Transformational Challenge Reactor Agile Design Enabled by Additive Manufacturing

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https://dx.doi.org/10.13182/T123-33159

INTRODUCTION

The major goal of the US Department of Energy Office of Nuclear Energy (DOE-NE) Transformational Challenge Reactor (TCR) Program is to change the deployment costs of new nuclear power generation by leveraging advances in multiple disciplines to accelerate the design, manufacturing, qualification, and deployment of advanced nuclear energy systems. To achieve this paradigm shift, the TCR program will design, build, and operate a microreactor using a rapid advanced manufacturing approach [1].

The preconceptual and conceptual [2, 3] reactor design phases of the TCR program implemented an agile design approach characterized by rapid prototyping, iterative interdisciplinary design sprints, and flexibility in adapting to changes in technologies and requirements. This approach is uniquely enabled by using additive manufacturing technologies and by adopting key agile development values. Implementing, demonstrating, and documenting this approach is a key component of the TCR program.

Agile refers to a set of practices popularized in software development that emphasize iterative design, short feedback loops, customer collaboration, and delivering working software [4]. The term is adopted in several other fields, including manufacturing and aerospace [5], to reflect the application of some or all these beneficial practices. The rapid iterative design cycle (Fig. 1) that is characteristic of additive manufacturing technologies facilitates the application of many of these principles and the reaping of their benefits. These agile design characteristics are not typical attributes of the nuclear reactor industry.

This summary presents a high-level review of this design approach, including guiding values, challenges, and tangible impacts on the resulting design.

DESIGN PRACTICES

The characterization of a process as agile relies on the four core values [6] and 12 principles [7] defining agile software development. Elements of the TCR design process are likened back to these values and principles in the following sections. In this context, working software is workable prototypes and the customer is program leadership and the DOE-NE (and more broadly the responsibility to the nuclear industry that this carries).

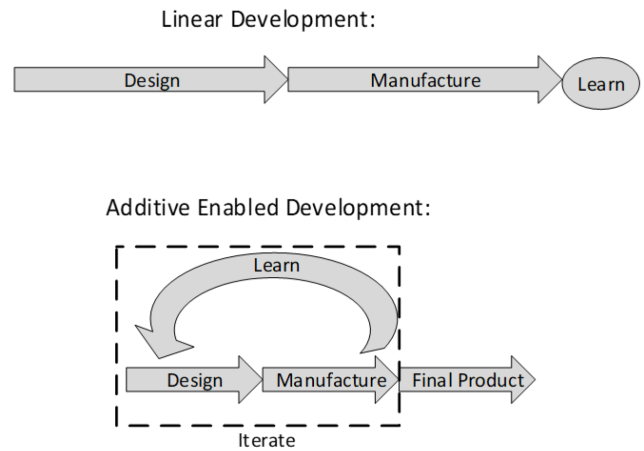

Fig. 1. Design development loop with and without additive manufacturing.

Welcoming Changing Design Requirements

*"**Responding to change** over following a plan"*

Initial preconceptual design activities started with two simple guidelines: (1) to design, build, and operate an advanced nuclear reactor within several years and (2) to leverage the fundamental characteristics of advanced manufacturing (e.g., Fig. 1) to accelerate this process. Instead of establishing a preferred reactor technology early in the design process, technologies were assessed based on these guidelines and technical decisions heavily emphasized viability and simplicity in design. Processes and materials for powder bed fusion, laser-directed energy deposition, and binder jet were assessed to determine feasibility for nuclear applications [8].

Candidate designs were quickly developed and continually refined as requirements, constraints, and available technologies continued to evolve (Fig. 2).

1. The earliest unmoderated preconceptual designs were deemed infeasible due to high-assay low-enriched uranium constraints [2, 9].
2. Incorporation of moderators that lower the fissile uranium requirement was performed in parallel with rapid progress in yttrium hydride manufacturing and characterization [10]. Sufficient progress allowed the use of this advanced moderator in the primary core design—this was not possible at the inception of the TCR program.

