Design Downselection for the Transformational Challenge Reactor

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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 of large nuclear power plants [1], including disciplines such as civil, mechanical, electrical, and nuclear engineering. Beyond applications for existing nuclear reactors, these new manufacturing methods, advanced materials, and dimensional constraints can be applied to the nuclear core design process [2-5]. In the nuclear industry, a manufacturing-informed design approach has the potential to yield the most benefit from advanced manufacturing, leveraging advanced materials, data science, and rapid testing and deployment to drive down costs and development times, ultimately improving future commercial viability. This approach is being demonstrated in the US Department of Energy Office of Nuclear Energy (DOE-NE) Transformational Challenge Reactor (TCR) program [6].

Core design and analysis activities in the TCR program are driven by manufacturing, with a focus on rapid prototyping and innovation to support near-term deployment. No specific design or application was selected or targeted before undertaking these core design activities. An initial set of apparent hard constraints was established to narrow the design space, and several candidate core designs were generated and evaluated based on manufacturability and performance. The results provide supporting technical information for design downselection [7]. This summary discusses these design decisions and their technical bases.

CONSTRAINTS

Five design constraints for the reactor demonstration effort eliminate or deprioritize specific design options:

1. The reactor system must be designed, licensed, and constructed on an accelerated timeline. A key objective of the TCR program is to leverage advanced manufacturing technologies to rapidly develop and deploy a nuclear system on an accelerated timeline. This includes (1) evaluation of multiple designs, (2) downselection to a single design, and (3) maturing of the selected design.
2. Major components and services that are not advanced manufactured must be readily available (e.g., material, specifications, vendors) and procurable to meet the demonstration timeline. These are not R&D efforts. The availability of components rated for specific reactor conditions is also a limiting factor.
3. Components made via advanced manufacturing must be designed from materials for which the manufacturing process is well characterized, to include microstructure analysis, imperfections, dimensional control, and surface roughness [2, 3]. Ongoing R&D advanced manufacturing efforts will be leveraged if approaches are sufficiently de-risked to fit the accelerated timeline.
4. The core must be relatively small, preferably fitting within an envelope of one square meter. A small core is more practical for deploying high-resolution advanced manufacturing technologies and can be physically situated in a smaller enclosure [8].
5. The core must use less than 250 kg of high assay low-enriched uranium (HALEU). The core design should be optimized for fuel utilization. This upper limit amount has already been secured for use by the TCR program.

DESIGN DECISIONS

Major design decisions defining the conceptual design and their technical reasonings are discussed below. Provided an available design choice, simplicity is preferred. The order of discussion provides a general chronology of decisions made.

Coolant

The primary considerations governing the choice of coolant are thermal performance, neutronics, thermal-hydraulics, and materials compatibility. Because the desired outlet temperature is greater than 400 °C, viable coolant choices are limited. Sodium has been a favored coolant candidate for fast spectrum reactors because of its excellent heat transfer and heat capacity characteristics, but as a reactor coolant, sodium has several inherent disadvantages, including radioactivity during operation, a positive void reactivity coefficient, and adverse reactions with water, concrete, and air. Molten salts also come with a host of materials compatibility and component availability issues.

Consequently, helium is the favored coolant for the TCR. Helium, which does not activate during reactor operation, has the ability to adopt more simple heat rejection systems without additional intermediate heat transfer loops. The relative opacity of helium to neutrons is also an advantage, as loss of coolant or system depressurization does not result in

a significant insertion of reactivity. Furthermore, using helium as the coolant simplifies the selection of component materials because it is compatible with most materials.

Complications with a helium coolant include the need for a highly pressurized system (a few MPa), high-performance requirements for pumps and valves, and mitigation of potential coolant leakage. These issues are not prohibitive and have been addressed in previous high-temperature gas reactor programs [9-12]. Overall, the advantages of using helium are strong enough to proceed with helium as the coolant material for most preconceptual TCR designs.

Spectrum

Early preconceptual core design efforts focused on fast-spectrum core concepts, but none of these concepts resulted in critical cores containing less than 250 kg of HALEU [7]. Therefore, incorporation of a moderator material was explored to reduce the required mass of fuel for a critical configuration (Figure 1). Fast spectrum designs may be revisited if requirements change.

Fuel Form

Two fuel forms emerged from the design activities: (1) a more familiar conventionally fabricated UO_2 in additively manufactured steel cladding, and (2) conventionally fabricated tristructural isotropic (TRISO) fuel particles dispersed in an additively manufactured and densified SiC fuel element [8].

The UO_2-in-steel design includes a double-walled 316L stainless-steel cladding structure that is additively manufactured using laser powder bed fusion additive manufacturing technology. The structure contains internal spring mechanisms to enhance heat transfer and to accommodate fuel thermal expansion and irradiation-induced swelling. Coolant flows through the double-walled structure around the fuel elements, and the flow can be optimized radially and axially, yielding uniform power and temperature distributions.

