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Evaluation of the IAEA INPRO Methodology for the Proliferation Resistance Assessment of the DUPIC Fuel Cycle

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ABSTRACT

The IAEA initiated an International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) in 2000 for fulfilling the energy needs in the 21st century along with its economics, sustainability and the environment, safety of nuclear installations, waste management, and proliferation resistance. With respect to proliferation resistance, INPRO suggested five Basic Principles, five User Requirements and their indicators and each User Requirement is composed of several levels of indicators and acceptance criteria.

The present study mainly aims at evaluating the INPRO Methodology for the proliferation resistance which is suggested by the IAEA and proposing the further development of the INPRO methodology from the proloferation resistance view points. Also, the Basic Principles and User Requirements were not only reviewed but their relationship was also found. And, the scales of the acceptance criteria for the indicators of User Requirements are recommended and five-point qualitative scales such as unacceptable (U), weak (W), moderate (M), strong (S) and very strong (V) are proposed.

1. INTRODUCTION

The INPRO, which was initiated by the IAEA in 2000, selected proliferation resistance as a key component for a fuel cycle for fulfilling the energy needs in the 21st century along with its economics, sustainability and the environment, safety of nuclear installations and waste management.

During Phase 1A of INPRO, a set of Basic Principles (BP), User Requirements (UR) and Criteria including Indicators and Acceptance Limits have been developed in the areas of Economics, Sustainability and the Environment, Safety, Waste Management, Proliferation

Resistance, and Cross Cutting issues in order to set out the boundary conditions for the desired innovations of the nuclear energy systems. Phase 1A was finished in June 2003 and its results were published in the INPRO Phase 1A report (IAEA-TECDOC-1362, June 2003. [1]

Following Phase 1A, Phase 1B started in July 2003 for case studies in order to verify whether or not the INPRO Methodology needs any readjustment by the application of INPRO BP, UR and the Criteria to the sample cases. The nuclear energy system proposed for the case study may comprise of an entire system including the reactor and the entire fuel cycle and encompass the complete life cycle.

The case study will assess the methodology set out in the INPRO Phase 1A report by identifying the strengths and weaknesses and making recommendations for further work. The evaluation of each BP, UR and Criteria will be performed in respect of (i) simple and easy application, (ii) completeness, (iii) relevance of the results, (iv) recommendations to retain, modify, delete, or add BP, UR and the Criteria, and (v) the assessments of the uncertainties.

The Ministry of Science and Technology (MOST) of the Korean government decided the Korea Atomic Energy Research Institute (KAERI) should participate in the INPRO Phase 1B Case Study on the DUPIC (Direct Use of PWR spent fuel In CANDU reactors) fuel cycle in July, 2003. The INPRO case study on the DUPIC fuel cycle is focused on the proliferation resistance evaluation because the DUPIC fuel cycle is considered as an advanced fuel cycle technology for the symbiotic use of PWR (Pressurized Water Reactor) and CANDU (Canada Deuterim Uranium) reactors in a proliferation resistance way.

The present study mainly aims at evaluating the INPRO Methodology for the proliferation resistance of the DUPIC fuel cycle and proposing further development of the INPRO methodology from the proloferation resistance view points.

2. REVIEW OF INPRO METHODOLOGY

The INPRO Phase 1A report [1] contains five BPs and five URs for achieving proliferation resistance in an innovative nuclear energy system (INS). The BPs and URs are intended to provide guidance to governments, sponsors, designers, regulators, investors and other users of a nuclear power and the fuel cycle facilities, which incorporate the proliferation resistance of the future nuclear energy system.

2.1 Intrinsic and extrinsic barriers

To assess the proliferation resistance of the nuclear energy system, the intrinsic features and extrinsic measures must first be identified. In the INPRO Phase 1A report, four types of intrinsic features are defined. Those that provide: (i) unattractiveness to a nuclear weapons program, (ii) prevention or inhibition of nuclear material diversion, (iii) prevention or inhibition of an undeclared production of directly-usable target material, and (iv) efficient and cost-effective safeguards.

The extrinsic measures are also divided into five categories: (i) States' decisions and undertakings for nuclear energy systems, (ii) agreements between exporting and importing nuclear materials and components of nuclear energy systems, (iii) commercial, legal or institutional arrangements to control the accessibility of nuclear materials and nuclear energy systems, (iv) application of the IAEA verification and the regional, bilateral and national measures, and (v) legal and institutional arrangements to address violations of nuclear non-proliferation or the peaceful-use undertakings.

