

EVALUATION OF PROLIFERATION RESISTANCE USING THE INPRO METHODOLOGY

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The IAEA launched the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and developed the INPRO Methodology to provide guidelines and to assess the characteristics of a future innovative nuclear energy system in areas such as safety, economics, waste management, and proliferation resistance. The proliferation resistance area of the INPRO Methodology is reviewed here, and modifications for further improvements are proposed. The evaluation metrics including the evaluation parameters, evaluation scales and acceptance limits are developed for a practical application of the methodology to assess the proliferation resistance. The proliferation resistant characteristics of the DUPIC fuel cycle are assessed by applying the modified INPRO Methodology based on the developed evaluation metrics and acceptance criteria. The evaluation procedure and the metrics can be utilized as a reference for an evaluation of the proliferation resistance of a future innovative nuclear energy system.

KEYWORDS : IAEA, INPRO, DUPIC, Proliferation Resistance, Evaluation Methodology

1. INTRODUCTION

The IAEA launched an International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) in 2000 to develop an innovative nuclear system (INS) that can fulfill the energy needs of the 21st century following the recommendations of the 44th General Conference. INPRO proposed proliferation resistance as a key component of a future innovative nuclear system along with the sustainability, economics, safety of nuclear installations and waste management.

The IAEA developed the INPRO Methodology to provide guidelines and for a quantitative assessment of the characteristics of a future innovative nuclear energy system in the areas of safety, economics, waste management and proliferation resistance. This was published as IAEA-TECDOC-1362 in June 2003, as a part of the INPRO Phase 1A program [1]. The revised methodology based on the results of various consultancy meetings and national case studies, including a Korean case study on DUPIC, was published as IAEA-TECDOC-1434 in December 2004, as a part of the INPRO Phase 1B, Part 1 program [2,3]. The INPRO Methodology in the proliferation resistance area was then re-evaluated for its completeness

and usefulness by applying it to the entire DUPIC fuel cycle as an extended Korean national case study in the INPRO Phase 1B, Part 2 program, which was completed in June 2006 [4]. As INPRO Phase 2 was started in July 2006, the INPRO Methodology in the proliferation resistance area, which was modified based on this study, will be studied further through the IAEA international collaborative research program to improve the comprehensiveness of the Methodology, in particular in the evaluation of robustness of proliferation resistant barriers.

In this study, the proliferation resistance of a nuclear energy system is defined and characterized. The INPRO Methodology of the proliferation resistance area, which was published in IAEA-TECDOC-1434, is then reviewed, and modifications to the methodology for further improvement are proposed. Evaluation metrics, including the evaluation parameters, evaluation scales and acceptance limits, are developed for a practical application of the methodology to assess the proliferation resistance. The proliferation resistant characteristics of the Direct Use of Spent PWR fuel in CANDU Reactors (DUPIC) fuel cycle is assessed by applying the modified INPRO Methodology based on the developed evaluation metrics and acceptance criteria.

2. CHARACTERISTICS OF PROLIFERATION RESISTANCE OF A NUCLEAR ENERGY SYSTEM

The concept of proliferation resistance has been discussed within several international societies, such as IAEA INPRO and the GIF working group. Proliferation resistance is defined as “Those characteristics of a nuclear energy system that impede the diversion or undeclared production of nuclear materials or misuse of technology by States in order to acquire nuclear weapons or other nuclear explosive devices” [2].

Proliferation resistance can be assured by use of an appropriate combination of intrinsic features and extrinsic measures. The main features of the intrinsic and extrinsic measures are analyzed below. These intrinsic features and extrinsic measures are used as a basis for the development of the INPRO Methodology for the assessment of proliferation resistant characteristics by arranging them in a logical way with the proposed acceptance criteria.

2.1 Intrinsic Features

Four types of intrinsic features are considered here.

First Type

This consists of the technical features of a nuclear energy system that reduce the attractiveness for a nuclear weapons program of nuclear material during the production, use, transport, storage and disposal (e.g., isotope content, chemical form, radiation field, heat generation or spontaneous neutron generation rate).

Second Type

This is comprised of the technical features of a nuclear energy system that prevent or inhibit the diversion of a nuclear material (e.g., design features that limit access to nuclear material, effectiveness of the prevention of a diversion of nuclear material, time required to divert or produce nuclear material and convert it to a weapons-usable form, bulk and mass).

Third Type

This consists of the technical features of a nuclear energy system that prevent or inhibit the undeclared production of a direct-use material (e.g., complexity of and time required for the modifications necessary to use a civilian nuclear energy system for a weapons production facility; the skills, expertise and knowledge required to divert or produce nuclear material and convert it to a weapons-usable form; difficulty in modifying the fuel cycle facilities and processes for undeclared production).

Fourth Type

This consists of the technical features of a nuclear energy system that facilitate verification, including the continuity of knowledge (e.g., diversion detectability, material stocks and flows).

2.2 Extrinsic Measures

The extrinsic measures considered here can be classified as follows;

First Category

This is a States' commitments, obligations and policies concerning nuclear non-proliferation. These include the NPT and nuclear-weapons-free zone treaties, comprehensive IAEA safeguards agreements and protocols additional to such agreements (e.g., safeguards agreements pursuant to the NPT, nuclear-weapons-free zone treaties, comprehensive IAEA safeguards agreements and additional protocols of the IAEA agreements).

Second Category

This consists of agreements between exporting and importing States that nuclear energy systems will be used only for agreed purposes and that they are subject to agreed limitations (e.g., export control policies, bi-lateral agreements for the supply and return of nuclear material, and bi-lateral agreements governing the re-exporting of nuclear energy system components).