3. Assessments of the performance of different fuel forms in transient scenarios were performed in parallel with rapid advancements in manufacturing and characterization of candidate fuel form geometries [11-13]. Sufficient progress and a higher margin to failure allowed the downselection to a TRISO-based fuel form.
4. The final major decision in core materials was the encapsulation of the yttrium hydride moderator, for which steel encapsulation matured most rapidly. This decision was made in fitting with the timeline to deliver the conceptual reactor design and to avoid design limbo.

Flexibility and responsiveness (i.e., agility) of the TCR program design thrust was critical in accommodating these changing requirements and taking on these new technologies to progress this design in less than a calendar year [14]. This has produced a viable and simple design that incorporates novel fuel and moderator forms.

Safety requirements and the fidelity of the analyses assessing them have continually evolved throughout the design process: from early preconceptual temperature limits to rigid core design limits and from coarse bounding analyses to more detailed transient analyses with sensitivities [15, 16]. Even into the preliminary design phase, changes to fuel and material specifications (e.g., impurities and actual densities) are met with now familiar technical responsiveness and design adjustments.

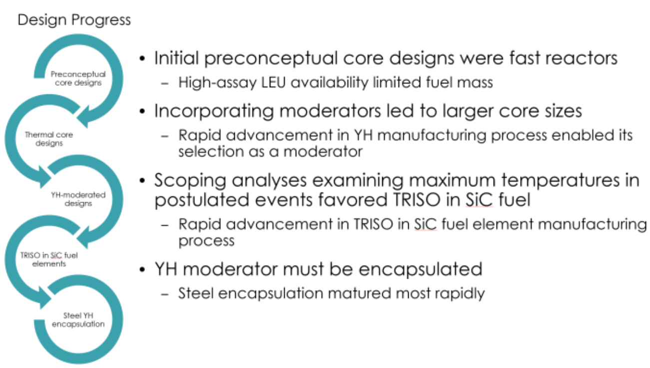

Fig. 2. Design progress through preconceptual and conceptual design phases.

Collocating Interdisciplinary Teams

*"**Individuals and interactions** over processes and tools"*

TCR program design activities regularly involve close collaboration between mechanical and material engineers familiar with manufacturing processes and material characteristics and nuclear and system engineers familiar with nuclear reactor physics, thermofluidics, and safety. These collaborations are necessary to inform the nuclear design of manufacturing and material constraints, properties, and tolerances. Individual engineers are empowered to set technical constraints and tolerances within their area of expertise.

This results in an informed design approach, where manufacturability and material compatibility are considered immediately before significant design progress or optimization in any specific concentration (e.g., reactor physics or thermofluidics). This is unlike typical nuclear reactor design activities that treat manufacturability as a given. This is necessary given the TCR deployment timeline—feasibility in manufacturing must be known and demonstrated as the design progresses. Data and constraints from manufacturing processes (e.g., minimum thicknesses, actual material densities, moderator impurities and stoichiometry) are incorporated immediately into the design activities to understand impacts and sensitivities on reactor performance.

Collocation of key staff members at the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) facility allows for consistent communication between materials, manufacturing, nuclear, thermofluidic, and thermomechanical experts and analysts. Furthermore, this colocation provides direct access to additively manufactured prototypes and test components as well as the experts operating the machines and performing characterization on manufactured parts*.

Developing Working Prototypes

*"**Working software** over comprehensive documentation"*

Drawings of the earliest preconceptual designs of the TCR core were sent to additive machines and were printed in candidate materials (e.g., steel, SiC, and Inconel). This includes the initial monolithic core structures, different types of stackable fuel elements, fuel element retention structures, and insulated-moderator core concepts [3]. The current design of the TCR is very far from these early concepts. Initial monolithic core structures performed poorly under temperature gradients, cores consisting of hundreds to thousands of stackable fuel elements raised operations issues, and two-pass insulated systems presented significant design challenges.

