Power Level 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].

Initial core design activities demonstrated the feasibility and safety of a reactor operated for a few hours at less than 1 MWt. After this initial feasibility assessment, candidate core designs [7, 8] were analyzed for operation at higher powers up to and including 19 MWt to determine the impact of uprating and to select a power level that meets TCR programmatic objectives without adding significant risk or costs. This summary presents these analyses and describes selection of the power level.

BACKGROUND

The baseline system design for uprating analyses has a single primary pressurized helium loop transferring heat to a secondary ambient air loop (Figure 1). The small cylindrical core fits within an envelope of 1 m^3 and consists of yttrium hydride in steel moderator forms. Two fuel implementations were used in these analyses: conventionally manufactured uranium nitride (UN) tristructural isotropic (TRISO) fuel contained in SiC, and conventionally manufactured UO_2 in steel (Figure 2). This simple system was designed for a low power level and requires additional design changes to accommodate higher power levels.

The reactor must operate safely under all anticipated operating conditions. Core conditions are being assessed at steady state and during unlikely and extremely unlikely events. These analyses include core neutronic design, source term analysis, thermal hydraulic design, safety analyses, system design, and cost estimation. Analyses presented herein leverage the Shift transport and depletion code [9, 10], and MCNP6 [11] for neutron transport and reactor physics, SCALE [12-14] for source term analyses, TRACE [15] and RELAP [16] for safety analyses, and COMSOL [17] for thermal hydraulics.

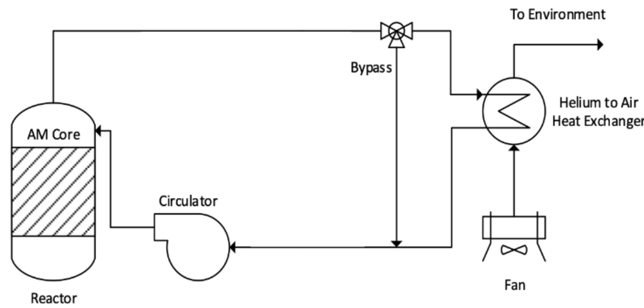

Fig. 1. Simple system diagram for power uprate analyses.

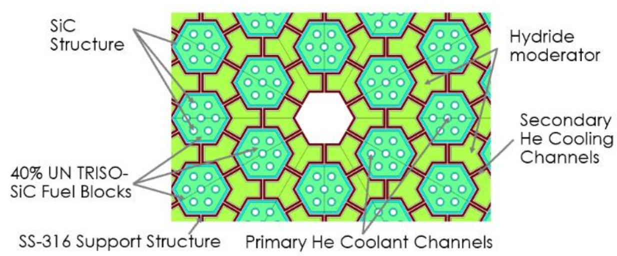

Fig. 2. Core subsection of TRISO-in-SiC–fueled preconceptual design.

BACKGROUND

Core conditions such as material temperatures and power densities, as well as design considerations such as component availability and cost are being evaluated to understand the limitations and constraints impacting a potential uprate.

Reactor Physics and Source Term

Criticality is independent of power level, but design changes must accompany an increase in core power density to maintain sufficiently low fuel material temperatures during

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steady-state operation. Potential options include increasing coolant flow rate, increasing coolant volume fraction, decreasing coolant pitch (i.e., fuel thickness), and increasing fuel volume. Analyses show that with these increases, the fuel demand is not limiting (Figure 3). Still, a power uprate (1) increases reactivity feedback from xenon buildup and (2) adds complexity to the control system, as an increase in core size reduces the reactivity worth of external control elements.

The radiological source term scales with power and operating time, but even with conservative release assumptions, the total effective dose equivalent at the site boundary is within limits. Due to the short operation time, this source term is not expected to be limiting.

Thermal Hydraulics

An increase in core power density requires improved heat transfer to coolant to maintain acceptable material temperatures. A feasible reduction in coolant pitch (i.e., fuel thickness), an increase in coolant volume, and an increase in mass flow rates are able to maintain acceptable peak steady-state temperatures for UO_2-in-steel and TRISO-in-SiC fuel forms (Table I). However, inflexibility in the design of the UO_2 fuel forms and higher power densities drive higher peak temperatures in the UO_2-in-steel design at steady state. Additionally, high coolant flow rates may worsen flow-induced vibration issues and increase system complexity. Therefore, the TRISO-in-SiC fuel was selected instead of the UO_2-in-steel form.

