ADVANCED MANUFACTURING FOR NUCLEAR CORE DESIGN

B. R. Betzler[1], B. J. Ade[1], A. J. Wysocki[1], M. S. Greenwood[1], J. J. W. Heineman[1], P. C. Chesser[1], P. K. Jain[1], F. Heidet[2], and A. Bergeron[2*]

[1]Oak Ridge National Laboratory
1 Bethel Valley Rd., Knoxville, TN 37934

[2]Argonne National Laboratory
9700 Cass Ave., Lemont, IL, 60439

betzlerbr@ornl.gov

ABSTRACT

Advanced manufacturing has the potential to revitalize US manufacturing, with valuable applications in several industries, including aerospace, automotive, and construction. Some of these applications have clear-cut objectives (e.g., maintain component performance while reducing mass). Applications of advanced manufacturing of nuclear components have aimed at recapturing lost manufacturing capabilities or addressing maintenance of legacy reactor components. Through the Department of Energy, Office of Nuclear Energy, Transformational Challenge Reactor design and analysis thrust, applications of advanced manufacturing, in particular, additive manufacturing, to core design has yielded reactor designs that are free from conventional manufacturing constraints. For applications in core design, the multiphysics nature of the key core metrics (e.g., peak temperature, peak power) in addition to transient safety performance requirements provides a more complex set of objectives that requires more advanced modeling and simulation tools. Additive manufacturing provides high dimensional control and design flexibility to produce complex coolant channel shapes for improved heat transfer properties and low peak material temperatures. Additional mechanisms for improved heat transfer characteristics and temperature-controlled feedback mechanisms have also been explored and incorporated into designs. While some of these enhancements are not directly beneficial for the current operating pressurized water reactor fleet, benefits may be realized in specific reactor applications that have a more constrained design space (e.g., mass, size, material type) or design metrics (e.g., fuel utilization).

KEYWORDS: advanced manufacturing, core design, additive manufacturing

* This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE).

1. INTRODUCTION

Continued developments in advanced manufacturing technologies are fundamentally altering the way components are designed and manufactured. The potential application space for these technologies within the nuclear industry is very broad because of the rigorous requirements and inherent multidisciplinary nature (e.g., civil, mechanical, electrical, and nuclear engineering) of large nuclear power plants. Beyond applications for existing nuclear reactors, these new manufacturing methods, advanced materials, and dimensional constraints can be applied to the nuclear core design problem. A manufacturing-informed design approach has the potential to yield the most benefit from the application of advanced manufacturing in the nuclear industry—leveraging advanced materials, data science, and rapid testing and deployment to drive down costs and development times, and ultimately improving future commercial viability. This approach is being demonstrated under the US Department of Energy Office of Nuclear Energy (DOE-NE) Transformational Challenge Reactor (TCR) program.

Nuclear reactor design includes nuclear, thermal hydraulic, fluid mechanics, and thermomechanical components. An understanding of complex dynamic behaviors and feedback mechanisms is necessary to quantify conditions during steady-state operation and during potential transient scenarios to ensure fission product retention and safe reactor operation. These complex physics behaviors and rigorous requirements drive reactor design and the development of modeling and simulation methods: the simulation of this complex physics problem is simplified for repeating core geometries. With additional consideration of fabrication (e.g., materials, densities, dimensions), fuel cycle (e.g., fuel shuffling and cycle lengths), and performance (e.g., power density and peak temperatures) complexities, axially uniform plate- or pin-type fuel geometries are ubiquitous (Table I). Most research and commercial reactors use repeating fuel geometries.

Table I. Power densities, fuel geometries, and active core height for selected reactor designs.

