ASSESSING A PROLIFERATION RESISTANCE METHODOLOGY: SODIUM-COOLED FAST REACTOR CASE STUDY

Conducting case studies of a sodium-cooled fast reactors and other advanced reactor designs to support the development of a proliferation resistance methodology

M.M. ARNO [1], A.J. BRUNETT[2], T. FEI[2], S.S. Chirayath

[1]Oak Ridge National Laboratory, Oak Ridge, USA
[2]Argonne National Laboratory, Lemont, USA

Corresponding author: M.M. ARNO, arnomm@ornl.gov

INTRODUCTION

The Proliferation Resistance Optimization (PRO-X) program provides a framework for integrating proliferation resistance into nuclear system designs to maximize proliferation resistance while optimizing system performance for peaceful uses. Managed by the Office of Reactor Conversion and Uranium Supply (NA-231) within the Office of Material Management and Minimization within the US Department of Energy's National Nuclear Security Administration, the PRO-X program is composed of two components—a research reactor project (PRO-RR) and a project on advanced reactors and their associated fuel cycles (PRO-AR&FC). PRO-AR&FC began in mid-2024. The project's goal is to integrate intrinsic proliferation resistance attributes into the optimization of advanced reactor designs, including small modular reactors and microreactors, and their associated fuel cycles to impede the production, extraction, and utility of weapons-usable nuclear material. With this goal in mind, this project defines proliferation resistance as the characteristics of a reactor or fuel cycle facility, system, or material that impede the production, extraction, and/or utility of weapons-usable nuclear material. This definition of proliferation resistance is slightly different from the one used by the International Atomic Energy Agency (IAEA), which is "that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States intent on acquiring nuclear weapons or other explosive devices" [1]. Instead, the PRO-AR&FC definition of proliferation resistance aligns more with the IAEA's definition of intrinsic proliferation resistance features, which is "those features that result from the technical design of nuclear energy systems, including those that facilitate the implementation of extrinsic measures" [1]. The PRO-AR&FC project's Phase I work scope includes developing a methodology to assess proliferation resistance, testing the methodology by applying it to case studies focused on different types of advanced reactors, and planning for engagements with advanced reactor stakeholders on intrinsic proliferation resistance measures. The paper provides an overview of the assessments work scope, focusing on the sodium-cooled fast reactor design.

1. CASE STUDY ASSESSMENTS

To support the PRO-AR&FC goal, preliminary reactor facility design assessments will be conducted to inform the development of a framework for integrating proliferation resistance into advanced nuclear system designs. The objective of the assessments is to evaluate and test the proliferation resistance methodology [2] by applying it to various advanced reactor systems. This process will help ensure that the methodology captures all relevant intrinsic design features that contribute to proliferation resistance.

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In Phase I of the PRO-AR&FC project, the scope of the assessments is bounded by the reactor types and assessment scenarios that will be considered. Four types of advanced reactors of nonproprietary design nature were chosen that represent a wide swath of the advanced reactor landscape: integral pressurized water reactors, liquid-fuelled molten salt reactors, pebble bed reactors, and sodium-cooled fast reactors (SFRs). The specific design of each reactor type was limited to designs for which adequate data necessary to perform the assessments are publicly available.

In addition to evaluating the four advanced reactor designs, the proliferation resistance methodology will be assessed in the context of a fifth reactor: a representative large light water reactor (LWR). This fifth assessment aims to establish a benchmark for evaluating and testing the methodology's effectiveness and reliability.

To comprehensively assess the proliferation resistance methodology, the project team must assess the intrinsic features of reactor systems, reactor and fuel cycle facilities, fuel cycle decisions, and materials associated with each advanced reactor design in the context of different scenarios. The PRO-AR&FC project's assessment scenarios will initially consider only reactor facility attributes, including limited fuel cycle decisions such as fresh fuel chemical and isotopic composition and the material form of the irradiated fuel.

