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Updating and Enhancing the INPRO Proliferation Resistance Methodology for Better Sustainability Assessments

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ABSTRACT

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), begun in 2001, developed a methodology to assess the sustainability of nuclear energy systems. The INPRO methodology covers six key areas: infrastructure, economics, environmental impacts (particularly depletion of resources and impact of stressors), waste management, safety, and proliferation resistance. The methodology undergoes review and updating on a regular basis. The proliferation resistance (PR) area was the last area to undergo a recent update. A group of international experts, including many from the Generation IV International Form (GIF) Proliferation Resistance and Physical Protection Working Group (PR&PP), were instrumental in the update to the PR manual. The updates in the PR methodology were in streamlining the assessment process and enhancing the methodology in the user requirements for attractiveness of the nuclear energy system, as well as implementation of multiple measures to deter proliferation. These enhancements in the user requirements, criteria, and evaluation parameters, better support the nuclear community's definition of PR by considering intrinsic features and extrinsic measurers, to improve sustainability assessments in PR for innovative nuclear energy systems. These enhancements are especially important for innovative systems that encompass advanced small modular reactors (SMRs) and microreactor designs. The outcome of a nuclear energy system assessment (NESA) in sustainability is the identification of criteria that are not met, so designs can be improved or to identify research and development needs to close the gaps, which is especially important for innovative designs.

1. INTRODUCTION

The International Project for Innovative Nuclear Reactors and Fuel Cycle Facilities (INPRO), by the International Atomic Energy Agency (IAEA) began in 2001 to develop a methodology for

[a] "The views presented are those of the author and do not necessarily represent the views of the U.S. Department of State."

assessing the long-term sustainability of innovative nuclear energy systems (NES). The methodology relied on the United Nations (UN) concept of sustainable development, defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1]." The UN sustainable development concept covers four key areas: economics, environment, society, and political.

The main objective of INPRO is to "ensure nuclear energy is available to contribute, in a sustainable manner, to the growing energy needs of the current century and beyond [2]". The second objective is to "bring together both technology holders and technology users to consider jointly the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles [2]."

The INPRO section of the IAEA created a methodology integrating the input of over 300 international experts. The original INPRO methodology for performing nuclear energy system assessments (NESA) was published in 2003 [3]. The methodology underwent updates in 2004 [4] and 2008 when it was published as nine manuals [5] where proliferation resistance was Volume 5 [6]. Additionally, the methodology goes through updates on a regular basis using the experience from assessors, documentation from lessons learned [7], and reviews by the international community. Also, there were recommendations on how to update the methodology by the INPRO steering committee, IAEA experts, and the INPRO section. In 2012 the INPRO section began updating all 9 volumes in the INPRO methodology. The INPRO manuals for the Overview (Vol. 1) and Proliferation Resistance (Vol. 5) are the last volumes to need revision.

The latest revision of the INPRO manual for proliferation resistance incorporates lessons learned from the publication "Lessons Learned from Nuclear Energy System Assessments (NESA) Using the INPRO Methodology" (2009), specifically Section 4 which dealt with a NESA in PR [7]. Recent work covered acquisition and diversion path analysis, as described in IAEA-TECDOC-1684 "INPRO Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (PRADA)," published in 2012 [8]. This document incorporates work done under an INPRO project on "Proliferation Resistance and Safeguardability Assessment Tools (PROSA)," published in 2021 [9], which had a major focus on PR and lessons learned from applying PROSA to an illustrative case.

2. KEY DEFINITIONS FOR PROLIFERATION RESISTANCE

2.1. Proliferations Resistance

The INPRO methodology definition for proliferation resistance is from the IAEA publication on Proliferation Resistance Fundamentals. Hence, proliferation resistance is "that characteristic of a nuclear energy 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 [10]." The Generation IV International Forum's Proliferation and Physical Protection Working Group (GIF PRPPWG) accepts this same definition [11]. Furthermore, the degree of proliferation resistance results from a combination of, inter alia, intrinsic technical design features, operational modalities, and extrinsic measures, such as institutional arrangements and implementation of international safeguards [10].