Fuel type	Typical core power density [kW/L-core]	Active core height [m]	Fuel geometry type
Commercial reactor fuels			
PWR	100	3.66	pin
BWR	50	3.05–3.66	pin
AGR [1]	3	8.30	pin
Research reactor fuels			
MTR [2]	varies	0.61	plate
TRIGA [3]	varies	0.36	pin
VVR [4]	varies	0.60	plate
IRT [5]	varies	0.60	plate
High-performance research reactor fuels			
ATR [6]	1,000	1.18	plate
MITR [7]	70	0.57	plate
HFIR [8]	1,700	0.51	plate
NBSR [9]	40	0.56	plate
MURR [10]	300	0.61	plate

PWR = pressurized water reactor. BWR = boiling water reactor. AGR = advanced gas-cooled reactor. MTR = Materials Testing Reactor. TRIGA = Training, Research, Isotopes, General Atomics. VVR= water-water reactor (Russian). IRT = research reactor thermal (Russian). ATR = Advanced Test Reactor. MITR = MIT Reactor. HFIR = High Flux Isotope Reactor. NBSR = National Bureau of Standards Reactor. MURR = University of Missouri Research Reactor.

When the constraints of conventional manufacturing methods are relaxed, the design space opens, enabling the exploration of more heterogeneous geometries with spatial geometry and material flexibility. Additional modeling and simulation advancements must be implemented to quantify the design performance of these more complex geometries and to predict conditions during steady-state and transient scenarios to the rigor required for a reactor safety basis, including associated uncertainties and safety margins [11]. The degree of benefit that can be realized from this design flexibility depends on the desired performance metrics (e.g., peak temperature and fuel utilization) and design envelope (e.g., core size and power density limits). More benefits may be realized for a small core size constraint than for an unbounded size constraint. For example, advanced manufacturing approaches may offer more limited benefits for large light water reactor fuel assemblies.

This paper discusses the applications of advanced manufacturing technologies to the core design problem as informed by the design and analysis activities of the DOE-NE TCR [12]. It is not intended as a complete discussion of potential applications or quantification of the benefits from this manufacturing-informed approach, but it is a discussion of the potential benefits for desired reactor metrics.

2. BACKGROUND

Advanced manufacturing technologies comprise a constantly evolving set of methods that reimagine the approach to traditional manufacturing processes, tapping into multiple advances across many fields—computer modeling, advanced instrumentation, data science, and automation—to recapture manufacturing capabilities, improve component performance, and reduce component costs and development and procurement lead times. Current activities in the nuclear industry are targeting some of these objectives [13,14,15]. At present, the TCR program is focused on the demonstration and development of additive manufacturing methods as applied to structural materials (e.g., stainless steel, silicon carbide). This approach enables advanced functional cladding and fuel compacts containing uranium fuel materials that are produced using conventional methods (e.g., spark plasma sintering for monolithic fuel materials or internal gelation sol gel followed by fluidized bed chemical vapor deposition for coated particle fuels).

Because of its revolutionary potential and increased private and public investment, industries such as aerospace, transportation, construction, manufacturing, and nuclear power are pursuing advanced manufacturing applications. Examples of successful applications include the following:

- redesign of manufacturing components (e.g., composite molds) with additive and subtractive techniques to reduce lead times for delivering these components, enabling a more rapid design-build-test cycle [16,17],
- redesign of existing multi-part transportation components (e.g., aerospace) for additive manufacturing processes to reduce part count and weight [18], and
- development of manufacturing methods for existing components using additive and subtractive techniques to reduce scrap metal waste [19].

These examples encompass some of the most direct benefits of advanced manufacturing processes: redesigning components or fabrication processes to maintain or improve performance and reduce material use, weight, lead times, or wastes.

Leading candidate advanced manufacturing technologies for nuclear reactor core applications include powder bed fusion, laser-directed energy deposition, and binder jetting [20].

- **Powder bed fusion** builds components layer by layer by melting thin layers of powder.
- **Laser-directed energy deposition** builds components by generating a small melt pool into which additional metal powder is blown.
- **Binder jetting** uses a solvent-polymer solution to bind powder and build a low-density part. Follow-on sintering or other densification techniques are commonly used.