2.2 INPRO methodology

The INPRO methodology calls for the assessment of the intrinsic features and extrinsic measures of an INS to evaluate the indicators. The approach taken in the INPRO methodology is to aggregate the results of the evaluation of the indicators to obtain an evaluation for the URs, and to aggregate these results to obtain an evaluation of the BPs. Methods for: (1) evaluation of the indicators, (2) aggregation of the indicators to evaluate the URs, and (3) aggregation of the URs to evalute the BPs, are not given in IAEA TECDOC 1362. In addition, the relationship between the URs and BPs is not clearly stated and are not obvious, thus making evaluation of the BPs difficult. Finally, many of the BPs and URs appear to overlap significantly. Recommendation for a simplified set of BPs and URs with an explicit mapping of the URs onto the BPs is needed.

The five BPs and five URs, which are defined in the INPRO Phase 1A report, have possible links with each other as shown in Figure 1.

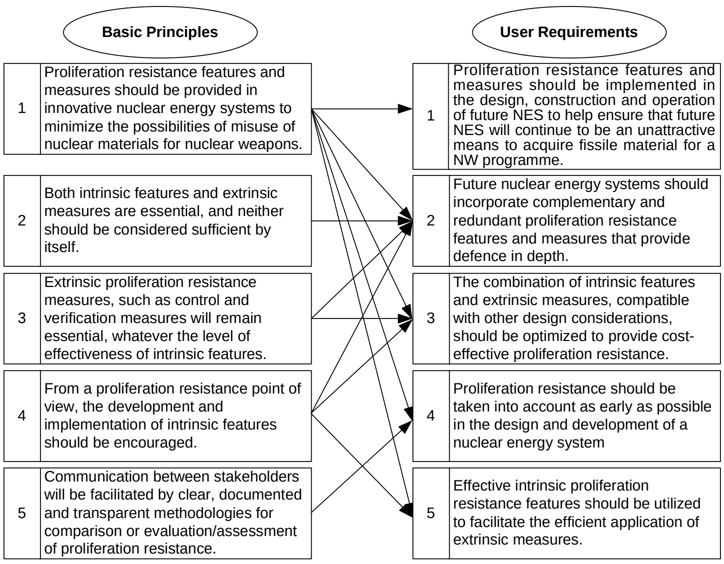

Figure 1. Possible links between BPs and URs

3. FRAMEWORK OF THE INPRO EVALUATION

3.1 General description

The framework of the INPRO evaluation methodology of the proliferation resistance is described, including the 3rd level indicators of UR1, which are not clearly defined in the Phase

1A report. These 3rd level indicators are selected in this study to clearly define the guidelines for the evaluation of the proliferation resistance, and they are then linked to the 2nd level indicators. The evaluation of each indicator is performed based on five levels, which range from the unacceptable to very strong levels.

At an early stage in the development of a system such evaluations are necessarily performed at a high level using expert judgments. Formal techniques such as the Delphi method, or expert elicitation may be applied to gain a consensus and address issues of bias or imbalance. In the future, as the system design becomes more mature, other formal analytical methods may be applicable for the evaluation of the indicators. A summary of the potential methods can be found in the NPAM report. [2]

The assessment approach used to evaluate the INPRO methodology and described in this study is based on the use of the Delphi method to directly evaluate the criteria, URs and BPs as laid out in IAEA TECDOC 1362. The intent was to examine the issues with a direct application of the INPRO methodology and to recommend improvements. Where possible at the criteria level, established standards or norms were used to create an evaluation scale. For example, the scale for the radiation field is based on IAEA INFCIRC/225 [3] and a DOE guideline document [4]. Once such scales were defined, evaluation of DUPIC for each criterion was performed using the Delphi method. The Delphi method was also used to aggregate the criteria for the evaluation of the URs, and for the aggregation of the URs for the evaluation of the BPs.

This assessment is for the resistance that the DUPIC would pose to an industrialized proliferant state who aspires to the acquisition of reliable nuclear weapons. The assessment assumes that the state has made all of the commonly accepted nonproliferation commitments including being a signatory to the NPT, and member of the nuclear suppliers group, etc. It further assumes that the state is sufficiently developed, where cranes, flasks, hotcells, and other infrastructure and equipment are available for use in the proliferation; specifically, that the state is capable of developing a clandestine reprocessing facility without detection. The assessment assumes that the state would not want to be detected and is therefore limited to clandestine scenarios.

3.2 Assumptions and limitations

- Intrinsic barriers

Many different indicators have been suggested by different experts and/or institutes. However this study refers mainly to the TOPS report [5] for the selection of the 3rd level indicators because the TOPS report is the most up-to-date as far as the evaluation attributes are concerned, which is also referred to in the INPRO Phase 1A study.

- Diversion scenarios

In general, evaluation of proliferation resistance depends on the diversion scenarios such as the covert diversions by the sub-national group, developing country and the developed country. Because the proliferation resistance is defined as “Diversion by States” in the INPRO Phase 1A report, this study will focus on the diversion by the nation.