Third Category

This category consists of commercial, legal or institutional arrangements that control the access to nuclear material and nuclear energy systems. This can include use of multi-national fuel cycle facilities as well as arrangements for spent fuel returns (e.g., commercial, legal or institutional arrangements that control the access to nuclear material and nuclear energy system; relevant international conventions; and multi-lateral ownership, management or control of a nuclear energy system).

Fourth Category

This is an application of the IAEA verification and when appropriate, regional, bilateral and national measures, to ensure that States and facility operators comply with non-proliferation or peaceful use undertakings (e.g., verification activities; State's or regional systems for an accounting and control; and safeguards approaches for a State's or a regional safeguards system, which should be capable of detecting a diversion or undeclared production).

Fifth Category

This consists of legal and institutional arrangements to address violations of nuclear non-proliferation or peaceful use undertakings (e.g., effectiveness of the international response mechanism for violations).

3. MODIFICATION OF THE INPRO METHODOLOGY

In general, the INPRO Methodology consists of a set of Basic Principles (BP), User Requirements (UR) and criteria including indicators, evaluation parameters and

acceptance limits. In order to evaluate an innovative nuclear system in terms of the INPRO goals, the characteristics of an innovative nuclear system are assessed in terms of the indicator, user requirements and basic principles using a bottom-up manner.

The INPRO methodology calls for an assessment of the intrinsic features and extrinsic measures of a nuclear system to evaluate the indicators. The approach taken in the INPRO methodology is to aggregate the results of an evaluation of the indicators to obtain an evaluation for the URs, and to aggregate those results to obtain an evaluation of the BPs. However, the methods for: (1) the evaluation of the indicators, (2) the aggregation of the indicators to evaluate the URs, and (3) the aggregation of the URs to evaluate the BPs have yet to be developed.

Two BPs and five URs were suggested in the proliferation resistance area of the INPRO Methodology, which was published as IAEA-TECDOC-1434. These structures are shown in Fig. 1.

The indicators of the URs under BP 1 in the INPRO Methodology of IAEA-TECDOC-1434 were set to one for each UR. Each indicator is similar to the meaning of the corresponding UR, but expressed in concise words to represent the role of the indicator. However, the intrinsic features and extrinsic measures, which represent the most important barriers for proliferation resistance, are expressed as variables under the corresponding indicator.

However, it is desirable that the indicator itself be

considered as a measure of the technical barriers that it should have its own meaningful characteristics regarding proliferation resistance. Hence, a new modified structure for the BPs and URs including the indicators is proposed, as shown in Fig. 2.

The modified URPR1.1 (User Requirement of Proliferation Resistance 1.1) in Fig. 2 comes mainly from the previous URPR1.2 in TECDOC-1434. Moreover, the “Variables” in TECDOC-1434 are rearranged, and four new indicators for URPR1.1 are proposed. In particular, the words “nuclear technology” were added to the User Requirement, as nuclear technologies such as the possession of an enrichment facility, technology capability for the extraction of fissile material and the irradiation capability of a target by a reactor or an accelerator are directly linked with the meaning of the “Attractiveness of an undeclared nuclear material that could credibly be produced or processed in the innovative nuclear system for a nuclear weapons program should be low”. This UR is to evaluate the characteristics of the proliferation resistance of a nuclear energy system in terms of both the attractiveness of the material being produced in the system and the attractiveness of the technology that is available in the system for the acquisition of a nuclear weapon.

The four new indicators are divided into twelve detailed evaluation parameters, which are important for evaluating the intrinsic barriers regarding the materials characteristics and the nuclear technology. The first indicator evaluates

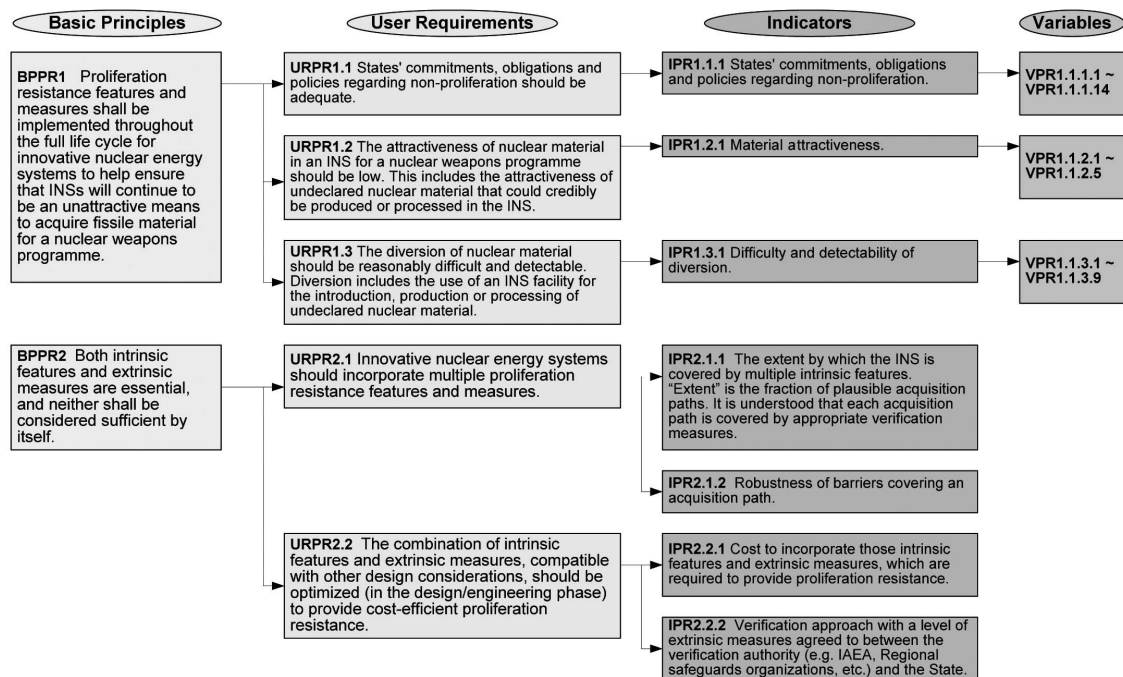


Fig. 1. Hierarchy of the INPRO Methodology in the Proliferation Resistance Area of IAEA-TECDOC-1434