Along with their own unique challenges, these technologies adhere to some general principles:

- For additive manufacturing technologies, an increase in the material deposition rate generally results in poorer dimensional control. Geometries with smaller (e.g., millimeter-scale) features generally require technologies with high dimensional control, limited manufacturing envelopes (e.g., $80 \times 40 \times 50$ cm^3), and lower deposition rates.
- Minimum comfortable geometric feature sizes for additive technologies are on the 100-micron scale.
- Designs requiring smoother surfaces than are provided by the additive process must accommodate post-machining techniques.
- Additive manufacturing of a given material is unique. For example, a process or method for a given steel alloy may not be applicable for a different steel alloy.
- Hybrid systems deploying both additive and subtractive methods or using two different materials are still being actively researched and developed.
- Several trial builds are needed to refine the build parameters and approach to successfully manufacture a given component.
- Because of the rapid development in advanced manufacturing technologies, new literature must be reviewed no less frequently than every 4 years [20].

3. CORE DESIGN WITH ADDITIVE MANUFACTURING

Most operating cores consist of pin- or plate-type fuel geometries arranged in a repeating lattice (Table I). This design is used in part because of three major drivers:

1. Plates, tubes, and cylindrical fuel rods are relatively simple to manufacture, particularly when the same fuel pin or plate is repeated throughout the geometry.[1]
2. Repeating geometries are expandable (i.e., configurable to different sizes) and, if necessary, they may be broken down further to implement cost-effective maintenance and fuel management approaches such as assembly loading patterns, fuel shuffling, and operating cycle times.
3. Simple, axially uniform repeatable geometries are easier to simulate than more complex heterogeneous geometries.[2] The predictability of modeling and simulation tools is necessary to ensure that the system will remain in a safe condition during steady-state and transient scenarios.

Most large commercial reactors have repeating pin-type geometries broken into subassemblies for fuel cycle management. Long, thin tubes are relatively easy to manufacture and seal, and they are mechanically robust. Pin- and plate-type fuel geometries are common in research reactors worldwide. Many of these systems have a relatively low power density [21]. Cores in high-performance research reactors in the United States consist of thin fuel plates. These cores have relatively short fuel elements, and most have very high power densities. The geometry of thin plates is more effective than the geometry of thin cylinders for high fuel-to-cladding ratios and effective cooling.

In addition to these operating core designs, many reactor core concepts have been developed. However, many of these are impractical with respect to material limitations, economic concerns, or safety issues. Some of these core designs do not consider manufacturability. In core design informed by additive manufacturing, most restrictions resulting from current conventional processes are alleviated; but the expandability and simulatability of repeatable geometries still impacts the design process.

[1] This is as perceived from current conventional processes.

[2] The first nuclear reactors were designed without computers.

4. CORE DESIGN APPLICATIONS

Several potential applications of additive manufacturing technologies have been identified and are being explored as part of the TCR design and analysis activities [22]. Fuel design [23] and embedded instrumentation [24,25] applications are not included in this discussion, but they are being explored.

4.1. Topology Optimization

Structural and cladding materials within a nuclear core support the fuel and retain fission products. Parasitic neutron absorption in these materials contributes negatively to the fuel cycle economy of the reactor, so reducing the amount of these materials within the core without adding risk to component critical functions has a positive effect on performance and cost savings.

Additive manufacturing processes are currently used in several industries to build minimalized geometries of existing components to reduce weight or waste. In nuclear design, the requirements are more complex, as the material must withstand a high radiation environment and changing temperature gradients for the lifetime of the given component. These complex designs (Figure 1) must perform well thermomechanically. Performance enhancements from a neutron economy perspective are relatively simple to quantify using geometric or material density changes. Potential applications in boiling water reactors (BWRs) and pressurized water reactors (PWRs) include channel boxes, grid spacers, bottom nozzles, and upper fuel handling mechanisms.

