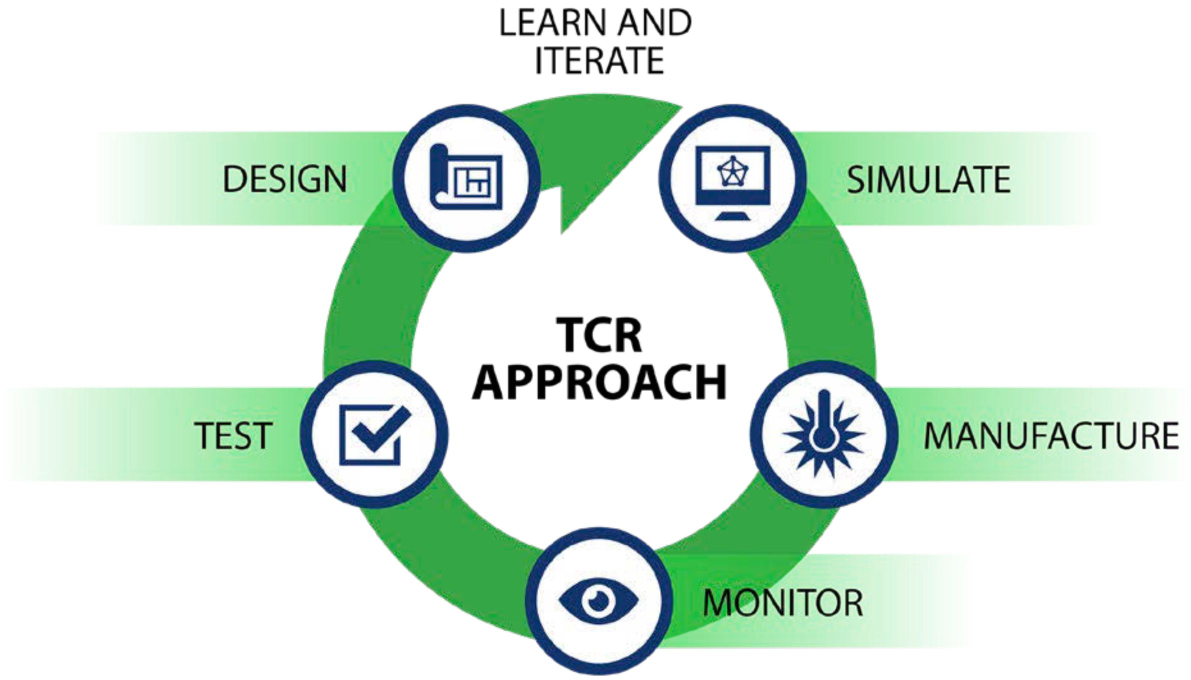

Adam Malin, ORNL

The TCR program is leveraging an agile approach—one that is centered around continuously informing the process—to accelerate deployment timelines and introduce performance improvements.

Accelerating the deployment of advanced nuclear energy systems

The DOE's Transformational Challenge Reactor program is harnessing recent advances in manufacturing, materials, and computational sciences to rapidly build and operate an advanced reactor core.

By Kurt Terrani

Soon after Enrico Fermi's Chicago Pile-1 went critical for a brief duration in December 1942, the construction of the first continuously operating reactor, the X-10 Graphite Reactor, was initiated in February 1943 at Clinton Engineer Works in Oak Ridge, Tenn. On November 4 of that year, a mere nine months after the start of construction, the reactor began operation. This marked the onset of what Alvin M. Weinberg referred to as "the first nuclear era," during which many reactors of various designs and operating parameters were built and demonstrated across the United States. Forty years ago, the Fast Flux Test Facility was the last U.S. non-light-water reactor to reach criticality, and it has since been decommissioned.

