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Application of Laser Powder Bed Fusion for Transformational Challenge Reactor Core

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OAK RIDGE NATIONAL LABORATORY
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ABSTRACT

The following report focuses on the utility of Laser Powder Bed Fusion (LPBF) for the construction of components for the Transformational Challenge Reactor (TCR) core. Multiple additive manufacturing processes are under investigation to evaluate the advantages and viability of each process for direct manufacturing of complex structures needed for future nuclear reactors. Technologies under investigation include binder jet, direct energy deposition (DED), electron beam powder bed fusion (EBPBF), and laser powder bed fusion (LPBF). Each process has advantages and disadvantages. For the core design, two manufacturing approaches are under consideration—one involving the exclusive use of LPDF to fabricate the entire core and the other consisting of integration of LPBF and DED where LPBF is used for the core's top and bottom manifolds (where complexity is high) and DED is used for the manufacture of the cladding where complexity is still high but geometric variability, size, and speed are better suited for DED. For both approaches, LPBF research has focused on processing parameter development, core design, and manufacturing tolerances for integration of fuel elements. The following report highlights reactor core design as it relates to LPBF and experimental validation of test components necessary for finalizing the core design.

1. OVERVIEW OF ADDITIVE MANUFACTURING PROCESSES

There are conventionally seven different methods used for additive manufacturing, with an eighth category focusing on hybrid systems that combine multiple manufacturing processes into one system (see Figure 1). (Hernandez 2012) Vat polymerization, material jetting and material extrusion are generally limited to polymers with the prime application being rapid 3D models and prototypes. Powder bed fusion (PBF), binder jetting, sheet lamination and direct energy deposition are the standard metal additive manufacturing processes. (Frazier 2014) Both powder bed fusion and binder jetting build three dimensional structures in by depositing and selectively fusion material layer by layer. In terms of locally fusing material each layer, powder bed fusion processes can use lasers (single or multiple) as well as an electron beam (guiding energy electromagnetically). The laser powder bed process has a relatively low powder bed temperature (under 200 C) which has the advantage of very easy powder removal (pours away like sand) which the disadvantage of high residual stress. On the other hand, electron beam powder bed uses the energy source to elevate the powder temperature (over 600 C). In addition, the nature of the electron beam enables simultaneous control of numerous weld pools (in excess of 50). The combination of high powder bed temperature and ability to spread heat out through controlling numerous weld pools provides significantly lower residual stresses but makes power removal more challenging that laser powder bed. Binder jetting works in a similar nature to laser and electron beam powder bed fusion except that a binder fuses the material rather than melting. The advantage of this process is the ability to manufacturing almost any powder (polymer, metal, ceramic…) at room temperature (e.g. low manufacturing residual stress). The challenges for this process are handling the parts while removing from the powder bed. The parts are held together, relatively weakly, by a binder which leads to limitations in manufacturing extremely delicate structures. The parts are likewise porous requiring a post sintering and back infiltration process to create fully dense parts. In all three of these processes, unfused powder in each layer provides mechanical support enabling production of extremely complex geometries. The third family of metal additive processes is sheet lamination. Rather than using a powder for the feedstock, sheet lamination uses thin foils of soft metal and fuses layer to layer through solid state welding via an ultrasonic horn. The advantage of this process, like the binder jet, is a low manufacturing temperature enabling integration of sensors within a single structure. The process does require post machining and is limited to relatively soft metals (copper, bronze, aluminum).

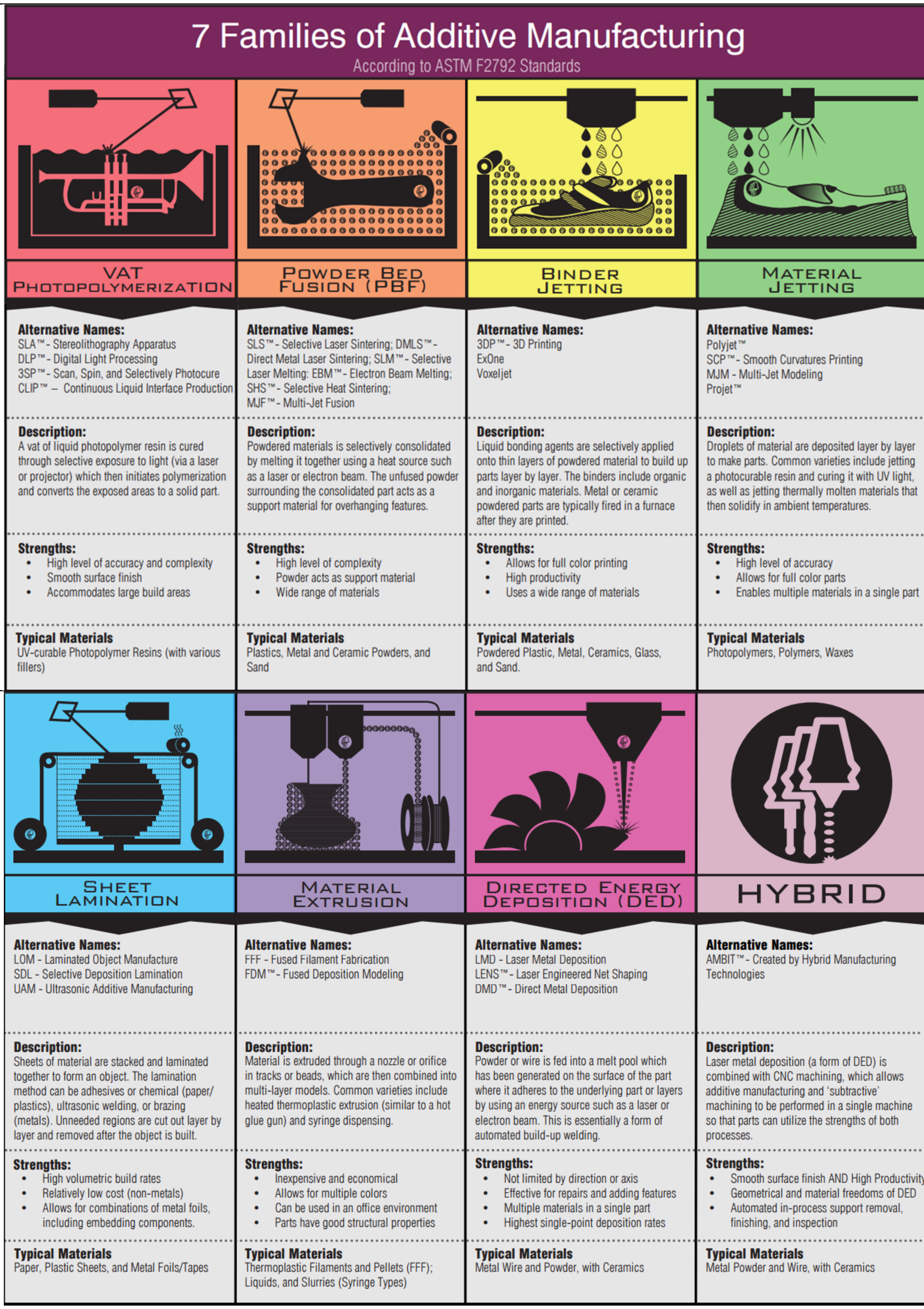

Figure 1: Additive Manufacturing Processes[1]

[1] Image created and designed by Hybrid Manufacturing Technologies http://www.hybridmanutech.com/resources.html.

