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

Conducting case studies of a SFR and other advanced reactor designs to support the development of a proliferation resistance methodology

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INTRODUCTION

The Proliferation Resistance Optimization Program (PRO-X) provides a framework for integrating proliferation resistance in nuclear system designs to maximize the proliferation resistance while optimizing system performance for peaceful uses. Managed by the US Department of Energy (DOE), National Nuclear Security Administration (NNSA), Material Management and Minimization's Office of Reactor Conversion and Uranium Supply (NA-231), PRO-X is comprised 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 and has a goal to integrate intrinsic proliferation resistance attributes into the optimization of advanced reactor designs, including small modular and micro reactors, and their associated fuel cycles in order 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 impedes the production, extraction, and/or utility of weapons usable nuclear material. This definition of proliferation resistance is slightly different than the one used by the IAEA which is defined as "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 are "those features that result from the technical design of nuclear energy systems, including those that facilitate the implementation of extrinsic measures." [1]

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 focusing on different types of advanced reactors, and planning for engagements with advanced reactor stakeholders on intrinsic proliferation resistance measures. [2] This abstract aims to give an overview of the assessments work scope, focusing on the sodium-cooled fast reactor (SFR) 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 methodology by applying it to various advanced reactor systems. This process will help ensure that the methodology will capture all relevant intrinsic design features that contribute to proliferation resistance.

In Phase I of the PRO-AR&FC project, the scope of the assessments is bounded by the reactor type and the 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 (*i*PWR), liquid-fueled molten salt reactors (MSR), pebble bed reactors (PBR), and SFRs. The choice of a specific design of each reactor type is limited to designs for which adequate data necessary to perform the assessments is publicly available in the open source.

In addition to evaluating the four advanced reactor designs, an assessment of the methodology will also be performed 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, assessments of the intrinsic features of reactor systems, reactor and fuel cycle facilities, fuel cycle decisions, and materials associated with each advanced reactor design must be done in the context of different scenarios. The PRO-AR&FC project's assessment scenarios will initially consider only the attributes of the reactor facility, 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 data sets 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 conducting 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 refining 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

As part of the assessment study, the Advanced Burner Test Reactor (ABTR) [3] (FIG. 1) has been 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 transuranic elements recovered from light water reactor fuel without necessitating plutonium separation. Moreover, the reactor design incorporates innovative design features that can 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 is configured as a pool-type design, with the core, primary pumps, intermediate heat exchangers (IHXs), and decay heat removal systems (direct reactor auxiliary cooling system, DRACS) immersed in a sodium pool that is within the reactor vessel, with hot and cold sodium pools being separated by a redan (a divider). This 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 which utilize a Brayton cycle power conversion system. In the absence of a loss of heat sink event, the DRACS loop can be utilized 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 is utilized which is passively cooled using primary sodium coolant. Fuel handling is accomplished using two separate machines which are each purposed 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, meaning 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 inter-building transfer cask, similar to the system utilized at the Experimental Breeder Reactor (EBR-II). [1]

TABLE 1. ABTR DESIGN PARAMETERS [1]

Parameter	Value
Reactor power	250 MWt
Coolant	Sodium
Driver fuel	Metallic (20% TRU, 80% U) rods in hexagonal assemblies
Cladding	HT9 stainless steel
Design life	30 yr
Refueling cycle	4 mo
Power conversion cycle	SCO_2 Brayton
Thermal efficiency	38%

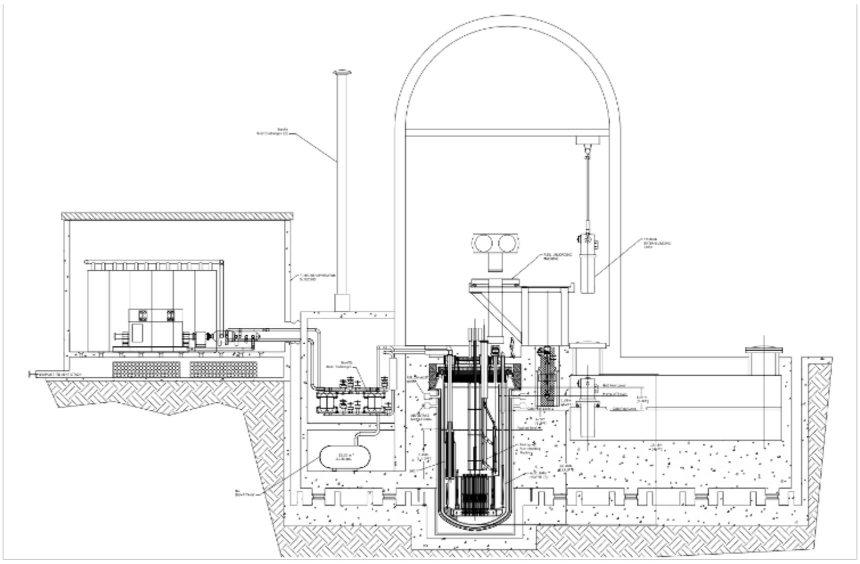

FIG. 1. Layout of the ABTR facility. [3]

3. CALCULATION OF ATTRIBUTES

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

Once the heavy metal mass flow is determined from the REBUS/DIF3D calculation, the spent fuel characteristics (e.g., radioactivity and decay heat) would be calculated using ORIGEN [6] coupled with REBUS. The ORIGEN calculation would provide detailed fission product information whereas the REBUS calculation is based on lumped fission products. At last, the MCNP code is used to evaluate the radiation dose rate for bare critical mass. 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 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 that assumes the reactor is operating in a state with no other nuclear fuel cycle capabilities and that the reactor itself is stationary and terrestrial-based. As the PRO-AR&FC project continues, the reactors will be assessed in additional contexts, such as any introducing additional fuel cycle capabilities and deployment schemes.

It is recognized that in defining each non-proprietary reactor design, certain assumptions had to be made in order 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 to comprehensively stress test the proliferation resistance assessment methodology.

5. SUMMARY

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

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