PROLIFERATION RESISTANCE ASSESSMENT METHODOLOGY
Development of a Methodology for Proliferation Resistance Optimisation of Advanced Reactors and Fuel Cycle Using Intrinsic Attributes

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INTRODUCTION

The Proliferation Resistance Optimization Programme (PRO-X) was developed to provide a framework for integrating proliferation resistance in nuclear system designs to maximise proliferation resistance while optimising system performance for peaceful uses. The PRO-X programme is sponsored by the Office of Reactor Conversion and Uranium Supply (NA-231) within the US Department of Energy's National Nuclear Security Administration. The PRO-X Advanced Reactor and Fuel Cycle (PRO-AR&FC) project, that started in mid-2024, is a component of PRO-X program with the goal of optimising 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 materials. Design optimisation will focus on the intrinsic design features of advanced reactors with the objective of increasing proliferation resistance by recommending needed changes to the reactor facility design and associated fuel cycle decisions.

The PRO-AR&FC project defines *intrinsic 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 materials. It should be noted that this definition differs from the International Atomic Energy Agency (IAEA) adopted definition of proliferation resistance in their publication, Safeguards Technical Report Series No. 332 [1]. The IAEA defines proliferation resistance as that characteristic of a nuclear system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear explosive devices. In the IAEA definition, both intrinsic features and extrinsic measures of proliferation resistance are considered, whereas the PRO-AR&FC project focuses only on the intrinsic features. PRO-AR&FC project Phase I work scope includes developing a methodology to assess proliferation resistance, assessing publicly available advanced reactor designs of non-proprietary nature through case studies to test the methodology, and planning for PRO-AR&FC engagements with advanced reactor stakeholders. This paper discusses the development of a methodology for an intrinsic proliferation resistance assessment.

1. METHODOLOGY DEVELOPMENT

Proliferation resistance methodology development consisted of creating a list of attributes suitable to evaluate the intrinsic proliferation resistance of various types of advanced nuclear reactor facilities and their associated fuel cycle decisions. The physical and chemical forms and quantities of fresh and irradiated fuel present at the reactor facility will depend on the advanced reactor design and the associated fuel cycle decisions. They form important inputs for proliferation resistance assessment.

A three-step methodology development framework is being followed in the PRO-AR&FC project. The first step is to produce a list of intrinsic proliferation resistance attributes. Establishing a procedure to generate values for these attributes to ensure the reproducibility of the attribute values is the second step. The third step of the methodology is to establish a scheme to interpret and represent the results of the proliferation resistance attribute datasets to help guide refinements to facility design. This three-step framework for this methodology is shown in Fig. 1.

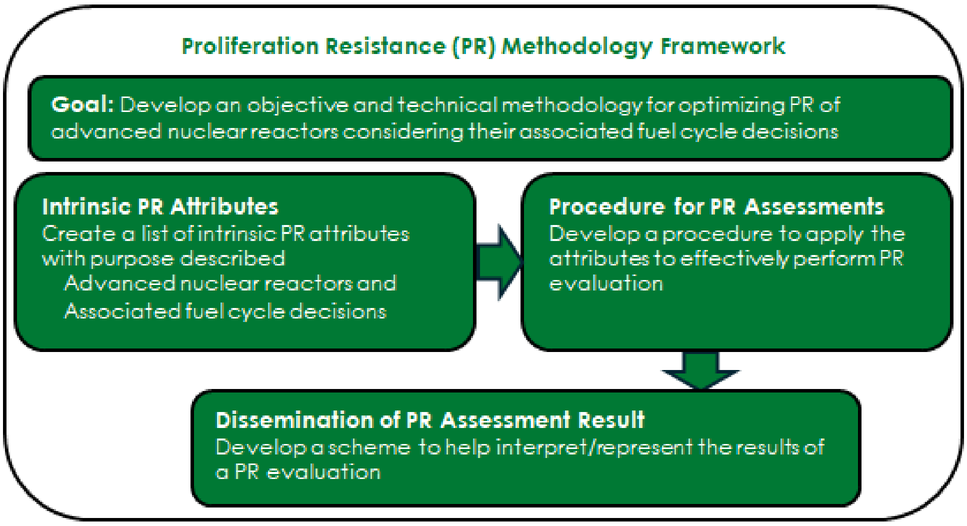

FIG. 1. Framework for developing an intrinsic proliferation resistance evaluation methodology.