The INPRO Methodology for proliferation resistance applies to declared nuclear material and facilities, which means the material and facilities the State declared to the IAEA in accordance with safeguards agreements concluded between the State and the IAEA. The assessment regards the diversion of this nuclear material or misuse of these facilities and technology by a State (the

proliferator) seeking to acquire a nuclear weapon or other nuclear explosive device. For a State to successfully proliferate there are four requirements: (1) a sufficient quantity of nuclear material, (2) access to technology, (3) specialized knowledge and skills, and (4) time [12, 13]. The INPRO methodology for proliferation resistance takes into account all four requirements.

2.2. Intrinsic Features and Extrinsic Measures

Intrinsic features are technical elements or design characteristics of a nuclear fuel cycle, the facilities, processes, and equipment that make it difficult to gain access to nuclear material or misuse facilities to obtain nuclear material for a nuclear weapon [10]. Intrinsic features relate to physical design features. Extrinsic measures are a State's commitments, obligations, and policies regarding nuclear non-proliferation; bilateral agreements between exporting and importing States; commercial, legal or institutional arrangements that control access to nuclear material and nuclear energy systems; verification activities (including IAEA, regional, bilateral and national); and arrangements to address violations of nuclear non-proliferation undertakings [12]." Hence, extrinsic measures include treaties, agreements, the application of IAEA safeguards, security forces and equipment to impede proliferation [10].

3. INPRO METHODOLOGY

The INPRO methodology uses a hierarchical approach to assess the long-term sustainability of an NES. The methodology starts with a *basic principle* (BP), a fundamental goal that the NES must achieve to be sustainable in the long term, which provides broad guidance for the necessary development and design of the NES [14]. There is one BP for each assessment area.

The BP is supported with *user requirements* (URs), with 2 to 7 URs per BP. A UR defines what should be done to meet the target/goal of the INPRO methodology basic principle (BP). Each UR has *criteria* (CR), with 1 to 6 CRs per UR. A CR enables the INPRO assessor to determine whether or how well a UR is being met by a given NES. [14] A CR is composed of *indicators* (IN) and *acceptance limits* (AL), which further define the CR for an assessment. Figure 1 illustrates the structure and relationships between BP, UR, and CR.

