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# INPRO Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (PRADA)

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# INPRO COLLABORATIVE PROJECT: PROLIFERATION RESISTANCE: ACQUISITION/DIVERSION PATHWAY ANALYSIS (PRADA)

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2012

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# FOREWORD

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched in 2000, on the basis of a resolution of the IAEA General Conference (GC(44)/RES/21). INPRO intends to help to ensure that nuclear energy is available in the 21st century in a sustainable manner, and seeks to bring together all interested Member States — both technology holders and technology users — to consider, jointly, actions to achieve desired innovations. As of November 2011, 34 countries and the European Commission are members of INPRO.

Programme Area A of INPRO, Nuclear Energy System Assessments (NESAs) using the INPRO Methodology, is aimed at assisting Member States in assessing existing or future nuclear energy systems in a holistic way to determine if such systems meet national sustainable development criteria. A NESA using an internationally validated tool, the INPRO Methodology, aids Member States in strategic planning and decision making on long term nuclear energy deployment.

This report presents the results of the INPRO Collaborative Project on Proliferation Resistance: Acquisition/Diversion Pathway Analysis (PRADA), undertaken under INPRO Programme Area A. The basic principle for proliferation resistance requires that intrinsic features and extrinsic measures of proliferation resistance be implemented throughout the full life cycle of an innovative nuclear energy system to help ensure that the system will continue to be unattractive as means of acquiring fissile material for a nuclear weapons programme. In this context, the overall objective of this project is to further develop the INPRO Methodology in the area of proliferation resistance.

A key user requirement demands that innovative nuclear systems should incorporate multiple proliferation resistance features and measures. PRADA focuses on identifying and analysing high level pathways for the acquisition or diversion of fissile material for a nuclear weapons programme, using the direct use of spent PWR fuel in CANDU reactors (DUPIC) fuel cycle as a case study with an assumed diversion scenario. The study will also make recommendations for assessing the multiplicity and robustness of barriers against proliferation, including institutional, material and technical barriers and also barriers resulting from the implementation of international safeguards.

Initiated in 2008 and led by the Republic of Korea, which is conducting the DUPIC case study, the project also involves the participation of Canada, China, the USA and the European Commission and is being run in close cooperation with the IAEA Safeguards Department. Also, progress and results of the study are being harmonized with an assessment methodology for proliferation resistance and physical protection developed by Generation IV International Forum (GIF) for Generation IV nuclear energy systems.

The IAEA would like to express its thanks to Hong-Lae Chang and Won-Il Ko, (Korea Atomic Energy Research Institute, Republic of Korea) and other PRADA team members (listed as contributors) for organizing the meeting and editing the report. The IAEA officers responsible for this publication were S. Sakaguchi of the Division of Nuclear Fuel Cycle and Waste Technology and E. Haas, of INPRO and the Department of Safeguards.

*EDITORIAL NOTE*

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# EXECUTIVE SUMMARY

This report presents the results of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) Collaborative Project on Proliferation Resistance: Acquisition/Diversion Pathway Analysis (PRADA), undertaken under INPRO Programme Area A. INPRO was launched in 2000, on the basis of a resolution of the IAEA General Conference (GC(44)/RES/21) to ensure that nuclear energy is available in the 21st century in a sustainable manner, and seeks to bring together all interested Member States — both technology holders and technology users — to consider actions to achieve innovation. Programme Area A of INPRO, Nuclear Energy System Assessments (NESAs) using the INPRO Methodology, is aimed at assisting Member States in assessing existing or future nuclear energy systems in a holistic way to determine if such systems meet international sustainable development criteria.

One important factor for sustainability is deploying innovative nuclear energy systems (INS) in a safe and secure way to reduce the risk of nuclear weapons proliferation. The basic principle for proliferation resistance (minimizing proliferation risk) requires that intrinsic features (features that result from the technical design of the INS) and extrinsic measures (States' commitments, obligations, and policies) of proliferation resistance be implemented throughout the full life cycle of the INS to ensure that the system will be an unattractive means of acquiring fissile material or technology for a nuclear weapons programme. An INS should incorporate multiple proliferation resistance features and measures. These features and measures must overlap in a layered fashion to provide multiple barriers to each of the possible proliferation pathways. In this context, the overall objective of this project was to further develop the INPRO proliferation resistance assessment methodology.

The specific objectives of the PRADA study were to:

- develop appropriate methods for the identification and analysis of pathways for the acquisition of weapon-useable nuclear material;
- evaluate the multiplicity and robustness of barriers against proliferation for the pathway by logic trees (e.g. success/failure trees, event trees) and/or qualitative methods; and
- on the basis of the above results, recommend an assessment approach for User Requirement 4 (UR4) of the *INPRO Methodology*, regarding the multiplicity and robustness of barriers against proliferation.

As a test of the methodology, PRADA focused on identifying and analysing only some of the higher level pathways for the acquisition of fissile material for a nuclear weapons programme. A case study was made using the process known as DUPIC (direct use of PWR spent fuel in CANDU reactors). The CANDU reactor used in the DUPIC system served to develop appropriate methods for the identification and analysis of plausible acquisition paths. The study also resulted in recommendations for assessing the multiplicity and robustness of barriers against proliferation, including institutional, material, and technical barriers, as well as barriers due to the implementation of international safeguards. This was not a comprehensive study of DUPIC or CANDU reactors.

The PRADA project was initiated in 2008. The Republic of Korea, which had been developing the DUPIC process, assumed the project lead and was supported by participation from Canada, China, the USA, and the European Commission. In addition, the Russian Federation and Japan, participating as observers, contributed to the project. Within the IAEA, the PRADA study was conducted in close cooperation with the Departments of Nuclear Energy and Safeguards. The PRADA study was completed within the planned project schedule. The final working group meeting took place 8–10 November 2010 at the IAEA Headquarters in Vienna, during which the final report was reviewed and approved for IAEA publication.

The main conclusions of the PRADA study are that:

- the proliferation resistance assessment should be performed at three levels: the State level, the INS level, and the facility level including facility specific pathways.
- the robustness of barriers against proliferation depends on the State capabilities and the relevance of barriers is not the same at the different levels of evaluation listed above.
- the robustness of barriers is not a function of the number of barriers or of their individual characteristics but is an integrated function of the whole, and is measured by determining whether and with what confidence the safeguards goals can be met.
- in addition, the INPRO assessment methodology needs information regarding proliferation risks from more quantitative analyses performed jointly by technology developers (suppliers), safeguards experts, and experts in proliferation resistance.

The PRADA study identified several areas where the INPRO proliferation assessment methodology could be expanded and improved:

- A better explanation of acceptance limits.
- A reformatting and restructuring of the evaluation tables to include needed details.

The PRADA study also recognized the desirability of forming a 'GIF/INPRO coordinated set of proliferation resistance and safeguardability assessment tools'. This set of tools would bring together the complementary strengths of the GIF and INPRO approaches and clearly demonstrate that the two methods could be used in harmony and provide consistent results.

The PRADA study recommended that an expanded test of the methodology be applied to a new example study to demonstrate usefulness and validate the approach, and this study should address a complete nuclear energy system in a State. The expanded test should cover transportation and multiple facilities, including a reactor and waste disposal. The example studies proposed include: (1) an open fuel cycle in an emerging nuclear State, a country interested in beginning a commercial nuclear power programme, and (2) a generic pyroprocessing fuel cycle not attached to any State but building on the GIF ESFR study, using an INPRO based approach.

# 1. INTRODUCTION

The INPRO proliferation resistance (PR) evaluation methodology provides both a framework for assessing PR, and guidance to improve the PR of an innovative nuclear energy system (INS) [1]. It is based on the principle that PR intrinsic features and extrinsic measures shall be implemented throughout the full life cycle of the INS to help ensure that the INS will continue to be an unattractive means of acquiring fissile material for a nuclear weapons programme. The methodology has one basic principle and five user requirements, along with relevant criteria, indicators, and evaluation parameters.

The assessment indicators and procedures for the first three user requirements regarding States' commitments, attractiveness of nuclear material and technology, and difficulty and detectability of diversion, were established through Korean national case studies [2, 3]on direct use of spent pressurized water reactor (PWR) fuel in the CANDU reactor (DUPIC) fuel cycle and by various consultancy meetings. However, the assessment indicators and procedure for User Requirement 4 (UR4) regarding multiplicity and robustness of barriers against proliferation (*innovative nuclear energy systems should incorporate multiple proliferation resistance features and measures*) needed to be developed. Therefore, the specific objectives of the project were to:

- develop the appropriate methods for the identification and analysis of pathways for the acquisition of weapon-usable nuclear material;
- evaluate the multiplicity and robustness of barriers against proliferation for the pathway by logic trees (e.g. success/failure trees, event trees) and/or qualitative methods; and
- on the basis of the above results, recommend the assessment approach for User Requirement 4 of the INPRO PR methodology, regarding the multiplicity and robustness of barriers against proliferation.

In this regard, the INPRO Phase 2 Collaborative Project on Proliferation Resistance: Acquisition/Diversion Pathway Analysis (PRADA) was proposed by the Republic of Korea at the 10th INPRO Steering Committee Meeting held in Vienna in December 2006 [4].

TABLE 1: THREE-YEAR PROJECT IN THREE STAGES

| ***Goal*** | ***Work Scope*** | ***1st Year*** | | | | ***2nd Year*** | | | | ***3rd Year*** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *1/4* | *2/4* | *3/4* | *4/4* | *1/4* | *2/4* | *3/4* | *4/4* | *1/4* | *2/4* | *3/4* | *4/4* |
| Selection of prospective pathways | Description of proliferation objectives | | | | | | | | | | | | |
| | Study of possible strategies of proliferation | | | | | | | | | | | | |
| | Systematic approach for possible pathways | | | | | | | | | | | | |
| Analysis of pathways | Characteristics of design and process information of facility | | | | | | | | | | | | |
| | Development of logic trees (or, probability approach, if necessary) | | | | | | | | | | | | |
| | Evaluation of each process flow of the prospective pathway | | | | | | | | | | | | |
| Assessment of multiplicity & robustness | Evaluation of multiplicity & robustness of barriers | | | | | | | | | | | | |
| | Review and recommendation of Assessment methodology | | | | | | | | | | | | |

The kick-off meeting of the INPRO Phase 2 Collaborative Project on PRADA was held in Vienna on 19–20 November 2007, and several follow-on consultancy meetings were held — in Vienna, Jeju City (Republic of Korea) and Vancouver (Canada) — in line with the three-year project schedule shown in Table 1. One of the decisions taken in the early consultancy meeting and reinforced afterwards was to develop procedures and metrics for the evaluation of UR4 benefitting from the work done in the context of the Proliferation Resistance and Physical Protection (PR&PP) Working Group of the Generation IV International Forum (GIF) [5].

## 2. PROPOSED SYSTEMATIC APPROACH FOR ACQUISITION/DIVERSION PATHWAY ANALYSIS

The objective of a potential proliferant State is to acquire nuclear material that could be used for nuclear explosive devices. It was assumed that the actor, i.e. proliferant State, is an industrialized non-nuclear weapon State that has indigenous uranium resources, physical control over the commercial nuclear energy system and nuclear material being evaluated, declared facilities and material subject to international safeguards under a comprehensive safeguards agreement and an additional protocol.

The proliferation target could be nuclear material, equipment or processes that can be misused for the production of undeclared nuclear weapon-usable material, or equipment and technology that can be replicated in an undeclared facility. Table 2 summarizes the threat definition and possible proliferation strategies.

TABLE 2: THREAT DEFINITION SUMMARY

| Category | Element | Results |
|---|---|---|
| Host State objectives | Special fissionable material | Acquisition of at least 1 significant quantity (SQ) per year for nuclear explosive devices purpose |
| Host State capabilities | Technical skills | Weapon State equivalent |
| | Resources (money, personnel, uranium resources) | Significant |
| | Industrial capability | Significant |
| | Nuclear capability | Significant |
| Proliferation strategy | Diversion | Concealed diversion |
| | Misuse | Concealed misuse of declared facility, equipment and technology |
| | Facility | Use of declared and undeclared facilities (the possibility of/need for an undeclared facility is taken into account but not modelled in this study) |

One strategy that a proliferant State could use to manufacture nuclear weapons is shown in Figure 1:

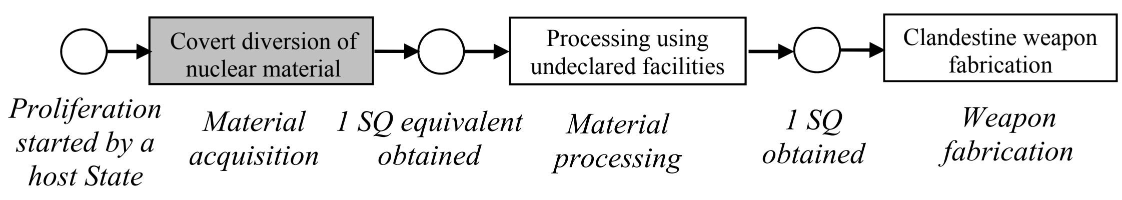



*FIG. 1. Proliferation strategy of host State.*

The acquisition/diversion pathway analysis of a nuclear energy system should ensure that all possible targets and pathways have been identified and analysed. First, the proliferation objectives and technical capabilities of the host State should be defined. Next, the proliferation targets in the nuclear energy system should be identified. The nuclear energy system will then be analysed in detail, through the identification of 1) potential diversion routes, 2) physical and design barriers to removal of targets, 3) IAEA safeguards measures in place which may include surveillance cameras, seals, neutron and gamma detectors, inventory key measurement points (KMPs), and flow KMPs. The pathway analysis should be reproducible for its objectiveness and comprehensiveness. In this regard, a step-by-step approach is proposed for the acquisition/diversion pathway analysis as presented in Figure 2.