2. TRANSFORMATIONAL CHALLENGE REACTOR SPRINT

As described above, each additive process has advantages and disadvantages. For the TCR, rather than committing to one technology that may be used to print the entire reactor, the program is exploring which technology best fits each component within the system. To help accelerate the design and manufacturing process and reduce risk in terms of the manufacturing process, the team is conducting a "sprint" activity to rapidly manufacture a scaled version of the reactor to test and evaluate the materials, processes, assembly and integration. The sprint core, shown in Figure 2 through Figure 5, will have the same basic components as the full core but fewer chambers. The full-scale reactor will be very similar with additional rings that are the same size as the sprint reactor (see Figure 5). The reactor core will have printed components for the upper and lower manifold, fuel cans and cladding. Analysis of material and geometric requirements coupled with the analysis in the prior section on additive processes suggests:

- Binder jet for fuel cans where high temperature materials (e.g. silicon carbide)
- Laser powder bed for upper and lower manifolds where part complexity is high
- Direct energy deposition where part complexity is moderate, but sizes and speeds exceed other processes.

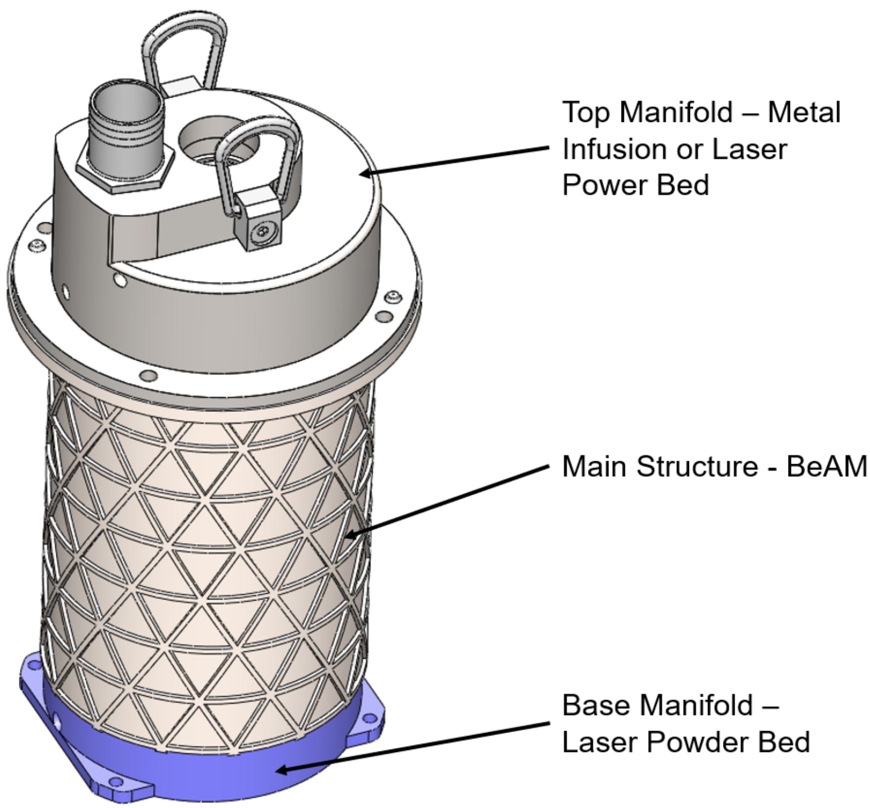

Figure 2: TCR Prototype System

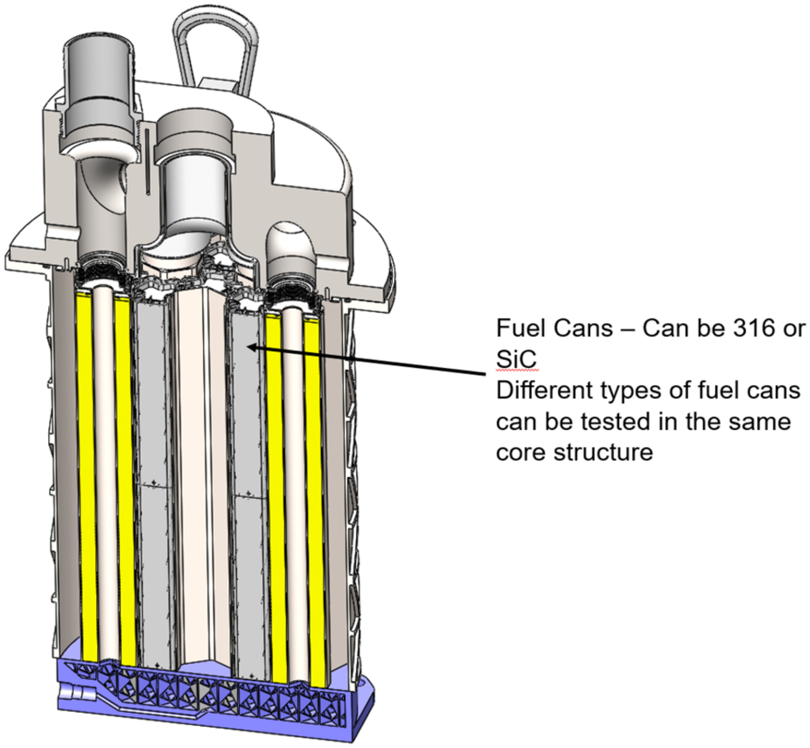

Figure 3: Reactor cross section

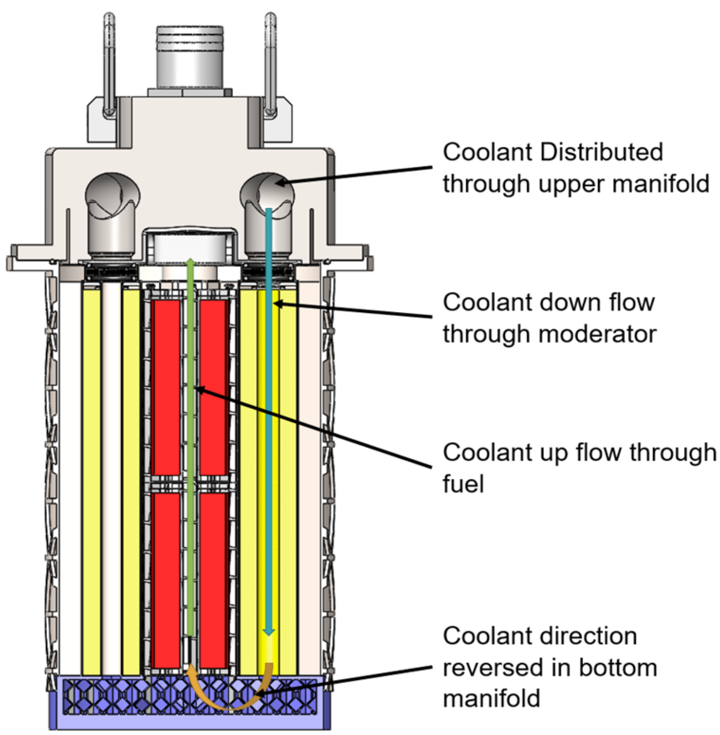

Figure 4: Gas flow

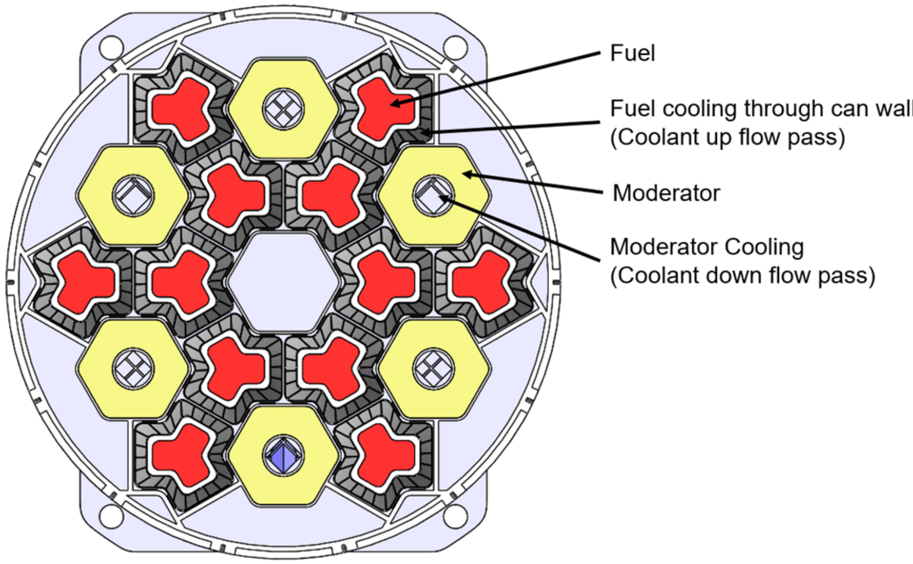

Figure 5: Top view of TCR

Other reports will cover the details on the binder jet and directed energy deposition platforms as they pertain to the sprint design. This effort focuses on reviewing the LPBD process and its contribution to the main structure of the TCR core.