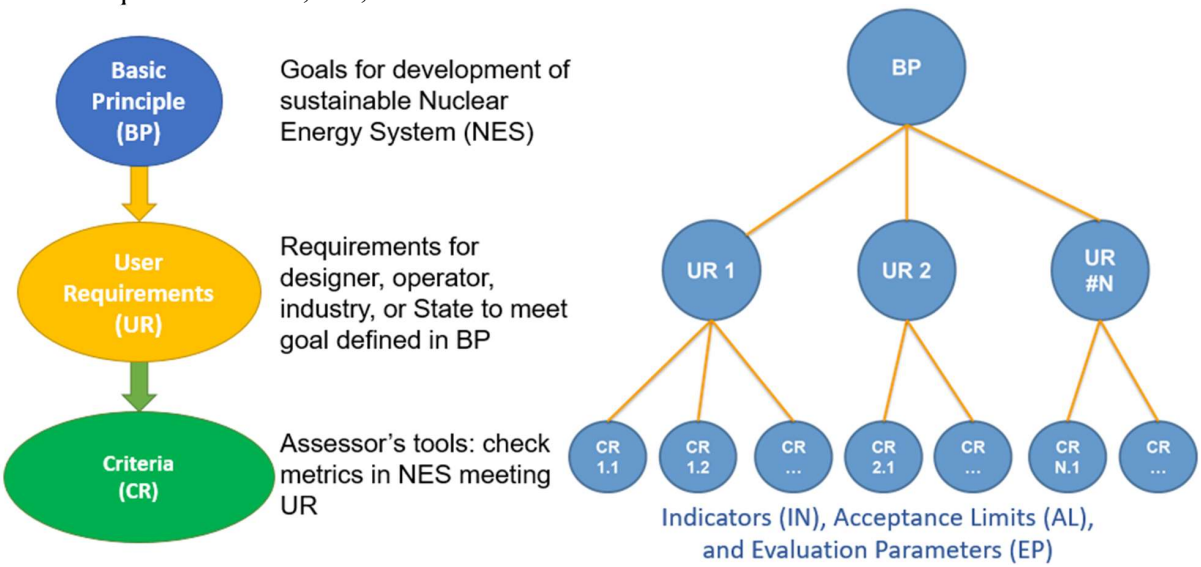

Figure 1. Diagram showing INPRO framework and relationship of basic principle (BP), user requirements (UR) and criteria (CR), (adapted from Ref. [15]).

The NESA is a process for making a judgement about the long-term sustainability of an evolutionary or innovative NES using the INPRO methodology. The fulfilment of URs is checked by an assessor via the CRs. When the CRs are met the NES is considered sustainable. When the CRs are not met the assessor identifies gaps, thus giving the developer, designer, or State an opportunity to change the design so the NES will be sustainable. [16]

4. INPRO MANUAL: PROLIFERATION RESISTANCE

The main goal for revising the INPRO methodology in proliferation resistance was to streamline the assessment process for the assessor. The following are key areas identified for improvement to the manual.

(1) Put in similar format to previously updated INPRO manuals, standardize application of INPRO methodology
(2) Provide a better explanation of the rationale for acceptance limits (AL)
(3) Reformat the evaluation tables to improve clarity (for assessor)
(4) Restructure the evaluation parameters (EP) to provide needed details to the user (assessor)
(5) Better define sustainability in the area of proliferation resistance

4.1. Previous structure of INPRO Proliferation Resistance – 2008

Figure 2 shows the structure of the BP, UR, and CR for the INPRO assessment in PR according to the 2008 manual [6].