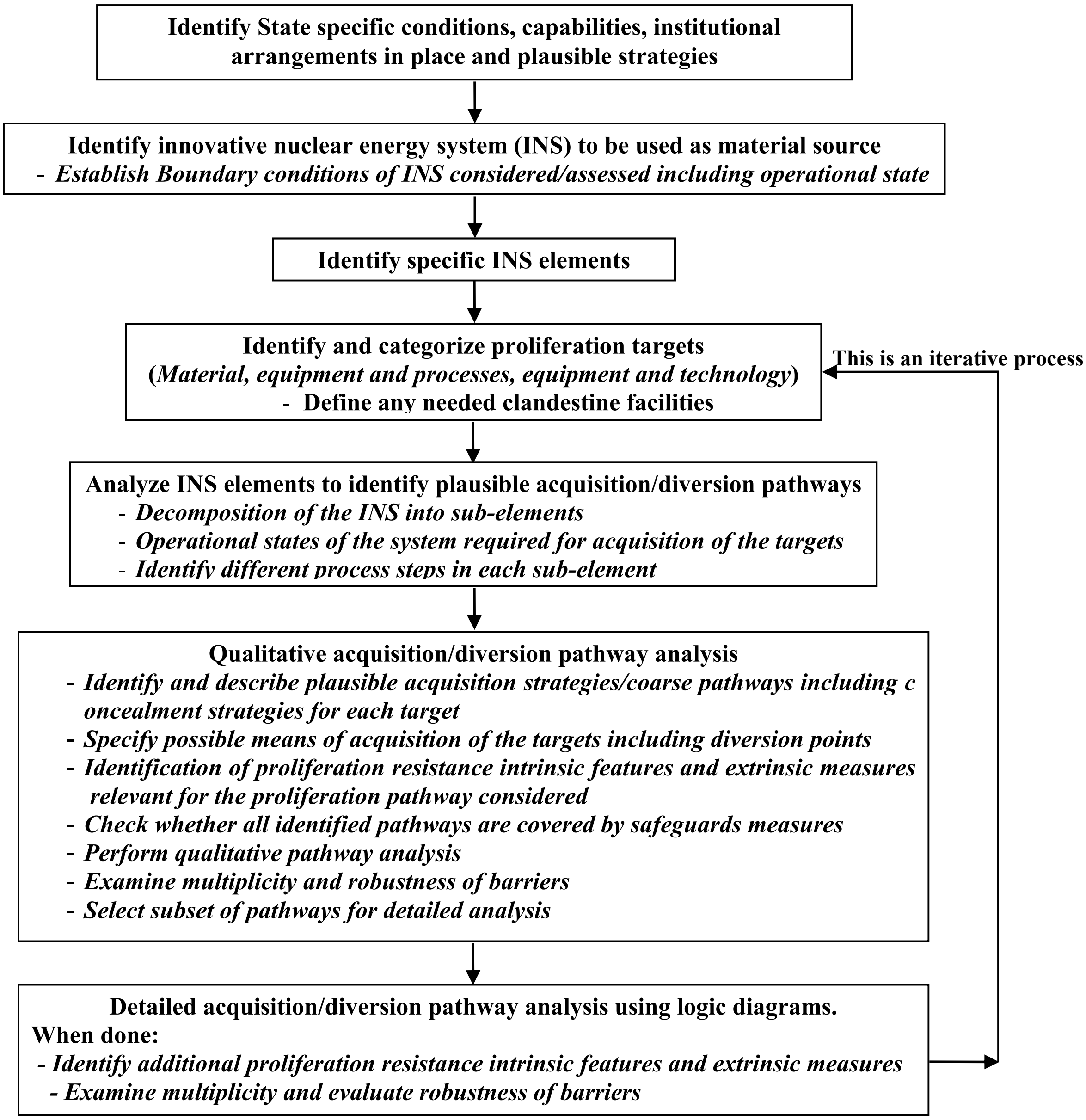



*FIG. 2. Systematic approach to acquisition/diversion pathway analysis.*

Once the nuclear material is acquired from the nuclear energy system, the material will be transported to the clandestine processing facility for the production of weapon-usable material. In the next section, very coarse pathways for covert diversion of nuclear material in the DUPIC fuel cycle are described. For the purpose of this study, only a specific acquisition path will be considered in detail.

# 3. COARSE ACQUISITION/DIVERSION PATHWAY ANALYSIS FOR DUPIC FUEL CYCLE

The degree of PR results from a combination of factors, including technical design features, operational modalities, institutional arrangements and safeguards measures [6]. The effectiveness of barriers to proliferation can be categorized as: (1) technical difficulty in making weapons (as a State level concern, not related to a specific facility), (2) barriers representing the difficulty in handling and processing material (both at the State and at the facility level): (3) barriers leading to difficulty/detectability and safeguardability (at a facility-specific pathway level). Therefore, this study has determined that there are, in fact, effectively three levels of INPRO PR assessment with associated indicators: State level, INS level and facility level, including facility specific pathways. Note, however, that for the pathway analysis in this case study only the facility level application was considered.

In this section, the DUPIC fuel cycle has been analysed using the proposed systematic approach. When determining the barrier function of intrinsic features, the questions to be considered are whether an intrinsic feature is:

- relevant to the pathway considered.
- associated with the level of assessment (see Figure 2).

## 3.1. DEFINITION OF PROLIFERATION OBJECTIVES AND TECHNICAL CAPABILITIES OF HOST STATE

As described in Section 2, the proliferation objective of the host State is to acquire at least 1 significant quantity (SQ) of nuclear material from the DUPIC fuel cycle that could be used for nuclear explosive devices. The technical capabilities of the host State are summarized in Table 2.

## 3.2. IDENTIFICATION OF NUCLEAR ENERGY SYSTEM, DUPIC FUEL CYCLE

The basic concept of a DUPIC fuel cycle is to fabricate CANDU nuclear fuel from PWR spent fuel using dry thermal/mechanical processes without separating any fissile material, and then use the fabricated DUPIC fuel in a CANDU reactor. It is assumed that the host State will divert fissile nuclear material from the DUPIC fuel cycle for the manufacture of nuclear explosive devices.

## 3.3. IDENTIFICATION OF SPECIFIC INS ELEMENTS

The DUPIC fuel cycle is composed of 1) an on-site spent fuel storage facility at the PWR power plant, 2) a DUPIC fuel fabrication facility that will extract fuel material from spent PWR fuel, perform the oxidation and reduction of oxide fuel (OREOX) treatment for pelletizing and then fabricating DUPIC fuel, 3) a CANDU reactor, 4) an interim spent fuel dry storage facility, and 5) a final repository. The reference feedstock for the DUPIC fuel cycle is the Korean Yonggwang nuclear station unit 1&2's 17x17 standard spent PWR fuel assemblies with a minimum of 10 years of cooling time after discharge from the reactor with 35 000 MWD/MTU of final burnup.

In this case study, only the diversion of fissile nuclear material from the DUPIC fuel cycle facility is considered. A conceptual DUPIC fuel fabrication facility with a throughput of 400 metric tons of heavy metal (MTHM) per year [7] is postulated, as shown in Figure 3. The facility is assumed to meet international requirements for safety and security, and also all IAEA safeguards requirements under a comprehensive safeguards agreement (based on [8]) and an additional protocol (based on [9]).

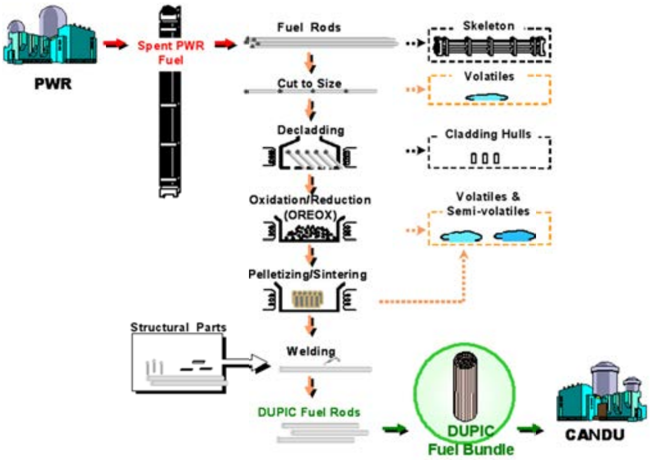



*FIG. 3. DUPIC fuel fabrication process.*

It is also assumed that this facility allows for normal process system startup and shutdown, scheduled and unscheduled plant equipment maintenance and repair activities, material accountability related tasks that affect plant operation, and any scheduled plant-side outage period for major systems refurbishing activities. Runouts will be performed at the completion of each production campaign. Cleanouts will also be performed several times per year.

The Wolsong CANDU-6 power plant (unit 1) was selected for a detailed study of a specific acquisition path. A site visit was made to the plant in July 2008 to study the IAEA safeguards measures in a CANDU reactor, and identify possible diversion routes for DUPIC fuel bundles. Table 3 shows technical specifications of Wolsong unit 1, and Figure 4 shows the principal safeguards measures in a typical CANDU-6 reactor [10], including the flow of DUPIC fuel bundles.

A conceptual away-from-reactor spent-fuel interim dry storage facility with silos is postulated. The spent DUPIC fuel bundles will be stored at the CANDU power station for some time and then transported to an interim dry storage facility using transport casks, and stored there until final disposition in the spent fuel repository.

The reference spent fuel repository consists of two parts: a surface facility and an underground facility, i.e. a room-and-pillar configuration consisting of a series of regularly spaced disposal rooms and connecting channels. The spent fuel bundles are sealed into containers in a fuel packaging facility before transportation to the disposal vault or temporary storage area. The disposal vault is reached and serviced by shafts. The containers are transported into the underground facilities and are placed into vertical boreholes drilled into the floor of the disposal rooms. The container is surrounded by clay-based buffer material within each borehole. Each disposal room is backfilled with clay-based backfill material, and the room entrance is sealed when all boreholes have been filled.

TABLE 3: TECHNICAL SPECIFICATIONS OF WOLSONG CANDU-6 UNIT 1

| Reactor parameters | CANDU | |
|---|---|---|
| - Electric power (MW(e))<br>- Thermal efficiency (%)<br>- Thermal power (MW(t))<br>- Specific power (MW(t)/ton U)<br>- Load factor<br>- Cycle length (full power day)<br>- No. of fuel assemblies or bundles per core<br>- Loading per core (tU) | 713<br>33<br>2,161<br>25.5<br>0.9<br>-<br>4,560<br>84.7 | |
| | Characteristic Parameters | |
| | CANDU with NU fuel | CANDU with DUPIC fuel |
| Reactor<br>- Loading per core (tU or tHM)<br>- Annual fuel requirement (tU or tHM) | <br>84.7<br>94.63 | <br>84.7<br>46.09 |
| Fuel<br>- Initial enrichment<br>- No. of fuel rods per assembly<br>- Discharge burnup (MWD/kgHM) | <br>Nat. U<br>37<br>7.5 | <br>Spent PWR fuel<br>43<br>15.4 |
| Normalization of Fuel<br>- Required fuel amount for 1 GW(e)-a (tU or tHM) | <br>132.73 | <br>64.64 |

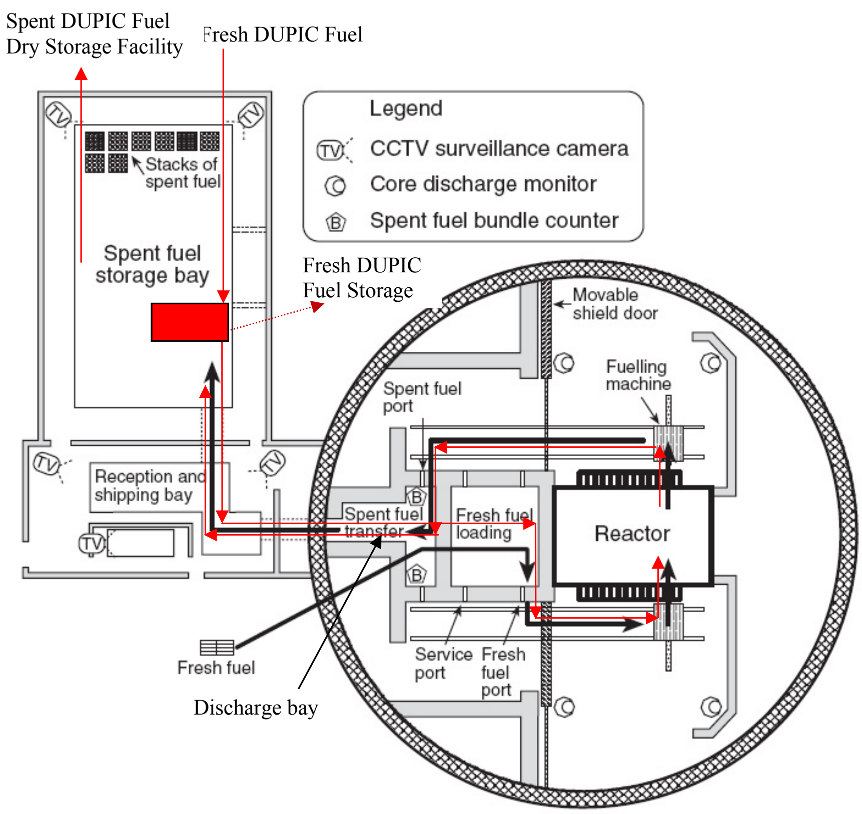



*FIG. 4. IAEA safeguards measures and flow of DUPIC fuel bundles in CANDU-6 reactor*[10].