1.1 List of intrinsic proliferation resistance attributes

Various proliferation resistance assessment methods, such as PR&PP (Proliferation Resistance and Physical Protection) [2], PRAETOR (Proliferation Resistance Analysis and Evaluation Tool for Observed Risk) [3,4,5], and INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles) [6,7] were reviewed by the PRO-AR&FC team members. Based on this review and discussions with a group of experts from multiple US Department of Energy national laboratories, the PRO-AR&FC team developed a list of intrinsic proliferation resistance attributes, which is shown in Table 1. This list of attributes will become the foundation of the proliferation resistance evaluation methodology development.

The draft list of attributes (Table 1) is categorized broadly into three groups. Ongoing case studies of different advanced reactor types will further refine these attributes toward a final version. Group 1 attributes capture the reactor design features that influence intrinsic proliferation resistance. Group 2 attributes capture the intrinsic proliferation resistance of the nuclear material present (or potentially present) at the reactor facility. Group 3 attributes capture reactor facility design features that influence intrinsic proliferation resistance.

1.2. Procedures to generate values for intrinsic proliferation resistance attributes

Procedures have been developed and documented to calculate attribute values needed for evaluating the intrinsic proliferation resistance of advanced reactors. Procedures will help in reproducibility and repeatability of the proliferation resistance evaluation. To calculate some of the Group 1 and Group 2 attribute values, data on fresh and irradiated nuclear fuel, such as mass, volume, composition, enrichment, and actinide content (uranium, plutonium, and thorium fractions), are required. Hence, reactor core physics simulations will need to be performed to generate data on irradiated nuclear fuel for both normal reactor operation and representative off-normal cases for proliferation resistance evaluation.

During Phase I of the project, the PRO-AR&FC team will complete five case studies and generate multiple datasets consisting of a range of values for each attribute for the five categories of non-proprietary reactor designs, considering normal reactor operations and specific misuse cases. These reactor design categories include four advanced reactor designs: an integral pressurized water reactor, a sodium-cooled fast reactor, a pebble bed reactor, a liquid-fuelled molten salt reactor. A fifth reactor design will represent traditional large light water reactors. Production of these datasets will stress test the methodology consisting of attributes, procedures to obtain values for the attributes, and the scheme to represent results. Stress test results will guide further methodology development during Phase II of the PRO-AR&FC project in evaluating proliferation resistance of a developer's specified advanced reactor designs (so-called baseline advanced reactor designs). Such an evaluation is ultimately intended to provide recommendations to reactor developers to refine the baseline reactor designs to optimize proliferation resistance while still achieving operational objectives.