3. LASER POWDER BED FUSION

The Laser Powder Bed Fusion (LPBF) method uses a focused laser beam to melt and fuse sequentially layers of powder particles. The layers, typically ranging in thickness from 20 to 100 μm, are applied using a re-coater system, and the position of the laser beam is controlled during melting using a scan head. (Figure 6).

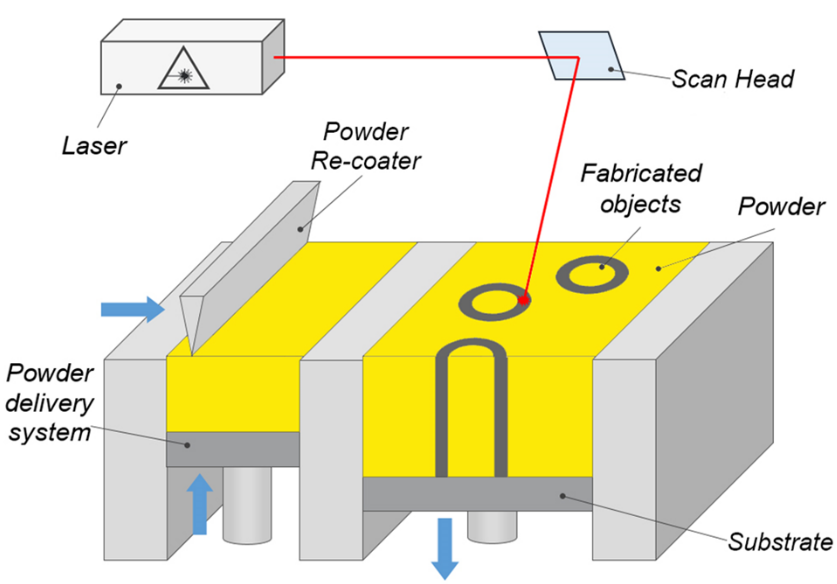

Figure 6: A schematic representation of a LPBF system

Three LPBF systems within the ORNL MDF have contributed to progress toward the goals of TCR project. Table 1 compares the characteristics of the three systems. The smallest is the GE Concept M2 Cusing system (M2) (Figure 7). The M2 has been used to fabricate tubes for burst testing, tensile bars, fuel cans, base manifolds, and a scaled down monolithic base manifold/main cladding structure.

Table 1: LPBF system capabilities.

Mfr. / Model	Max. Build Volume (W x D x H) in mm	Max. Laser Power	Material
GE Concept M2 Cusing	800 x 400 x 500	2 @ 1000W ea	Inconel 718
AddUp FormUp 350	350 x 350 x 350	2 @ 500W ea	Maraging Steel
GE Concept X-Line 2000R	250 x 250 x 280	2 @ 400W ea	316L Stainless Steel

Figure 7:GE Concept M2 Cusing LPBF system.

The AddUp FormUp 350 system (AddUp) is pictured in Figure 8 and has been used principally to assess designs having shallow overhang angles and fine resolution requirements. The largest LPBF system, the GE Concept X-Line 2000R (X-Line) has been used to build the top manifold and a monolithic version of the base manifold/main cladding structure (Figure 9).

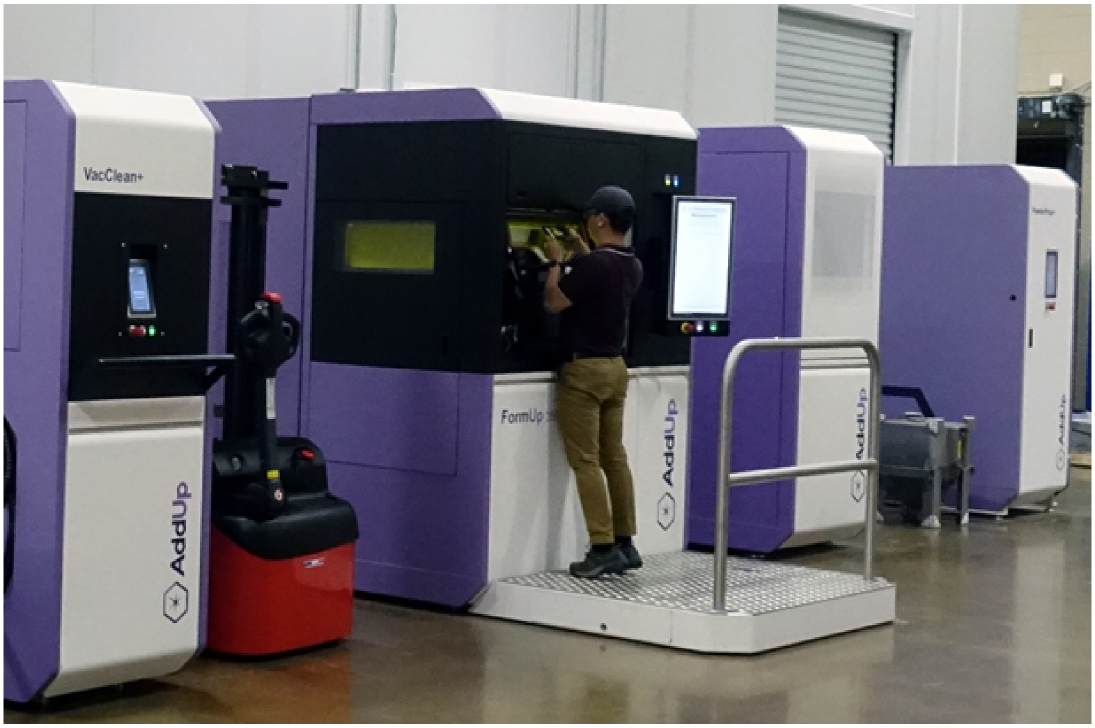

Figure 8: AddUp FormUp 350 LPBF system.