- Time effect of the proliferation resistance

Expert groups have addressed the importance of the time effect of the proliferation resistance because the self-protecting field of the penetrating radiation emitted from the spent fuel steadily decreases with time and effectively disappears after several hundreds of years of cooling. After this period, the spent fuel could be processed in a contact-handled glove box rather than in a shielded and remotely-operated facility. It was suggested that this might provide a strong motivation for the proliferator to mine the long-cooled spent fuel from the repository [6, 7]. They insist that the repository is just a plutonium mine and, therefore, it is more important to achieve the near-total “destruction” of the plutonium [8]. In this regard, the total amount of plutonium based on the electricity generation of 1 GWe-yr, for example, could be another measure of the proliferation resistance. However this study does not consider the plutonium inventory because the issue of the plutonium inventory is still disputable and not considered in the TOPS report either.

- Integration method of the indicators

Unlike other indicators, the proliferation resistance indicators consist of several levels, for example, three levels for UR1 and two levels for UR2. Therefore it is recommended to introduce a method that integrates the evaluation results of the lower level indicators for the evaluation of the higher level indicator as well as accounting for the importance (or weighting) of each indicator. The integration method and weighting factors are available from the conventional decision making tools such as AHP (Analytical Hierarchy Process), MAUT (Multi-attributes Utility Theory) and the Delphi method. In this study, it was decided to use the Delphi method, which is an expert group discussion technique. Regarding the importance, it would be different from country to country when performing the case study, because it depends on the threat or diversion scenario.

- Extrinsic measures

Most of the extrinsic barriers have the answer in the form of “Yes” or “No”. For example, if a nation has not signed the NPT, the nation does not have any barrier to the NPT. In fact, the extrinsic measure is not dependent on the facility/process but most of the extrinsic measures reflect the nation’s committment even though a certain measure like the safeguards system is related to the facility. This study tries to treat facility specific elements such as the intrinsic indicators, aiming at consistently evaluating them with “Yes” or “No” for the extrinsic measures. Regarding the nation’s committment that varies with time, only the current committment is evaluated in this study for simplicity and consistency.

3.3 Evaluation frame of User Requirement 1

Table 1 shows an evaluation framework for UR1, which will be used in the case study. The 1st and 2nd level indicators are the same as those recommended by the INPRO Phase 1A report. Tables 2 and 3 show the evaluation framework for the 3rd level indicators of UR1 for the intrinsic and extrinsic indicators, respectively. The key parameters of the evaluation are in the 2nd column of Table 2.

Table 1. Proposed hierarchy of the indicators of the UR1

First Level	Second Level	Third Level
Confidence that the proliferation resistance features and measures that are implemented in the design, construction and operation of future nuclear energy systems to help ensure that futures nuclear energy systems will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme	States' commitments, obligations and policies regarding non-proliferation and disarmament.	• Non-proliferation related treaties and convention - NPT - NW-free zone treaties - CTBT • Export control - Export control policies - Bilateral arrangements for supply and return of nuclear fuel - Bilateral agreements governing re-export of NES components • Commercial, legal or institutional arrangements that control access to NM and NES - Multi-national ownership - Management or control of a NES • Safeguards agreements, verification and response - Safeguards agreements pursuant to the NPT - State's or regional safeguards systems - Safeguards approaches for the state's or regional safeguards systems - An effective international response mechanism for violations
	Unattractiveness of nuclear material for a nuclear weapons programme.	• Isotope content • Chemical form • Radiation field • Bulk and mass • Heat generation • Spontaneous neutron generation rate • Detectable radiation
	Prevention or inhibition of the diversion of nuclear material.	• Diversion detectability • Effectiveness of prevention of diversion of nuclear material
	Prevention or inhibition of the undeclared production of direct-use material.	• Difficulty to modify fuel cycle facilities and process

With regards to the evaluation scale, INPRO recommended using qualitative scales ranging from an unacceptable to an outstanding level. In this study, five-point qualitative scales are chosen: unacceptable (U), weak (W), moderate (M), strong (S) and very strong (V).

Table 2. Evaluation frame for the 3rd level intrinsic indicators of UR1

Third level indicator	Key parameter	Evaluation scale of Acceptance Limit				
		U	W	M	S	V
Isotope content	^{239}Pu/Pu (wt%)					
Chemical form	Chemical form					
Radiation field	Dose (rem/hr)					
Bulk and mass	Mass (kg)					
	Size (cm)					
Heat generation	^{238}Pu/Pu (wt%)					
Spontaneous neutron generation rate	(^{240}Pu+ ^{242}Pu) /Pu (wt%)					
Detectable radiation	Detectability					
Diversion detectability	MUF					
Effectiveness of prevention of diversion of nuclear material	Environment					
Difficulty to modify fuel cycle facilities and process for undeclared production	Degree of difficulty					

