Control Element Design for the Transformational Challenge Reactor (TCR)

J.R. Burns,[1]* B.R Betzler,[1] B. Ade,[1] F. Heidet,[2] A. Bergeron[2]

[1]Oak Ridge National Laboratory, Oak Ridge, TN 37831
[2]Argonne National Laboratory, Lemont, IL 60439
**burnsjr@ornl.gov*
https://dx.doi.org/10.13182/T122-32325

INTRODUCTION

The Transformational Challenge Reactor (TCR) program is a reactor design, manufacturing, and demonstration effort that leverages recent scientific achievements in advanced manufacturing, nuclear materials, machine learning, and computational modeling and simulation to design, license, construct, and operate a nuclear reactor. These scientific advances enable a paradigm shift in reactor design and deployment [1, 2]. In particular, the incorporation of advanced manufacturing techniques such as laser powder bed fusion and binder jet printing enables the realization of structures free from the geometric and material constraints inherent to conventional manufacturing, thereby opening the design space for the targeted achievement of desired reactor performance outcomes [1—4]. In addition, the synergy between the reactor design and manufacturing allows for application of an agile approach to facilitate an accelerated development timeline relative to conventionally manufactured reactor systems.

A small yet critical facet within the TCR core design thrust is the design of control elements. TCR takes advantage of a compact core design and unique control elements for safe and reliable operation of the reactor. This work covers the design philosophy behind the key features of the TCR control elements and discusses the approach to and justification for the current control element design.

DESIGN CONSIDERATIONS AND PERFORMANCE

The TCR is a helium-cooled thermal spectrum reactor. The major reactor design features are highlighted in Fig. 1 (reproduced from Terrani [2]). The reactor core is housed in a steel vessel, which is enclosed by a control shroud, steel radial reflector, and biological shield. The absence of industrially available nuclear-grade high temperature gas seal technologies precludes penetrations into the vessel for moving control components. Development of seals and drive mechanisms that can withstand the thermo-mechanically demanding conditions of a high-temperature gas reactor is well beyond the scope of TCR demonstration that is focused on advanced design, manufacturing, monitoring, and qualification of the compact nuclear core. Therefore, taking advantage of control components external to the reactor vessel primary coolant pressure boundary provides for the simplest implementation.

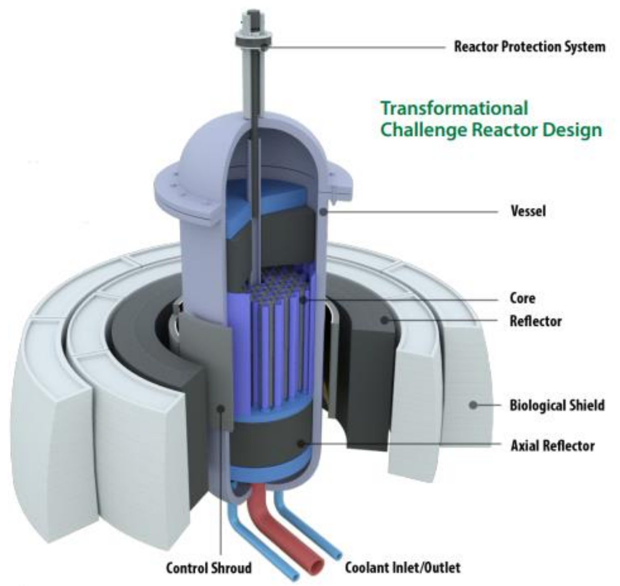

Fig. 1. TCR design [2].