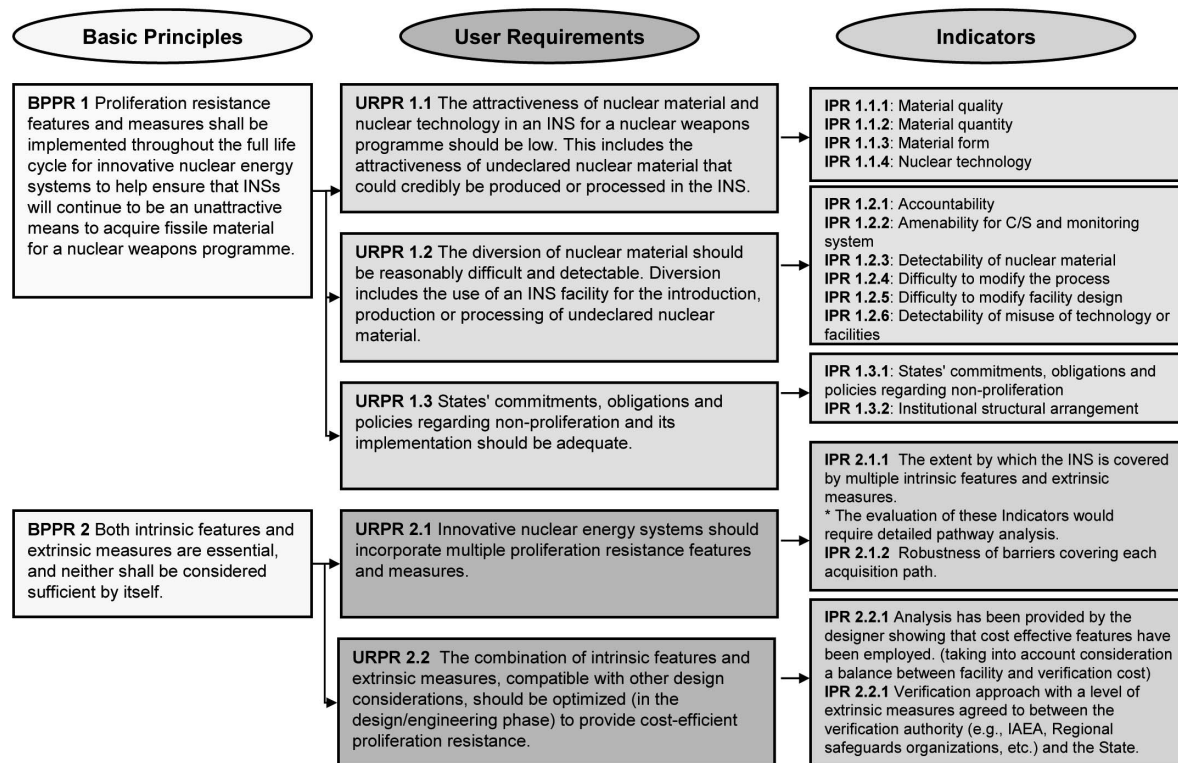


Fig. 2. Newly Modified Structures of the BPs, URs and Indicators of the INPRO Methodology in the Proliferation Resistance Area

the material quality in terms of the isotopic composition, material type, radiation field, heat generation rate and spontaneous neutron generation rate. Highly enriched uranium or weapons grade plutonium is most attractive for weapons applications. The material type is a classification of the nuclear material. For example, depleted uranium is least attractive, while direct-use unirradiated material (DUM) is most attractive for weapons applications. The radiation field is a significant barrier to the accessibility of diversion. The heat generation and spontaneous neutron generation from a nuclear material complicates the design and fabrication of a weapon. The material quantity is evaluated in terms of the mass of an item, implying that the heavier it is, the more difficult the diversion. Moreover, it is evaluated in terms of how many items are necessary in the diversion of a significant quantity, and how many significant quantities can be produced during the process flow. The material form refers to the difficulty of the process required to extract weapons-usable materials from them.

The evaluation metrics including the criteria and acceptance limit were mainly chosen by an expert judgment based on a survey of the relevant literature. While the proposed acceptance limit for each evaluation scale is generally accepted by relevant experts, the establishment of a consensus on the internationally acceptable criteria is still required.

URPR1.2 comes from the previous URPR1.3 in TECDOC-1434. However, six new indicators and thirteen new evaluation parameters are proposed to clarify the meaning of the evaluation criteria and the variables given in IAEA-TECDOC-1434. The accountability is related to the accuracy of the IAEA safeguards measurement. The amenability evaluates the capability of monitoring the movement of nuclear materials, including the containment and surveillance. The detectability evaluates the nature of the detection system. The difficulty in modifying the process and facility design is related to the difficulty in modifying the process, such as the complexity of the modification, the cost of the modification, safety implications of such a modification and the time required for the modification.