There are additional manufacturers of LPBF and additional systems not explored due to resources at the Manufacturing Demonstration Facility such as EOS, SLM Technologies, 3D Systems, Renishaw, Sisma, Trumpf, Velo 3D, etc. All of these systems were not evaluated under the project outlined. However, all of these systems utilize the basic technology described above to fabricate complex 3D metal components. It should be noted that the size and speed at which these printers operate is increasing, leading to reduced costs, larger components, more reliable, and certified components. Most notable for the TCR project is that of General Electric Additive Manufacturing termed 'Atlas' that was first reveled in 2017. This machine will likely be critical for the TCR program as the size scale of the system is 1m by 1m by 0.3m but may be expandable to 1m by 1m by 1m with minimal engineering. With this sized system, the full-scale core reactor structure including the base and upper manifold designs would be possible to fabricate. Based on the technology, the same resolution and geometric accuracy of the current systems, the M2 and the X-Line 2000 system will be achievable. The system and associated components fabricated are shown in Figure 10.

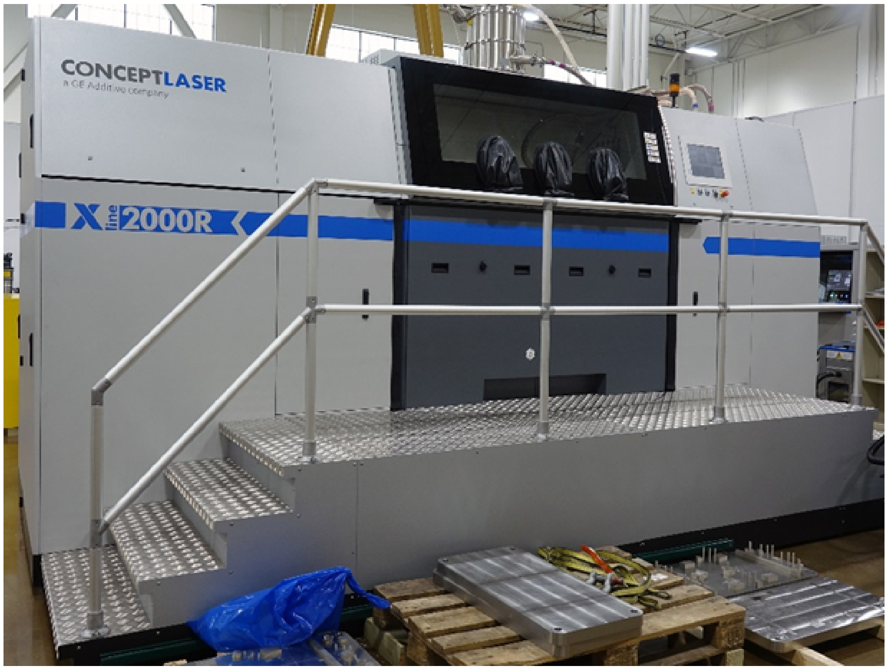

Figure 9:GE Concept X-Line 2000R LPBF system.

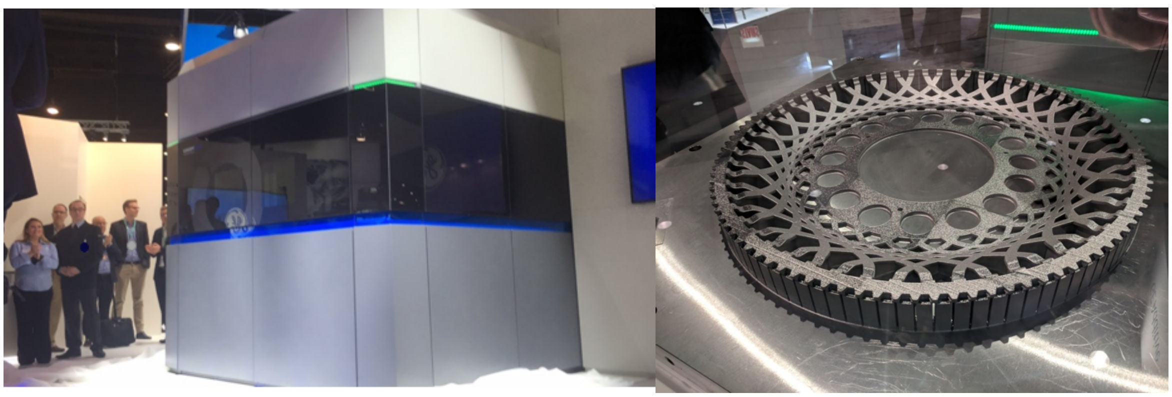

Figure 10: GE ATLAS system with build volume of 1m x 1m x 0.3m and an example component fabricate on the system.

4. LPBF COMPONENTS RELATED TO TCR SPRINT

As described in Section 1, a critical analysis was conducted on the manufacture of the TCR core. The realization was different manufacturing processes may be better suited than others for different components of the core. As shown in Figure 2 and 3, binder jet is being explored for fuel cans, LPBF for the upper and lower manifolds, and direct energy deposition and LPBF for the main cladding structure.

4.1 LPBF FUEL CANS

Several LPBF designs for fuel cans were initially considered. Figure 11 shows two geometries, one with a hexagonal cross-section and the other with a “wye” cross-section. Because of concerns with heat transfer and operating temperature, the LPBF 316L stainless steel fuel cans are presently viewed as place holder structures for the prototype core and likely not suitable for operation with actual fuel. A partial assembly of 24 LPBF fuel cans on a LPBF base manifold is shown in Figure 12. LPBF offers significantly increased design flexibility in comparison to other conventional manufacturing processes.

There are several noticeable features demonstrated in Figure 11 that are important for the design. Firstly, complex heat exchanger designs can be fabricated in the fuel housing to improve the heat condition away from the fuel materials. An example of this is clearly shown in Figure 11b in which there is a double walled structure with structural support material separating the two walls. Independent of design, there is significant flexibility in creating the geometry classes and rapid fabrication can be completed in order to assess the design functionality. A typical build of these geometries takes on the order of several days.

In addition to the internal cooling structure, additional structures can be included to improve the thermal conductivity between the fuel material and the wall structure holding the cooling medium. Various sprint structures have been explored and evaluated for testing. These can be seen in Figure 11a down the center of the can design. In this example, there is a wavy structure used. This may not be the ideal design, but these types of structure can be rapidly integrated into the fuel can with ease. In addition, assembly features can be printed into the can to ease the assembly of the core material. Spring geometries have been added to the outside of the can to improve the geometric accuracy and tolerance of the individual cans during the loading process.

Lastly, the two builds shown in Figure 11 also include caps of different geometries that will be welded in place after the fuel is inserted in the can. These caps can have complex structures printed into them as well. The hexagonal array utilized in these designs is a demonstration of what can be accomplished in order to give the proper functional strength. The geometric accuracy of the cap and core structure can be made such that simply by fitting the cap into the cladding can create a seal such that water does not leak from the structure. This does not imply welding will not be performed in order to make the seal but does demonstrate the ability to fabricate components with high geometric precision.