TABLE I. Steady-state thermal hydraulic analysis of TRISO-in-SiC core design.

Parameter	**1 MW**	**6 MW**	**12 MW**
Thermal hydraulics			
Reynolds number	4,635	12,128	18,032
Velocity [m/s]	8.9	19.8	26.1
Heat transfer coefficient [W/m^2-K]	1,152	2,330	3,045
Friction factor [-]	0.059	0.055	0.054
Core pressure drop [Pa]	2,388	12,174	22,342
Power density [MW/m^3]			
q''' (fuel volume)	7.61	45.7	91.3
q''' (total volume)	1.93	11.6	23.2
Temperatures [K]			
Coolant Inlet	704	604	534
Coolant Outlet	773	773	773
Fuel Surface	787	814	836
Fuel Peak	787	816	840
ΔT [K]			
Coolant	68.9	169	239
Convection	13.9	41.3	63.2
Fuel	0.3	1.7	3.3

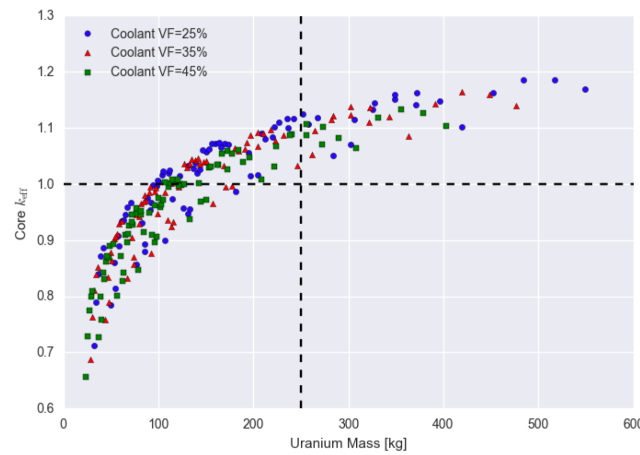

Fig. 3. Criticality of a simple core model as a function of coolant volume fraction showing a range of feasible designs below 250 kg of uranium.

Safety Analyses

Several very unlikely transient events were analyzed to determine the impact of power on peak material temperatures. The following three scenarios capture the limiting constraints.

1. **Depressurized loss of forced cooling (DLOFC).** For the DLOFC analysis, no natural circulation was assumed, and a two-dimensional core slice model was used to perform the heat conduction from the core to the reflector (Figure 4). Uprating increases residual decay heat and increases temperature increase during the event (Figure 5). A power of 6 MWt or higher would require a system redesign to eliminate this scenario or an improved decay heat removal mechanism.

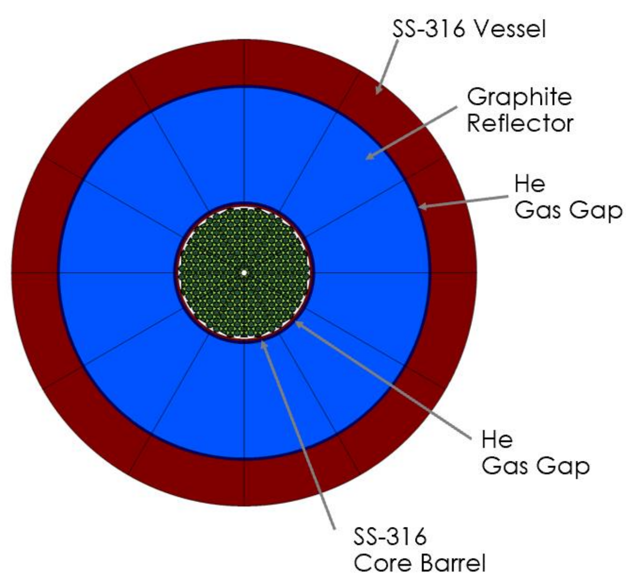

Fig. 4. Two-dimensional core slice model for DLOFC simulations.