The TRISO-in-SiC fuel form includes a binder jetted SiC fuel element with integrated cooling channels, which is filled with uranium nitride (UN) TRISO and SiC powder and is then densified using chemical vapor infiltration . This process yields a fuel element block that is densely packed with TRISO (~50% packing fraction), with cooling channels that can be highly optimized radially and axially, again yielding uniform power and temperature distributions.

The TRISO-in-SiC fuel form is more robust at high temperatures than UO_2-in-steel [13] fuel, but it is more technically challenging to fabricate than UO_2 in a metal cladding. Technology maturation of TRISO-in-SiC fabrication processes over the course of several months has sufficiently de-risked this fuel form, resulting in a viable fuel option. In addition to these considerations, the incorporation of steel in a thermal spectrum environment produces a significant reactivity penalty.

Moderator Form

Hydrogenous moderators are uniquely spatially efficient (Figure 2), providing for a smaller core volume [14]. Beryllium presents complicated handling issues, water is not compatible with these higher operating temperatures, and graphite greatly increases core volume. Technology maturation of yttrium hydride fabrication processes over the course of several months has sufficiently de-risked this moderator type, resulting in a viable option.

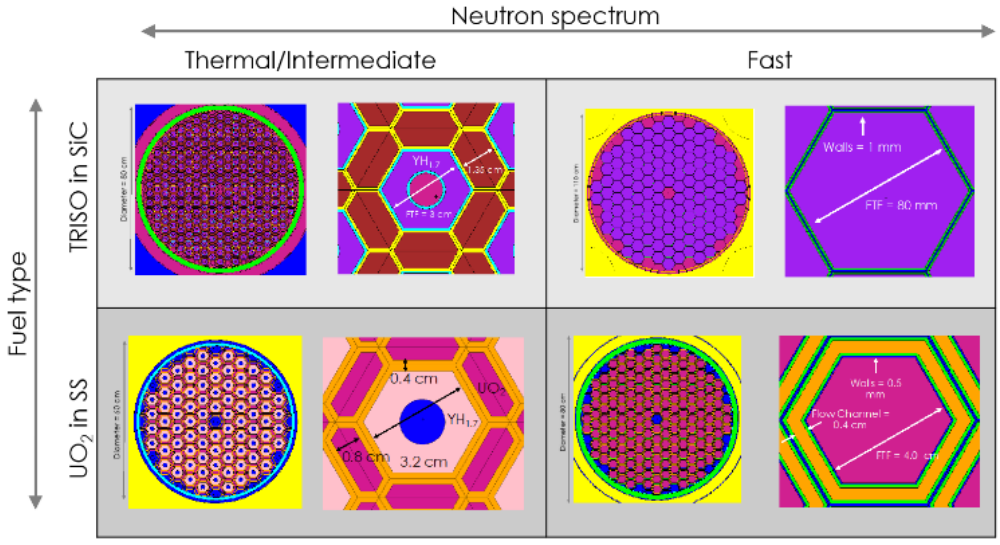

Fig. 1. Candidate preconceptual core design comparison.

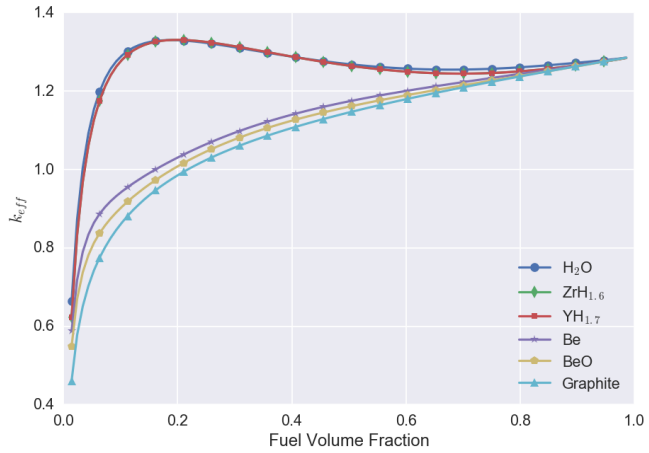

Fig. 2. k_{eff} as a function of fuel volume fraction for a 1-meter reflected spherical reactor core showing that only hydrogenous moderators yield increased reactivity when fuel is displaced.

While zirconium has a lower neutron capture cross section than yttrium, both are relatively low, so there is no significant difference in terms of neutron capture (Figure 2). Yttrium hydride exhibits improved thermal stability over zirconium hydride, with an equilibrium partial pressure of hydrogen as a function of temperature roughly three orders of magnitude smaller for yttrium hydride (Figure 3) [15, 16]. For elevated temperature application of metal hydride moderators, this represents a distinct advantage of yttrium hydride over zirconium hydride. In addition, the use of yttrium in other industries has made a stock of relatively pure yttrium metal available. Yttrium hydride within the core must be encapsulated.