All of these structures can be fabricated and optimized to improve the overall design of the reactor core. In addition, all of the core cladding structures can be easily evaluated and certified by using the multi length scale characterization approach outlined in alternate reports. Additional modeling will need to be conducted in order to optimize the design structure. The work outlined in this section concludes that these core structures can be fabricated in a reliable and repeatable manufacturing process.

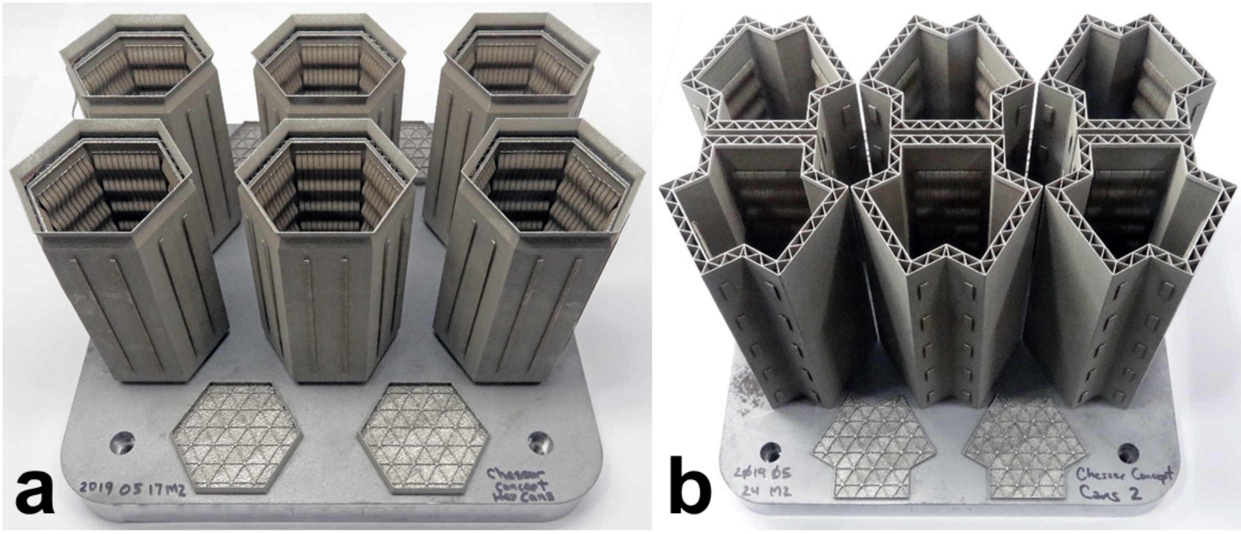

Figure 11: Fuel cans and caps of different geometries have been fabricated in the M2; a) simple "hex" cans, b) simple "wye" cans.

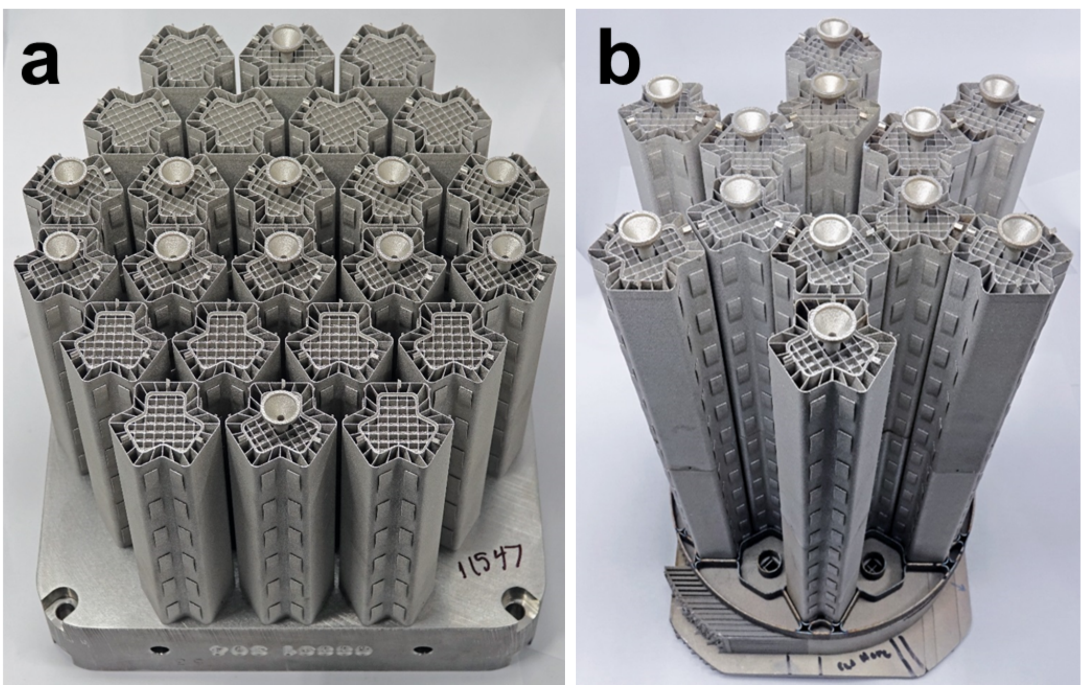

Figure 12: 24 LPBF fuel cans; a) As-built, b) Stacked and assembled on a LPBF base manifold.

4.2 LPBF BASE MANIFOLDS

Base manifolds have been designed to be fabricated of 316L stainless steel in the Concept M2. Two build orientations have been demonstrated, one with the core axis horizontal (Figure 13a) and the other with the core axis vertical (Figure 13b). The horizontal axis orientation enables two base manifolds to be located on a single substrate and is less prone to substrate warpage than the vertical axis orientation (Figure 13b). However, support of internal structures within the manifold is more challenging for the horizontal orientation.

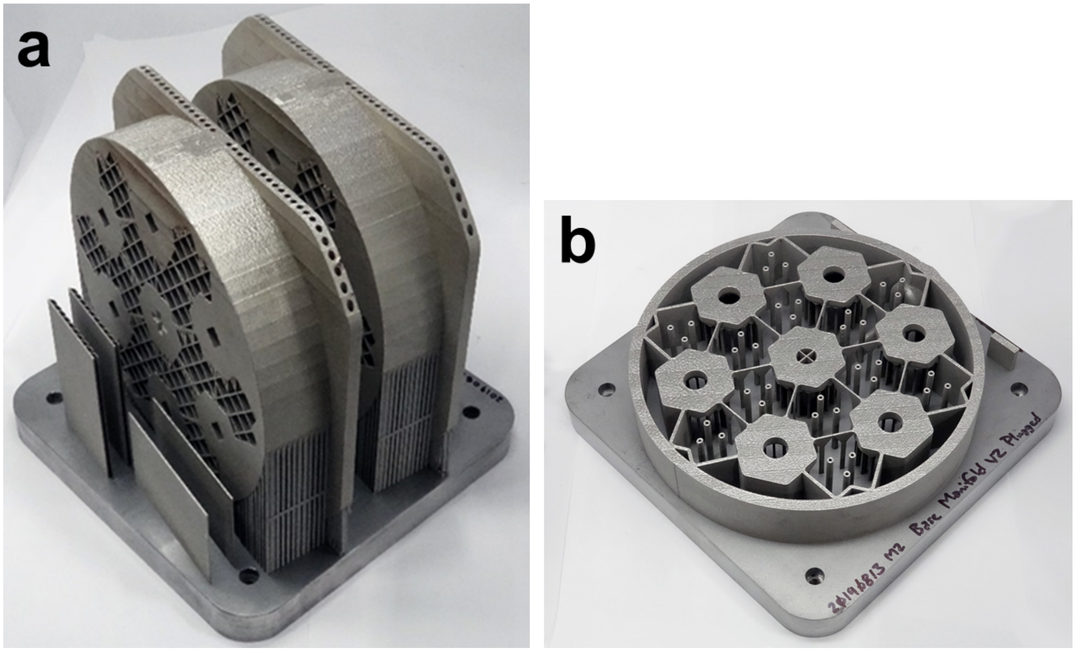

Figure 13: Base manifolds from the M2 with different orientations; a) horizontal core axis, b) vertical core axis.