URPR1.3 comes from the previous URPR1.1 in TECDOC-1434. It has two new indicators and thirteen new evaluation parameters to evaluate extrinsic measures related to state-specific information. While intrinsic features are more closely related to the system design and characteristics, extrinsic measures are also critical requirements for ensuring the proliferation resistance of a nuclear system. INPR1.3.2 is newly proposed to emphasize an institutional arrangement and facility/enterprise undertakings such as multi-lateral ownership, which was considered as a part of the previous INPR1.1.1 in TECDOC-1434.

4. APPLICATION OF THE INPRO METHODOLOGY TO THE DUPIC FUEL CYCLE

To assess the proliferation resistance of an innovative nuclear system in terms of the evaluation parameters, evaluation scales are required. Some barriers can be quantified but other barriers, such as the extrinsic measures or 'safeguardability', may be expressed only in logical terms such as "Yes" or "No". The present study suggests a five-stage scale of VW (Very Weak), W (Weak), M (Moderate), S (Strong) and VS (Very Strong) regarding quantifiable evaluation parameters. Here, "S" signifies "strong in terms of proliferation resistance". For example, if the Pu-239 isotopic content in a material is less than 60%, it is designated as "S". If the Pu-239 isotopic content in a material is larger than 93%, it is designated as "VW".

For a logical scale, U (Unacceptable) and A (Acceptable) for the extrinsic measures, and W (Weak) and S (Strong) for several of the intrinsic features related to safeguardability are suggested.

In order to evaluate the proliferation resistance of a nuclear system, the system characteristics should be analyzed first. The results of the proliferation resistance assessment of the Direct Use of Spent PWR Fuel in CANDU Reactors (DUPIC) fuel cycle using the modified INPRO Methodology is shown here.

4.1 Properties of the DUPIC Fuel Cycle

The basic concept of the DUPIC fuel cycle is to fabricate CANDU nuclear fuel from PWR spent fuel using dry thermal/mechanical processes without separating the stable fission products. As a CANDU reactor utilizes natural uranium fuel, the contents of the remaining fissile materials in PWR spent fuel are large enough to be reused in a CANDU reactor despite the fact that the fuel nevertheless contains fission products. The basic concept of the DUPIC fuel cycle is schematically shown in Fig. 3.

The main element of the DUPIC fuel cycle is the manufacturing step of the DUPIC fuel from PWR spent fuel. As shown in Fig. 3, PWR spent fuel is first disassembled and the PWR spent fuel elements are extracted from the assembly. The spent fuel elements are cut into small rod-cuts for easy handling. The rod-cuts are de-cladded using a mechanical and/or thermal method to retrieve the PWR spent fuel materials. The PWR spent fuel materials are subject to a series of oxidation and reduction processes to render them re-sinterable by a process known as OREOX (Oxidation and REDuction of OXide fuel). The oxidation and reduction steps are performed at 450°C in air and 750°C in an Ar-4% H₂ atmosphere, respectively. During the oxidation and reduction, an approximate 30% volume change provides spent fuel material with finer particles and soft materials with numerous microcracks,

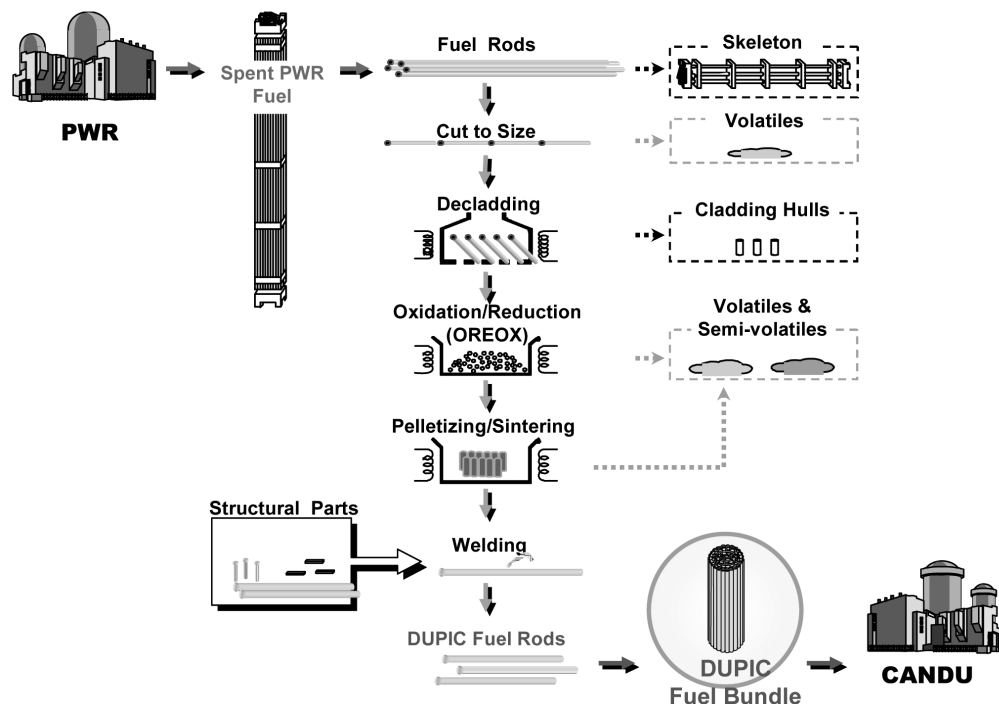


Fig. 3. Concept of the DUPIC Fuel Cycle

resulting in a re-sinterable powder.