Table 3. Evaluation frame for the 3rd level extrinsic indicators of UR1

Third level indicator	Key parameter	Evaluation scale of Acceptance Limit				
		U	W	M	S	V
Non-proliferation related treaties and convention	NPT					
	NW-free zone treaties					
	CTBT					
Export control	Export control policies					
	Bilateral arrangements for supply and return of nuclear fuel					
	Bilateral agreements governing re-export of NES components					
Commercial, legal or institutional arrangements that control access to NM and NES	Multi-national ownership					
	Management or control of a NES					
Safeguards agreements, verification and response	Safeguards agreements pursuant to the NPT					
	State or regional systems for accounting and control					
	Safeguards approaches for the state's or regional safeguard systems					
	An effective international response mechanism for violations					

Tables 4 and 5 show the evaluation framework for the 2nd level and 1st level indicators, respectively. At first, the evaluation results of the 3rd level indicators have to be integrated to evaluate the 2nd level indicator. For the integration, this study introduces a weighting factor concept with three qualitative weighting factors scales. The weighting factors for the integration of the 3rd level indicators can be obtained from the group discussion

Table 4. Evaluation frame for the 2nd level indicator of UR1

Second level indicator	Third level indicator	Import-ance*	Evaluation scale of Acceptance Limit				
			U	W	M	S	V
Score of 2nd level evaluation (1)							
States' commitments, obligations and policies regarding non-proliferation and disarmament.	Non-proliferation related treaties and convention						
	Export control						
	Commercial, legal or institutional arrangements that control access to NM and NES						
	Safeguards agreements, verification and response						
Score of 2nd level evaluation (2)							
Unattractiveness of nuclear material for a nuclear weapons program.	Isotope content						
	Chemical form						
	Radiation field						
	Bulk and mass						
	Heat generation						
	Spontaneous neutron						
	Detectable radiation						
Score of 2nd level evaluation (3)							
Prevention or inhibition of the diversion of nuclear material.	Detection by radiation						
	Design Features that limit access to nuclear material						
Score of 2nd level evaluation (4)							
Prevention or inhibition of the undeclared production of direct-use material	Difficulty to modify fuel cycle facilities and process for undeclared production						

*qualitative scale (low, medium, high) will be used

Table 5. Evaluation frame for the 1st level indicator of UR1

First level indicator	Second level indicator	Import-ance	Evaluation scale of Acceptance Limit				
			U	W	M	S	V
Score of 1st level evaluation							
Confidence that the proliferation resistance features and measures that are implemented in the design, construction and operation of future nuclear energy systems to help ensure that futures nuclear energy systems will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme	States' commitments, obligations and policies regarding non-proliferation and disarmament.						
	Unattractiveness of nuclear material for a nuclear weapons programme.						
	Prevention or inhibition of the diversion of nuclear material.						
	Prevention or inhibition of the undeclared production of direct-use material.						

techniques such as the Delpi concept or the attribute techniques. The 1st level indicator can also be evaluated in the same way.

It is also important that the evaluation procedure should be setup before performing the evaluation based on the suggested INPRO methodology such as the top-down derivation and the bottom-up fulfillment of the indicators required in UR 1. The detailed evaluation scheme of the proliferation resistance based on an UR1 is shown in Figure 2.

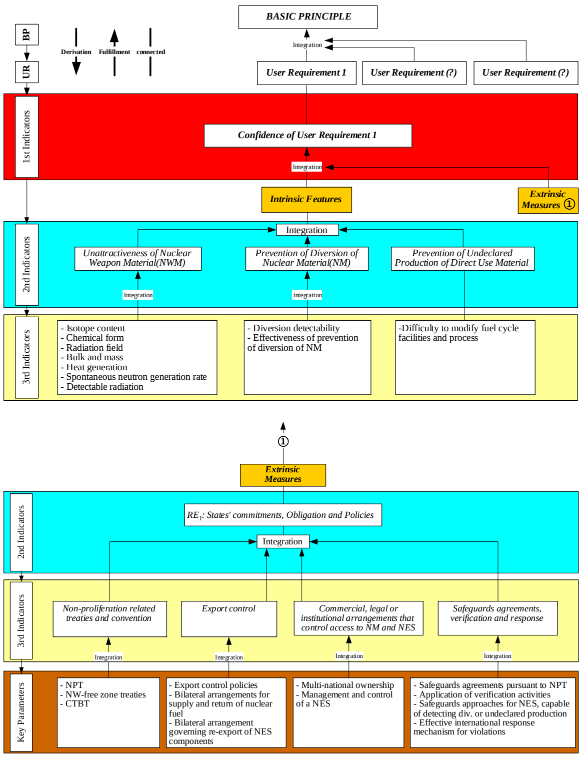

Figure 2. UR1 evaluation scheme

3.4 Evaluation frame of User Requirement 2

UR2 consists of the 1st and 2nd level indicators in the Phase 1A report. The indicators of UR2 are focused on "a defense in depth" concept even though most of the UR2 indicators are already assessed in UR1. However the definition of the 2nd level indicator is not clearly described in the

Phase 1A report. Therefore the 2nd indicators need to be defined for a clear evaluation. In this study, the 2nd level indicators are defined as follows to avoid a duplication among the indicators.