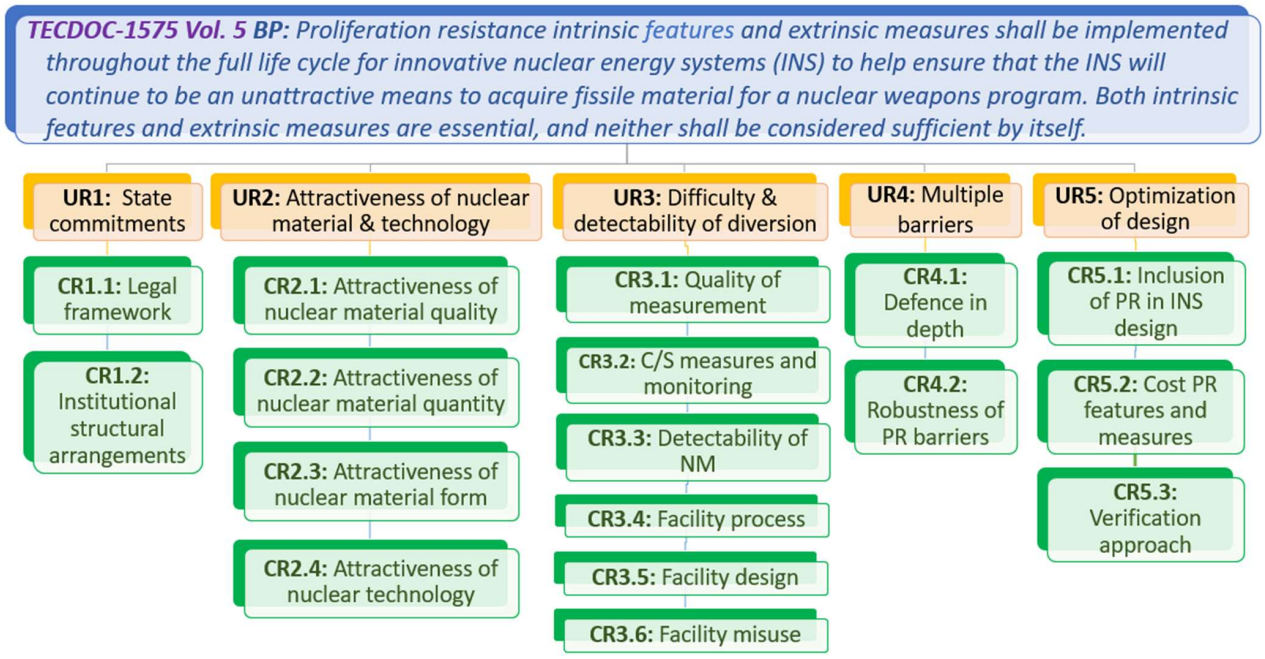

Figure 2.The INPRO assessment in PR from 2008 manual; 1 BP, 5 UR, 17 CR.

4.2. Basic Principle

Early proliferation resistance manuals had more than one BP [4]. The 2008 manual streamlined BP to one per assessment area [5]. Below is the BP in the 2008 manual followed by the 2023 BP with

changes highlighted with *italic* text. Over the years the INPRO methodology evolved from using innovative nuclear energy system (INS) to nuclear energy system (NES).

> **2008 BP:** Proliferation resistance intrinsic features and extrinsic measures shall be implemented throughout the *full* life cycle *for innovative* nuclear energy systems (INS) to help ensure that the INS will continue to be an unattractive means to acquire fissile material for a nuclear weapons program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself [6].
>
> **2023 BP:** Proliferation resistance intrinsic features and extrinsic measures *should* be implemented throughout the life cycle of a nuclear energy system (*NES*) to help ensure that the *NES* will continue to be an unattractive means to acquire *nuclear* material for a nuclear weapon *or other nuclear explosive device (NED);* both intrinsic features and extrinsic measures are essential, and neither can be considered sufficient by itself [17].

Some of the key changes regard the change from fissile to nuclear material, and to consider other nuclear explosive devices and not just a nuclear weapon programme. The INPRO manual changed the word 'shall' to 'should' to align with IAEA condition that "shall" is for safety standards.

5. NEW INPRO MANUAL: PROLIFERATION RESISTANCE

Overall, the revised INPRO manual now has a deeper development of PR and better consistency. Section 2 of the document, General Features of a Proliferation Resistance Assessment, has a improved description of the concept of PR, robust definitions for PR, and clear explanations of intrinsic features and extrinsic measures, including an overview of safeguards and additional support material for the user requirements. The new manual no longer contains phrases such as proliferation risk and proliferation barriers. This aligns the manual with international standards and other PR entities, such as GIF. The new PR manual is streamlined, with a reduction in the CRs from 17 to 11, as shown in Figure 3. Additionally, the UR/CR and EPs have clearer definitions in the new manual, which make assessments easier and more consistent. Language in the manual reflects current practices in INPRO and proliferation resistance. For example, nuclear energy systems (NES) replaced innovative nuclear energy systems (INS). Much effort went into refining IN and better describing AL.