Once the re-sinterable powder feedstock is prepared, the followed manufacturing processes are similar to the conventional CANDU fuel manufacturing processes using a powder/pellet route. These processes include pre-compaction, granulation, compaction, sintering, grinding, end cap welding using a laser, and a final assembling of the DUPIC bundle.

As there is no process step for the separation of the fission products and transuranic materials while the volatile and semi-volatile elements are removed during the thermal/mechanical treatments, the process materials are highly radioactive throughout the manufacturing processes. Therefore, the manufacturing processes should be performed inside a heavily shielded hot cell. These characteristics lead to difficulties for material handling during manufacturing, but this is a strong incentive in terms of the proliferation resistance of the DUPIC fuel. [5,6,7]

Based on this assumption, the plutonium isotopes and radiation fields in the DUPIC fuel cycle are determined, as shown in Table 1 and Table 2, respectively.

4.2 Evaluation of User Requirement 1.1

Due to the dry process, no fissile material can be separated in a pure form. The material requires a further chemical reprocessing in order to obtain material suitable for a weapon.

The presence of some fission products leads to a high dose rate arising from the material. The DUPIC process must be carried out in a heavily shielded hot cell as it involves highly radioactive materials. This process is self-contained, and there is no transporting of intermediate materials outside the facility. Therefore, access to the nuclear materials is extremely difficult.

The material type during the DUPIC fabrication process is characterized as an irradiated direct-use material. The isotopic composition, $^{239}\text{Pu}/\text{Pu}$, is ~60 wt%. Regarding the radiation field, dose rate of a DUPIC fuel bundle is ~0.15 Sv/hr. The heat generation rate is related primarily to $^{238}\text{Pu}/\text{Pu}$, which is 1.7wt% for DUPIC. The spontaneous neutron generation comes from $(^{240}\text{Pu}+^{242}\text{Pu})/\text{Pu}$, which is ~30 wt%.

Regarding the material quantity, there are three evaluation parameters of the “Mass of an item”, “Number of items needed to obtain one SQ (Significant Quantity)” and “Number of SQs in a material stock or flow”. The mass of an item is ~ 24 kg; the number of items necessary to obtain one SQ is ~ 48 assemblies, as ~0.9 MTHM is required to make one SQ of Pu from DUPIC fuel. The material form of the DUPIC process is spent fuel.

Regarding the nuclear technology, the entire process employs only thermal and mechanical processes; there is no chemical process. Therefore, it is impossible to extract fissile materials and modify the DUPIC fuel cycle facility

Table 1. Pu Isotope Composition in Various Spent Fuels

Isotopes	Spent PWR Fuel		Fresh DUPIC Fuel		Spent DUPIC Fuel	
	g / MtHM	Wt % of Pu	g / MtHM	Wt % of Pu	g / MtHM	Wt % of Pu
Pu^{238}	1.54E+02	1.7	1.54E+02	1.7	3.88E+02	4.9
Pu^{239}	5.33E+03	59.9	5.33E+03	59.9	3.16E+03	39.7
Pu^{240}	2.20E+03	24.8	2.20E+03	24.8	2.79E+03	35.1
Pu^{241}	7.52E+02	8.4	7.52E+02	8.4	5.24E+02	6.6
Pu^{242}	4.57E+02	5.1	4.57E+02	5.1	1.10E+03	13.8

Table 2. Dose Rates of Various Nuclear Fuels (Unit:Sv/h)

Items		Dose rate for diversion of one assembly or one bundle	Total dose rate for 1000kgHM diversion	Dose rate for diversion of 1 SQ (8kg Pu)
Spent PWR Fuel	35 GWD/MtU, 10 yrs cooling	10.37	23.56	21.21
Fresh DUPIC Fuel	35 GWD/MtU, 10 yrs cooling	0.15	7.97	7.17
Spent DUPIC Fuel	15 GWD/MtU, 10 yrs cooling	0.61	32.16	32.32
Spent CANDU Fuel	7.5 GWD/MtU, 10 yrs cooling	0.22	11.51	22.84

and processes for enrichment. In addition, there is no irradiation capability of a target in the DUPIC process. The evaluation results for URPR1.1 are tabulated in Table 3.

4.3 Evaluation of User Requirement 1.2

Six indicators for URPR1.2 are suggested in this study. The first indicator is “Accountability”, which considers the ratio of the sigma MUF (Material Unaccounted For)

to a SQ. In the DUPIC process, the sigma MUF/SQ in terms of Pu or ^{233}U is evaluated as ~ 0.5 , based on the assumption of some measurement error and a period of 0.01 and 3 months, respectively. For the measurement method/equipment, a near-real-time accounting system (NRTA) for a fissile accountability system is used in the plant. The NRTA system is integrated with an individual nuclear material measurement system. The item accounting for both the PWR incoming fuel and outgoing