- *Number of barriers comprising of the intrinsic features and the extrinsic measures*: The number of barriers comprising of the intrinsic features and the extrinsic measures is defined as the number of barriers which have "acceptable" scores in UR1. As shown in Table 1, there are a total of 10 intrinsic and 12 extrinsic barriers.
- *Robustness of each barrier:* The robustness of each barrier is a little bit ambiguous because each barrier has already been evaluated and scored in UR1. In the case study, the robustness of each barrier is evaluated to see if there are any very important intrinsic or extrinsic barriers, which need to be declared. In other words, the barriers with "acceptable" scores in UR1 can be examined to see if they have any very important intrinsic or extrinsic barriers. The very important intrinsic or extrinsic barriers could be, for example, a barrier that should be absolutely met for the innovative nuclear system.

Table 6. Assessment of UR2

Second level indicator	Key parameter	Evaluation scale of Acceptance Limit				
		U	W	M	S	V
Number of barriers comprising intrinsic features and extrinsic measures	The number of barriers which have score of "acceptable" in UR1					
Robustness of each barrier	Are all of radiation field, NPT and safeguards agreement accepted?					
Redundancy or complementarity within intrinsic features	The number of barriers which have score of "acceptable" in intrinsic features					
Redundancy or complementarity within extrinsic measures	The number of barriers which have score of "acceptable" in extrinsic measures					
Assessment of system strength and weakness to ensure that all potential vulnerabilities are covered by intrinsic features, extrinsic measures and combinations thereof	Are potential vulnerabilities covered by intrinsic and extrinsic?					

Table 7. Evaluation frame for the 1st level indicator of UR2

First level indicator	Second level indicator	Import-ance*	Evaluation scale of Acceptance Limit				
			U	W	M	S	V
Score of 1st level evaluation							
Confidence that an INS makes effective use of redundant and complementary features and measures to achieve defence in depth	No. of barriers						
	Robustness						
	Redundancy or complementarily within intrinsic features						
	Redundancy or complementarily within extrinsic measures						
	Assessment of system strength and weakness to ensure that all potential vulnerabilities are covered by intrinsic features, extrinsic measures and combinations thereof						

- *Redundancy or complementarity within the intrinsic features:* This indicator is defined as the number of barriers which have "acceptable" scores in UR1 within the intrinsic features. If the acceptance limit is assumed as four, there should be at least four intrinsic barriers with acceptable scores.

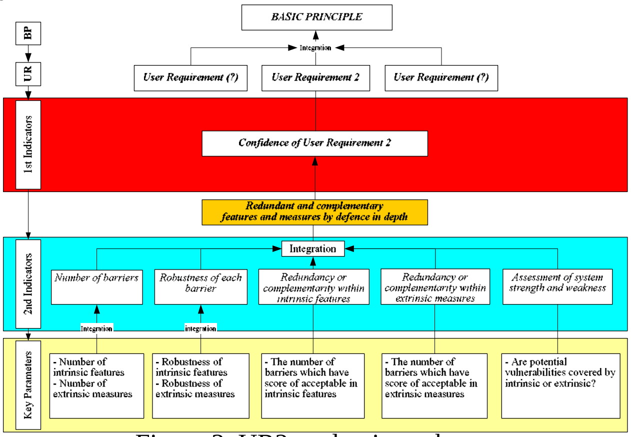

Figure 3. UR2 evaluation scheme

- *Redundancy or complementarity within the extrinsic measures:* This indicator is defined as the number of barriers which have "acceptable" scores in UR1 within the extrinsic measures.
- *Assessment of the system's strengths and weaknesses:* The assessment of a system's strengths and weaknesses is a little bit ambiguous and redundant when compared to UR1, because the

assessment of each barrier in UR1 already includes the assessment of the system's strengths and weaknesses in terms of proliferation resistance.

Table 6 shows the evaluation frame and key parameters of UR2. Table 7 shows the evaluation frames for the 1st level indicator. The 2nd level indicators can be integrated into the 1st level indicator by an appropriate method which was described for UR1. The weighting factors as well as the three qualitative scales can be obtained from the group discussion and the integration can be performed for the 2nd level indicators. The evaluation scheme of UR 2 is shown in Figure 3.