In order to successfully join a LPBF base manifold to the main structure cladding produced with DED, the base manifold design was adjusted to best match the interface requirements of the DED process. Figure 14 shows top views of four designs of the LPBF base manifold that were used for building of the main structure cladding with DED.

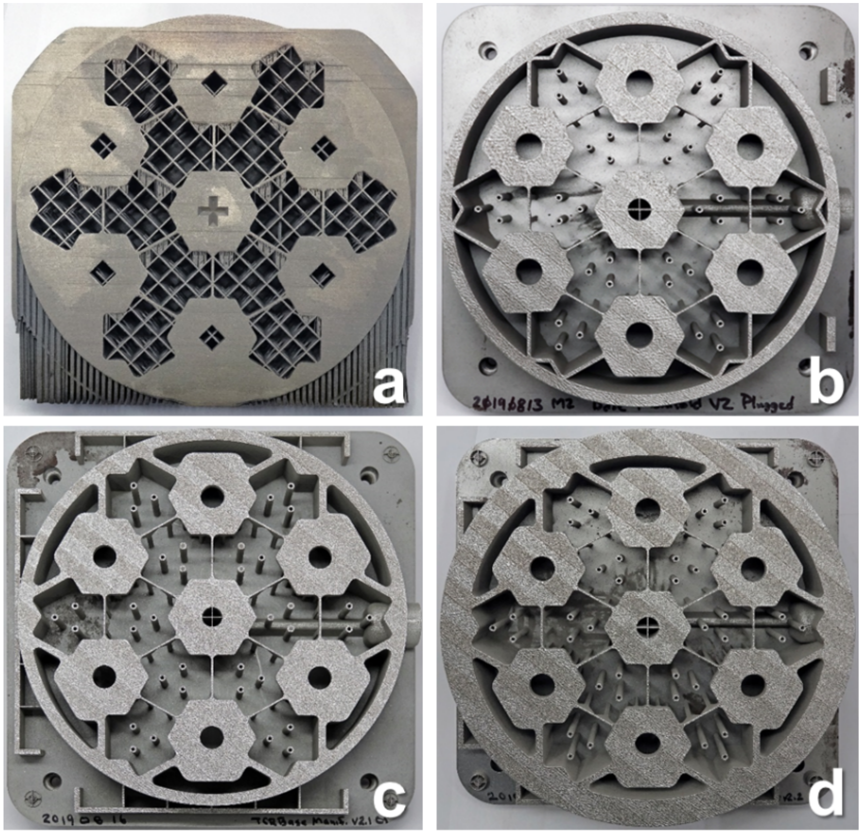

Figure 14: Top views of four LPBF base manifolds for subsequent DED processing.

4.3 LPBF TOP MANIFOLDS

A top manifold has been designed and successfully fabricated of Inconel 718 in the Concept X-Line. Figure 15 shows an image midway during the fabrication of the top manifold in the X-Line showing some of the internal structure of the top manifold. The completed manifold design is shown in Figure 16. As can be seen, these manifold structures can be fabricated using the laser powder bed process. The design of these structures is critical to the success of the printing process. The manifold shown in Figure 16 was designed to limit downward facing surfaces such that minimal support structure must be utilized during the fabrication process. The manifold design build had downward facing surfaces limited to 45 degrees from the vertical direction. If the structure is more horizontal, support material would be necessary to fabricate a quality build. However, with the amount of area deposited in these geometries, support structurers are not recommended as the amount of residual stress in these components can cause the build component to delaminate from the support material and cause a degradation in component quality.

Some systems such as the AddUp LPBF system can build structures with no supports up to a recommended 10 degrees from the horizontal direction. It is unclear what aspects of the technology allow for this to happen. It is expected this is a combination of the system manufacturer using finer powder on the order of 15 microns or smaller, utilization of a roller distribution mechanism for spreading powder across the build chamber, the accurate laser calibration and resulting beam size uniformity, or other aspects not identified. Additional evaluation would need to be conducted in order to determine how this can be achieved in other technologies. Although this appears promising for reactor manifolds, the size limitation on the system (350mm x 350mm x 350mm) may limit the size of the manifolds that can be completed with limited support structures and the conventional design constraints of 45 degrees overhanging surfaces may be utilized for TCR manifolds.

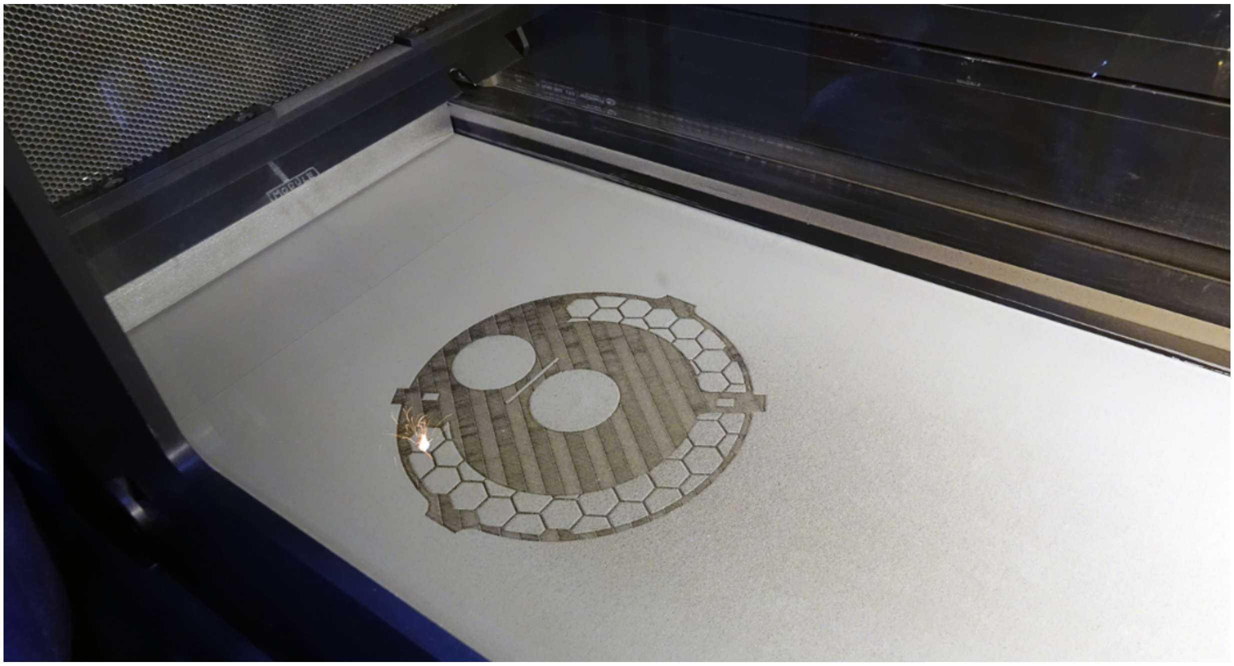

Figure 15: View within the Concept X-Line midway during building of a top manifold