Table 3. Evaluation of User Requirement 1.1

Indicators	Evaluation Parameter		Evaluation Scale				
			W			S	
			VW	W	M	S	VS
Material quality	Isotopic composition	$^{239}\text{Pu}/\text{Pu}(\text{wt}\%)$	> 93	80~93	70~80	60~70	< 60
		$^{235}\text{U}/\text{U}(\text{wt}\%)$	> 90	50~90	20~50	5~20	< 5
		$^{232}\text{U}_{\text{contam. for } ^{233}\text{U}}(\text{ppm})$	< 1	1~100	100~4000	4000~7000	> 7000
	Material type		DUM	DIM	L	N	D
	Radiation field	Dose (mSv/hr)	< 10	10~150	150~1000	1000~10000	> 10000
	Heat generation	$^{238}\text{Pu}/\text{Pu}(\text{wt}\%)$	< 0.1	0.1~1	1~10	10~80	> 80
	Spontaneous neutron generation rate	$(^{240}\text{Pu}+^{242}\text{Pu})/\text{Pu}(\text{wt}\%)$	< 1	1~10	10~20	20~50	> 50
Material quantity	Mass of an item (kg)		10	10~100	100~500	500~1000	> 1000
	No. of items for SQ		1	1~10	10~50	50~100	> 100
	No. of SQ (material Stock or flow)		> 100	50~100	10~50	10~1	< 1
Material form	Chemical/physical form	U	Metal	Oxide/Solution	U compounds	Spent fuel	Waste
		Pu	Metal	Oxide/Solution	Pu compounds	Spent fuel	Waste
		Thorium	Metal	Oxide/Solution	Th compounds	Spent fuel	Waste
Nuclear technology	Enrichment		Yes			No	
	Extraction of fissile material		Yes			No	
	Irradiation capability of target		Yes			No	

DUPIC fuel is based on the modified curium counter. The weighing and NDA systems for bulk accounting in the DUPIC process are applied.

As the second indicator, “amenability” for the C/S

(Containment and Surveillance) measures is proposed. It is composed of three types of evaluation parameters, including the amenability of the containment measures, the amenability of the surveillance measures and the ame-

Table 4. Evaluation of User Requirement 1.2

Indicators	Evaluation Parameter		Evaluation Scale				
			W			S	
			VW	W	M	S	VS
Accountability	σ MUF/SQ	Kg Pu or ²³³ U	> 2	2~1	1~0.5	0.5~0.1	<0.1
		Kg ²³⁵ U With HEU	> 2	2~1	1~0.5	0.5~0.1	<0.1
		Kg ²³⁵ U With LEU	> 2	2~1	1~0.5	0.5~0.1	<0.1
	Inspectors measurement capabilities						
Amenability of C/S and monitoring system	Amenability of containment measures		No			Yes	
	Amenability of surveillance measures		No			Yes	
	Amenability of other monitoring systems		No			Yes	
Detectability of nuclear material	Possibility to identify nuclear material by NDA		No			Yes	
	Detectability of radiation signature		No reliable signature			Reliable signature	
Difficulty to modify the process	Extent of automation		N/A	Manual operation	N/A	Partial automation	Full automation
	Availability of data for inspectors		Very low	Low	Medium	High	Very high
	Transparency of process		No			Yes	
	Accessibility of material to inspectors for verification		No			Yes	
Difficulty to modify facility design	Verifiability of facility design by inspectors		No			Yes	
Detectability of misuse of technology or facilities	Possibility to detect misuse of the INS facilities for processing of undeclared nuclear material		No			Yes	

nability of other monitoring systems. These evaluation parameters can be applied to the DUPIC fuel fabrication facility, as the C/S system is easily installed at a hot cell facility, and a feed material measurement can be performed by a PWR spent fuel rod scanning system. Moreover, process monitoring can also be installed in an unattended continuous hot-cell monitoring system.

Regarding the “Detectability of a nuclear material”, two evaluation parameters are proposed. These are the prospect of identifying a nuclear material by NDA and the hardness of a radiation signature. Considering the characteristics of the DUPIC fuel fabrication process, the radiation signature during a fuel fabrication process is hard due to its strong radioactivity, and the nuclear material during a fuel fabrication process is identified easily and passively.

Regarding “the difficulty to modify the process”, some fabrication processes may not be automated, and all of the data acquired through the DUPIC fabrication process can be transmitted on-line to the operator. For the transparency of the process, all of the activities in the fabrication facility are open to the IAEA.

Regarding “the difficulty to modify a facility design”, it is very difficult to modify the relevant facilities. A hot cell facility is required for treating PWR spent fuel. The facility design is easily verified by inspectors. From the above considerations, the evaluation results for URPR1.2 are tabulated in Table 4.

4.4 Evaluation of User Requirement 1.3

The assessment of the proliferation resistance of the extrinsic measures is not dependent on the system elements but on the States. Hence, extrinsic measures are evaluated by considering the institutional arrangement of the relevant State. The Korean situation, as an example, can be described as outlined below in order to evaluate the proliferation resistance in terms of User Requirement 1.3.

Safeguards Agreements Pursuant to the NPT

Korea joined the NPT as a non-nuclear weapon State in 1975 and supported the extension of the NPT for an indefinite duration without any conditions in 1995.

Nuclear-Weapons-Free Zone Treaties

Regarding nuclear weapon-free zone treaties, there is a similar agreement around the Korean peninsula. For example, North and South Korea signed a joint declaration on the denuclearization of the Korean peninsula. This joint declaration officially entered into force on February 19, 1992 and remains valid. This was confirmed at the June 2001 summit in Pyongyang. For the CTBT, it is open for the signature of each country based on the U.N. resolution. Korea signed the treaty in 1996.

Comprehensive IAEA Safeguards Agreements

Korea signed the INFCIRC/153 agreement, “Agree-

ment between Korea and the IAEA for the application of safeguards in connection with the treaty on the non-proliferation of nuclear weapons”, in 1975.

Additional Protocols of IAEA Agreements

Korea signed and ratified the Additional Protocol to the Agreement(s) between State(s) and the IAEA for an application of safeguards (INFCIRC/540) in 2004.