### 3.4. IDENTIFICATION OF PROLIFERATION TARGETS IN DUPIC FUEL CYCLE

Table 4 shows the SQ for different target material as defined in the IAEA Safeguards Glossary [11]. The international safeguards detection goal is to detect the diversion of 1 SQ of nuclear material with a certain detection probability within a given time.

In the DUPIC fuel cycle, target material is uranium and reactor grade plutonium 1) in spent PWR fuel rods/pellets, 2) during the DUPIC fuel fabrication processes, 3) in fresh DUPIC fuel bundles fabricated at the DUPIC fuel fabrication facility, and 4) in spent DUPIC fuel bundles discharged from the CANDU reactor core. Diverted uranium could be used for undeclared enrichment in a clandestine enrichment facility. However, the uranium acquisition path is not considered in this study. To get separated plutonium from the diverted fissile nuclear material, the host State has to design and construct a clandestine reprocessing plant. Table 5 shows the plutonium isotopic vector for spent PWR fuel and for fresh and spent elements of the DUPIC fuel cycle [7]. The amount of spent PWR fuel needed for 1 SQ of 8 kg plutonium is 867 kg whereas the number of fuel bundles (18 kg HM/bundle) needed for 1 SQ are 49 for fresh and 54 for spent DUPIC fuel bundles, respectively.

TABLE 4: SAFEGUARDS SIGNIFICATNT QUANTITIES FOR TARGET MATERIAL (1SQ)

| | Material | 1 SQ |
|---|---|---|
| Direct-use nuclear material | Plutonium (containing less than 80% $^{238}Pu$) | 8kg Pu |
| | $^{233}U$ | 8kg $^{233}U$ |
| | HEU ($^{235}U \geq 20\%$) | 25kg $^{235}U$ |
| Indirect-use nuclear material | Low-enriched, natural and depleted uranium ($^{235}U<20\%$) | 75kg $^{235}U$ (or 10 tonnes NU, or 20 tonnes DU) |
| | Thorium | 20 tonnes |

TABLE 5: TECHNICAL SPECIFICATIONS OF SPENT PWR FUEL AND DUPIC FUEL BUNDLES c[7]

1) Plutonium isotopes in spent PWR fuel and DUPIC fuel bundles

| Isotopes | Spent PWR Fuel | | Fresh DUPIC Fuel | | Spent DUPIC Fuel | |
|---|---|---|---|---|---|---|
| | g/MTHM | Pu (wt %) | g/MTHM | Pu (wt %) | g/MTHM | Pu (wt %) |
| $^{238}Pu$ | 1.54E+02 | 1.7 | 1.54E+02 | 1.7 | 3.88E+02 | 4.9 |
| $^{239}Pu$ | 5.33E+03 | 59.9 | 5.33E+03 | 59.9 | 3.16E+03 | 39.7 |
| $^{240}Pu$ | 2.20E+03 | 24.8 | 2.20E+03 | 24.8 | 2.79E+03 | 35.1 |
| $^{241}Pu$ | 7.52E+02 | 8.4 | 7.52E+02 | 8.4 | 5.24E+02 | 6.6 |
| $^{242}Pu$ | 4.57E+02 | 5.1 | 4.57E+02 | 5.1 | 1.10E+03 | 13.8 |
| **$^{tot}Pu$** | **8.89E+03** | | **8.89E+03** | | **7.96E+03** | |

*Mass of spent PWR fuel for 1 SQ of Pu (8kg Pu) = 866.74 kg ≈ 1.89 spent PWR fuel assemblies*

2) Number of fuel bundles for 1 SQ of plutonium

| | Fresh DUPIC Fuel | Spent DUPIC Fuel |
|---|---|---|
| kg HM/bundle | 17.64 | 17.64 |
| Pu content (wt %) | 0.923% | 0.840% |
| **No. of bundles for 1 SQ (8kgPu)** | **~49** | **~54** |

### 3.5. COARSE PATHWAY ANALYSIS OF DUPIC FUEL CYCLE

The DUPIC fuel cycle was subdivided into several elements to identify potential diversion points. The DUPIC fuel fabrication facility, CANDU power plant, interim dry storage, and permanent disposal repository, are shown in Figure 5. Potential diversion can occur: during transport of nuclear material (spent PWR fuel assemblies, fresh and spent DUPIC fuel bundles) (1) from one facility to another, (2) from the DUPIC fuel fabrication facility, (3) from the fresh and spent DUPIC fuel storage locations of the CANDU power plant, (4) from an interim dry storage, and (5) from the permanent disposal repository. Table 6 shows the potential diversion targets and facilities that diversion can take place in the DUPIC fuel cycle.

In the analysis of each element, operational state and steps are defined, possible diversion means identified, and potential safeguards barriers to be applied to detect diversion are considered to derive strategies that the host State could use to divert nuclear material.

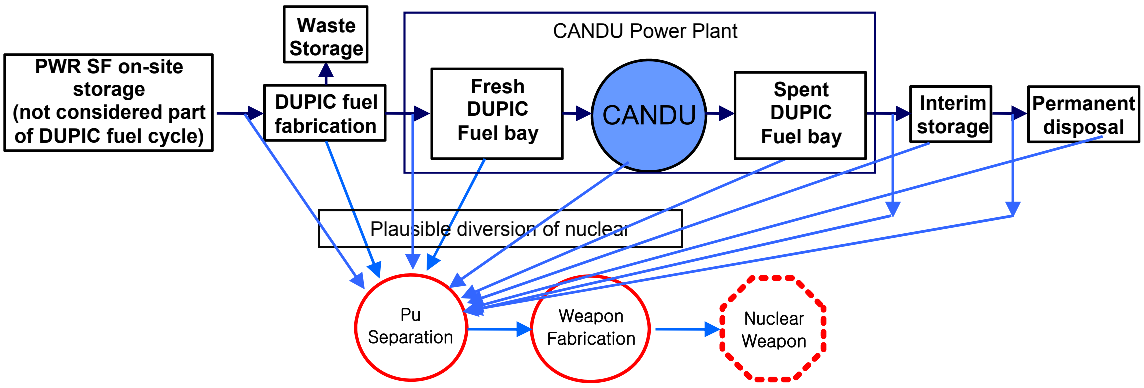



*FIG. 5. DUPIC material flow, possible diversion points, and coarse pathways considered.*

TABLE 6: DIVERSION TARGETS AND POSSIBLE DIVERSION POINTS IN DUPIC FUEL CYCLE

| **Diversion targets** | **Possible diversion points** |
|---|---|
| 1. Spent PWR fuel assemblies | 1. During transport of spent PWR fuel assemblies from on-site storage at PWR reactor to the DUPIC fuel fabrication facility (diversion from PWR onsite storage or transport are not considered in this study) |
| 2. Spent PWR fuel rod cuts | 2. DUPIC fuel fabrication facility (after shearing step) |
| 3. PWR spent fuel pellets or fuel material stuck on inside of hulls | 3. DUPIC fuel fabrication facility (feed line after decladding) |
| 4. DUPIC fuel powder | 4. DUPIC fuel fabrication facility (before pelletizing step) |
| 5. Sintered DUPIC fuel pellets | 5. DUPIC fuel fabrication facility (before welding stage) |
| 6. Sintered DUPIC fuel elements | 6. DUPIC fuel fabrication facility (before welding stage) |
| 7. Fresh DUPIC fuel bundles | 7. DUPIC fuel fabrication facility (product line in maintenance cell)<br>8. Transport from DUPIC facility to CANDU power plant<br>9. Fresh DUPIC fuel storage racks in the fuel storage bay |
| 8. Spent DUPIC fuel bundles | 10. Failed DUPIC fuel bundles from the reception bay of the plant<br>11. Spent DUPIC fuel storage racks of the CANDU power plant<br>12. Transport from CANDU plant to the interim dry storage<br>13. Interim dry storage (not considered in this study)<br>14. Transport from interim storage to permanent disposal repository (not considered in this study)<br>15. Permanent disposal repository (not considered in this study) |

The strategies that the host State would develop to overcome IAEA safeguards measures in the diversion of nuclear material are developed in the analysis. For example, an accident can be faked during the transport of nuclear material using the licensed rail-car or truck. The host State could declare fuel failures and remove selected fuel bundles at the DUPIC fuel fabrication facility, or declare short cycled fuel bundles as ‘failed’ fuel and sent to reception bay for subsequent diversion. The host State may use internal containers or external shielded containers to remove nuclear material from the DUPIC fuel fabrication facility. In such cases, the host State could introduce dummy material into the facility to help overcome safeguards measures.

*1) Transport of spent PWR fuel assemblies from PWR on-site storage to DUPIC fuel fabrication facility*

The spent PWR fuel assemblies at the PWR on-site storage will be put into transport casks and transported to the DUPIC facility site for DUPIC fuel bundle production. The mode of transport would be by sea at first, followed by licensed rail car or truck transport casks, then unloaded and stored dry at the DUPIC fuel fabrication facility. Two spent PWR fuel assemblies (440.0 kg HM per assembly) contain 1 SQ of plutonium. However, the spent PWR transport casks are not addressed as viable targets for covert diversion because of existing safeguards measures and the ease of detection.

*2) DUPIC fuel fabrication facility*

The DUPIC fuel fabrication facility is a complete fuel recycling plant with all functions and equipment for processing spent PWR fuel and converting it to DUPIC fuel. It uses only thermal and mechanical processes that recover fissile material remaining in spent PWR fuel for DUPIC fuel. It is assumed that the spent PWR fuel receiving and storage system will accommodate a minimum of three months operational feedstock capacity (about 100 MTHM of spent fuel, or equivalent to 4–5 years output from a PWR power plant). As shown in Figure 3, the non-fuel components required by the DUPIC fuel bundle (e.g. fuel cladding, end caps, spacers, end plates, and dysprosium poison fuel rods) will be fabricated at off-site facilities and shipped to the DUPIC facility.

The DUPIC fuel fabrication facility will contain all support systems (material handling/storage, waste processing, packaging, storage, and utilities) necessary for DUPIC fuel production. Transport casks/packages will have bolted closures to allow unpacking inside the reactor fuel pool prior to loading in the reactor. It is assumed that the storage and transport system will accommodate a minimum of six weeks of DUPIC production output (50 MTHM), and will be based on dry storage technology. It is assumed that the spent fuel is shipped in licensed rail car or truck transport casks, then unloaded and stored dry in a commercially available dry storage system.

It is assumed that nuclear material control and accounting (MC&A) scheme and containment and surveillance (C/S) systems which meet IAEA requirements are designed and installed in the DUPIC fuel fabrication facility in order to safeguard the nuclear material. It will include surveillance cameras, seals, neutron and gamma detectors, inventory KMPs and flow KMPs. Three material balance areas (MBAs) are defined on the basis of need for safeguards as shown in Figure 6. Table 7 shows the analysis work sheet from the INPRO manual for the DUPIC fuel fabrication facility.

The spent PWR fuel rods extracted from the fuel assembly after disassembling in MBA-1 are one of the potential diversion targets, but not considered to be material for potential diversion because the undetected removal of fuel rods using a large, most probably shielded, container without being detected is extremely unlikely in consideration of the exit locations and the physical and design barriers to removal of targets, including safeguards barriers such as surveillance, radiation detectors, and seals. Nuclear material for potential diversion from MBA-2 of the DUPIC fuel fabrication facility is: (1) the spent PWR fuel rod cuts after the chopping step, (2) spent PWR fuel pellets after decladding, (3) spent PWR fuel powder feed stock for sintering, (4) sintered DUPIC fuel pellets, and (5) fresh DUPIC fuel bundles produced at the end of the DUPIC fuel fabrication process. There are several operational states in MBA-2 — normal operation, maintenance, repair and testing — but only the normal operational phase is considered in the analysis.