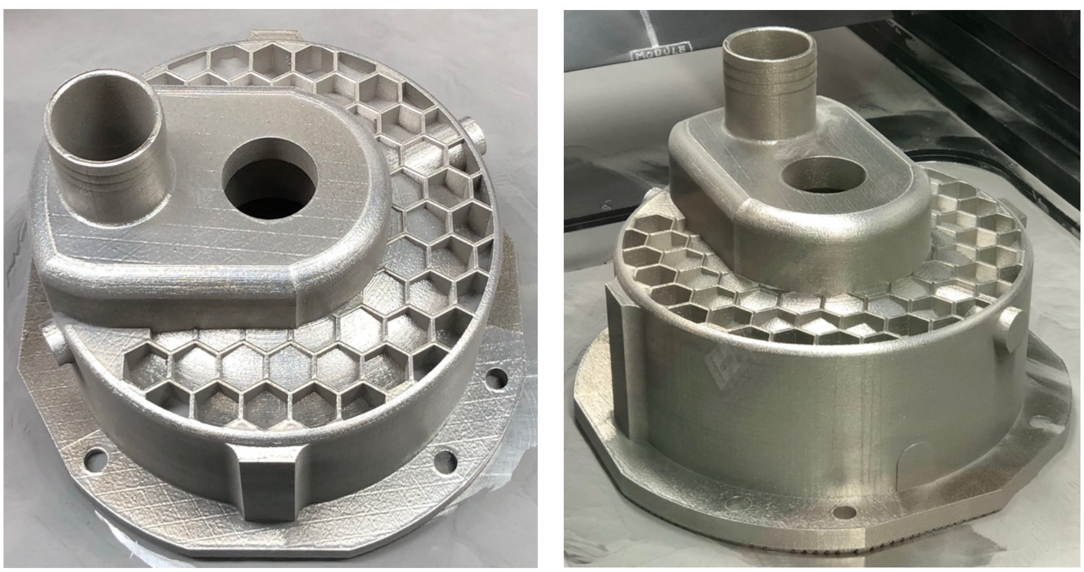

Figure 16: A manifold for the TCR sprint fabricated from Inconel 718 on the CL X-Line 2000R system at the MDF shown in cross section in Figure 15 taken from two different camera angles.

4.4 LPBF MONOLITHIC BASE MANIFOLD/MAIN CLADDING STRUCTURES

Efforts are presently underway in both the M2 and X-Line 2000 to demonstrate a monolithic structure consisting of both the base manifold and the main cladding of the core fabricated into a single structure. This would demonstrate the ability to fabricate the complex manifold cooling channel design with the main internal structure currently being fabricated using the BeAM DED technology. This would create a single structure for the base manifold and main structure shown in the sprint design in Figure 1.   Results are pending. The design is shown in Figure 17 and is currently printing in the systems and it appears the build will complete successfully.

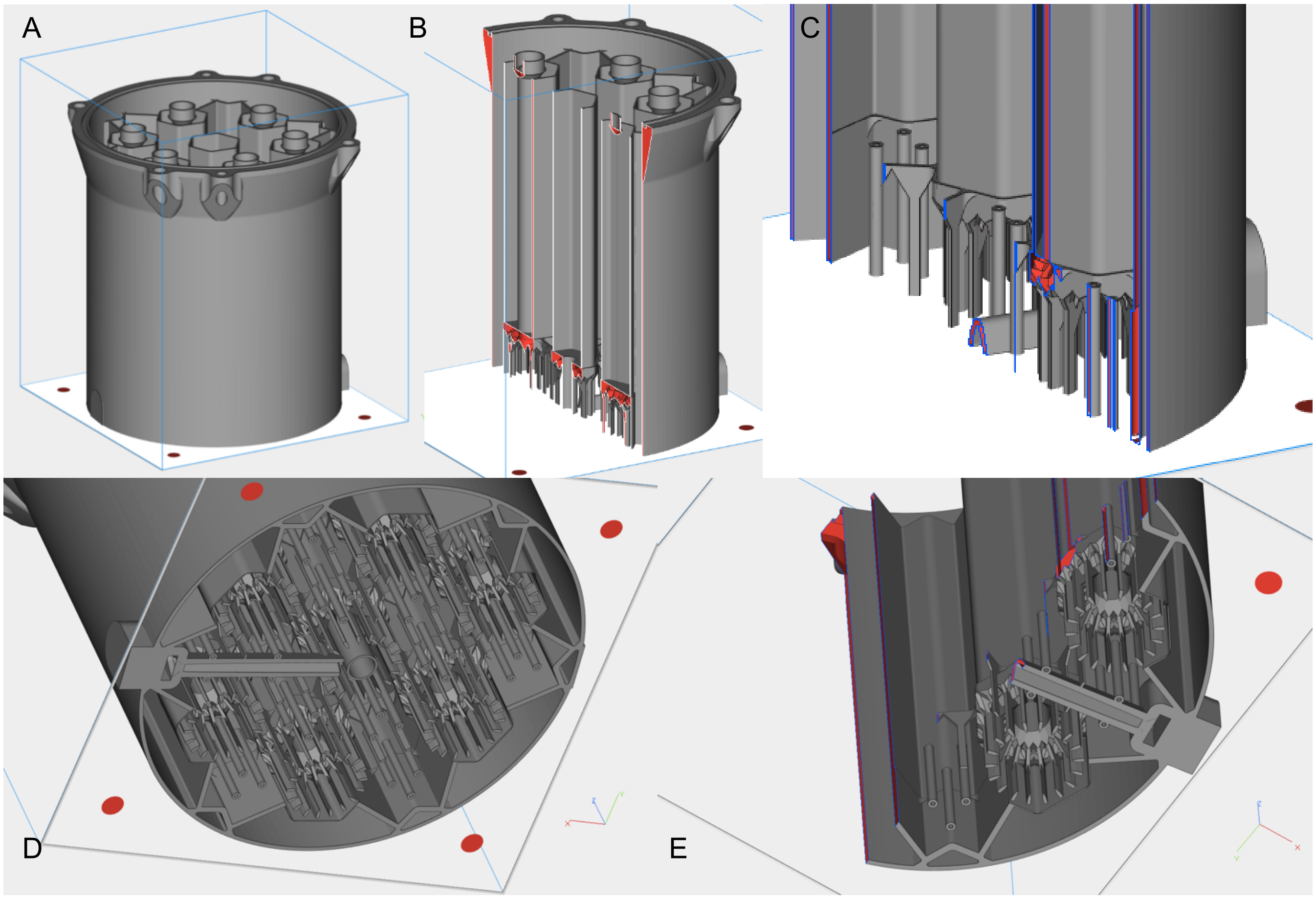

Figure 17: The integrated base manifold and core structure integrated into a single component.

4.5 OTHER LASER PROGRESS

The ability to identify and track components and subcomponents throughout the manufacturing process is essential for the success of the TCR project. A laser marker (LaserGear BOQX) has been used to scribe machine readable codes (bar and QR) directly on the as-built surfaces of LPBF components. Figure 18 shows some examples of laser marking on fuel cans at different scales. Figure 19 shows six fuel cans uniquely identified by QR codes containing the build date, can number, can orientation, and laser number.