Export Control Policies of NM and Nuclear Technology

Korea is strongly against nuclear weapons proliferation and is in favor of exercising necessary control and international supervision over nuclear material transfer so as to prevent the proliferation of nuclear weapons and related technologies. From this position, Korea joined the Zangger Committee in 1995, the Nuclear Supplier Group (NSG) in 1995 and the Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technology in 1996.

Relevant International Conventions

The IAEA has no authority to take coercive measures to stop or reverse nuclear proliferation. Therefore, it reports to the U.N. Security Council, and the U.N. Security Council may take forceful measures against proliferation under U.N. Charter VII.

State or Regional Systems for Accounting and Control

Concerning State's or regional systems for accounting and control, the Korean government enacted a nuclear law on national safeguards activities and established a mandatory body. Specifically, a Technology Center for Nuclear Control (TCNC) was founded in 1997, which became an independent institute termed KINAC (Korea Institute of Nuclear Nonproliferation and Control) in July 2006. Since then, national inspections have been performed for all facilities with nuclear materials in Korea. However, there is no regional system for accounting and control around Korea.

Verification Approach with a Level of Extrinsic Measures Agreed to between the Verification Authority and the State

According to the bi-lateral safeguards agreement between Korea and the IAEA, a Design Information Questionnaire (DIQ) for nuclear facilities in Korea is reported to the IAEA at the initial stages of construction. A Design Information Verification (DIV) is then performed by the IAEA. The safeguards approach and the design information are included in the DIQ. The IAEA then designs an appropriate verification approach including containment and surveillance approaches with the DIQ. Therefore, it can be said that the verification approach with a level of extrinsic measures agreed to between the IAEA and Korea is viable and robust.

Multi-lateral Ownership, Management or Control of Nuclear Energy System

Concerning multi-lateral ownership and/or management or control of a nuclear energy system, including bilateral agreements for the supply and return of nuclear fuel, Korea has imported nuclear materials mainly from Australia, Canada and the USA. Through the bilateral agreements, suppliers have the right to ask for a return of the nuclear material if Korea uses the transferred nuclear material non-peacefully. Regarding bilateral agreements governing the re-export of nuclear energy system components, Korea has entered into nuclear cooperation agreements with many countries including Canada, France, Japan and the USA. The re-export of components of a nuclear energy system is currently controlled by these agreements.

International Dependency with Regard to Fissile Materials and Nuclear Technology

Korea depends heavily on nuclear power for its electricity generation, with 20 nuclear power units in operation sharing 40 percent of the total production of electricity. Being poorly endowed with uranium reserves, all of the uranium is imported from foreign countries.

Regarding nuclear technology, Korea has specifically increased its nuclear power plant technology, and it is known that its localization ratio for nuclear power plant technology has reached nearly 95%. However, for technology related the nuclear fuel cycle, Korea continues to depend on foreign countries. Overall, it can be said that the international dependency of Korea concerning fissile materials and nuclear technology is "large".

Commercial, Legal or Institutional Arrangements that Control Access to NM and NES

International ownership of a nuclear material can definitely reduce the proliferation risk. Therefore, several ideas related to international ownership have been proposed, including international spent fuel storage and international plutonium management concepts. However, all of these proposals have yet to be substantiated.

Based on the above considerations, the evaluation results for URPR1.3 are tabulated in Table 5.

4.5 Evaluation of User Requirements 2.1 and 2.2

In order to evaluate the first set of user requirements under Basic Principle 2 regarding the robustness, multiple barriers, and other factors, a pathway analysis must be conducted. The diversion path and barriers in DUPIC fabrication can be considered from the viewpoints of the acquisition, processing and fabrication of a nuclear weapon.

Although a simplified acquisition path analysis was performed for the DUPIC fabrication process, the present paper does not include the results. A more comprehensive acquisition/diversion pathway analysis is planned in the future.

The second UR of Basic Principle 2 is related to the evaluation of the cost effectiveness for a given system in terms of additional costs to enhance the proliferation resistant

characteristics of a given system. As this requires detailed design information for a commercial scale of the DUPIC fabrication facility, an evaluation of its cost effectiveness is not considered at present.

5. DISCUSSION

The newly modified INPRO Methodology can provide a comprehensive and useful tool for assessing the proliferation resistance of a nuclear energy system compared with the previous methods proposed in IAEA-TECDOC-1362 and 1434. It has been modified to improve the correspondence between the BPs and the relevant URs, and to identify the crucial aspects of a nuclear energy system clearly for an evaluation of the proliferation resistant characteristics of a nuclear system by revising the indicators and evaluation parameters. The evaluation parameters and relevant acceptance criteria proposed in this study for Basic Principle 1, which mainly regards the intrinsic features of a nuclear system and extrinsic measures of a State, are shown to be useful, as applied to the DUPIC fuel cycle as a reference case. However, while Basic Principle 2 that addresses the robustness and multiplicity of barrier and cost effectiveness is very important in the assessment of all characteristics of the proliferation resistance of a nuclear system, additional research is required in order to establish detailed evaluation parameters and practical evaluation procedures.

In order to evaluate the proliferation resistance of a nuclear system, the following features should be considered in addition to the evaluation parameters of the intrinsic features and extrinsic measures, as has been pointed out at various international consultancy meetings organized by the IAEA, where the authors took a leading role in this area [2].

International centralization can provide for stronger international control of proliferation-sensitive enrichment and reprocessing technology. Co-location can limit the transportation and storage of a potentially proliferation-sensitive material. Closure of a fuel cycle, which can minimize the quantity of nuclear material in the fuel cycle and the production of a proliferation-sensitive material, provides benefits for proliferation resistance. Source materials such as natural uranium, depleted uranium, and thorium provide input material for many fuel cycles. Although they cannot directly be used in a nuclear weapon, these materials are also required for consideration in a proliferation resistance assessment as they can be used as source materials to generate weapons-grade materials.

