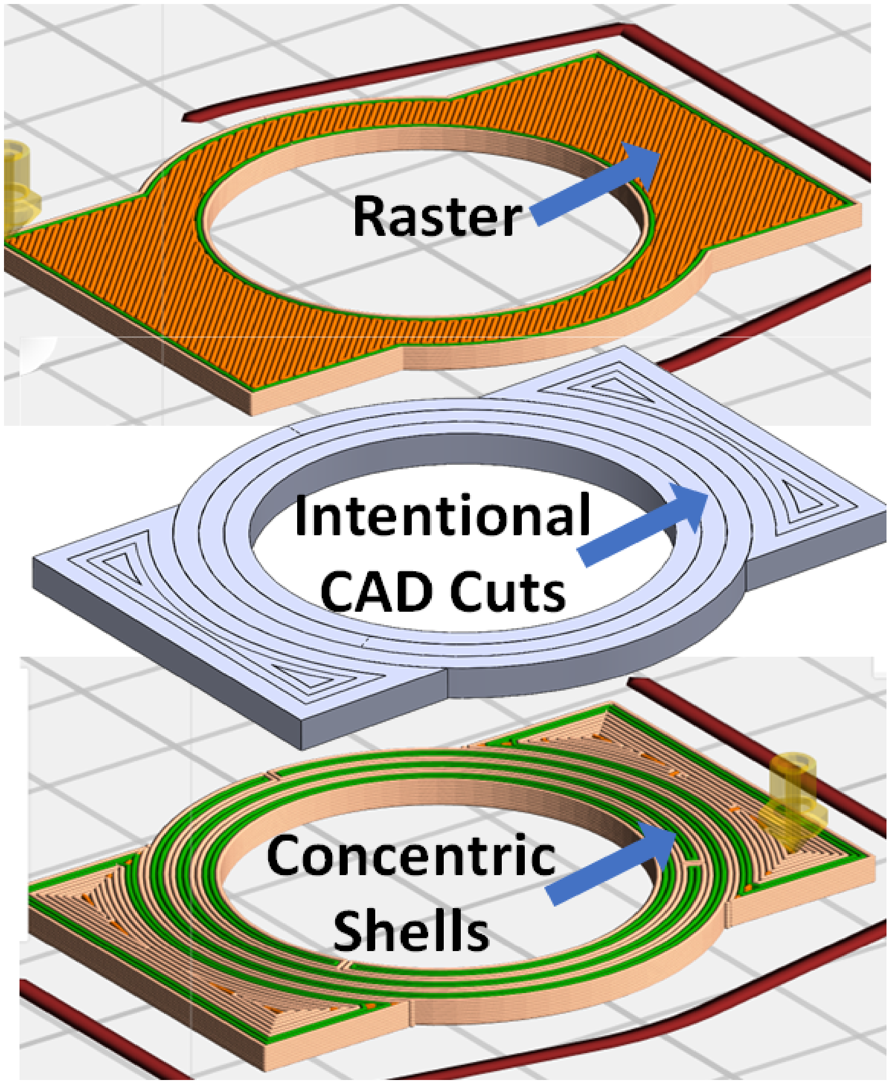

Figure 13: Raster infill pattern toolpathing (top), CAD changes to force a new fill pattern (middle), and the resulting toolpathing (bottom).

1.2.2.2 Manufacturing and Post-Processing

The first system was manufactured with CF-ABS, which costs between $5 and $8 per pound, depending on the quantity. The CF-ABS is a great material, but it ended up being much stronger than needed. The second iteration was produced with glass fiber reinforced ABS, a comparable material that is not quite as strong but typically costs about half the price. Using the new designs, ORNL was able to slice and manufacture all of the components from an off-white colored GF-ABS material, then ship the components to the Cadens for post-processing. Figure 14 shows a trailer load of BAAM components arriving at the Rome Mill.

Figure 14: BAAM components arriving at the Rome Mill site.

Once received, Cadens was able to being the post-processing steps required to prepare the components for assembly. Like the first iteration, this required manually sanding the interfaces with a belt sander, drilling holes, and applying epoxy. The improved designs with new toolpathing strategies required less time to post-process. Figure 15 shows the outlet of the draft tube after it has been sanded and coated with epoxy.

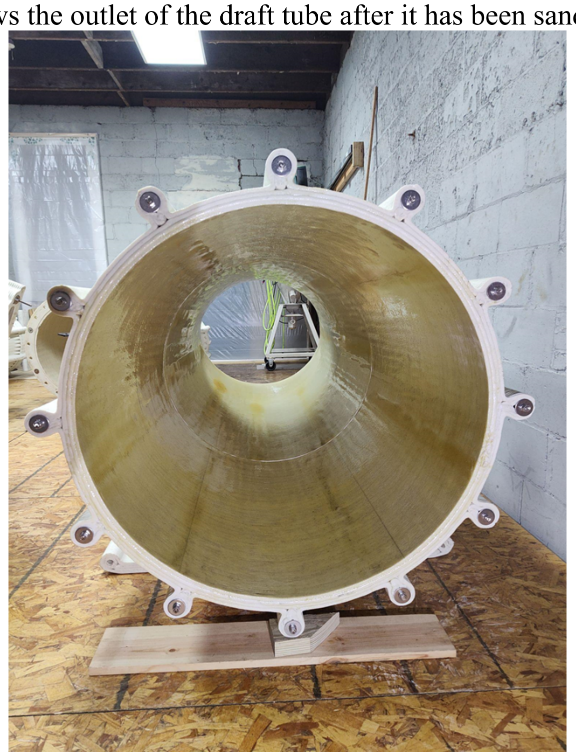

Figure 15: Outlet of the draft tube after post-processing.