In MBA-2, physical inventory verification (PIV) using destructive assay and weighing is carried out at each KMP, and the operator and the IAEA share the accounting data. The diversion of rod cuts from MBA-2 using the external shielded containers could use dummy fuel rod cuts introduced in advance into the MBA-2 by defeating the safeguards system, including the cameras. Similarly, diversion of other target material — such as spent PWR fuel pellets after decladding, DUPIC powder feed stock for sintering after OREOX processing, sintered DUPIC fuel pellets before welding which can be diverted using internal or external shielded containers — could use dummy fuel material introduced in advance into the MBA-2.

Finally, the fresh DUPIC fuel bundles assembled in MBA-2 will be non-destructively tested for welding quality, dimension fit, and clearance. Defective fuel bundles will be rejected and forwarded to the repair station or scrap material recycle station for further pertinent processing. The acceptable fuel bundles are subject to item counting for inventory verification, visual inspection and dimension measurement, and will be loaded into baskets and storage containers for transfer to the storage or transport area in MBA-3, and then transported to the CANDU power plant. Table 7 shows pathway analysis worksheet for the DUPIC fuel fabrication facility.

The transport of fresh DUPIC fuel bundles from the DUPIC fuel fabrication facility to the CANDU power station will be via licensed truck transport casks and sea. The fuel will then be transferred to the fresh DUPIC fuel storage racks in the spent fuel storage pool at the reactor building. Therefore, to divert nuclear material, the host State must replace fresh DUPIC fuel bundles with dummy fuel bundles.

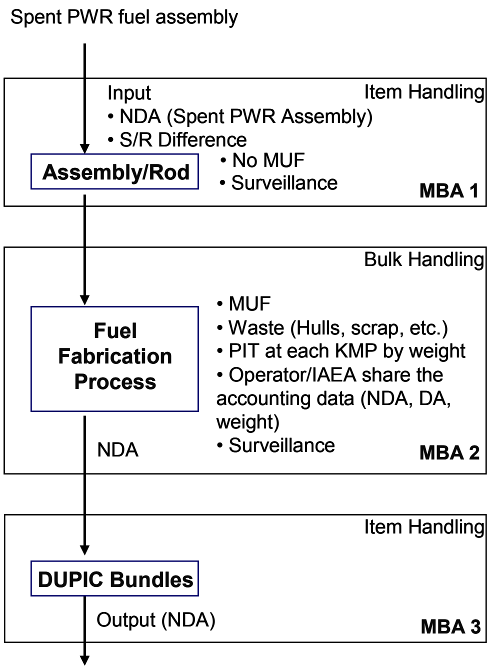



*FIG. 6. Nuclear material accounting scheme of DUPIC fuel fabrication facility.*

TABLE 7: PATHWAY ANALYSIS WORKSHEET TO BE USED FOR THE DUPID FUEL FAVLICATION FACILITY

| **Target ID in Table 6** | **Target description** | **Diversion point** | **Diversion means or device** | **Safeguards measures to be applied** | **Pathway description** | **Proliferator actions** |
|---|---|---|---|---|---|---|
| 2 | Spent PWR fuel rod cuts | After shearing step (MBA 2) | External shielded containers | Cameras, DA, NDA, weighing | -Use dummy rod cuts and remove real rod cuts in shielded containers | 1) Introduce dummy fuel rod cuts into MBA-2<br>2) Remove the real rod cuts in external shielded containers to the parking lot outside of the facility |
| 3 | Spent PWR fuel pellets or fuel material left in the hulls | After decladding (MBA 2) | Cladding hull baskets | Cameras, DA, NDA, weighing | - Overstate MUF for the spent fuel material stuck on spent fuel cladding hulls | 1) Overstate amount of fuel material stuck on inside of the hulls<br>2) Discard hulls as waste<br>3) Recollect nuclear material from discarded hulls at a undercover facility |
| | | | Cladding hull baskets | | -Use dummy fuel pellets and remove real fuel pellets in cladding hull baskets | 1) Introduce dummy fuel pellets into MBA-2<br>2) Remove the real pellets in cladding hull baskets to the parking lot outside of the facility |
| | | | External shielded containers | | -Use dummy pellets<br>- Declare MUF to divert real fuel pellets in external shielded containers | 1) Introduce dummy fuel pellets into MBA-2<br>2) Declare MUF<br>3) Remove the real pellets in external shielded containers to the parking lot outside of the facility |
| 4 | Spent PWR fuel powder feed stock for sintering | After OREOX processes (MBA 2) | External shielded canisters | Cameras, DA, NDA, weighing | -Use dummy fuel powder | 1) Introduce dummy fuel powder into MBA-2<br>2) Remove the real fuel powder to outside of the facility using external shielded containers |
| 5 | Sintered DUPIC fuel pellets | Before Welding stage (MBA 2) | External shielded canisters | Cameras, NDA, weighing | -Use dummy fuel pellets | 1) Introduce dummy sintered fuel pellets into MBA-2<br>2) Insert dummy fuel pellets into the cladding tubes<br>3) Remove the sintered pellets in shielded containers to the parking lot outside of the facility |
| 6 | Sintered DUPIC fuel elements | Before Welding stage (MBA 2) | External shielded canisters | Cameras, NDA, weighing | -Use dummy fuel elements | 1) Introduce dummy DUPIC fuel elements into MBA-2<br>2) Replace real fuel elements with dummy ones<br>3) Remove real fuel elements in shielded containers to the parking lot outside of the facility |
| 7 | Fresh DUPIC fuel bundles | Maintenance cell (MBA 3) | Transport baskets | Cameras, Item counting, visual inspection | - Use dummy fuel bundles | 1) Use heavy truck and trailer to move basket containers<br>2) Fool or disable the IAEA cameras<br>3) Replace a fresh DUPIC fuel basket with slightly enriched fresh CANDU fuel imbedded with radiation source such as $^{252}Cf$<br>4) Compromise the inventory measurement records with dummy fuels |

* A: Abrupt diversion, P: Protracted diversion.

*3) Transport of fresh DUPIC fuel bundles from DUPIC fuel fabrication facility to CANDU power station (Table 8)*

TABLE 8: PATHWAY ANALYSIS WORKSHEET TO BE USED FOR TRANSPORT OF DUPIC FUEL BUNDLES FROM DUPIC FUEL FABRICATION FACILITY TO CANDU POWER STATION

| Target ID in Table 6 | Target description | Diversion point | Diversion means of devices | Safeguards measures to be applied | Pathway description | Proliferator actions |
|---|---|---|---|---|---|---|
| 7 | Fresh DUPIC fuel bundles in transport basket containers | During transport | Transport basket containers | Application of seals, item counting | - Diversion during transport | 1) Replace fresh DUPIC fuel bundles in transport basket containers with dummy fuel bundles<br>2) Compromise the inventory with dummy fuel basket containers |

*4) CANDU power plant (Table 9)*

Only steady state operation is considered for the pathway analysis. When the fresh DUPIC fuel bundles arrive at the CANDU power plant, they are counted and stored in the fuel racks located at the bottom of the spent fuel storage bay, and remotely loaded into the channels of the reactor core by an operator. DUPIC fuel paths and some safeguard equipment in the CANDU reactor are shown in Figure 4.

The CANDU-6 reactor has 4560 fuel bundles in its core. During normal operation, eight spent DUPIC fuel bundles are replaced with fresh DUPIC fuel bundles per day. The fresh fuel bundles go through remote visual inspection using a mirror attached periscope and dimension measurement before loading. After a fuel manipulator moves the DUPIC fuel bundles from the fuel racks to the conveyor, the fuel bundle is transferred to the discharge bay, and the fuel elevator places the fuel bundle in the fuelling machine. The fuel bundles are remotely loaded into the fuel channels selected by the operator. The average fuel residence time in the core is 610 days. The fissile content of DUPIC fuel is 1.5 wt% when the fuel is loaded, while it is 0.7 wt% when discharged. During the operation, the integrity of the fuel is monitored by the radiation level of the coolant when the fuel channel is open for refuelling or inspection. As the fresh fuel bundles are loaded, the spent fuel bundles are automatically discharged from the core and transferred to the discharge bay. The spent fuel is then inspected for failure using the delayed neutron monitoring system and the intact bundles are moved from the discharge bay to the storage bay through the reception bay. The failed fuel bundles are stored in the reception bay until the next move.

It is not deemed possible to divert nuclear material from inside the CANDU reactor building to the outside of the CANDU reactor building without going through the fuel transfer channels during normal operation. Therefore, potential diversion materials in a CANDU power plant under normal operation are: (1) fresh DUPIC fuel bundles on the fresh fuel storage racks, (2) failed DUPIC fuel bundles in the reception bay, or (3) spent DUPIC fuel bundles on the spent DUPIC fuel storage racks in the spent fuel pool. Because the physical form of the fuel bundles does not change before and after depletion in the core, there is no loss of fuel material in each transfer step. The spent fuel bay is continuously monitored by CCTV, and IAEA inspection is regularly performed to trace spent fuel movement in the spent fuel storage bay and to measure the inventory of DUPIC fuel, including failed fuel in the reception bay, by the item counting. The IAEA safeguards approach for a CANDU reactor includes advance facility information, C/S measures, core discharge monitors, bundle counters, and surveillance in remote data transmission and in an unattended mode. An unattended monitoring scheme is also implemented for spent fuel transfers from the fuel storage bay to dry storage.

TABLE 9: PATHWAY ANALYSIS WORKSHEET TO BE USED FOR CANDU POWER STATION

| Target ID in Table 6 | Target description | Diversion point | Diversion means or devices | Safeguards measures to be applied | Pathway description | Proliferator actions |
|---|---|---|---|---|---|---|
| 7 | Fresh DUPIC fuel bundles | Fresh DUPIC fuel storage racks | Storage basket containers | Seals, cameras, NDA with gross neutron monitoring | - Replace a fresh DUPIC fuel basket with fresh CANDU fuel imbedded with radiation source | 1) Fool or disable the IAEA cameras<br>2) Replace fresh DUPIC fuel baskets with the baskets of slightly enriched fresh CANDU fuel bundles<br>3) Compromise the inventory measurement records with dummy fuels bundles<br>4) Use heavy truck and trailer to move basket containers |
| 8 | Spent DUPIC fuel bundles | Reception bay | Sealed storage containers | Seals, Cameras, NDA with gross neutron monitoring | - Intentionally classify DUPIC fuel in channel 'failed' and store in sealed containers | 1) Fool or disable the IAEA cameras<br>2) Replace failed DUPIC fuel bundle containers with dummy fuel bundle containers<br>3) Compromise the inventory measurement records with dummy fuel bundles<br>4) Use heavy truck and trailer to move containers |
| 8 | Spent DUPIC fuel bundles | Spent fuel storage racks | Transport basket containers | Seals, cameras, NDA with gross neutron monitoring | - Use dummy fuel bundle baskets and remove DUPIC fuel bundles in shielded containers | 1) Fool or disable the IAEA cameras<br>2) Replace spent DUPIC fuel bundles with slightly enriched fresh CANDU fuel bundles imbedded with radiation source such as $^{252}$Cf to cheat the re-verification tubes<br>3) Compromise the inventory measurement records with dummy fuels<br>4) Use heavy truck and trailer to move basket containers |

During normal operation, it is difficult to distinguish fresh DUPIC fuel from spent DUPIC fuel by the core discharge monitor through neutron and gamma radiation measurement. The bundle counter in the discharge bay cannot distinguish between movements of fresh or spent fuel. Therefore, dummy fuel bundles could be used to replace fresh/spent DUPIC fuel bundles for diversion. That is, the fresh DUPIC fuel bundles could be replaced with fresh CANDU fuel embedded with a radiation source like $^{252}$Cf or $^{137}$Cs. Likewise, spent DUPIC fuel and failed DUPIC fuel could be replaced with dummy spent fuel bundles. Dummy fuel bundles are used during maintenance of the fuelling machine and system. During either normal or abnormal operation, there is no way that fuel bundles are repositioned without using the fuelling machine. Passage to the reactor building is through the equipment door and through the spent fuel transfer canal. Failed fuel bundles are put into sealed containers and stored in the reception bay for a longer period.

*5) Transport of spent DUPIC fuel bundles from CANDU power station to an interim storage (Table 10)*

As in the scenario for transporting fresh DUPIC fuel bundles from the DUPIC fuel fabrication facility to the CANDU power station, the host State will fake an accident to divert spent DUPIC fuel bundles in transport casks.