In addition, the evaluation of proliferation resistance is more difficult than the evaluation of other technical areas such as safety and sustainability because it involves human behavior. While other technical areas are primarily concerned with technical aspects such as equipment/system failures, radioactive releases, costs, or human health, a proliferation resistance assessment is concerned with a

Table 5. Evaluation of User Requirement 1.3

Indicators	Evaluation Parameter	Evaluation Scale	
		U	A
States' commitments, obligations and policies regarding non-proliferation	Party to NPT	No	Yes
	Safeguards agreements according to the NPT in force	No	Yes
	For those who are not party to the NPT, Other Safeguards agreements (e.g., INFCIRC/66) in force	N/A	N/A
	Additional protocols in force	No	Yes
	Export control policies of NM and nuclear technology	No	Yes
	Regional SSAC in force	N/A	N/A
	State SSAC in force	No	Yes
	Relevant international conventions/treaties in force	No	Yes
	Party to Nuclear Weapons Free Zone (NWFZ) treaty	N/A	N/A
	Recorded violations of non-proliferation commitment	Yes	No
Institutional structural arrangement	Multi-lateral ownership, management or control of a NES (Multi-lateral/Multi-National)	No	Yes
	International dependency with regard to fissile materials and nuclear technology	Small	Large
	Commercial, legal or institutional arrangements that control access to NM and NES	No	Yes

malevolent human activity. Moreover, whereas in most areas it is assumed that agreements are respected and followed, in a proliferation assessment, it is assumed that non-proliferation agreements are broken.

A proliferation resistance assessment involves interactions between the two sides of the proliferators and the safeguarder/defender. Therefore, this is sometimes analyzed using gaming theory. The choices that each side makes depend to some extent on what choices they expect the other side to make. Therefore, this human element must be considered when making a comprehensive assessment of proliferation resistance; this is further complicated because many analysts believe that proliferators will disregard common safety and environmental norms.

Moreover, the assessment of proliferation resistance requires a means to handle sensitive information without disclosing its sensitive details. A detailed understanding of how the nuclear material characteristics (e.g., isotopic composition or chemical composition) affect a nuclear

explosive is generally classified information. This makes an assessment by material characteristics difficult.

The assessment of proliferation resistance is inherently qualitative and it is difficult to quantify many of the elements. Some elements, such as treaties, agreements, and policies, are difficult to quantify because of variations in their strength, quality and degree of compliance, which are political judgements. Others are also difficult to quantify because they involve human choices and activities that are outside the range of normal experience. For example, the technical difficulty of extracting Pu from irradiated targets can vary considerably depending on what the potential proliferator is prepared to do. If human health is not a significant consideration, then an extraction can be performed with a minimal amount of shielding and protective equipment.

Regarding the assessment methodology, a quantitative evaluation of proliferation resistance requires further development for the aggregation of the assessment results.

However, the aggregation methods may be misleading by possibly hiding weak links with a single score. It would be more feasible to perform a comparative assessment of the proliferation resistance of a nuclear system concerning a reference system. However, quantitative evaluation methodology in an absolute scale can more clearly describe the strong and weak points of a nuclear energy system in terms of proliferation resistance; this can be used as a basis for future design development and improvement.

The assessment of proliferation resistance requires both dependent and independent state-specific information. The strength of the proliferation resistance provided by some intrinsic features can depend on state-specific information such as the presence of indigenous uranium resources or the presence of other nuclear facilities. State-specific extrinsic measures such as fuel supply agreements for the procurement of fresh fuel and the return of spent fuel can affect the proliferation resistance of a nuclear system. However, the intrinsic features, which facilitate in verification, generally provide proliferation resistance as being independent of the State in which a nuclear energy system is deployed.

6. CONCLUSIONS

While the proliferation resistance evaluation methodology including the basic principles, user requirements and indicators presented in the IAEA-TECDOC-1434 are comprehensive and very informative for assessing the degree of the proliferation resistance of a nuclear energy system quantitatively, the evaluation methodology of IAEA-TECDOC-1434 has been further modified with the present study. The current modifications improve the correspondence between the Basic Principles (BP) and the relevant User Requirements (UR), and clearly identify the crucial aspects of a nuclear energy system for the evaluation of the proliferation resistant characteristics of the nuclear system by revising the indicators and evaluation parameters.

The INPRO Methodology emphasizes the importance of the attractiveness of the material and the technology, the safeguardability and detectability, and the State's commitment in the evaluation of the proliferation resistance of a nuclear system.

The newly modified INPRO Methodology including the evaluation parameters, metrics, scales, acceptance criteria and evaluation procedures for Basic Principle 1 can be utilized for an assessment of future innovative nuclear systems in the proliferation resistance area.

The newly modified INPRO Methodology was applied to the DUPIC fuel cycle to assess the usefulness and the

comprehensiveness of the INPRO Methodology. The result of this study showed that it is very practical and informative.

Basic Principle 2 of the INPRO Methodology mainly addresses the multiplicity and robustness of the barriers against proliferation and their cost effectiveness to assure proliferation resistance. In order to evaluate these characteristics, it is essential to have detailed design information for the nuclear system and a comprehensive establishment of an acquisition/diversion pathway analysis. Therefore, this can be an area for further development of the INPRO Methodology. Additionally, an IAEA international collaborative program is currently under development. An integration of assessment results and an effective presentation of the evaluation results for designers and policy makers are other important areas that call for further study.

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