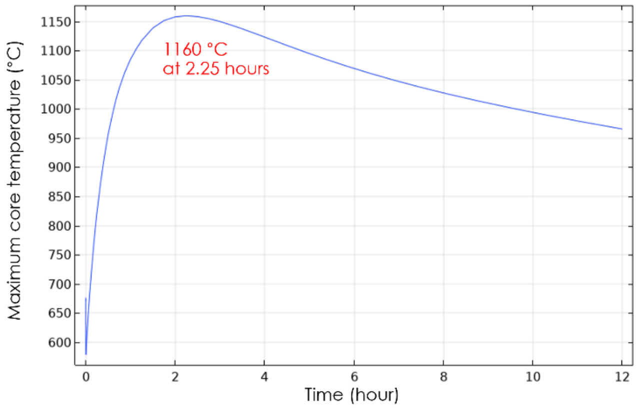

Fig. 5. Characteristic temperature increase during a DLOFC from a power of 6 MW.

2. **Pressurized loss of forced cooling (PLOFC).** For the PLOFC analysis, no scram was assumed. Uprating increases the peak temperature in a PLOFC, but an increase in natural circulation offsets some of this temperature rise (Figure 6). A power of 9 MWt and higher would require a system and/or core redesign to improve natural circulation or a change in coolant density. The core with TRISO-in-SiC fuel forms is safer due to the higher power density in the core with UO_2-in-steel fuel forms.

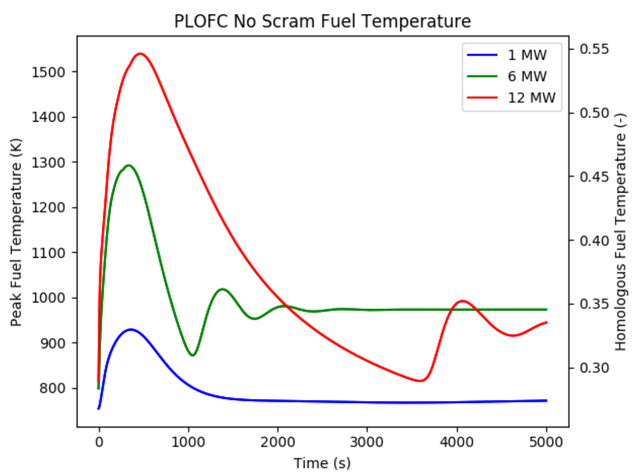

Fig. 6. Characteristic temperature increase during a PLOFC without scram for the core design with TRISO-in-SiC fuel.

3. **Reactivity insertion.** For the reactivity insertion analysis, no scram was assumed. Uprating increases the peak fuel temperature in a reactivity insertion accident, but outlet temperature is limited by negative fuel temperature feedback. The peak temperature is not limiting, but a reactivity insertion may result in a very high peak power density in microsphere kernels, requiring an additional negative reactivity feedback mechanism.

Costs

Costs of increasing core power are estimated from initial programmatic work breakdowns for all activities associated with the TCR program and estimates from system component scoping analyses. The cost increase from 0.5 to 3 MWt is estimated at 20%. This increase is primarily due to the larger sizes and performance requirements for system components. Beyond 3 MWt, cost increases at a much higher rate, as multiple units of the largest available components (e.g., heat exchangers and circulators) are necessary to reject nuclear heat from the core. Additional external heat dissipation structures, larger facilities, and decay heat rejection mechanisms are required to operate at some higher powers. For these reasons, a 6 MWt system is expected to cost approximately twice as much as a 0.5 MWt system.

CONCLUSIONS

The core with TRISO-in-SiC fuel forms outperforms the core with UO_2-in-steel fuel forms in transient scenarios without scram due to a lower power density, stronger feedback mechanisms, and larger margin to failure. An increase in core volume for the UO_2-in-steel design would reduce peak fuel temperatures, but this is limited by the feasibility of external control mechanisms.

Temperature increase during a DLOFC limits the maximum power at which the TCR may safely operate without additional complex decay heat removal systems to 6 MWt. In addition, the cost for a heat rejection system above 6 MWt is prohibitive. Increasing power from 3 to 6 MWt would require multiple units of the largest available components; furthermore, very large heat exchangers and high-performance circulators would be required. A power selection of 3 MWt is made, as it (1) maintains acceptable temperatures in unlikely transient scenarios with passive decay heat removal, (2) keeps the system footprint to a minimum, and (3) balances technical challenges with cost as appropriate for a short-term operation.

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