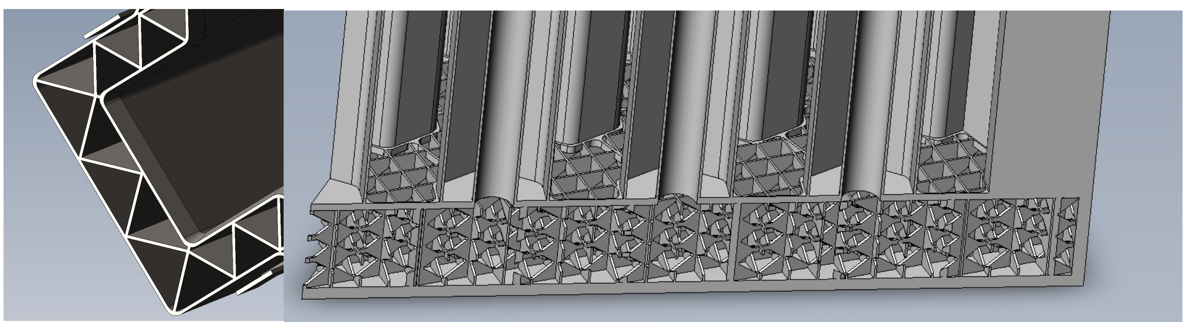

Figure 1. Samples of structures minimalized to maintain performance and reduce material volume.

4.2. Gap Conductivity

In BWRs and PWRs, an engineered fuel-cladding gap is designed into the fuel rods to accommodate the dimensional changes in the fuel pellet during irradiation at operating temperatures and to reduce the impact of the resulting pellet-cladding interaction on fuel integrity. This gap causes poor heat transfer between the fuel and the cladding, resulting in a large temperature drop (on the order of 100 °C in PWRs) across the gap and an elevated peak fuel temperature. Improving conductivity across this gap would reduce the temperature drop.

Additive manufacturing processes can be used to manufacture fuel cladding to a few hundred microns in dimensions, with very thin internal spring-like structures to accommodate a fuel form and to improve heat transfer across the gap between the form and the cladding wall. These spring-like structures (Figure 2) may be optimized to accommodate the dimensional changes within the fuel during reactor operation and to ensure contact with the fuel form at all times, which is important to ensure consistent heat transfer. While simulation tools are reasonably predictive, with additive-enabled rapid prototyping and testing, building several geometries and measuring the heat transfer characteristics help validate models.

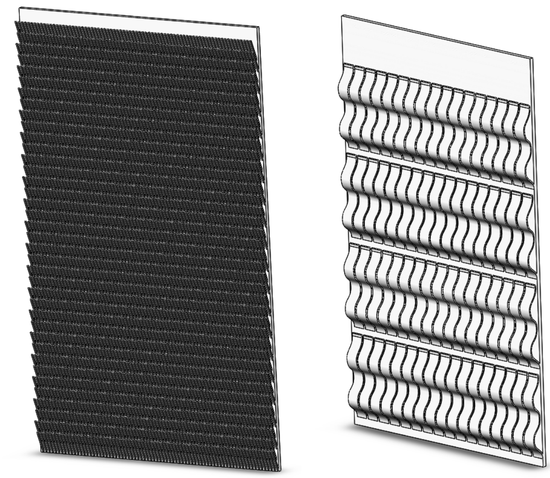

Figure 2. Candidate spring-like structures to enhance heat transfer between the cladding wall (shown) and fuel form (not shown).

4.3. Improved Heat Removal

The heat transfer between a fissioning fuel form and a forced flowing coolant depends on several factors, including geometry, materials, fluid type, flow rate, and power density. Optimizing this heat transfer requires balancing performance metrics such as peak temperatures, and constraints such as pressure drop and pumping power; and it requires system design information.

Additive manufacturing–informed heat exchanger designs are currently in development. Similar principles in design and analysis may be adopted for core design, as the fuel material in the core can be seen as the hot side of a heat exchanger. Additive manufacturing processes facilitate a departure from the typical axially uniform geometries, defining coolant flow paths that vary in the axial dimension to improve heat transfer into the flowing coolant (Figure 3). For these new designs, the roughness of additively manufactured components may be leveraged to improve turbulent heat transfer. Flow geometries designed to enhance bulk coolant mixing, particularly in the lateral direction, could reduce peak temperatures.