Today, nuclear energy is based exclusively on significantly scaled-up versions of Hyman G. Rickover's water-cooled and water-moderated design from those early times. Although these existing LWR plants are skillfully operated to the highest capacity factors for any energy source, they struggle to compete economically with low-cost natural gas burned in combined-cycle plants. Most existing nuclear plants are now quite old and are beginning to be phased out. The outlook for the development of new plants faces significant challenges associated with high up-front capital costs and multiple-decade-long development and deployment timelines. Investors are understandably hesitant to make large capital investments with such lengthy deployment timelines. A new approach to nuclear energy is needed.

We must demonstrate that we can develop and deploy advanced, efficient nuclear energy systems in a reasonable time frame. This is the essential objective of the Transformational Challenge Reactor (TCR) program: to show that highly improved, efficient systems can be created by harnessing the major advances in manufacturing, materials, and computational sciences that have emerged since the first nuclear era. To deliver real value by leveraging these advancements, the TCR program is developing technologies at the right readiness levels for industrial adoption. The TCR program is also implementing an agile approach to nuclear energy deployment. The program, which began in 2019, will use advanced manufacturing to create an operating nuclear reactor in 2023. This demonstration is the key to delivering tangible technologies that will enable a new approach for advanced,

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competitive nuclear deployment.

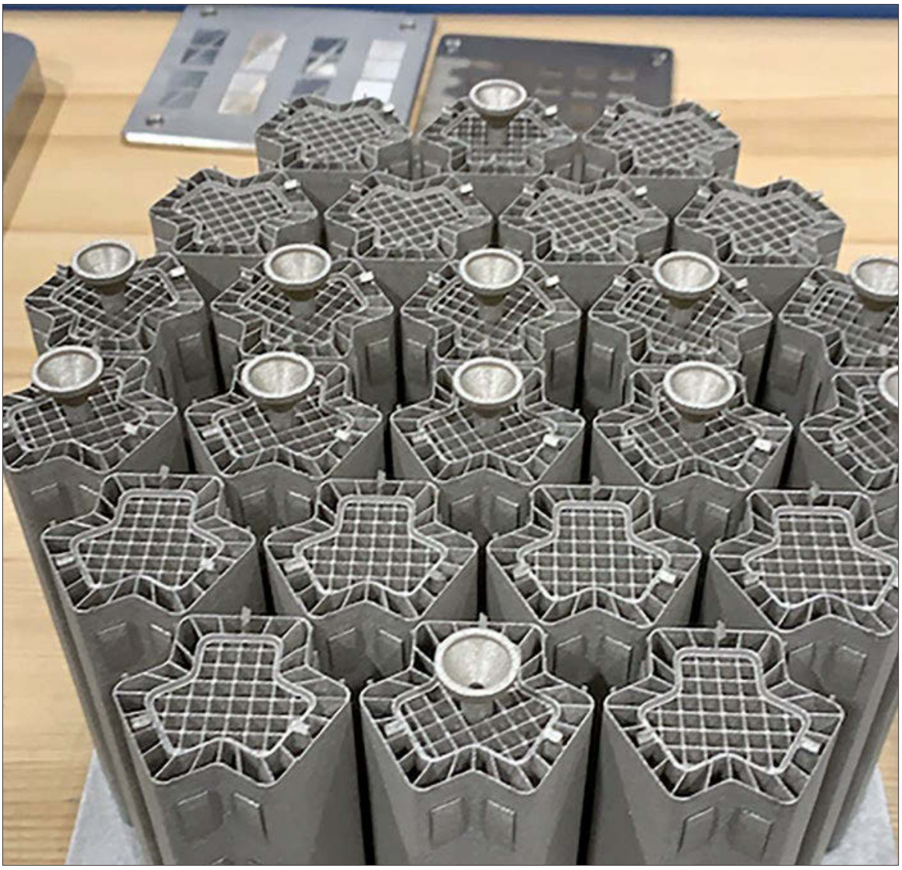
The TCR core is composed of advanced TRISO fuel particles embedded inside additively manufactured silicon carbide fuel elements with complex geometric features. The fuel elements are packed tightly together in individual assemblies, along with a high-temperature metal hydride moderator. The specific moderator selected is yttrium hydride, as it offers the highest thermal stability relative to any hydrogen-bearing solid compound. Additively and conventionally manufactured austenitic stainless steel, tactically used where sensible, ties the fuel assemblies together and encapsulates the moderator.