In Phase I, the PRO-AR&FC project team will complete five case studies, all within the same context, generating multiple datasets consisting of a range of values for each attribute defined in the proliferation resistance methodology for five categories of non-proprietary advanced reactor designs. The overall goal of these case studies is to assess whether the methodology captures the proliferation resistance–relevant aspects of a wide range of reactor designs. Results will be incorporated into further refinements of the methodology under the scope of Phase II of the PRO-AR&FC project. To illustrate, this paper provides additional detail on the SFR assessment.

2. OVERVIEW OF SFR DESIGN FEATURES

For the assessment study, the modified Advanced Burner Test Reactor (ABTR) [3] (Table 1, Fig. 1) was selected as the SFR case study. The ABTR design was originally developed as part of the Advanced Burner Reactor Program to demonstrate transmutation technologies that can produce energy while providing a reduction in the transuranic elements recovered from LWR fuel without necessitating Pu separation. Moreover, the reactor incorporates innovative design features that may lead to improvements in safety, efficiency, and reliability, primarily through its utilization of passive heat rejection systems and metallic fuels that present favourable inherent feedback characteristics.

The ABTR uses a pool-type design, with the core, primary pumps, intermediate heat exchangers, and decay heat removal systems (direct reactor auxiliary cooling system [DRACS]) immersed in a sodium pool that is within the reactor vessel. Hot and cold sodium pools are separated by a redan (a divider). This redan comprises the primary heat transport system (PHTS). The intermediate heat transport system transfers heat from the PHTS to a series of Na-to-CO_2 heat exchangers that use a Brayton cycle power conversion system. In the absence of a loss of heat sink event, the DRACS loop can be used to transfer decay heat-level loads from the PHTS to the atmosphere.

Given the short refuelling interval (4 months) and the need for efficient fuel handling, in-vessel fuel storage that is passively cooled using primary sodium coolant is used. Fuel handling is accomplished using two separate machines that are each used for one specific activity. In-vessel fuel movement (e.g., in-core subassembly rotation, in-vessel rotation from core to storage) is accomplished using a pantograph-type fuel handling machine (FHM). The FHM operates within a single rotating plug in the vessel head, which means that other access points are not necessary. Transfer of subassemblies from the reactor vessel to a fuel handling building is accomplished using a fuel unloading machine and an inter-building transfer cask, a system similar to the one used at the Experimental Breeder Reactor [1].

TABLE 1. ABTR DESIGN PARAMETERS [1]

Parameter	Value
Reactor power	250 MWt
Coolant	Sodium
Driver fuel	Metallic rods (90% HALEU, 10% Zr) in hexagonal assemblies
Cladding	HT9 stainless steel
Design life	30 years
Refueling cycle	4 months
Power conversion cycle	SCO_2 Brayton
Thermal efficiency	38%

Note: TRU = transuranic elements; SCO2 = supercritical CO2.