3.5 Evaluation frame of User Requirement 3

UR3 is used for the full scope evaluation of the cost effectiveness. The Phase 1A report recommends that the cost should include the following:

- All life-cycle costs associated with proliferation resistance, from the cradle to the grave and all the steps from mining to the final disposal.
- Costs of the incremental engineering, construction, operation, decommissioning and disposal are to include the intrinsic features in the design.
- Costs associated with the implementation of other extrinsic measures that are specific to a particular INS (e.g., incremental overhead to operate a multi-national fuel supply centre versus a state-owned fuel supply centre).
- Costs for the verification equipment (e.g., installed and portable equipment used for inspections).
- Costs for the independent verifications (e.g., IAEA and regional safeguards inspections).

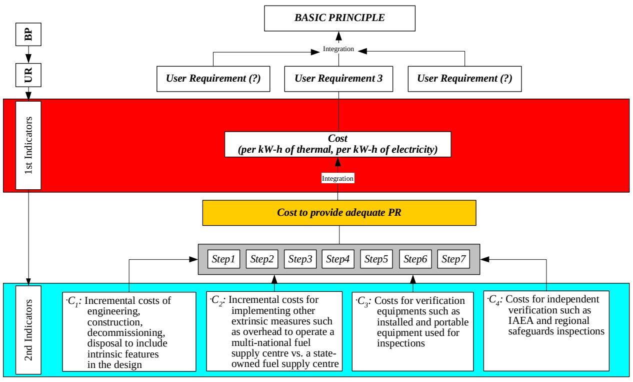

Figure 4. UR3 evaluation scheme

For the incremental cost required to include the intrinsic features, it is only necessary to calculate the cost of the intrinsic features that are added primarily to enhance the proliferation resistance. Intrinsic features that are included primarily for other reasons should not be included in this evaluation. The decision for intrinsic features to be included may not always be clear and may require a design review or other formal methods to be identified. The evaluation scheme of UR 3 is shown in Figure 4.

3.6 Evaluation frame of User Requirement 4

UR 4 is the consideration of the proliferation resistance in all the major decisions by the responsible bodies during the development/design stages of the innovative nuclear energy system. The evaluation scheme of UR4 is shown in Figure 5. Although this user requirement is also an important guideline for the system design, it is not clear how it will be utilized for the evaluation of an innovative system.

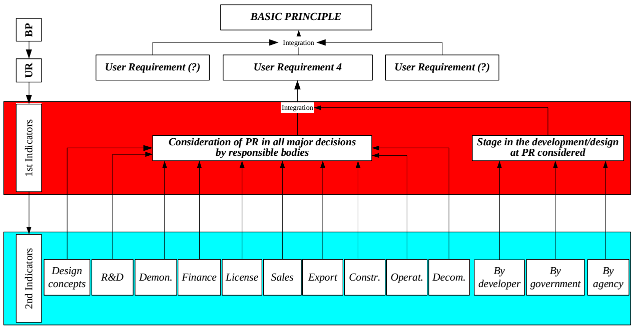

Figure 5. UR4 evaluation scheme

3.6 Evaluation frame of User Requirement 5

UR 5 has three kinds of 1st level indicators such as the awareness of the extrinsic measures by the designers, intrinsic features of the proliferation resistance to the extent of the verification approach and the safeguards approach with a reasonable level of the extrinsic measures. The evaluation scheme of UR5 is shown in Figure 6. Although this UR is an important guideline for the system design, it is not clear how it will be utilized for the evaluation of an innovative system.

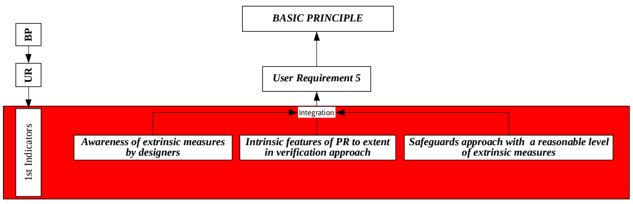

Figure 6. UR5 evaluation scheme

4. EVALUATION RESULTS OF THE INPRO METHODOLOGY

INPRO provides a framework for the overall evaluation of an innovative nuclear system including proliferation resistance. The INPRO methodology provides a structure but does not provide the methods for the evaluation of the proliferation resistance indicators.

4.1 Structure of the Basic Principles and User Requirements

Although the five BPs and five URs for the proliferation resistance described in the Phase 1A report are reasonable and practicable on an individual basis, there are several issues that make assessment using the INPRO methodology difficult.

First, there is a considerable overlap between the BPs and URs, sometimes obscuring the main intent of a particular BP. Some URs even appear to be completely redundant, perhaps being included for emphasis. Such overlaping and redundancy should be avoided to simplify an assessment and avoid issues of double counting.