The core is cooled by flowing pressurized helium inside a loop that transfers up to 3 megawatts of nuclear power to an air-cooled heat exchanger. The fuel and moderator are capable of operating at very high temperatures, but for this rapid demonstration, the TCR outlet temperature is limited to 550°C—still 250°C higher than the existing LWR fleet.

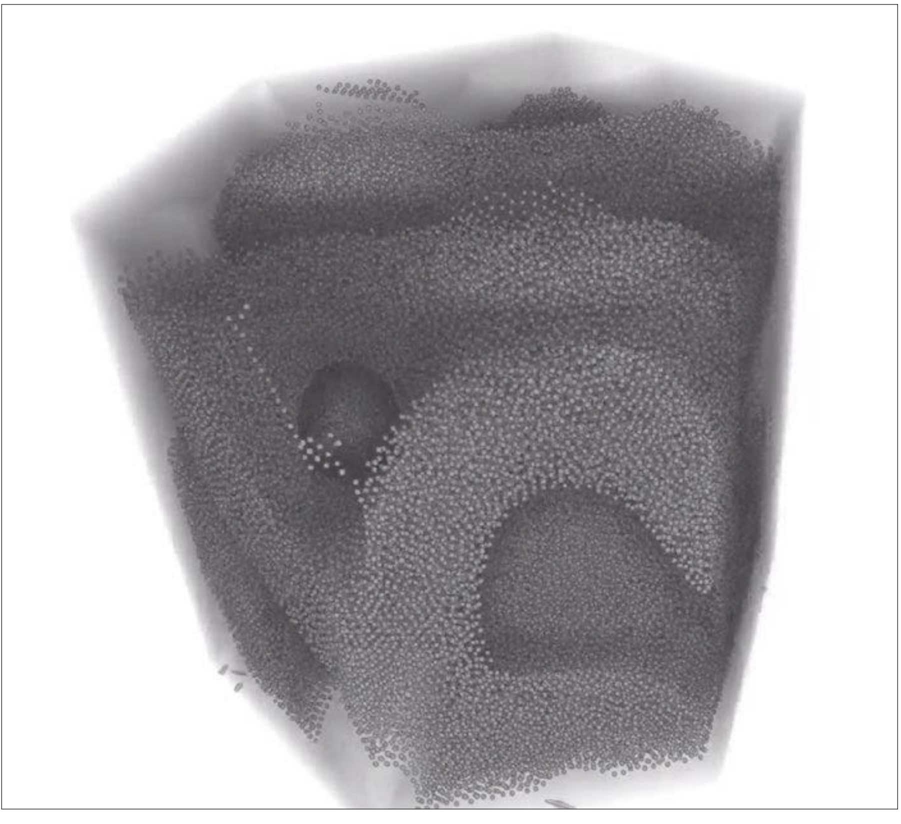
The Department of Energy's Oak Ridge National Laboratory leads the TCR program, which includes contributing partners from other DOE national laboratories and the U.S. nuclear industry. The program leverages some of the nation's best scientific and engineering leaders and is specifically pulling from ORNL's lengthy history, institutional knowledge, and capabilities in high-performance computing, materials science development, advanced manufacturing techniques, and nuclear science and engineering. This unique reactor demonstration will provide a path to take the newly developed methods and offer broad impact to the nuclear community.