Figure 18: Laser marking of QR and bar codes at several scales has been demonstrated for component identification.

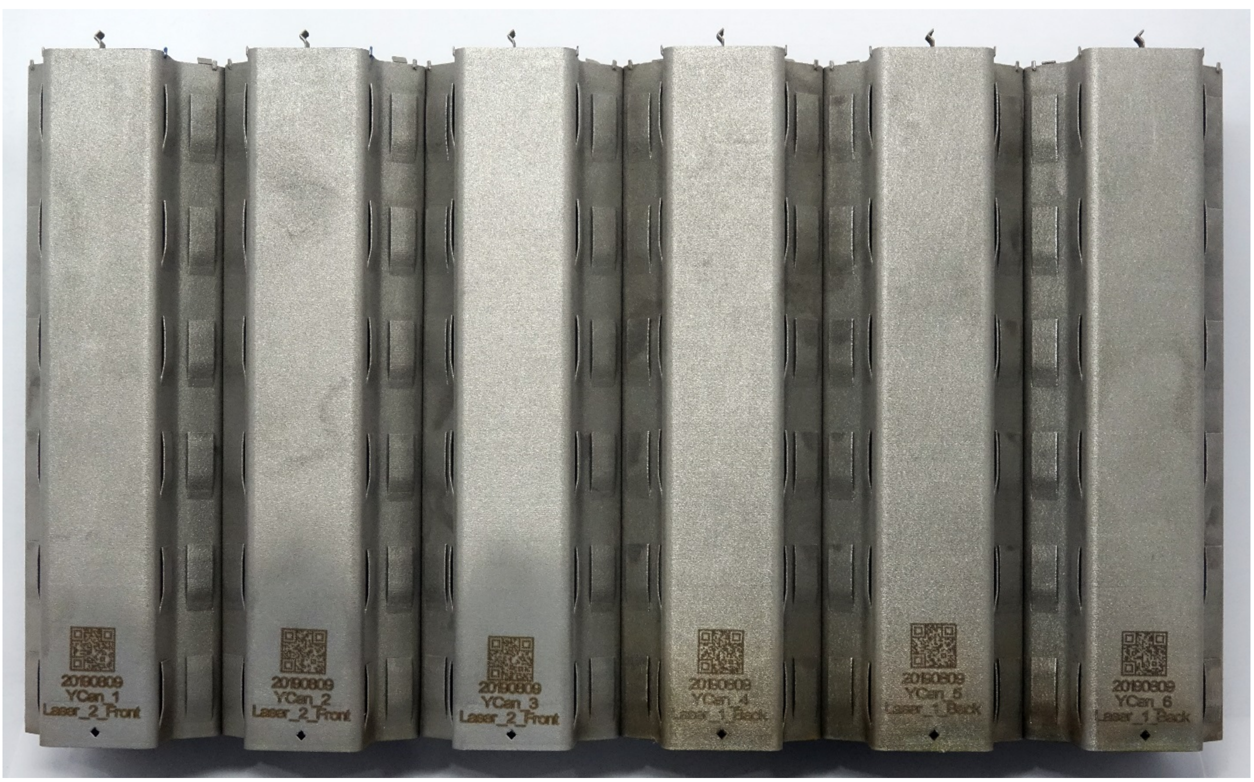

Figure 19: A series of six as-built LPBF fuel cans uniquely identified with a machine readable QR code.

4.6 CERTIFICATION OF LASER POWDER BED AM SYSTEMS

A significant challenge to the laser powder bed process certification is the total number of process variables associated with the technology. For simplicity, this can be broken into two major groups. Firstly, things that can be grouped into fundamental physics and physical scientific information based on the theoretical phenomenon. These include things like solidification behavior, solid state phase transformations, residual stress evolution, etc. that arise during the idealized additive manufacturing process. If the actual AM processing parameters are used, a multitude of different modeling methods can be used to describe the resulting behavior. However, in order for these models to be accurate, an accurate understanding of the processing parameters and scan strategy is required. The second major contribution to uncertainty is related to the actual additive manufacturing machine functionality and is related to how the machine is performing in relation to the actual specified target goals. Therefore, in order to determine how well a machine is performing, an accurate assessment of the different subsystems is required.

An additive manufacturing machine can be broken down into different subsystems described in Table 2: Subsystems in a laser powder bed system that determine the overall performance of the AM machine and impact the performance of the final component. which include the chassis, optics, elevator, powder management, powder recoating, and ventilation. In the ideal scenario, an operator would be able to isolate and independently study each subsystem. In order to accurately assess the overall machine performance, the performance of each individual subsystem must be evaluated. It is extremely difficult to isolate the influence of different subsystems on each other and the overall performance, however it will be critical in the certification and qualification process.

Table 2: Subsystems in a laser powder bed system that determine the overall performance of the AM machine and impact the performance of the final component.

Sub-System	1. Chassis	2. Optics	3. Elevator	4. Powder Management	5. Powder Recoating	6. Ventilation
Functions/ Requirements	• Process monitoring • ~6" cube build volume • Stiffness • Electrical grounding	• >1 laser (ideal 5-10) • Scan path control • Thin wall geometries • Laser power modulation	• 6" cube of Fe-Si weight • 6" sq. build plate • 4-6" z-travel • Precision of z-location • Velocity >50μm/s • Heated plate (200-500C)	• Load/unload powder • Powder storage • Powder delivery to recoater • Capture powder overflow	• Layer uniformity • Minimize power waste • Recoat speed	• Handle inert gas • Limit gas consumption • Soot control • Flow velocity>laser vel. • Filtration

An example of a subsystem that was evaluated is the optics of the system. The optics system uses a laser that is diverted through a series of optical lenses in an attempt to make a uniform weld pool. The effect of the optics calibration can be segmented from the other subsystems through careful calibration. An experiment was conducted to study the accuracy of the optical system and make sure that proper laser alignment was achieved on both lasers in the M2 and X-Line systems. This experiment/calibration was performed in the absence of powder spreading (no powder on plate), the ventilation system (cover gas) is not running and were conducted at the focal plane (build plate height) so that effects of the elevator could be ignored. It is expected there was no influence on the chassis system throughout the experiment although there have been reports that the chassis can heat up as a function of time on long duration builds resulting in thermal expansion that may have negative impacts on build quality. A complete evaluation of this will be conducted in the TCR project.

5. CONCLUSIONS

The report provides an overview of progress for the laser powder bed fusion effort and its potential for production of components in support of the Transformational Challenge Reactor. Based on the current findings, the laser powder bed systems are ideal for complex geometries required for many of the components in the reactor designs. The ability to fabricate extremely complex geometries with internal cooling passages is essential to the functionality of advanced designs and will be able to improve heat transfer in comparison to conventionally manufactured materials. In addition, there are many complex geometries that would not be possible to fabricate with conventional machining or manufacturing processes. These include curved internal channels in components such as manifolds needed for moving the cooling media inside of the reactor. Complex double walled cans were fabricated with significantly higher precision than can be fabricated conventionally. These structures will be useful in improving the overall performance of the reactor. Although the current machines have demonstrated the ability to fabricate core critical components, a complete evaluation of the different subsystems must be performed and certified with the digital platform to ensure nuclear grade quality on final components as the powder bed additive manufacturing technology will be a critical aspect to the TCR program.