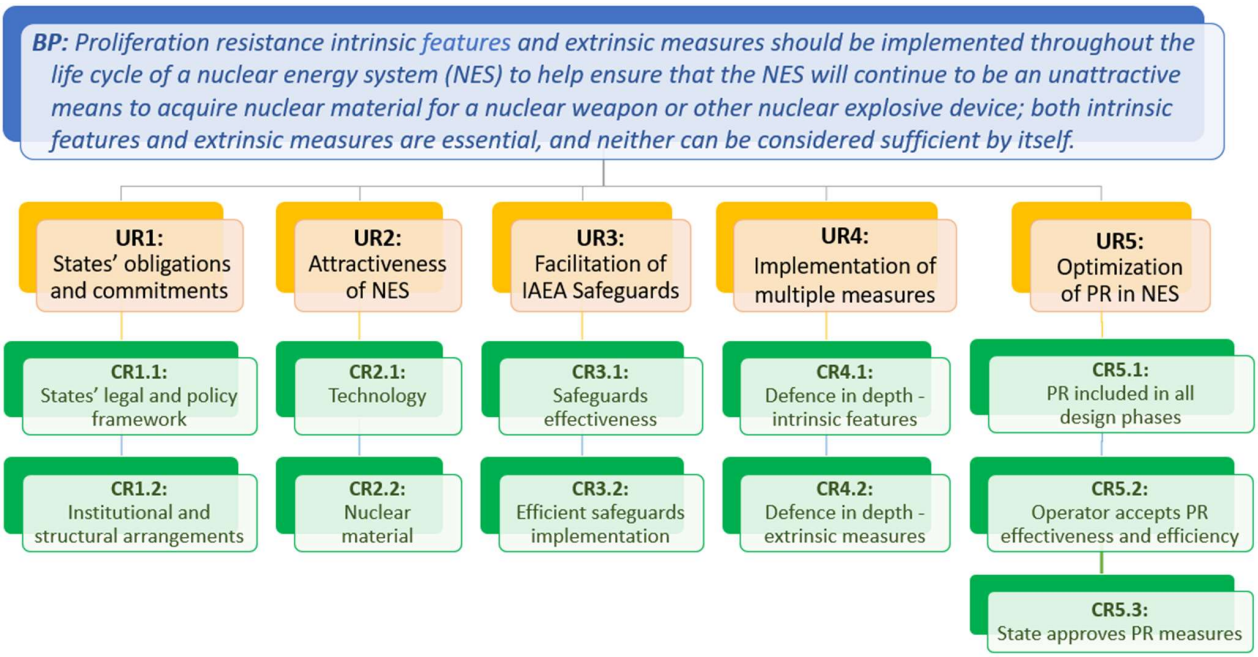

Figure 3.The INPRO assessment in PR from updated 2023 manual; 1 BP, 5 UR, 11 CR.

5.1. UR1: States' Obligations and Commitments

For UR1 there were additions of several more EP for CR1.1 to reflect activities in the international nuclear non-proliferation regime, such as UN Security Council Resolutions 1540 [18] and 1887 [19]; membership in nuclear-weapon-free-zones, signed and ratified comprehensive nuclear test ban treaty (CTBT) [20], amongst others. The AL is for the assessor to "determine if the State is in compliance with its nuclear non-proliferation obligations and adheres to its other non-proliferation commitments and follows best practices related to the nuclear non-proliferation regime [17]."

5.2. UR2: Attractiveness of NES

This UR underwent a major improvement in the new manual, with a more descriptive explanation of attractiveness of NES. There are now only two CRs, the first for the attractiveness of nuclear facilities in a State, and the second for the associated nuclear material. The assessment must consider the whole NES not just a new facility being added to a State's NES. For CR2.1, there is specific content regarding technologies of interest to a proliferator and their attractiveness to a proliferator. [17].

The assessment covers all nuclear material that theoretically could be used for a nuclear weapon or NED. The assessment EP align with safeguards concepts. There is an example of a UR2 assessment in the appendix of the manual. The example will assist users of the INPRO methodology. For nuclear material there are three key EPs: type and isotopic composition, quantity specifically in relation to IAEA significant quantities, and physical/chemical form. The assessor is expected to address if any alternative nuclear materials and technologies were evaluated and "why more attractive technologies or nuclear material were chosen, and how PR will be addressed in the NES and within the State [17]." One does not expect a State to not have attractive material or technologies but will implement additional measures based on attractiveness. This process is similar to a graded approach.

5.3. UR3: Facilitation of IAEA Safeguards

There were major changes to UR3, reducing the CR from 6 to 2. First, the assessment of the effectiveness of IAEA safeguards, that the IAEA can readily achieve technical objectives for safeguards. Second, the efficiency of safeguards implementation, that the "IAEA can thoroughly and without undue delay execute all planned safeguards activities [17]." This UR now takes into consideration an IAEA safeguards review, such as the State requested an IAEA SSAC (State System of Accounting for and Control of nuclear material) Advisory Service (ISSAS) mission or supplied a design information questionnaire (DIQ), aligning with IAEA safeguards requirements. The update of this section was through the support of the IAEA Safeguards Department. Additionally, all references to safeguards processes and activities reflect definitions from the recently updated 2022 edition of the IAEA Safeguards Glossary [21]. UR3 is specific to IAEA safeguards, and UR5 is specific to State and owner/operator.