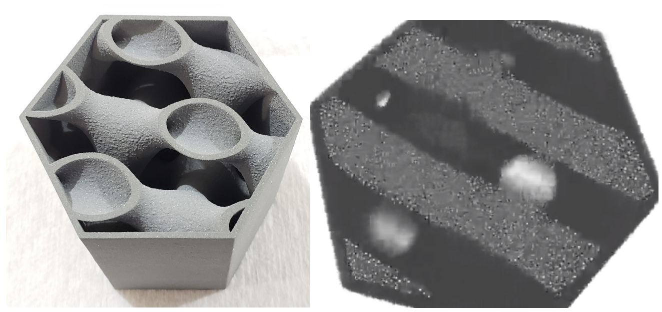

Figure 3. An example of design flexibility for coolant flow optimization (left) and an example tomogram of embedded particle distributions within this geometry (right).

4.4. Uncertainty Reductions

Factors are applied in safety calculations to account for material correlation uncertainties, material property uncertainties, and potential deviations of as-built parts within the specified design tolerance [26].

These uncertainty factors are applied to ensure conservative estimates of peak temperatures and safety margins.

Greater dimensional control in additive manufacturing processes enable reductions in those uncertainty factors. In situ monitoring during additive manufacturing processes, such as high-speed video and infrared thermography, captures specific deviations from an as-designed component. Greater dimensional control and in situ monitoring enable reductions in uncertainty to allow for operation closer to design limits, potentially improving reactor performance.

4.5. Core Heterogeneities

The dimensional control and automation in additive manufacturing processes may make heterogeneous core geometries more economically feasible. This advantage may be leveraged to optimize power distribution within the core. In addition, the flow paths of coolant passing through the core may be tailored to match this core power distribution, directing more coolant to the hotter regions of the core. Smooth transitions are achievable with additive processes that would allow for a flatter distribution in a characteristic of interest such as power.

5. DISCUSSION

Some of these potential improvements are uniquely enabled by additive manufacturing technologies (e.g., material reduction), while some represent the application of additive manufacturing to make heterogeneous designs more feasible (e.g., fuel loading distribution). This distinction is important: in some cases, increasing the design complexity does not require additive manufacturing; however, additive manufacturing may ultimately enable this design complexity through process automation, in situ monitoring, and repeatability. In addition, certain design complexities are implemented more easily though additive manufacturing processes. Implementing a core design that leverages many of these design improvements is the focus of the TCR design and analysis thrust [22].

ACKNOWLEDGMENTS

This work was funded by the Department of Energy, Office of Nuclear Energy Transformational Challenge Reactor program.

REFERENCES

1. Nonbøl, E. 1996. *Description of the Advanced Gas Cooled Type of Reactor (AGR), Risø National Laboratory Report*, NKS/RAK2(96)TR-C2.
2. Miller, R. F. and R. L. Sindelar. 1995. *Analysis for Materials Test Reactor (MTR Fuel Assemblies in Dry Storage)*, WSRC-TR-95-0121, Westinghouse Savannah River Company.
3. Cammi, A. et al. 2016. "Characterization of the TRIGA Mark II reactor full-power steady state," *Nuclear Engineering and Design* 300, 308–321. https://doi.org/10.1016/j.nucengdes.2016.01.026.
4. Pond, R. B. et al. 1998. "A Neutronic Feasibility Study for LEU Conversion of the Budapest Research Reactor," *Proceedings of the International Meeting on Reduced Enrichment for Research and Test Reactors*, Sao Paulo, Brazil, October 18–23, 1998.
5. Hanan, N. A. et al. 2006. "WWR-SM Conversion to LEU IRT-4M Oxide Fuel," *Proceedings of the International RERTR Meeting*, Cape Town, South Africa, October 29–November 2, 2006.
6. Stanley, C. J., and F. M. Marshall. 2008. "Advanced Test Reactor—A National Scientific User Facility," *Proceedings of 16th International Conference on Nuclear Engineering,* Orlando, Florida, May 11–15, 2008. https://www.osti.gov/servlets/purl/934543.