The constraint necessitating external control gives rise to the control component configurations identified in Fig. 1. Two independent reactivity control systems are included in the reactor design. Configurations resembling conventional control rods are selected for simplicity and ease of operation, whereby neutron-absorbing structures are moved toward and away from the active core to adjust the free neutron population. This reactivity control approach has precedence in operating research reactors, including the High Flux Isotope Reactor at Oak Ridge National Laboratory (ORNL) [5] and the University of Missouri Research Reactor [6]. The primary neutron-absorbing material that makes up the control elements is B_4C, which captures neutrons via the $^{10}B(n,\alpha)^7Li$ reaction. The reactivity worth of the control elements may be tuned by ^{10}B enrichment. To cover excess core reactivity, temperature and power defects, and uncertainties, an integral reactivity worth of 4000 pcm is required for control. Full-core models in MCNP are used to assess control component designs on their ability to meet this required reactivity worth.

A central vessel annulus is reserved for a safety shutdown rod. Given that thermal neutron flux naturally peaks in the center of the core, the reactor vessel annulus yields a safety rod with high reactivity worth without penetration of the vessel. This safety rod moves in the axial direction and is actuated by the reactor protection system [7]; it is fully withdrawn during normal operation and is only inserted in scram scenarios. The integral reactivity worth of the shutdown rod is roughly 4000 pcm.

The control shroud is the second reactivity control component, providing mechanical shim and power level adjustment during reactor operation. The shroud configuration—a cylindrical shell in eight individual segments enclosing the reactor vessel—affords the closest possible proximity to the core without penetrating the vessel, yielding the greatest achievable reactivity worth. Even so, adequate reactivity worth is difficult to achieve in this configuration; whereas the safety rod is positioned in a naturally high-worth position in the center of the core, the control shroud operates at the low-worth periphery of the core and competes with neutron absorption in the steel vessel. This challenge is evident in the neutron current spectra exiting the core into the control shroud region and reentering the control region from the reflector; these are plotted in Fig. 2. To improve the effectiveness of the ^{10}B in the control shroud without excessively costly enrichment, a graphite moderator is proposed for thermalizing neutrons in the control region, improving the likelihood of their absorption in both the B_4C and the steel reflector. A cross section of the resulting configuration is shown in Fig. 3. With the moderating region backing the absorbing region of the shroud, it is ensured that the shroud insertion does not increase reactivity; instead, the absorber filters the current entering the moderating region to yield a hard spectrum that is subsequently thermalized in scattering into the reflector and back into the core. The integral reactivity worth curve for this control shroud configuration is shown in Fig. 4, based on the assumption that all segments of the shroud move symmetrically. Figure 4 indicates that this design meets the requirement for 4000 pcm integral reactivity worth. These calculations were carried out under beginning-of-life conditions with unirradiated fuel compositions. Given the brief anticipated operating time of the TCR (< 1 day at full power), control element reactivity worth is expected to be minimally impacted by fuel depletion. This assertion will be explicitly evaluated in future analyses.

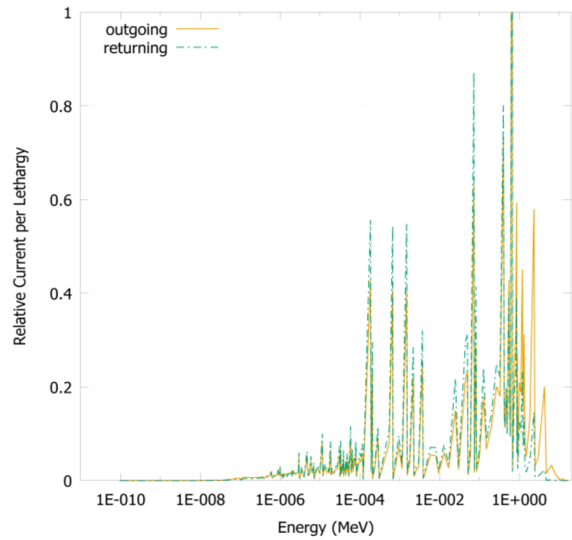

Fig. 2. Outgoing and incoming neutron current spectra in the control shroud region.