The second issue with the BPs and URs as proposed in IAEA TECDOC 1362 is that there is no clear link between the URs and BPs, even though such a link is generally described in Chapter 3 of the IAEA TECDOC 1362. According to that report, “The URs set our measures to be taken to ensure the fulfillment of the BP(s) to which they are related.” Because the relationship between URs and BPs is not stated and not obvious, direct application of the INPRO methodology to the INPRO URs and BPs is not possible. As a specific example, none of the URs appear to relate to BP5.

Finally, some basic principles and user requirements provide guidance or emphasis, that is, useful but should not be included in high level BPs and URs. For these reasons, it is recommended that the BPs and URs be structured more systematically for applying the INPRO methodology to the realistic evaluation of an innovative nuclear system.

4.2 Correspondence between Basic Principles, User Requirements and the Criteria

The proposed BPs are a set of general statements of the goals from the proliferation resistance viewpoint. The URs are another set of general requirements in the proliferation resistance area. Since the correspondence or the link between the BPs and URs is not described clearly, the objective evaluation of the proliferation resistance characteristics of an innovative nuclear system is difficult.

The main rationale of the INPRO methodology is that a derivation of the evaluation criteria including the acceptance limit is based on the “Top-down Approach”, and their evaluation is based on the “Bottom-up Approach”. The key to the Bottom-up Approach is to determine if a nuclear system can meet the acceptance limits suggested in the Phase 1A report, and then to judge the higher level requirements.

In order to apply this evaluation scheme, it is necessary to have clear links or correspondence between URs and BPs, which there is a lack of in the results of Phase 1A report. Using the Bottom-up Approach for the evaluation, first of all, the hierarchy among the BPs, URs and the Criteria (Indicator and Acceptance limit) has to be well described and linked directly to each other. The hierarchy among BPs, URs and the Criteria in the proliferation resistance area is inadequately described and they are not exactly linked to each other. It is, therefore, necessary that some BP/UR/Criteria be modified and/or deleted to apply the original Bottom-up Approach to the case study.

Moreover, it is not easy to use it for proliferation resistance, but it could be easily evaluated quantitatively in contrast to an effective evaluation of the economics and safety where the quantitative acceptance limits can be easily defined.

The proliferation resistance evaluation can be clearly performed by a relative comparison with another nuclear system and/or scenario analysis. The alternative method is to jointly use these methods with the INPRO methodology to provide a meaningful evaluation.

4.3 Evaluation of the Indicators

Issues with Evaluation of UR1

The approach taken in the evaluation of the (second level) indicators for UR1, was to evaluate the third level indicators (variables) on an individual basis and then to integrate the results. In this bottom-up process for the evaluation, it is necessary to perform the integration of the lower level evaluation results for each evaluation step.

In the case of the integration of the evaluation results in several low level indicators or key parameters, sound backup data for the “weighting” or “level of importance” should be provided. And, in some cases, a certain parameter should have a “veto power” or act as a “show stopper”. The determination of an unanimous selection of such a weight will be required to reach universal conclusions.

The simplest integration method is based on the expert judgment for the integration. In this case, however, the procedures for the expert elicitation provide a more formalized result. Other integration methods based on the multi attribute decision theory, etc. could also be applied to this integration problem.

With the proposed reformulation of the indicators for UR1 to be a single level, and to consider the 3rd level indicators as variables, this form of bottom up evaluation of the indicators would no longer be required by the INPRO methodology. However, some formal method for evaluation of the indicators for UR1 is required and there are no commonly accepted methods for such an evaluation. In order to obtain consistent assessment results that can be compared with other assessments, INPRO must establish some common basis for these evaluations. From the review of the past work on the assessments of this type, it is clear that further work is required.

Issues with the Evaluation of UR’s 3, 4 and 5

UR3: The main extrinsic cost for the DUPIC fuel cycle is expected to be safeguards. Costs associated with bilateral nuclear cooperation agreements, participation in the NSG, etc. are general costs associated with a nuclear activity and not specifically as a result of DUPIC. Therefore, these costs will not be assigned to DUPIC in this evaluation. The safeguards approach has not been developed for a production scale DUPIC facility. Prior to development of a detailed concept for a full scale plant, it would be difficult to estimate the cost of the safeguards for a DUPIC plant. Because DUPIC is innovative, it is not appropriate to simply extrapolate safeguards costs based on the costs for a PUREX plant or other current facility. Further detailed work with the IAEA would be required to develop a concept for the safeguards and from that to estimate the safeguards cost. With regards to intrinsic costs, it is difficult to identify specific intrinsic features that are implemented primarily to achieve proliferation resistance. The entire DUPIC fuel cycle was developed to be proliferation resistant, but assigning the entire DUPIC cost to proliferation resistance would not appear to meet the intent of this indicator. When a safeguards approach is developed for DUPIC, and as a result of the discussions on the approach, changes are made to the DUPIC facility design to simplify the safeguards, then it would be appropriate to assign costs for those changes to this indicator.