Reactivity Control

Designing a moving control rod or drive mechanism through a high-temperature helium pressure boundary is an extensive R&D effort outside the scope of this program. Internal core control mechanisms increase the complexity of the pressure vessel head, requiring additional stand-pipes to accommodate compatible drive mechanisms and control rods. However, with a core that fits within an envelope of one square meter, an external control mechanism (e.g., drums, plates, shrouds) is possible and preferred. These external control mechanisms must be located within the radial reflector or between the core and the primary reflector. If the reflector is within the pressure vessel, then external control still increases the complexity of the pressure vessel head.

The resolution is to position the radial pressure vessel boundary adjacent to the active core and use two mechanisms to add negative reactivity to the system: an external primary control mechanism and an internal shutdown mechanism [17]. The control system is made up of several shroud elements that move axially adjacent to the pressure vessel and between the active core and the radial reflector. The shutdown rod is placed within a channel at the center of the core and is driven with a magnetic mechanism that (1) requires only a single stand-pipe on the pressure vessel head, and (2) does not require vessel penetrations.

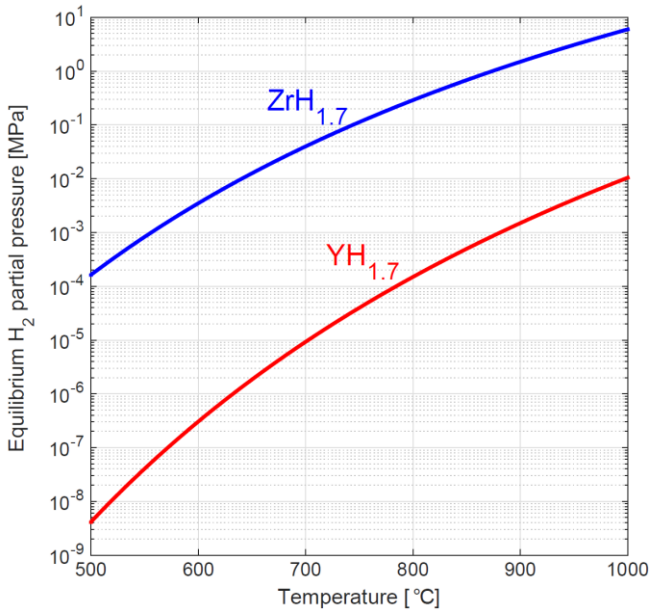

Fig. 3. Equilibrium partial pressure of H_2 as a function of temperature with zirconium and yttrium hydride with a hydrogen-to-metal ratio of 1.7.

Coolant Flow Path

The choice of coolant flow around and through the core was reduced to three coolant flow paths (Figure 4), as (1) side penetrations were eliminated as an option due to the control shroud running adjacent to the pressure vessel, and (2) an inlet and outlet at the bottom of the reactor are favored for ease of installation before fuel loading. Moderator temperature constraints (Figure 3) may be greatly mitigated by thermally insulating the moderator form. However, this leads to the most complex option, A, and is not necessary for the maximum temperatures reached in this demonstration. Options B is approximately as complex as option C, as moving the outlet to the top would increase the complexity of the pressure vessel head.

SUMMARY

The resulting downselected TCR core design has challenging design characteristics, yet it balances simplicity and robustness with safety, licensing, and operation. The core is

1. cooled with pressurized helium,
2. has a thermal-to-intermediate neutron spectrum,
3. contains TRISO-in-SiC fuel forms,
4. contains yttrium hydride in steel moderator forms,

5. uses an external control mechanism, and
6. flows coolant in and out from the bottom of the vessel and once through the core (top down).

Potential design changes may be implemented to accommodate changes to desired outcomes or performance metrics.

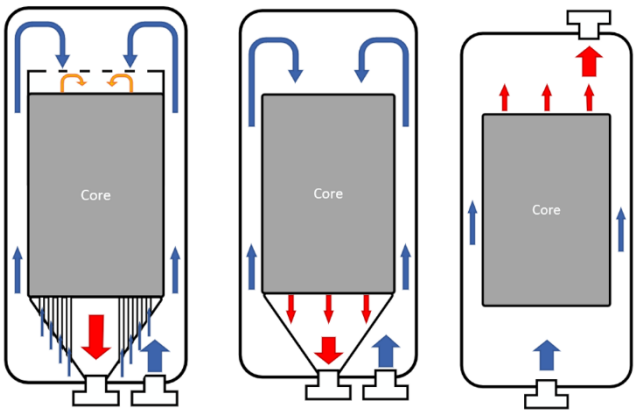

Fig. 4. Coolant flow options A, B, and C (left to right). The flange on the pressure vessel is head not shown.

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