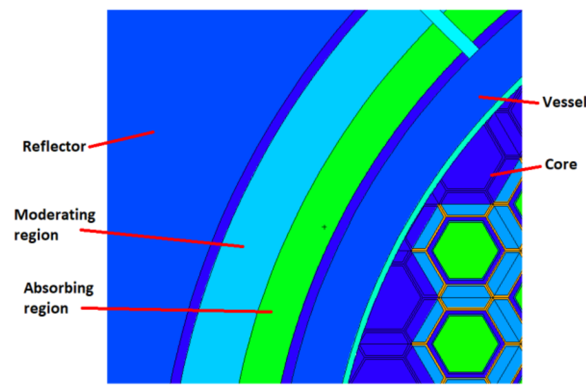

Fig. 3. Two-region control shroud configuration.

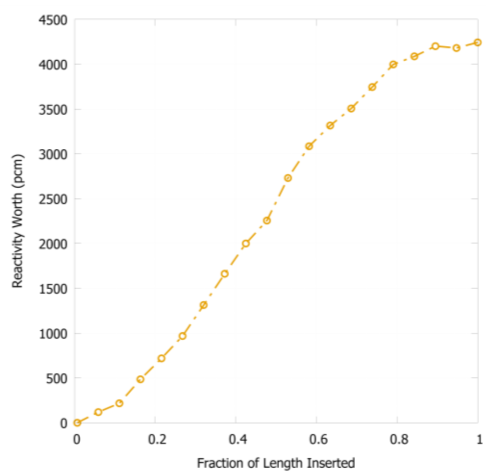

Fig. 4. Control shroud integral reactivity worth curve.

CONCLUSIONS

This work provides an overview of the TCR control element design task, highlighting the practical drivers of key design decisions. Two redundant control systems ensure reliable shutdown and fine shim operation capability with no penetration into the core internals. While the TCR core design continues to mature, the challenges and solutions identified here provide a template within which reliability of control components can be maintained throughout impending core design and optimization tasks. Control component manufacturing capabilities are under active development as well, leveraging established nuclear material vendors and advanced manufacturing technologies at ORNL.

ACKNOWLEDGEMENTS

The Transformational Challenge Reactor program is supported by the US Department of Energy Office of Nuclear Energy.

REFERENCES

1. J. BUSBY, M. HACKETT, L. LOVE, S. BABU, K. TOBIN, R. CAO, D. POINTER, A. WHARTON, L. QUALLS, B. BETZLER, "Technologies to reactors: Enabling accelerated deployment of nuclear energy systems," ORNL/SPR-2018/1025, Oak Ridge National Laboratory (2018).
2. K.A. TERRANI, "Transformational Challenge Reactor demonstration program" (2019). Retrieved from http://tcr.ornl.gov.
3. J. SIMPSON, J. HALEY, C. CRAMER, O. SHAFER, A. ELLIOTT, W. PETER, L. LOVE, R. DEHOFF, "Considerations for application of additive manufacturing to nuclear reactor core components," ORNL/TM-2019-1190, Oak Ridge National Laboratory (2019).
4. K. TERRANI, B. JOLLY, M. TRAMMELL, "3D printing of high-purity silicon carbide," *J. Am. Ceram. Soc.* 103 (2020) 1575—1581.
5. B.R. BETZLER, "High Flux Isotope Reactor operating conditions," ORNL/TM-2010/168, Oak Ridge National Laboratory (2010).
6. J.A. STILLMAN, E.E. FELDMAN, D. JALUVKA, E.H. WILSON, L.P. FOYTO, K. KUTIKKAD, J.C. MCKIBBEN, N.J. PETERS, "Accident analyses for conversion of the University of Missouri Research Reactor (MURR) from highly-enriched to low-enriched uranium," ANL/GTRI/TM-14/5 rev. 1, Argonne National Laboratory (2017).
7. S.M. CETINER, P. RAMUHALLI, "Transformational Challenge Reactor autonomous control system framework and key enabling technologies," ORNL/SPR-2019/1178, Oak Ridge National Laboratory (2019).