TABLE 10: PATHWAY ANALYSIS WORKSHEET TO BE USED FOR TRANSPORT OF SPENT DUPIC FUEL BUNDLES FROM CANDU POWER STATION TO AN INTERIM STORAGE FACILITY

| Target ID in (Table 6 | Target description | Diversion point | Diversion means or devices | Safeguards measures to be applied | Proliferator actions | Pathway description |
|---|---|---|---|---|---|---|
| 8 | Spent DUPIC fuel bundles | During marine transportation | Transport basket containers | Application of seals, item counting | - Fake an accident at sea | 1) Fake a collision of boats at sea<br>2) Declare loss of spent fuel transport basket containers<br>3) Replace the recovered fuel bundle basket containers with dummy fuel basket containers<br>4) Compromise the inventory measurement records with dummy fuel bundle baskets |

*6) Analysis of an interim dry storage facility (Table 11)*

As the transport basket containers arrive at the away-from-reactor storage, they are counted, inspected, and stored in silos or dry vaults. They will be inspected regularly for inventory verification. The storage vaults would have safeguards barriers similar to the on-site spent fuel pool at the CANDU power station. They are continuously monitored by the CCTV and IAEA inspection is regularly performed to trace any spent fuel movement in the storage facility. Therefore, the diversion pathway would be similar to that of the on-site dry storage facility of the CANDU power station.

TABLE 11: PATHWAY ANALYSIS WORKSHEET FOR AN INTERIM DRY STORAGE FACILITY

| Target ID in Table 6 | Target description | Diversion point | Diversion means or devices | Safeguards measures to be applied | Pathway description | Proliferator actions |
|---|---|---|---|---|---|---|
| 8 | Spent DUPIC fuel bundles in storage baskets | Silos or dry vaults | External transport basket containers | Seals, cameras, NDA with gross neutron monitoring | Use dummy fuel bundles in order to cheat the re-verification tubes | 1) Fool or disable the IAEA cameras<br>2) Use heavy truck and trailer to move basket containers<br>3) Compromise the inventory measurement records with dummy fuels |

## 3.6. SUMMARY OF COARSE ACQUISITION/DIVERSION FROM THE DUPIC FUEL CYCLE

Potential diversion scenarios listed in Table 6 have been examined to identify plausible diversion pathways with consideration of exit locations, physical and design barriers to removal of targets, and any safeguards barriers. Intrinsic features were intentionally not considered in the table, but when determining the barrier function of intrinsic features, it should be considered whether the feature is:

- relevant to the pathway considered.
- associated with the level of assessment (see Figure 2).

# 4. DETAILED PATHWAY ANALYSIS FOR DIVERSION OF FRESH DUPIC FUEL FROM STORAGE POOL

The diversion of nuclear material from the fresh DUPIC fuel storage bay was selected for detailed pathway analysis.

## 4.1. DESIGN AND PROCESS INFORMATION OF FUEL STORAGE POOL OF DUPIC FUEL CYCLE

Design and process information of the storage pool from the reference plant, Wolsong CANDU-6 power plant unit 1, was used to analyse the diversion pathway of fresh DUPIC fuel bundles from the fresh fuel storage bay, as follows:

- It is assumed that fresh DUPIC fuel bundles fabricated in a fuel fabrication facility with a throughput of 400 MTHM/a are stored in the fuel storage pool of a CANDU power plant. The CANDU power reactor has the same technical specifications as the Wolsong CANDU-6 power plant unit 1.
- The fuel storage pool consists of two bays, one for fresh DUPIC fuel bundles (fresh DUPIC fuel bay) which will be loaded onto the CANDU power reactor at the loading rate of eight bundles per day, and another for spent DUPIC fuel bundles discharged from the CANDU power plant (spent DUPIC fuel bay).
- When fresh DUPIC fuel bundles arrive at the CANDU power plant, they are counted and stored on the fuel trays stored in the fresh DUPIC fuel bay.
- Eight fresh DUPIC fuel bundles are loaded daily onto the DUPIC reactor through the existing spent fuel discharge route, which requires a stringent fuel management schedule. These fresh DUPIC fuel bundles are subject to visual inspection and dimension measurement before loading. A fuel manipulator transports them to the DUPIC reactor core through the discharge bay, i.e. in the reverse way to discharging spent DUPIC fuel from the reactor to the storage pool. The average fuel residence time in the core is 610 days. The fissile content of the DUPIC fuel is 1.5 wt% when it is loaded, while it is 0.7 wt% when discharged.
- The spent DUPIC fuel from the reactor is transported to the discharge bay, then to the spent fuel bay in the storage pool. The discharged spent DUPIC fuel will, after six years cooling in the pool, be transported to the dry storage facility via a heavy-duty truck until a decision has been made for it to be sent to the repository for final disposal.
- Figure 7 shows material flow at the CANDU power plant, including designated key measurement points (KMPs) for safeguards purposes: one material balance area and several KMPs — five flow KMPs and four inventory KMPs are as follows:

*Flow KMPs*

- o KMP 1: measuring the receipt of nuclear material from outside the MBA, i.e. receipt of fresh fuel from the fuel manufacturing plant. It can be receipt from abroad (RF) or domestic receipt (RD).
- o KMP 2: measuring the daily on-loading rate of fresh fuel to the reactor core.
- o KMP 3: measuring the discharge rate of spent DUPIC fuel from the reactor core to the spent fuel storage pool.
- o KMP 4: measuring the flow outside the plant, shipping abroad (SF) or shipping to a domestic destination (SD).
- o KMP 5: measuring the flow of spent fuel to the dry storage facility, KMP D.

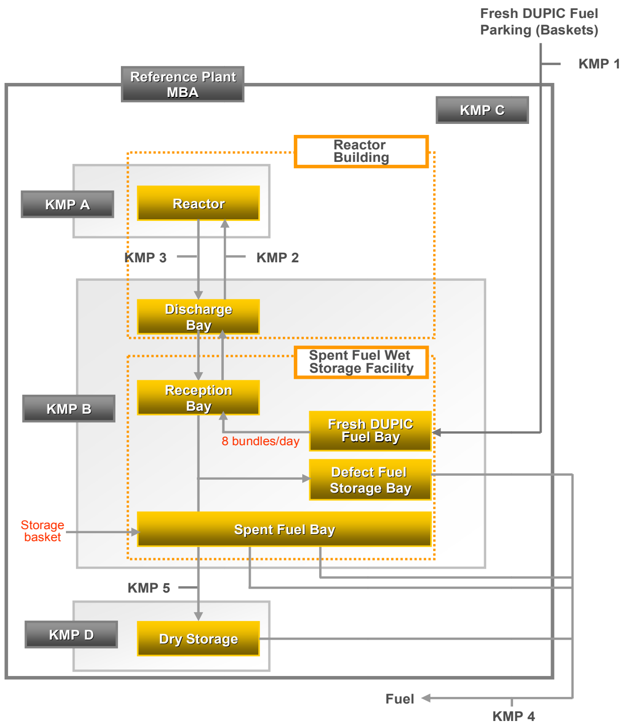
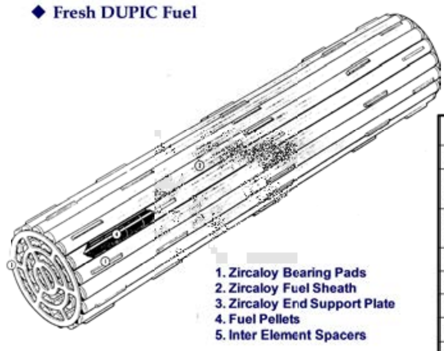



*FIG. 7: Material flow of DUPIC fuel at CANDU power plant.*

*Inventory KMPs*

- KMP A: reactor core zone
- KMP B: fuel storage area.
- KMP C: other areas where nuclear material is stored outside the above designated areas or dry storage area.
- KMP D: dry storage zone which will be in operation 10 years after the power plant starts operation.
- The spent DUPIC fuel storage pool is assumed to have a storage capacity of 26 077 bundles of spent DUPIC fuel (460 tons heavy metal) which is equivalent to 10 years' operation, and the fresh fuel bay a storage capacity of 1034 bundles (23 tons heavy metal) which is equivalent to six months' operation [4]. In the pool, 24 fuel bundles are loaded on each tray, and 19 loaded trays are piled up in a stack. Figure 8 shows the physical dimensions of a fresh DUPIC fuel bundle and Table 5 shows the technical specifications of spent PWR fuel and fresh and spent DUPIC fuel material.

◆ **Fresh DUPIC Fuel**




| | Dimensions |
|---|---|
| Bundle diameter | 102.5 mm max |
| Number of large rods (13.5 mm outer dia.) | 8 |
| Number of small rods (11.5 mm outer dia.) | 35 |
| Length | 49.53 mm |
| Heavy metal weight per bundle | 17.64 kg |
| Bundle weight | 23.6 kg |
| Number of pellets in a large pin | 30 |
| Number of pellets in a small pin | 36 |
| Pellet density | 10.4 (±0.15) g/cm3 |

*FIG. 8. Physical dimension of fresh DUPIC fuel.*

## 4.2. IAEA SAFEGUARDS MEASURES APPLICABLE

The technical objectives of IAEA safeguards are the timely detection of the diversion of SQs of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices, and deterrence of such a diversion by the risk of early detection [8]. IAEA safeguards, authorized by Article III.A.5 of the IAEA's *Statute*, comprise four functions — accountancy, C/S, inspection/in-field verification, and evaluation of information — and are based on assessment of the correctness and completeness of a State's declared nuclear material and nuclear-related activities. Verification measures include on-site inspections, visits, and ongoing monitoring and evaluation.

Basically, two sets of measures are carried out in accordance with the type of safeguards agreements in force with a State. The first set relates to verifying State reports of declared nuclear material and activities authorized under the comprehensive safeguards agreement pursuant to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), and are based largely on nuclear material accountancy, complemented by C/S techniques, such as tamper-proof seals and cameras that the IAEA installs at nuclear facilities. The second set adds measures to strengthen the IAEA's inspection capabilities. These include those measures incorporated in an additional protocol, a legal document complementing comprehensive safeguards agreements [6]. The measures enable the IAEA not only to verify the non-diversion of declared nuclear material but also to provide assurance of the absence of undeclared nuclear material and activities in a State.

In this study, the IAEA safeguards approach as applied to a typical CANDU reactor [8] is used for the DUPIC fuelled power plant to evaluate the effectiveness of existing safeguards barriers to the diversion of fresh DUPIC fuel bundles from the fresh DUPIC fuel bay.

### 4.2.1. IAEA inspections for material control and accounting (MC&A)

The IAEA requires a State to report the types and quantities of nuclear material under its control via the State System of accounting for and control of nuclear material (SSAC). The SSAC activities include support for IAEA verification activities, including design information verification (DIV), physical inventory verification (PIV), ad hoc inspection, regular inspection, and special inspection. Records and reports that a State provides to the IAEA include:

- general ledger for each KMP
- inventory change records
- physical inventory list
- material balance report
- nuclear material transaction report
- refuelling data
- location map
- other information related to MC&A (fuel element history records, burnup data, etc. as necessary).

The IAEA then carries out its own on-site inspections and visits under the safeguards agreement in force with a State on the basis of information and reports/records provided by the State. Activities IAEA inspectors perform during and in connection with on-site inspections or visits at facilities may include auditing the facility's accounting and operating records and comparing these records with the State's accounting report to the IAEA; verifying the nuclear material inventory and inventory changes; taking environmental samples; and applying C/S measures (e.g. seal application, installation of surveillance equipment and radiation monitors).

Physical inventory verification by the IAEA of the nuclear material at the power plant is performed for:

- fresh DUPIC fuel bundles in the storage bay
- spent DUPIC fuel bundles in the storage pool
- spent DUPIC fuel bundles at the dry storage facility.

The IAEA also carries out DIV whenever there is a modification to the facility, and at least once a year in consideration of the inspection procedures.

#### 4.2.2. Containment and surveillance (C/S) system

In order to provide continuity of knowledge as a complementary measure to MC&A, the IAEA installs containment and surveillance (C/S) systems at nuclear facilities, such as tamper-proof seals, radiation monitors and cameras.

**(1) Fuel storage area**

It is assumed that a surveillance system is installed in the fuel storage pool of the power plant consisting of a set of surveillance cameras that monitor any movement of fresh/spent fuel in the fuel storage pool as shown in Figure 4. The collected surveillance data are then verified against the recorded fuel movement log provided by the facility operators.

**(2) Reactor core**

Bundles discharged from the core are monitored using radiation detectors. The system records the movement of high radiation emitting nuclear material. System data in the reactor core are verified against refuelling data provided by the facility operator using the radiation review programme.

**(3) Transport of spent fuel from storage pool to dry storage facility**

Spent fuel stored for more than six years in the fuel storage pool of the power plant are transported to the dry storage facility, which is located at a difficult-to-access area. An unattended remote monitoring system is used during the transport of spent DUPIC fuel to the dry storage as is the case with CANDU power plants. Figure 9 shows the transportation of spent DUPIC fuel to the dry storage facility.

Spent fuel bundles on trays in the pool are transported to the underwater working table using a fuel tray lifter, and spent DUPIC fuel bundles are loaded into a storage basket using a fuel lifting tool. Each of these spent fuel bundles is checked using a CANDU bundle verifier for baskets (CBVB) and high sensitivity gamma monitor (HSGM) before being loaded into the storage basket. When the loading of sixty fuel bundles into the storage basket is complete, two randomly selected fuel bundles are checked again using CBVB and HSGM for gross defect.