TCR technology thrusts

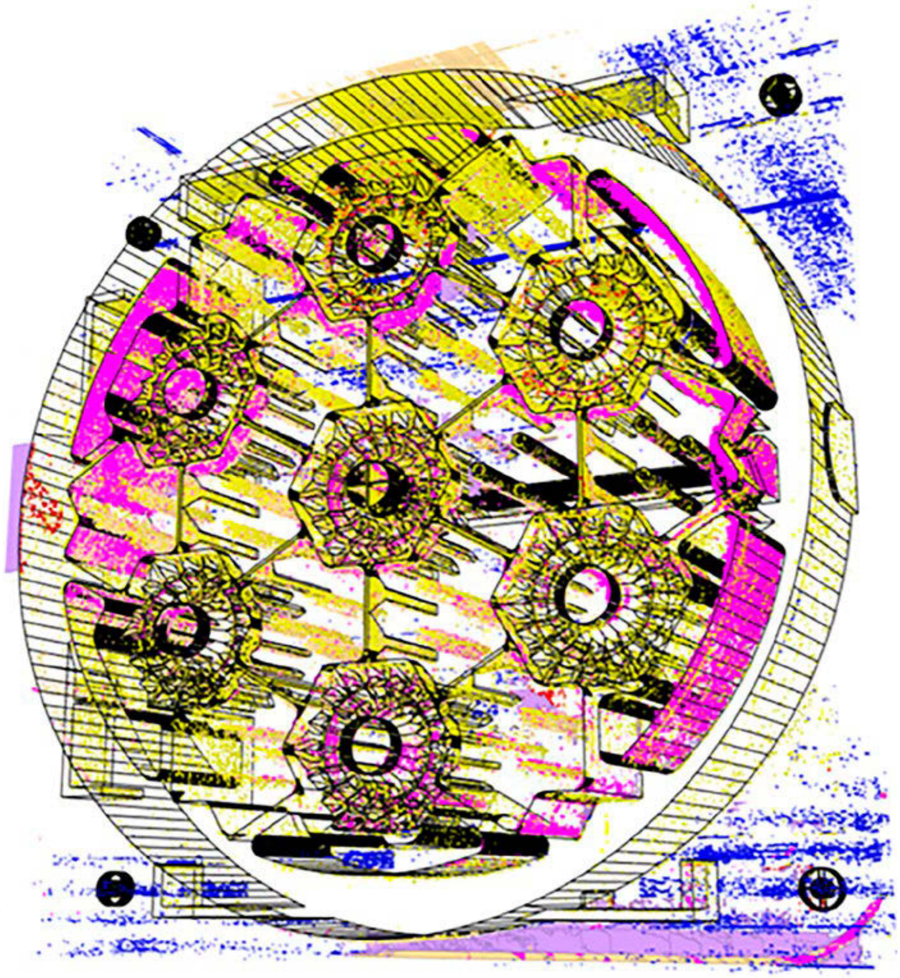
Four key technological thrusts are being developed under the TCR program. The first thrust is the exploitation of **additive manufacturing** to create nuclear reactor components unconstrained by the limits of conventional manufacturing. Core designs are no longer limited to simplified geometries like rods, plates, or pebble fuel forms. Instead, geometric complexities can be manipulated to enhance desired performance characteristics. For example, surface features can be added to a complex nuclear fuel element to greatly increase its performance in transferring fission heat to adjacent coolant; the topology of components can be optimized to achieve better neutron economies or heat transfer characteristics; and improved dimensional controls can reduce or quantify the difference between a designed and a manufactured component. Using these methods, power and coolant distributions may be tuned to reduce temperature gradients and maintain low stress levels in


Ryan Dehoff, ORNL

TCR is showcasing the power of additive manufacturing to realize high-performance designs. This photo shows a fuel element with double-walled cladding and cooling channels that incorporate high surface area and helical guides.


Brian Jolly and Andres Marquez Rossy, ORNL

TCR is working with advanced materials. This image shows X-ray tomography of additively manufactured silicon carbide with complex cooling channels and embedded nuclear fuel particles. The additive process is tuned to yield high-purity and fully crystalline material, ensuring radiation stability to very high doses.