7. MIT. 2019. Massachusetts Institute of Technology Nuclear Reactor Laboratory: Reactor. Accessed 29 July 2019. https://nrl.mit.edu/reactor
8. Adamson, G. M. Jr., and R. W. Knight. 1968. *HFIR Fuel Element Production and Operation*, ORNL-TM-2196, Oak Ridge National Laboratory.
9. Stevens, J. G. 2010. *Technical Challenges for Conversion of U.S. High-Performance Research Reactors*, NAS/RAS Committee on Conversion of Research Reactors, 29 November 2010.
10. MU Research Reactor. 2019. University of Missouri. Accessed 29 July 2019. https://www.murr.missouri.edu/about/operations/
11. Sobes, V. et al. 2020. "Artificial Intelligence Design of Nuclear Systems Empowered by Advanced Manufacturing," *Proceedings of PHYSOR 2020*, Cambridge, United Kingdom, March 29–April 2, 2020.
12. Betzler, B. R. et al. 2019. *Advanced Manufacturing for Nuclear Core Design*, ORNL/TM-2019/1258, Oak Ridge National Laboratory.
13. Gandy, D., and G. Stover. 2018. "Advanced Manufacturing to Enable the Next Generation of Nuclear Plants," *Presentation at Molten Salt Reactor Workshop—Creating a Self-Sustaining Environment for MSR Success*, October 3–4, 2018.
14. Hehr, A. et al. 2016. "Five-axis ultrasonic additive manufacturing for nuclear component manufacture," *JOM* 69:3, 485–490. doi:10.1007/s11837-016-2205-6.
15. Houts, M. G. et al. 2012. "Nuclear Thermal Propulsion for Advanced Space Exploration," Proceedings of Space Propulsion 2012, Bordeaux, France, May 7–10, 2012.
16. Guinness World Records Limited. 2016. *Guinness World Records 2016*, "Largest solid 3D-printed item," Guinness World Records, 29 August 2016. Accessed 29 July 29, 2019. https://www.guinnessworldrecords.com/world-records/432579-largest-solid-3d-printed-object.
17. Post, B. K. et al. 2019. "Using Big Area Additive Manufacturing to directly manufacture a boat hull mould," *Virtual and Physical Prototyping* 14:2, 123–129. doi: 10.1080/17452759.2018.1532798
18. DeHoff, R. R. et al. 2013. "Case Study: Additive Manufacturing of Aerospace Brackets," *Advanced Materials and Processes* 171:3, 19–22.
19. Holshouser, C. et al. 2013. Out of Bounds Additive Manufacturing," *Advanced Materials and Processes* 171:3, 15–17.
20. Simpson, J. et al. 2019. *Considerations for Application of Additive Manufacturing to Nuclear Reactor Core Components*, ORNL/TM-2019/1190, Oak Ridge National Laboratory.
21. NEAC. 2017. Nuclear Energy Advisory Committee. *Assessment of Missions and Requirements for a New US Test Reactor.* https://www.energy.gov/ne/downloads/neac-report-assessment-missions-and-requirements-new-us-test-reactor. Accessed 5 August, 2019.
22. Ade, B. J. et al. 2020. "Candidate Core Designs for the Transformational Challenge Reactor," *Proceedings of PHYSOR 2020*, Cambridge, United Kingdom, March 29–April 2, 2020.
23. Nelson, A. T. 2019. *Features that Further Performance Limits of Nuclear Fuel Fabrication: Opportunities for Additive Manufacturing of Nuclear Fuels*. ORNL/SPR-2019/1183, Oak Ridge National Laboratory.
24. Tobin, K., and S. Aumeier. 2018. *Technologies to Reactors: Enabling Deployment of Nuclear Energy Systems*, ORNL-SPR-2018/1025, Oak Ridge National Laboratory.
25. Cetiner, S. M. and P. Ramuhalli. 2019. *Transformational Challenge Reactor Autonomous Control System Framework and Key Enabling Technologies*. ORNL/SPR-2019/1178, Oak Ridge National Laboratory. doi:10.2172/1530084.
26. Chandler, D. et al. 2019. "Neutronic and thermal-hydraulic feasibility studies for High Flux Isotope Reactor conversion to low-enriched uranium silicide dispersion fuel," *Annals of Nuclear Energy* 130, 277–292. https://doi.org/10.1016/j.anucene.2019.02.037.