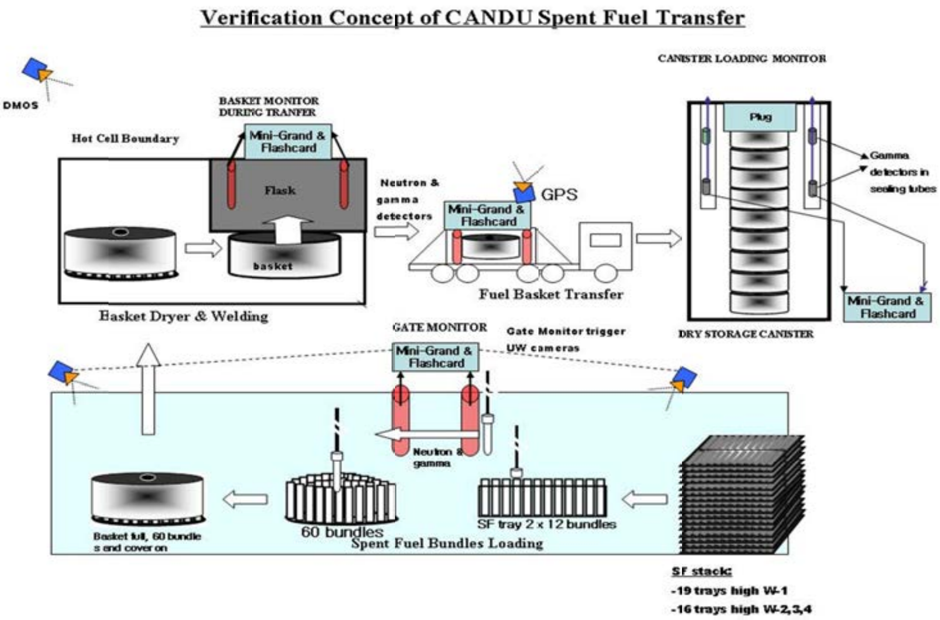



*FIG. 9. Transportation of spent DUPIC fuel to dry storage.*

Each loaded basket is dried in the hot cell area, and its identification number is checked through CCTV before welding. The welded basket is loaded into a transport flask and is transported to the dry storage via a heavy-duty truck. A camera system and a neutron detector are attached to the surface of the transport flask to continuously monitor the fuel basket in the transport flask during transport to dry storage. A metal seal is attached to the case of the neutron detector to protect it. During the IAEA inspection, neutron detector data is verified against total defect of a fuel storage basket in the transport flask. A metal seal on the neutron detector case is also checked for tampering.

When the storage container is loaded with nine baskets, the container cap is welded by the operator, then sealed by an IAEA inspector for continuity of knowledge. Fingerprints of the canister for nine baskets are then recorded using the spent CANDU fuel finger-printer at dry storage, and stored in the computer for future verification purposes. The spectrum of $^{137}Cs$ is also measured at a randomly selected point of the canister to reinforce the fingerprint information.

### 4.3. STATE ACQUISITION/DIVERSION STRATEGY FOR FRESH DUPIC FUEL BUNDLES

In the example strategy that will be used in thisa case study to demonstrate the evaluation process, the objective of the State is to acquire at least 1 SQ of fresh DUPIC fuel bundles from the fresh fuel bay of the fuel storage pool of the CANDU power plant for the manufacture of nuclear explosive devices. It is assumed that the proliferant State is an industrialized non-nuclear weapon State with significant resources and technical capabilities for nuclear proliferation, and has concluded a comprehensive safeguards agreement and an additional protocol with IAEA.

There are many pathways for the diversion of fresh DUPIC fuel. In this study, it was assumed that the host State covertly diverts fresh DUPIC fuel bundles from the fresh fuel storage bay in a storage basket during normal operation of the CANDU power plant as shown in Figure 10. Since the fuel storage basket has a capacity of 60 fuel bundles, abrupt diversion would be the strategy used by the State for the diversion of 1 SQ of nuclear material (1 SQ = ~49 fresh DUPIC fuel bundles).

Since the host State is subject to safeguards implementation as a party to a comprehensive safeguards agreement and additional protocol, it could undertake such actions as tampering with IAEA surveillance cameras and containment seals, borrowing nuclear material from other facilities to replace diverted material for the duration of the IAEA inspection period, or replacing diverted material with material of lower strategic value to reduce the probability of detection through IAEA safeguards activities. Such action may begin before the removal of material and may be continued over a considerable time.

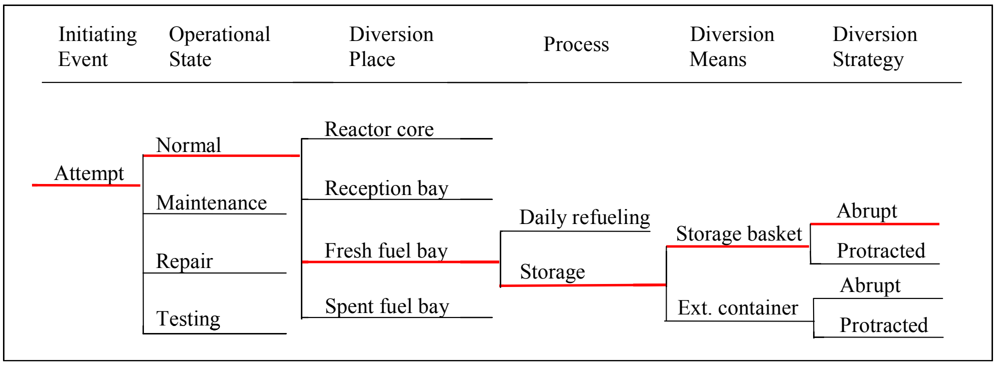



*FIG. 10. Diversion scenario for fresh DUPIC fuel bundles in CANDU power plant.*

## 4.4. EVENT SEQUENCE DIAGRAM FOR DIVERSION OF FRESH DUPIC FUEL BUNDLES FROM STORAGE BAY

The State has two scenarios for the concealed diversion of 60 fresh DUPIC fuel bundles: namely, the first scenario by replacing diverted material with material of lower strategic value (Cs-implemented natural uranium fuel), and the second without replacing the diverted material.

The first scenario (Scenario-1) for the diversion of 1 SQ of fresh DUPIC fuel bundles from the spent fuel storage bay of the Power plant can be described as a sequential pathway:

Segment-1: Bring in 60 dummy DUPIC fuel bundles (Cs-implanted natural uranium fuel) in a shielded storage basket into the storage pool through the extension building.

Segment-2: Put the fuel storage basket with dummy fuel on the workstation at the bottom of the fuel storage pool through the basket welding station in the storage pool area.

Segment-3: Transport three trays of fresh DUPIC fuel bundles to the underwater workstation.

Segment-4: On the underwater workstation, replace the dummy DUPIC fuel bundles in the storage basket with the fresh DUPIC fuel bundles transported from the fresh fuel storage bay using a fuel lifting tool.

Segment-5: Transport three trays of dummy DUPIC fuel bundles back to the fresh DUPIC fuel bay.

Segment-6: Take the loaded storage basket out of the pool area to the extension building through the basket welding station.

Segment-7: Transport the loaded storage basket from the extension building to the outside parking lot using a heavy-duty truck.

Figure 11 shows the Scenario-1 for the diversion of fresh DUPIC fuel bundles from the storage bay.

The second scenario (Scenario-2) is without replacing the diverted material, i.e. selective diversion of fresh DUPIC fuel bundles from the trays in the storage bay, the capacity of which is more than 1300 fresh DUPIC fuel bundles. The sequential pathway would be:

Segment-1: Transport fuel bundle storage trays using the bridge crane to a convenient place in the pool.

Segment-2: Take out one fuel bundle from each tray and put it in the storage basket using the fuel lifting tool.

Segment-3: Return the fuel trays to the original place using the bridge crane.

(Repeat this process until there are enough (60) fresh DUPIC fuel bundles loaded into the storage basket)

Segment-4: Take the loaded storage basket out of the pool area to the extension building through the basket welding station.

Segment-5: Transport the loaded storage basket from the extension building to the outside parking lot using a heavy-duty truck.

This second scenario may take longer to finish than the first one. In the current case study, only the first scenario is analysed.

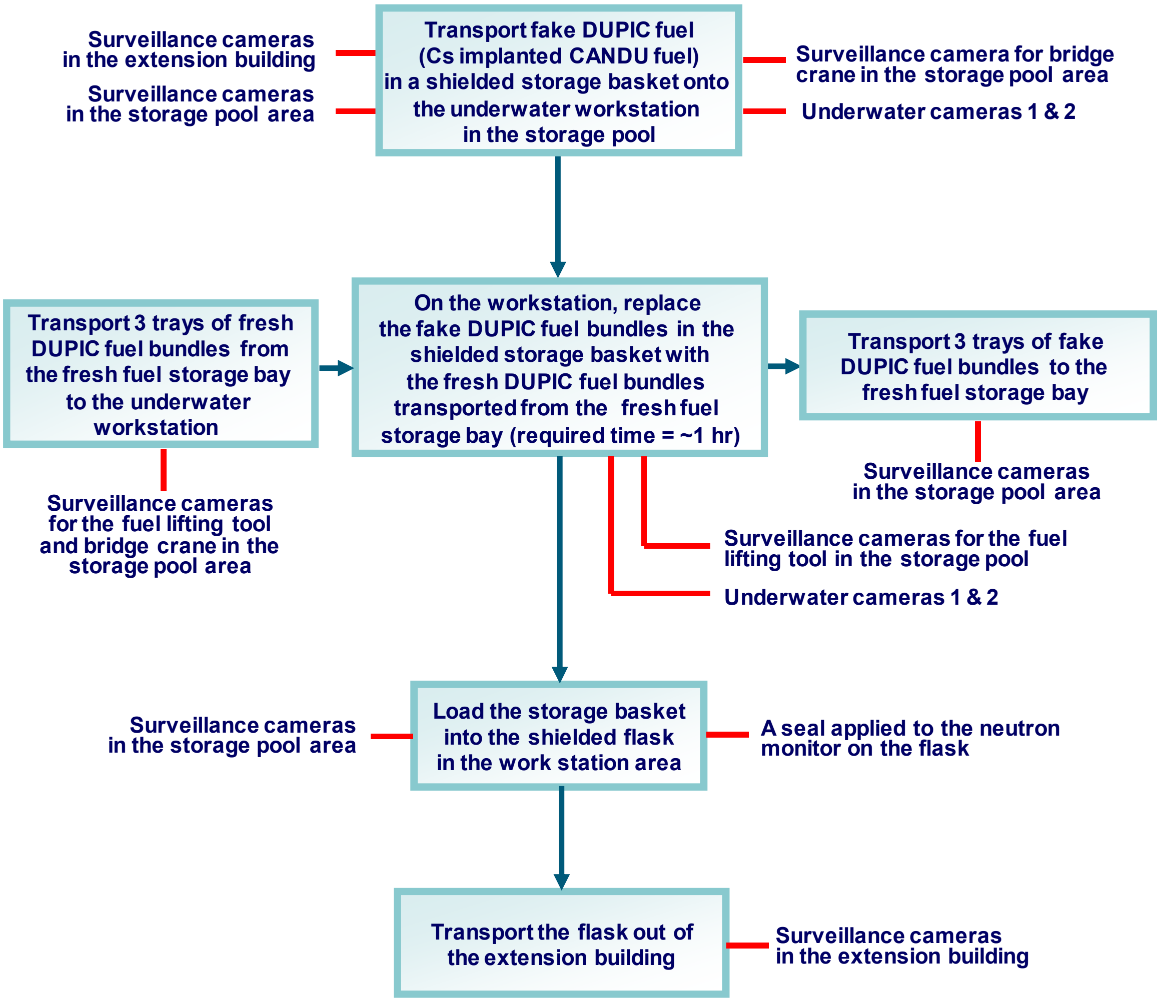



*FIG. 11. Scenario-1 for diversion of fresh DUPIC fuel bundles from storage bay.*

## 4.5. DETAILED ACQUISITION/DIVERSION PATHWAY ANALYSIS FOR FRESH DUPIC FUEL FROM DUPIC FUEL STORAGE POOL, BY USING USER REQUIREMENTS 1, 2 AND 3

In order to evaluate the multiplicity and robustness of barriers against proliferation, the PR characteristics of each segment along the selected pathway, Diverting Fresh DUPIC Fuel Bundles from the DUPIC Fuel Storage Pool, were identified and analysed according to User Requirements 1, 2 and 3 of the INPRO PR methodology. The INPRO PR Manual [1] should be consulted to determine explanations for table results.

In the subsequent tables, the yellow indicates which criteria apply to the considered pathway. The ratings in the text are relative to the other items evaluated for the level under consideration (State, INS, or facility) rather than suggesting an absolute quantitative result. In addition, the relative importance of each evaluation parameter is not expressed in the tables.