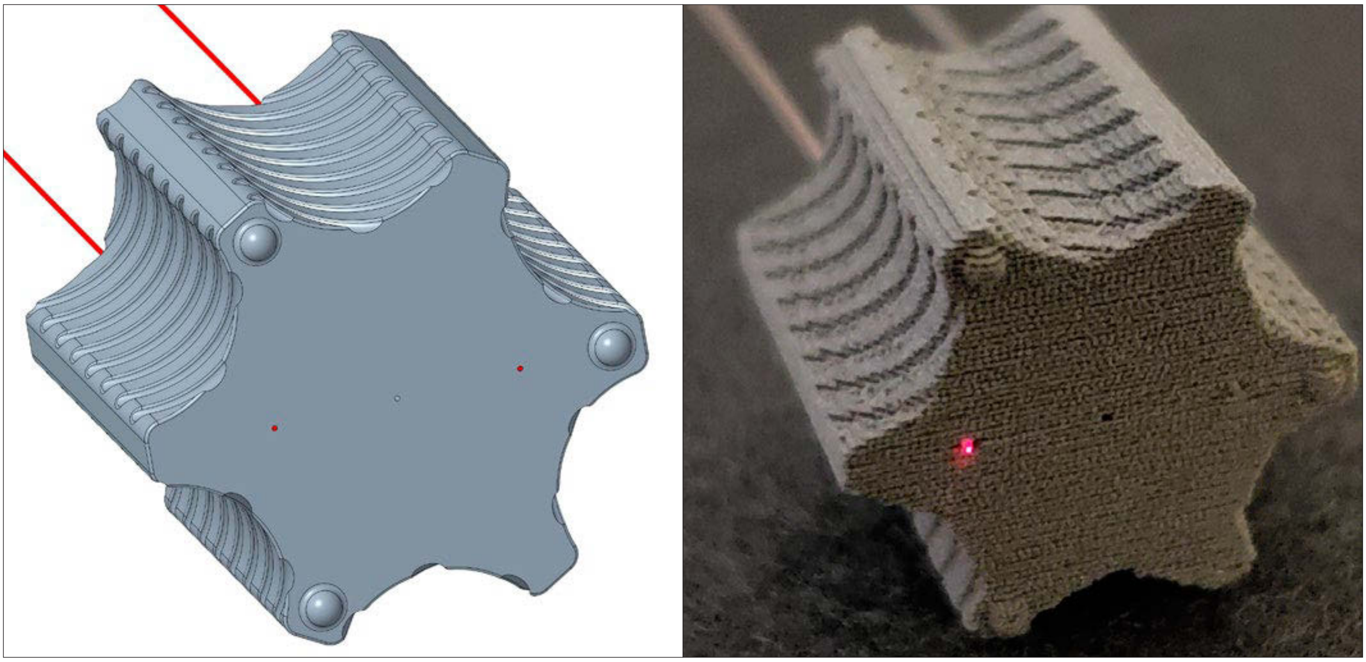
Vincent Paquit, ORNL

The TCR program is using on-the-fly assessment and qualification. By doing this, the team performs neural network analysis of *in situ* build image data detecting anomalies in the component at specific locations.

core components. This provides for pushing designs to higher power for a given core volume. The opportunity to leverage additive manufacturing is particularly enabled by advanced modeling and simulation tools available today that can analyze these complex geometries and guide design. An understanding of complex dynamic behaviors and feedback mechanisms is necessary to quantify conditions during normal operation.

The second TCR technology thrust is the introduction of **advanced materials** into nuclear reactors. The few materials used in light-water and advanced reactor designs originated almost exclusively during or prior to the 1970s. Nuclear energy systems have not exploited new high-performance materials to improve performance. Since material properties are largely functions of their processing parameters, using additive techniques will result in materials with performance behaviors that differ from their conventionally manufactured variants. Depending on the processing parameters, the materials may be better, worse, or the same. Fortunately, the current state of knowledge in integrated materials engineering and radiation effects allows us to design processing parameters that yield materials with the microstructures and properties ideal for nuclear application.