Despite the preconceptual feasibility of these early designs, prototypes were continuously manufactured through targeted design sprint activities because (1) it was made possible with the resources at the ORNL MDF and fuel facilities, (2) it tested potential manufacturing processes (e.g., determining geometric constraints such as minimum thicknesses and surface roughness), and (3) it provided a valuable means for generating design feedback in both

* Although this physical colocation is now interrupted due to COVID-19, given the relationships that were established under this posture during the first year of the TCR program, the team continues to enjoy full integration of these areas while working mostly remotely.

quantitative and qualitative ways. Advanced characterization techniques for determining fuel form and moderator characteristics (e.g., material properties, hydrogen densities, particle distributions, impurity content, and as-built dimensional deviations from the original CAD) are used to update design parameters and explore sensitivities to these characteristics. Examining physical prototypes in-person with a multidisciplinary team is conducive to identifying potential issues and considering new design constraints. For example, the design of the fuel forms and fuel assemblies evolved quickly as several prototypes were manufactured and the difficulty in handling smaller, separate fuel forms was apparent (Fig. 3).

For prototyping, additive manufacturing has been critical in manufacturing prototypes within days, providing for manufacturing-informed decision-making, and reducing the risk inherent in proposing new concepts and designs. The oft-touted *fail fast* philosophy that preferentially evaluates designs through extensive testing and incremental development is effective because additive manufacturing is efficient in time and staffing—failure and the follow on learning becomes a necessary and essential part of the design process.

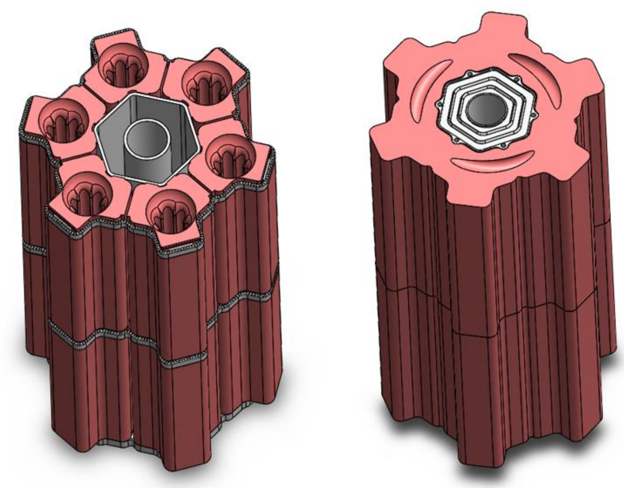

Fig. 3. Candidate preconceptual fuel assembly concepts.

Communicating Design Progress

*"**Customer collaboration** over contract negotiation"*

Throughout the design process, reactor physics, thermofluidic, thermomechanical, and safety analyses have continued to generate refined technical constraints leading to impacts on design. In keeping with the philosophy to welcome changing design requirements, these constraints and working prototypes have been rapidly shared with TCR program technical and programmatic leadership to help make technical design decisions. This close collaboration and tight feedback loop ensures that the developed design meets high-level requirements, but also, these requirements are consistent with the scope, schedule, and other programmatic constraints (e.g., realistic availability of the type and quantity of fissile material). Technical information, rapidly harnessed from this agile design process, have been used on multiple occasions to refine system specifications and inform the decision making processes with the program's local and national leadership. In addition, interested parties (e.g., our DOE regulator) are kept apprised of new design developments.

Regularly throughout design progress, the team evaluates the design progress against the few-month plan, identifies the need for additional design sprints, and adjusts upcoming objectives. This progress is also gauged against a longer-term schedule—progress and any identified issues are communicated to program leadership. For example, current COVID-19 restrictions have slowed design and testing sprints due to facility access issues, and attention has been given to refining other components and finalizing the preliminary design of the reactor components.

DISCUSSION

The TCR program design thrust has adopted many agile practices in its design process to maximize the use of additive manufacturing processes and to quickly arrive at a feasible and manufacturable reactor design. This is driven by an interdisciplinary team rapidly generating working designs, iteratively refining requirements with TCR program leadership. A vertical integration of key technical contributors enables constant communication.

Ongoing design sprints focused on determining the feasibility of specific design features are to be completed before delivery of a preliminary reactor design. Following this, the iterative nature of the design process is expected to slow with the approach of final design, which involves generating requirements documents, performing safety analyses, and finalizing documentation and models. Emerging effectively from this agile design process to deliver a final design will involve a significant change in design approach but will still continue to emphasize technical excellence.

ACKNOWLEDGMENTS

This research was sponsored by the Transformational Challenge Reactor Program of the US Department of Energy Office of Nuclear Energy.

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