5.4. UR4: Implementation of Multiple Measures

There was a major effort to enhance and better describe this UR. UR4 addresses the application of intrinsic features with extrinsic measures, and their layering to provide multiple impediments to diversion by the State. The previous manual used acquisition path analysis, which is a term reserved for IAEA safeguards at the investigation of the state level, including the possibility of undeclared facilities. The PR in the INPRO manual covers declared nuclear material and declared facilities, which is a diversion path analysis. [17]

The AL for the IN in UR4 is the NES should incorporate "complementary and diverse intrinsic features to reduce attractiveness of nuclear material and inhibit diversion or misuse [17]", and "complementary and redundant extrinsic measures to cover diversion of nuclear material and misuse by the State [17]." This is a kind of defence in depth approach to PR, and dependent on the attractiveness determined under UR2. There were extensive additions in the EP and attributes useful to States and designers to enhance PR in the NES. [17]

Some of the features to enhance PR are specific to reducing the attractiveness of nuclear material, inhibit diversion of nuclear material, inhibit undeclared production of nuclear material, and lastly to facilitate verification, including continuity of knowledge. For extrinsic measures the assessor needs to identify diversion pathways and misuse scenarios for the NES. The analysis will indicate whether the State or designer should implement additional extrinsic measures that enhance PR [17].

5.5. UR5: Optimization of PR in the NES

The UR5 is effective and efficient PR for the State and operator. This UR requires PR be implemented throughout all design phases (CR5.1). It is similar to safeguards/security/safety by design. More effective and efficient PR features and measures can be included when considered earlier in design phases; additionally, it is important to reconsider PR when designs change, or there are upgrades to already operating facilities. CR5.2 requires the implementation of PR intrinsic features and extrinsic measures be effective and efficient for the operator. This gives the operator a chance to alter the design to better accommodate operations. Further, CR5.3 gives the State a chance to review and approve the implementation of PR measures in the NES to ensure they also meet State requirements. The implementation of PR features and measures must cover the NES for its lifecycle, from design, through construction, operation, and decommissioning. The assessor may note when there is opportunity to enhance PR or make the NES run more efficiently. [17]

6. SUMMARY

Today the UN has 17 sustainable development goals, to address poverty, and improve health and education, reduce inequality, spur economic growth, while tackling climate change and working to preserve the planet's oceans and forests [22]. The INPRO section of the IAEA has an important mission in helping Member States consider the sustainability of their existing and planned NES and the role of technology and institutional innovations in achieving their long-range nuclear energy strategy. The INPRO methodology through the NESA process helps Member States identify gaps in sustainability. The revised INPRO PR manual helps States and designers with identifying sustainability gaps in PR and provides ideas for resolution of those gaps.

The new INPRO manual has value as a seminal work for providing an encompassing definition for PR and emphasizing the need to assess the attractiveness of nuclear material and technologies in the NES as a key component of PR. The INPRO methodology and NESA in PR is greatly enhanced through the revision of the PR manual. The work aligns with other departments in the IAEA such as Safeguards and Office of Legal Affairs (OLA). The definitions in the paper align with the new IAEA Safeguards Glossary 2022 edition [21], and where appropriate uses legal definitions. The manual aligns with the current implementation process for IAEA safeguards, encouraging the consideration of safeguards obligations as early as possible in the design of a nuclear facility. The PR manual is an additional building block to the 3S (Safety, Security, and Safeguards) by design.

Other improvements to the PR manual are the addition of checklists to specifically help the assessor in the NESA process. Furthermore, in many places there are ideas for enhancing PR in the NES. The new PR manual regards the effectiveness and efficiency of PR intrinsic features and extrinsic measures for both IAEA Safeguards implementation and State compliance along with the operator to uphold their safeguards and non-proliferation commitments .

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