The third TCR technology thrust also takes advantage of additive manufacturing techniques to create **embedded sensors** within core and reactor structures. Incorporating sensors in this manner provides an unprecedented view into these complex systems, allowing information



Michael Trammell and Christian Petrie, ORNL

On the left is a prototype design developed by the TCR team, and on the right is the printed silicon carbide structure with embedded sensors. The TCR program is targeting the application of embedded optical fiber sensors throughout the system for extracting temperature and strain data across the span of core components.

to be collected that was previously unavailable. Today, the availability of sensors that provide distributed information (e.g., optical fibers with gratings) unlocks an opportunity to harvest big datasets from these systems. These data can be collected at targeted locations within nuclear energy systems that not only enhance system health monitoring and operational practices, but also feed digital twins and facilitate autonomous operation. These factors are some of the key enablers of cost-competitive nuclear energy.

Finally, the fourth and perhaps most effective TCR technology thrust is to define and demonstrate a new approach to **critical component qualification**. We can exploit the inherent characteristics of additive manufacturing, producing any given part by serially building it in small volumes instead of using the conventional manufacturing processes of forging, rolling, and casting, in which a bulk component is made within a given processing window. This simple difference allows us to see into the finest details of the part. It is accomplished by continuously monitoring the additive manufacturing process and collecting information for every small, finite volume of the build. *In situ* monitoring data during additive manufacturing may consist of images, acoustics, or many other signals. Once these signals are compiled, the result is a digital portrait of the build showing each voxel associated with a specific location in the physical part. Using big data acquisition and processing capabilities, this information is combined with data analytics tools to assess component quality almost immediately after being manufactured. This mode of certification requires establishing strong correlations using artificial intelligence techniques between component performance data collected from post-manufacturing testing and *in situ* signals collected during manufacturing. This approach can greatly reduce the cost and time burden of manufacturing critical components, not only for nuclear energy systems, but for any manufacturing process that necessitates strict performance requirements.

Agile approach to deployment

The TCR program has adopted the agile development approach, which has been popular in software development for decades. The agile approach breaks with traditional linear development models, such as waterfall, to exercise an iterative, dynamic development process. It lends itself particularly well to complex projects like TCR, in which a large, multidisciplinary team works closely to complete a complex product. The agile approach will drastically accelerate deployment timelines and will minimize risk for nuclear reactor demonstration projects. A given design for a component, subsystem, or system is rapidly moved forward, being informed by high-fidelity modeling and simulation, additive manufacturing (with monitoring), assembly trials, and relevant testing. These iterations transpire over periods of days or weeks instead of months and years, quickly identifying solutions, opportunities for optimization, and the unknowns that pose risk to success. At the same time, these trials feed an expansive database that collects and unifies all the design, analysis, manufacturing, monitoring, and test data, enabling application of artificial intelligence for rapid certification of critical components. This fundamentally different approach is not only faster, but it also offers significant performance improvements. Faster and better is exactly what is needed to deploy economical nuclear energy.

Transformational outcomes

The TCR program will work to emulate the pioneers of the first nuclear era to build and deliver a tangible advanced nuclear energy system. The reactor itself is only a small portion of the TCR impact: The program's technological objectives and logistical road maps will benefit the domestic nuclear community as a whole and across all sectors. TCR technologies that are matured, codified, and fully demonstrated to the ripe technology readiness level for industrial adoption will be key enablers of economic, carbon-free nuclear energy.

The TCR program works closely with many industrial partners, engaging them in the development process. In parallel, the Nuclear Regulatory Commission has assigned key staff members to interact with and learn about TCR development activities. In essence, the transfer of knowledge and practices to key sectors of the domestic nuclear community is already happening. As a nation, we have the opportunity to fully exercise our capabilities across government and industrial sectors to progress from concept to full deployment and testing of an advanced nuclear reactor, breaking the four-decade pause and establishing a clear regulatory, logistical, and technological road map for others in the nation to follow. A new approach to nuclear energy is under way.

Acknowledgments

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