1.2.2.3 Assembly

Once all components were post-processed, Cadens began work assembling the components to ensure proper fitment before being installed at the dam. This mean inserting all of the threaded rods to be used as reinforcement, then bolting sections together. Figure 16 shows the outlet of the turbine housing as water would flow through the draft tube. Figure 17 shows the full assembly of all BAAM components. The images were taken of the actual printed components and a green screen, then connected together to show the full final assembly at scale. Randy, of Cadens, can be seen standing next to the assembly for reference.

Figure 16: Assembled components that fit up to the outlet of the turbine housing.

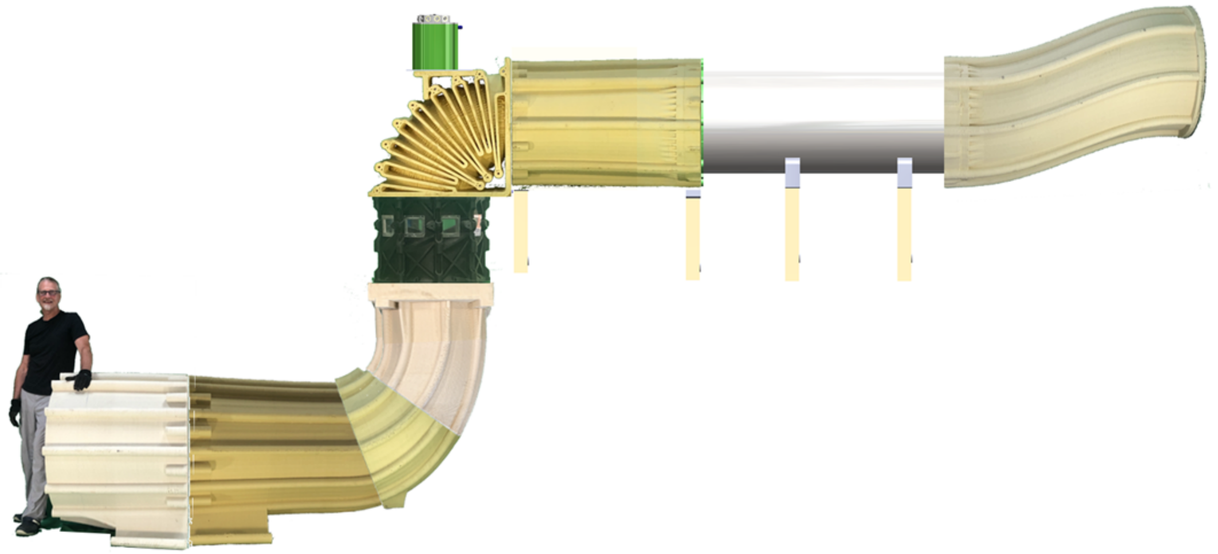

Figure 17: Full assembly drawing of the second design.

1.3 IMPACTS

This project had an impact in several areas of hydropower technology development including lowering costs, reducing process energy usage, and enables new markets. The volume of components needed for the hydropower industry is low, so part production costs are generally high. Site conditions also vary from location to location, which results in custom, site-specific designs. This project showcased how additive manufacturing was used to overcome these challenges to develop an operational hydropower generator.

This project report, along with a published journal article titled *Large Format Composite Additive Manufacturing for Low-Head Hydropower*, provides other companies and the public access to information describing the print process, assembly, and commercial coating/sealing techniques for finishing end-use parts. This information can provide a path forward for cost reduction in the manufacturing of small batch hydropower systems.

1.4 SUBJECT INVENTIONS

NA

1.5 CONCLUSIONS

This partnership between ORNL's MDF and Cadens LLC focused on designing, manufacturing, and testing various components for a new hydropower installation in Wisconsin. ORNL and Cadens worked together to design the components and make proper modifications for printability using BAAM. ORNL manufactured all of the components, primarily from ABS reinforced with carbon fiber and glass fiber, and Cadens did the post-processing, coating, and installation at the Rome Mill Test Facility. The first iteration components were used for more than a year continuously without any failures. To date, the components have been in use for over three years without failing. This project has shown the adaptability and resiliency of additive manufacturing to enable low-head hydropower generation. Future work will continue to focus on design and printing optimization to reduce the print time and cost of the components. Research will also investigate advanced modeling and simulation to develop more efficient turbine designs to maximize the efficiency and power generation. Cadens is still operating the AM components and continuing to collect data.

2. CADENS BACKGROUND

Cadens is a clean energy startup located in Sullivan, WI advancing environmentally compatible, low-cost hydropower specifically with additive manufacturing. Cadens plans to lead the way in the development of new hydropower technologies. They are building a team to actively address conversions to produce clean, renewable energy at existing non-power dams and existing powered dams in need of maintenance and upgrades. With an agile combination of off-the-shelf and standardized parts, along with site-specific turbines generated on 3D printers, they envision modular, drop-in hydropower systems that are lightweight, energy dense, and optimized for each specific site. A particular focus are dams with a capacity of <1MW, which represent 98% of the 54,000 suitable NPD's. River communities, private landowners, and businesses that must rebuild vital dam infrastructure can partner with Cadens to retrofit non-hydropower dams with new, lightweight hydro turbine machines.