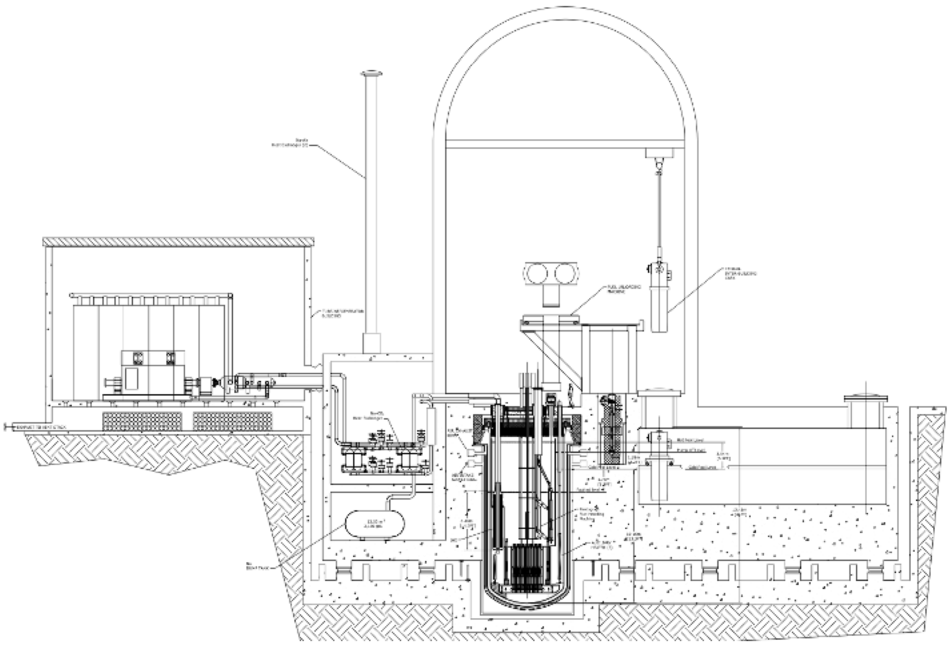

FIG. 1. Layout of the ABTR facility [3].

3. CALCULATION OF ATTRIBUTES

The Argonne Reactor Computation (ARC) fast reactor tool suite is employed for the calculation of the proliferation resistance attributes. More specifically, the REBUS/DIF3D [4] [5] code is used to evaluate the performance of the selected fast reactor. DIF3D evaluates neutronic characteristics such as neutron flux and *k*-eff, whereas REBUS relies on the DIF3D data to perform depletion calculations and assess fuel cycle characteristics, such as determining the fissile content required to reach the target power and cycle length and determining the discharged fuel actinide vectors/isotopics.

Once the heavy metal mass flow is determined from the REBUS/DIF3D calculation, the spent fuel characteristics (e.g., radioactivity and decay heat) are calculated using the Oak Ridge Isotope GENeration (ORIGEN) code [6] coupled with REBUS. The ORIGEN calculation provides detailed fission product information, whereas the REBUS calculation is based on lumped fission products. Finally, the Monte Carlo N-Particle (MCNP) code is used to evaluate the spent fuel characteristics.

These calculations will help characterize the proliferation resistance attributes defined by the methodology team.

4. NEXT STEPS

After the initial case studies are completed and the results and lessons learned are integrated into the methodology, this project will consider additional contexts and additional reactor design features. In the initial assessments, each reactor design will be considered in the same context—one that assumes that the reactor is operating in a state with no other nuclear fuel cycle capabilities and that the reactor itself is stationary and terrestrially based. As the PRO-AR&FC project continues, the reactors will be assessed in additional contexts (e.g., contexts that introduce additional fuel cycle capabilities and deployment schemes).

The project team recognizes that in defining each non-proprietary reactor design, certain assumptions must be made to complete the assessment. Throughout the initial assessment, these assumptions and alternative design choices are being documented so that future assessments can consider alternative design options. Considering a broad range of assessment contexts and alternative reactor design features will allow the PRO-AR&FC project to comprehensively stress test the proliferation resistance methodology.

5. SUMMARY

The PRO-AR&FC project team is developing a technical, objective, and repeatable methodology to assess and optimize for proliferation resistance. A three-step process is in progress to develop the proliferation resistance methodology. Case study assessments of different advanced reactor designs are being conducted to ensure that the proliferation resistance methodology incorporates design details and operational features across a range of reactor designs.

REFERENCES

[1] IAEA, “Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems INPRO Manual - Proliferation Resistance,” IAEA, Vienna, 2008.

[2] S. Chirayath, R. Chamberlin, K. Hogue, J. Osborn, S. Skutnik, L. Crabtree, N. Hubley, L. Evans, J. Joshi, M. Arno and T. Hanlon, “Proliferation Resistance Assessment Methodology: Development of a Methodology for Proliferation Optimisation of Advanced Reactors and Fuel Cycle Using Intrinsic Attributes,” in *IAEA Technical Meeting on Proliferation Resistance of Fast Reactors and Associated Fuel Cycles*, 2025.

[3] Y. Chang and et al., “Advanced Burner Test Reactor Preconceptual Design Report,” Argonne National Laboratory, 2006.

[4] W. Yang and M. Smith, “Theory Manual for the Fuel Cycle Analysis Code REBUS,” Argonne National Laboratory, 2020.

[5] M. Smith, E. Lewis and E. Shemon, “DIF3D-VARIANT 11.0, A Decade of Updates,” Argonne National Laboratory, 2014.

[6] Oak Ridge National Laboratory, “Scale: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design, Version 6.1,” 2011.