### 4.5.1. Evaluation of UR1 on the State's commitments and implementation

Compliance with User Requirement 1 (UR1), State's obligations, policies and commitments, has considerable impact on the PR of an INS. On the one hand, it demonstrates a State's compliance with non-proliferation commitments and, on the other hand, it establishes the tools to detect non-compliance at the State and INS/facility levels. UR1 has two criteria: criterion 1.1 (CR1.1) Legal Framework and criterion 1.2 (CR1.2) Institutional Structural Arrangements at the State level. CR1.1 asks the State to establish a sufficient legal framework addressing international non-proliferation, i.e. ensuring the adequacy of the State's commitment, obligations and policies regarding non-proliferation, and CR1.2 determines if the implementation is adequate to fulfil international standards in the non-proliferation regime. UR1 also addresses the capability of the IAEA to detect undeclared nuclear material and activities. In Table 12, the yellow boxes indicate which entries apply to the selected pathway. There is no indication of relative importance.

It was assumed that the host State was a party to the NPT and other non-proliferation-related international conventions and treaties. Therefore, indicator 1.1.5 is not applicable. The State had a comprehensive safeguards agreement based on IAEA/INFCIRC/153 and an additional protocol based on IAEA/INFCIRC/540 in force. It was also assumed that the State was a Party to a Nuclear Weapons Free Zone (NWFZ) treaty and had established legal instruments for nuclear export and import control, as a contracting party to such international regimes as the Nuclear Suppliers Group, Zangger Committee and Wassenar Arrangement on export control for conventional arms, dual use goods, and nuclear material and technology.

It was assumed that the State had been operating several PWR reactors, CANDU reactors, and DUPIC reactors. The State was also assumed to have an SSAC in place, and may be under a regional safeguards accounting and control regime. The assumption of no multilateral ownership or control of the DUPIC fuel cycle system was assumed. Commercial, legal and institutional arrangements were assumed to be in force with other States for access to nuclear material and nuclear energy systems. The State had the technical capability to build and operate the DUPIC fuel cycle system. The State was also assumed to have no recorded violation of non-proliferation commitments.

- On the basis of this evaluation, the State is in compliance with all aspects of UR1 concerning legal framework and institutional structural arrangements. However, not all evaluation parameters are relevant for the detailed pathway considered in this study.

TABLE 12: EVALUATION TABLE FOR INPRO USER REQUIREMENT 1 (YELLOW BOXES INDICATE ENTRIES APPLICABLE TO THIS PATHWAY)

**Basic Principle:** ***PR intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for INS to help ensure that INS will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.***

**User requirement UR1:** ***States' commitments, obligations and policies regarding non-proliferation and its implementation should be adequate to fulfill international standards in the non-proliferation regime.***

| Indicators IN | Evaluation Parameter EP | Evaluation Scale* | | | Acceptance Limit (AL) |
|---|---|---|---|---|---|
| | | W | S | N/A | |
| **IN 1.1:** State's commitments, obligations and policies regarding non-proliferation to fulfil international standards. | **EP1.1.1:** Party to NPT | No | Yes | | **AL1.1: Yes, in accordance with international standards** |
| | **EP1.1.2:** Party to NWFZ treaty. | No | Yes | | |
| | **EP1.1.3:** Safeguards agreements according to the NPT in force | No | Yes | | |
| | **EP1.1.4:** Additional protocol in force | No | Yes | | |
| | **EP1.1.5:** For those who are not party to the NPT or other safeguards agreement(e.g. INFIRC/66) in force | No | Yes | | |
| | **EP1.1.6:** Export control policies of NM and nuclear technology | No | Yes | | |
| | **EP1.1.7:** RSAC in force | No | Yes | | |
| | **EP1.1.8:** SSAC in force | No | Yes | | |
| | **EP1.1.9:** Relevant international conventions/treaties in force | No | Yes | | |
| | **EP1.1.10:** Recorded violation of non-proliferation commitments. | Yes | No | | |
| **IN 1.2:** Institutional structural arrangements. | **EP1.2.1:** Multilateral ownership, management or control of an NES (multilateral, multinational). | No | Yes | | **AL1.2: Yes**** |
| | **EP1.2.2:** International dependency with regard to fissile material and nuclear technology. | No | Yes | | |
| | **EP1.2.3:** Commercial, legal or institutional arrangements that control access to NM and INS. | No | Yes | | |

* W = Weak; S= Strong; N/A = Not Applicable (this is only for EP that may not be relevant because the treaty or commitment is not available for the country being assessed).

** Note that this AL is deemed to have been met ('Yes') despite two negative results and one positive result in the assessment of Evaluation Parameters. The reason for this is the relative significance of EP 1.2.3 (the one positive result within IN 1.2) to current standards of international safeguards. This result suggests the need for further guidance on completing EP assessments in the INPRO manual.

### 4.5.2. Evaluation of UR2 on attractiveness of nuclear material (fresh DUPIC fuel) and technology

User Requirement 2 (UR2) states that the INS should have low attractiveness of nuclear material and technology for use in a nuclear weapons programme. This user requirement refers to key proliferation barriers related to material and technology characteristics at the facility level. The role of the INPRO assessor is to determine whether an INS has achieved a level of attractiveness that is acceptably low by assessing the corresponding criteria. The attractiveness of nuclear material is determined by two intrinsic features: the conversion time and the total mass needed to achieve 1 SQ of nuclear material that is directly usable in a nuclear explosive device. The attractiveness of nuclear material increases with shorter conversion time of the acquired material and by smaller mass of acquired nuclear material needed to form 1 SQ that is directly usable.

It was again observed that not all evaluation parameters were relevant for the detailed pathway considered in this study. Currently UR2 is presented in a table that describes the proliferation target material in the system, regardless of the level of evaluation (State/INS/facility), but not a specific proliferation target material for specific pathways. The assessment table should provide a means for identifying the target being described in a pathway, and therefore an additional column could be added: *Not applicable to pathway or level of assessment*. The proliferator's strategy will determine the level of detail. Therefore, the tables should reflect the impact of State capabilities on the strength of proliferation barriers to address the different assessment levels. The table should be self-documenting. This process could be performed at higher level in the early design phases, with updates as the design matures.

In the case of fresh DUPIC fuel with $PuO_2$ which is an irradiated direct use material with the content of $^{238}Pu$ at less than 80%, the conversion time to get weapons usable material is on the order of months (1~3) and the SQ is 8kg plutonium. Table 6 above shows the plutonium isotopic vector for fresh DUPIC fuel, indicating that the number of fresh DUPIC fuel bundles (~18 kg HM/bundle) required for 1 SQ is 49. The design data of the fresh DUPIC fuel storage bay were defined in Section 4.1 as follows:

1) The storage capacity of the fresh DUPIC fuel bay is 23 MTHM (1304 fuel bundles), equivalent to six months operation.

2) The storage capacity for the spent DUPIC fuel in the ponds and dry storage is 460 MTHM (26 077 bundles), equivalent to 10 years of normal operation.

3) Daily refuelling rate is eight bundles.

Based on the fresh DUPIC fuel isotopic vector and the fresh DUPIC fuel storage bay design data, the factors involved in the assessment of indicators for UR2 for fresh DUPIC fuel are:

1) Indicator 2.1, material quality:

A. Material type/category: Fresh DUPIC fuel is of the same material type as PWR spent fuel so that it is irradiated direct use material.

B. In fresh DUPIC fuel, the weight per cent of $^{239}Pu$ is around 59.9 % (see Table 6) and it is considered irradiated direct use material.

C. Radiation field: the dose rate of a fresh DUPIC fuel bundle at 1 metre distance is around 15 rem/hr so it is considered to present a 'weak' barrier.

D. Heat generation: the content of $^{238}Pu$ in fresh DUPIC fuel is about 1.7 weight per cent.

E. For plutonium, spontaneous neutron production depends on the relative concentration of even-mass plutonium isotopes, ($^{240}Pu$ and $^{242}Pu$) / Pu. For DUPIC fuel the ratio is ~31 % for even mass Pu divided by total Pu, and spontaneous neutron production is considered a weak barrier.

2) Indicator 2.2 on material quantity:

In the current version of the *INPRO PR Manual*, material quantity is evaluated in terms of the mass (kg), number of items to obtain 1 SQ, and number of SQs involved during material stock or flow:

A. Mass of an item: this evaluation parameter evaluates how easily an item could be removed from the process with or without using special equipment. If the mass of an item is heavier, its PR barrier is stronger. Otherwise it is weaker. For the current case, the mass of a fuel bundle is 17.64 kg. Not a strong barrier.

B. Mass of bulk material: this parameter evaluates how much material must be removed from the process to get 1 SQ. As indicated in Table 6, the mass of fresh DUPIC fuel for 1 SQ is 867 kg. For the example here, this is a stronger barrier than the mass of an item

C. Number of items for 1 SQ: this parameter evaluates the number of items of nuclear material (throughput) in terms of SQ. More throughput per period of time implies a weaker barrier to diversion; lower throughput per period of time implies a stronger barrier to diversion. In the fresh DUPIC fuel storage bay, enough material is stored to constitute a lower barrier.

3) Indicator 2.3 on material classification:

The material form refers to the extent and difficulty of the chemical process required to separate weapon-usable material from accompanying diluents and contaminants, and convert it to metallic form. For illustrative purposes, suggested metrics of chemical/physical form are the categories of *metal, oxide/solution compound, spent fuel* and *waste*. In this study, fresh DUPIC fuel is classified as spent fuel because it is composed of spent fuel from which the fission products and actinides have not been removed.

4) Indicator 2.4 on attractiveness of nuclear technology:

Nuclear technology can be used for the production of weapon-usable material. The evaluation parameters for the attractiveness of nuclear technology include *enrichment*, *extraction of fissile material* and *irradiation capability* (such as reactor/accelerator) *of undeclared fertile material*. However, in case of fresh DUPIC fuel storage bay, none of these parameters are applicable because the whole process in the fresh fuel storage employs no such technology as chemical or irradiation processes at all and the fresh fuel has not changed its original form.

Table 13 shows the applicable evaluation parameters for the case study for the fresh DUPIC fuel storage bay for the selected acquisition path, highlighted in yellow. Again, this table does not show the results of the assessment, but the questions under consideration. All values are relative and there is no indication of the relative weights.

The technology developer should consider the indicators shown above with the goal of keeping the material attractiveness of the INS under development low. The attractiveness of fresh DUPIC fuel and nuclear technology, associated with the storage system, is considered acceptably low, because it is of similar material quality, quantity and classification to spent PWR fuel.

With regard to lessons learned about improving the assessment tool, it should be noted that:

- material quality and material classification overlap in many reader's minds. Clear guidance as well as the results of the analysis must be documented.
- uranium is also present in spent fuel, so the assessment must also consider the chemical/physical form of the uranium.
- the concept of $^{240}Pu_{effective}$ has been useful in describing the neutron output of various plutonium isotopic distributions.

TABLE 13: EVALUATION TABLE NECESSARY FOR INPRO USER REQUIREMENT 2; YELLOW HIGHLIGHTS INDICATE PARAMETERS OF CONCERN, NOT NECESSARILY RESULTS