UR4: Consideration of proliferation resistance has been taken into account in all the major decisions for DUPIC to date, and is expected to continue to be taken into account in all the major decisions in the future. DUPIC development is expected to consider proliferation resistance at all the appropriate stages and therefore DUPIC fully meets all criteria for the UR4.

UR5 indicator 5.1: DUPIC designers have been aware of proliferation resistance from the earliest discussions and are involved in regular meetings that include proliferation resistance. DUPIC includes a safeguards group that continues to keep the designers aware of proliferation resistance and safeguards and provides them with the knowledge necessary to ensure a strong consideration of proliferation resistance in all of their work.

Indicator 5.2: The verification approach for a production scale DUPIC facility has not been developed. Any verification approach is supposed to take all the features of the facility into account including the intrinsic proliferation resistance features. It would appear that any INS should be able to legitimately claim that all the intrinsic features are used to the extent possible in the verification approach. The intent of this indicator requires clarification.

Indicator 5.3: The safeguards approach has not been developed for a production scale DUPIC facility. Prior to the development of a detailed concept for a full scale plant, it would be difficult to propose and discuss a safeguards approach, let alone evaluate the level of effort. The IAEA does not normally agree to a safeguards approach prior to the availability of sufficient detail to formulate an approach, and therefore it is not possible for any INS to meet the acceptance criteria for this indicator until closer to deployment of an actual system. This indicator would appear to be meaningful and important to an assessment conducted closer to the deployment time and for that reason should not be discarded. However, it should be formulated so as to only be applicable at an appropriate stage in the INS development.

4.4 Uncertainty analysis

Since the evaluation will be performed on an innovative nuclear system to be implemented in the future, there will be a lot of uncertainties in the design specifications, which will be improved by further research and development. The sensitivity analysis on how the variation of an evaluation factor would affect the eventual evaluation results is of interest. The uncertainty associated with the basic technical information and its effect on the integrated evaluation results is recommended to be stated in the results. While a specific indicator such as a commitment to the NPT can be evaluated as “Yes/No”, other indicators such as isotopic content can be evaluated as a continuous value. For example, 100 % proliferation resistance for the materials of more than 80 % of ^{238}Pu, 80 % proliferation resistance for the materials of more than 60 % of ^{238}Pu, 0 % proliferation resistance for the materials of less than 10 % of ^{238}Pu, etc. The variation of the proliferation resistance against a specific indicator would vary either linearly, exponentially, inverse exponentially in a continuous way, or it will have discrete values. A complete sensitivity analysis of all the indicators would be very complicated, but the important factors which should be considered for the sensitivity analysis had better be recommended.

4.5 Determination of the quantitative acceptance criteria

In the Phase 1A report, all the acceptance limits for proliferation resistance were not quantified. For the case study, it is first required to define quantitatively or at least qualitatively the acceptance limits. Even though several technical documents are available for the references, there are a lot of arguments regarding the validity of the specific criteria. In order to have convincing evaluation results, a consensus on the detailed acceptance criteria had better be established in advance.

Another alternative to avoid any difficult work is to evaluate the proliferation resistance relatively with a comparison of the other nuclear fuel cycle alternatives. But in that case, it does not actually abide by the INPRO methodology

4.6 Format of the results to be presented

Even though the evaluation will be performed by the system designer, fuel cycle experts and safeguards professionals, the main purpose of the evaluation will be the easy utilization of the INPRO methodology by the policy decision makers and system designers. Therefore, the format of the evaluation results should be clear enough for the policy decision makers to understand the characteristics of the system in terms of the proliferation viewpoint, and it should be detailed enough for system designers to consider the design elements for improving the proliferation resistant characteristics. INPRO should suggest a format for presenting the evaluation results.

5. CONCLUSIONS

INPRO provides a framework for the overall evaluation of an innovative nuclear system including proliferation resistance. The INPRO methodology proposes a structure but does not propose the methods for the evaluation of the proliferation resistance indicators.

The present study shows that the INPRO methodology, the BPs, URs, and the Criteria and Indicators proposed in the Phase 1A report (IAEA-TECDOC-1362) are basically comprehensive and useful guidelines for the evaluation of an innovative nuclear reactor and the fuel cycle system.

However, it was found through the Korean National Case Study on the DUPIC fuel cycle that several improvements of the INPRO methodology such as the method of the integration of the results, clarification of the links between the BPs and URs, a clear definition of the grading of each Indicator, etc. are required.

A more practical description of the INPRO methodology with a step-by-step application procedure is recommended for the easy application of the Methodology for the Member States without an exhaustive study on the methodology by each Member State.

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