TABLE 1. DRAFT LIST OF INTRINSIC PROLIFERATION RESISTANCE ATTRIBUTES

No.	Intrinsic Proliferation Resistance Attribute
Group 1 Attributes: Nuclear Reactor Features	
1	Fissile material production capacity of the reactor in kilograms (kg) per year per thermal power (MWth).
2	Cumulative amount of all types of fissionable and fertile nuclear material (Pu, U, Th) in number of SQs* present at the reactor facility at the end of each year for ten years, evaluated separately for fresh fuel, fuel in the core, and spent fuel.
3	Total material mass (kg) of removed material that contains 1 SQ of nuclear material.
4	Volume of the total removed material in cubic meters (m^3) that contains 1 SQ of nuclear material.
5	Number of items to be removed to obtain 1 SQ of nuclear material (number of fuel assemblies, or storage containers for bulk material, etc.).
Group 2 Attributes: Fresh and Irradiated Nuclear Fuel	
6	Time needed in days for converting the removed material from the reactor facility to metallic form. (Ref. Table 3 of IAEA Safeguards Glossary [8] provides guidance on material conversion times).
7	What steps are required to convert removed material from the reactor facility to its pure (U or Pu) metallic form?
8	Bare-sphere critical mass (BCM) in kilograms.
9	Radiation level (gamma and neutron radiation) in sieverts per hour (Sv/h) 1 meter from the surface of a BCM.
10	Spontaneous fission neutron rate in seconds per BCM.
11	Thermal power in watts per BCM (W/BCM).
Group 3 Attributes: Facility Features	
12	Presence of operational modes of reactor design features that could enable proliferation, e.g., online refuelling, specialised remote tools suitable for operator to access and transfer nuclear material, target irradiation space.

* The International Atomic Energy Agency (IAEA) defines a *significant quantity* (SQ) as the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. PRO-AR&FC uses IAEA-defined values of SQs [8].

2. BRIEF DESCRIPTION OF INTRINSIC PROLIFERATION ATTRIBUTES

A brief description of first ten attributes listed in Table 1, which will be the focus during Phase I of the PRO-AR&FC project, is provided in this section.

2.1. Group 1 attributes

Attribute 1 evaluates proliferation resistance due to the new fissile material production by the reactor. This attribute is measured on a per-year basis and normalized to the design thermal power (MWth) capacity of the reactor assuming that the overall scale of a civilian nuclear program is driven by a power generation requirement. Attribute 2 evaluates proliferation resistance due to the presence of all fissile and fertile materials at the reactor facility. This attribute value is intended to gauge the ease of obtaining 1 SQ of material from the reactor facility and is not normalized by the power output of the reactor. Attribute 3 estimates the amount of total material mass that a proliferator needs to remove to obtain 1 SQ of nuclear material. This attribute captures the dilution of nuclear material in the removed material, which in turn captures the level of effort associated with removing the material from the reactor facility. Attribute 4 estimates the total volume of material that a proliferator needs to handle to obtain 1 SQ of nuclear material. Attribute 5 estimates the level of effort associated with removing 1 SQ of nuclear material from the perspective of the number of items that need to be removed.

2.2. Group 2 attributes

Attributes 6 and 7 capture the level of effort respectively in terms of time and number of steps needed for a proliferator to convert the removed nuclear material (e.g., fresh or irradiated low-enriched uranium/high-assay low-enriched uranium oxide fuel, pebble fuel, molten salt reactor salt fuel, mixed oxide fuel) from the reactor facility to its metallic form. Attribute 8 assesses the amount of converted material in terms of bare-sphere critical mass (BCM) by considering all the isotopes of the target element that are present in the removed material. Attribute 9,10, and 11 captures the intrinsic proliferation barriers presented by the converted material with respect to the radiation level, spontaneous fission neutron rate, and heat emission rate (thermal power), respectively by one BCM.

2.3. Group 3 attributes

Group 3 attribute number 12 captures the reactor facility design features, specifically the presence of operational modes of design features that could enable proliferation. These design features for proliferation resistance assessment include, online refuelling and their usage frequency, specialised remote tools for the operator access/transfer of nuclear material and the usage frequency, additional space and volume available for target irradiation.

3. SUMMARY

The PRO-AR&FC project team is developing a technical, objective, and repeatable methodology to assess and optimise for proliferation resistance in advanced nuclear reactor facilities. A three-step process to develop the proliferation resistance assessment methodology is described. This methodology is distinct from existing proliferation resistance methodologies because it considers only intrinsic design features of the reactor (i.e., external measures like safeguards agreements are not considered); includes optimisation to modify reactor facility designs toward increasing proliferation resistance; and aims to be primarily quantitative.

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