<table>
<tr><td colspan="9">Basic Principle: PR intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for INS to help ensure that INS will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.</td></tr>
<tr><td colspan="9">User requirement UR2: The attractiveness of nuclear material and technology in an INS for a nuclear weapons programme should be low.</td></tr>
<tr><th rowspan="2">Indicators IN</th><th rowspan="2" colspan="2">Evaluation Parameter EP</th><th colspan="5">Evaluation Scale*</th><th rowspan="2">Acceptance Limit (AL)</th></tr>
<tr><th>VW</th><th>W</th><th>M</th><th>S</th><th>VS</th></tr>
<tr><td rowspan="6">IN 2.1: Material quality</td><td colspan="2">EP2.1.1: Material type/ category</td><td>UDU</td><td>IDU</td><td>LEU</td><td>NU</td><td>DU</td><td rowspan="6">AL2.1: Attractiveness considered in design of INS acceptably low based on expert judgment (EJ)?</td></tr>
<tr><td rowspan="2">EP2.1.2: Isotopic composition</td><td>$^{239}Pu/Pu$ (wt %)</td><td></td><td colspan="2">(59.9) > 50</td><td colspan="2">< 50</td></tr>
<tr><td>$^{232}U$contam. for $^{233}U$ (ppm)</td><td>< 400</td><td>400~1000</td><td>1000~2500</td><td>2500~25000</td><td>> 25,000</td></tr>
<tr><td>EP2.1.3: Radiation field</td><td>Dose (mGy/hr) at 1 metre</td><td>< 150</td><td>150~350 (150mGy/hr γ)</td><td>350 ~ 1000</td><td>1000~10000</td><td>> 10000</td></tr>
<tr><td>EP2.1.4: Heat generation</td><td>$^{238}Pu/Pu$ (wt %)</td><td></td><td colspan="2">(1.7) < 20</td><td colspan="2">> 20</td></tr>
<tr><td>EP2.1.5: Spontaneous neutron</td><td>($^{240}Pu+ {}^{242}Pu$) / Pu (wt %)</td><td></td><td>(~30)**</td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">IN 2.2: Material quantity</td><td colspan="2">EP2.2.1a: Mass of an item (kg)</td><td>10</td><td>10~100 (17.64 kg)</td><td>100~500</td><td>500~1000</td><td>>1000</td><td rowspan="4">AL2.2: Attractiveness considered in design of INS acceptably low based on expert judgment (EJ)?</td></tr>
<tr><td colspan="2">EP2.2.1b: Mass of bulk material for SQ (dilution) (kg)</td><td>10</td><td>10~100</td><td>100~500</td><td>500~1000</td><td>>1000</td></tr>
<tr><td colspan="2">EP2.2.2: No. of items for SQ</td><td>1</td><td>1~10</td><td>10~50 (49)</td><td>50~100</td><td>>100</td></tr>
<tr><td colspan="2">EP2.2.3: No. of SQs (material stock or flow)</td><td>>100</td><td>50~100</td><td>10~50</td><td>10~1</td><td>< 1</td></tr>
<tr><td rowspan="3">IN 2.3: Material classification</td><td rowspan="3">EP2.3.1: Chemical/ physical form</td><td>U</td><td>Metal</td><td>Oxide/ Solution</td><td>U compounds</td><td>Spent fuel</td><td>Waste</td><td rowspan="3">AL2.3: Attractiveness considered in design of INS acceptably low based on expert judgment (EJ)?</td></tr>
<tr><td>Pu</td><td>Metal</td><td>Oxide/ Solution</td><td>Pu compounds</td><td>Spent fuel</td><td>Waste</td></tr>
<tr><td>Thorium</td><td>Metal</td><td>Oxide/ Solution</td><td>Th compounds</td><td>Spent fuel</td><td>Waste</td></tr>
<tr><td rowspan="3">IN 2.4: Nuclear technology</td><td colspan="2">EP2.4.1: Enrichment</td><td></td><td colspan="2">Yes</td><td colspan="2">No</td><td rowspan="3">AL2.4: Attractiveness of technology considered in design and found acceptably low on basis of expert judgment?</td></tr>
<tr><td colspan="2">EP2.4.2: Extraction of fissile material</td><td></td><td colspan="2">Yes</td><td colspan="2">No</td></tr>
<tr><td colspan="2">EP2.4.3: Irradiation capability of undeclared fertile material</td><td></td><td colspan="2">Yes</td><td colspan="2">No</td></tr>
</table>

* VW = Very Weak, W = Weak; M = Moderate, S= Strong, VS = Very Strong; It was determined that the mixture of 5-column and 2-column headings within the Evaluation Scale assessment is confusing to the first-time user, and perhaps could be clarified in future revisions of the INPRO PR Manual.

** The Pu-238, Pu-240, and Pu-242 content depends strongly on Pu-239 content (see EP 2.1.2).

### 4.5.3. Evaluation of UR3 on detectability and difficulty of diversion of nuclear material

User Requirement 3 (UR3) asks for reasonable difficulty and detectability of diversion of nuclear material, and is to be fulfilled by the technology holder (developer) at the facility level. UR3 must be seen in the context of UR1 that provides the necessary framework to implement safeguards. The evaluation parameters of UR3 have, in principle, similar issues as those of UR2, and the results in the assessment matrix table should be related to a specific acquisition pathway and material. All assessments concerning barriers and diversion difficulty should be related to specific proliferator actions. The specific equipment and C/S measures involved should be addressed in the evaluation of UR3 for specific acquisition pathways and, therefore, this UR is associated with *Safeguards by Design*.

Attractiveness of nuclear material and nuclear technology in an INS for a weapons programme (UR2) and the detectability and difficulty of diversion of nuclear material (UR3) are not independent parameters. Attractiveness of an INS (or component thereof) decreases with an increase in detectability/difficulty of diversion of nuclear material. Indicators (barriers against proliferation) defined under UR2 that might be weak at facility level can paradoxically increase e.g. the detectability of unrecorded movements of nuclear material. Therefore, some of the characteristics of nuclear material and technology discussed in UR2 are also relevant for UR3.

On the basis of the above analysis, the PR indicators and evaluation parameters in User Requirement 3 for the specific acquisition/diversion pathway of the fresh DUPIC fuel from the storage bay are rationalized as follows:

1) Indicator 3.1 on accountability:

A. For the verification of the status of the material accounting data, the IAEA must be able to derive a statement of MUF, and a statistical limit of error for the MUF.

B. However, there is no MUF for fresh DUPIC fuel bundles because the inspector measurement capability for fresh DUPIC fuel bundles in the storage pool is item counting complemented with a qualitative passive non-destructive assay (NDA) method; i.e. the physical inventory of fresh DUPIC fuel bundles in the storage is verified using item counting and qualitative NDA based on the sample size and sampling plan.

2) Indicator 3.2 on amenability for C/S and monitoring systems:

A. This indicator considers the related evaluation parameters to monitor the nuclear material movement, and requires detailed acquisition pathway analysis for the installation of C/S measures.

B. The use of C/S measures is aimed at verifying information on the movement of nuclear or other material, equipment and samples, or preservation of the integrity of safeguards-relevant data. In many instances, C/S measures cover the period when the inspector is absent, thus ensuring the continuity of knowledge for the IAEA and contributing to the cost effectiveness.

C. The collected C/S data from the system can be verified using the review software program against the inventory change report (ICR).

D. In the fresh DUPIC fuel storage bay, an underwater radiation monitoring system can be installed to check the movement of fresh DUPIC fuel.

3) Indicator 3.3 on detectability of nuclear material:

A. This indicator is evaluated by the nature of the detection system and the nuclear material to be detected.

B. The evaluation parameters of the detectability include the possibility to identify nuclear material by NDA, the hardness of radiation signature and the need for passive/active mode.

4) Indicator 3.4 on difficulty to modify the process:

A. The difficulty of modifying the process depends on the complexity of the modification, its cost, safety implications, and the time required to perform it.

B. There are four categories of evaluation parameters addressing the difficulty of modifying the process.

5) Indicator 3.5 on difficulty to modify facility design:

A. The difficulty of modifying a fuel cycle facility depends on the complexity of the modification, cost, safety implications, the time required to perform it, and the ease with which inspectors can detect such modifications.

B. Such a modification might be detected by DIV measures.

6) Indicator 3.6 on detectability of misuse of technology or facilities:

A. Misuse of the INS facilities/technology can be the *overproduction of nuclear material* using undeclared material, *presence of nuclear material* that should not appear in a system element in accordance with declaration, *higher enrichment* than declared, and *undeclared irradiation*.

B. The probability of detecting such misuse is linked to the transparency of the facility design and process and to the availability of data.

Table 14 shows the resulting values for the case study for the fresh DUPIC fuel storage bay. It was assumed that the CANDU power plant had similar safeguards measures in place to those for the existing CANDU-6 power plant, meeting international standard practice. Also, the evaluation parameters of UR3 on detectability and difficulty of diversion of nuclear material have the same general issues as UR2, and the results in the assessment table of the current *INPRO PR Manual* should be related to a specific pathway and material and the State capability. All assessment concerning barriers and diversion difficulty should be related to the actions involved, and the equipment and C/S measures should be addressed in the evaluation of UR3 for specific acquisition pathways. In this regard, UR3 criteria could be related to the safeguards-by-design concept.

The technology developer should consider the indicators shown above with the goal of keeping the detectability and difficulty of diversion equal to or better than that of existing designs. For this case study, it can be concluded that the diversion of fresh DUPIC fuel through the selected pathway from the fresh DUPIC fuel bay is reasonably difficult and detectable by applying the safeguards tools and measures of the CANDU-6 power plant.

## 4.6. EVALUATION OF UR4 ON MULTIPLICITY AND ROBUSTNESS OF BARRIERS AT EACH SEGMENT OF DIVERSION PATHWAY

User Requirement 4 (UR4) asks for the INS to incorporate multiple PR features and measures, to be implemented by the technology developers in cooperation with PR experts. INPRO has defined two criteria for user requirement UR4: multiplicity (defence in depth) and robustness of barriers.

UR4 can be assessed at the State level, the INS level, and the facility level, including facility specific pathways, although different issues are involved. Some of the characteristics of nuclear material and technology discussed in UR2 and detectability and difficulty of diversion in UR3 are integral elements in assessing UR4. In addition, UR1 provides a State-level barrier against proliferation, the necessary legal framework for implementing safeguards and, in this context, the evaluation of UR3. The multiplicity of proliferation barriers should be considered together with their robustness in assessing UR4. Accordingly, the concern is how to demonstrate the robustness of barriers and how to relate this to State capabilities.

TABLE 14: EVALUATION PARAMETERS FOR INPOR USER REQUIREMENT 3

Yellow highlights indicate parameters of interest, relative ranking is based on expert judgement.

| Indicators IN | Evaluation Parameter EP | | Evaluation Scale | | | | | Acceptance Limit (AL) |
|---|---|---|---|---|---|---|---|---|
| **Basic Principle:** *PR intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for INS to help ensure that INS will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.* | | | | | | | | |
| **User requirement UR3:** *The diversion of nuclear material should be reasonably difficult and detectable.* | | | | | | | | |
| | | | **VW** | **W** | **M** | **S** | **VS** | |
| **IN 3.1:** Accountability | **EP3.1.1:** $\sigma_{MUF}$ /SQ | Pu or $^{233}U$ | > 2 | 2~1 | 1~0.5 | 0.5~0.1 | **(0)** < 0.1 | **AL3.1:** Based on expert judgement equal or better than existing designs, |
| | | $^{235}U$ with HEU | > 2 | 2~1 | 1~0.5 | 0.5~0.1 | < 0.1 | |
| | | $^{235}U$ with LEU | > 2 | 2~1 | 1~0.5 | 0.5~0.1 | < 0.1 | |
| | **EP3.1.2:** Inspectors' measurement capability | | IC only | DA only | Combination NDA/DA | NDA active | NDA passive | |
| **IN 3.2:** Amenability for C/S and monitoring systems* | **EP3.2.1:** Amenability of containment measures | | | No | | Yes | | **AL3.2=** Based on expert judgement equal or better than existing designs, |
| | **EP3.2.2:** Amenability of surveillance measures | | | No | | Yes | | |
| | **EP3.2.3:** Amenability of other monitoring systems | | | No | | Yes | | |
| **IN 3.3:** Detectability of nuclear material | **EP3.3.1:** Possibility to identify nuclear material by NDA | | | No | | Yes | | **AL3.3= AL3.1** |
| | **EP3.3.2:** Detectability of radiation signature | | | No reliable signature | | Yes Reliable signature | | |
| **IN 3.4:** Difficulty to modify the process | **EP3.4.1:** Extent of automation | | N/A | Manual operation | N/A | Partial automatio | Full automatio | **AL3.4= AL3.2** |
| | **EP3.4.2:** Availability of data for inspectors | | Operators data available | ** | ** | ** | NRTA active | |
| | **EP3.4.3:** Transparency of process | | | No | | Yes | | |
| | **EP3.4.4:** Accessibility of material to inspectors | | | No | | | | |
| **IN 3.5:** Difficulty to modify facility design | **EP3.4.4:** Verifiability of facility design by inspectors*** | | | No | | Yes | | **AL3.5= AL3.2** |
| **IN 3.6:** Detectability of misuse of technology or facilities. | **EP3.5.1:** Possibility to detect misuse of the technologies and the INS facilities for processing of undeclared nuclear material. | | | No | | Yes | | **AL3.6= AL3.2** |

* Evaluation of this indicator requires detailed acquisition pathway analysis first; it is related to system elements rather than to facilities within an INS.

** Detailed scale is illustrative only, and subject to further considerations. This parameter may include standard operator reporting information flow and NRTA.

*** This parameter is linked to the transparency of design and depends on the willingness of the operator/State to demonstrate its level of transparency.

### 4.6.1. Evaluation of multiplicity of proliferation barriers

Table 15 shows proliferation barriers identified at each segment of the acquisition/diversion of fresh DUPIC fuel from the CANDU power plant using UR1, UR2 and UR3.

The acceptance limit for the multiplicity requirement of UR4 is that all plausible acquisition/diversion pathways of the INS (composed of several sequential segments) are or can be covered by extrinsic measures at the facility/State level and by intrinsic features compatible with other design requirements. The primary purpose of this indicator is to encourage designers to incorporate intrinsic features in an INS in order to facilitate the implementation of safeguards, to decrease the impact of safeguards implementation on the facility, and to make the INS an unattractive means to acquire fissile material for a nuclear weapons programme. Therefore, the assessment procedure and metrics to evaluate Indicator 4.1 on multiplicity of UR 4 should be:

1) Identify proliferation target material and related plausible acquisition/diversion pathways in an INS using the INPRO approach for acquisition/diversion pathway analysis as shown in Figure 2 (*A case study is shown in Section 3*).

2) Carry out detailed pathway analysis for the selected pathway from the plausible acquisition/diversion pathways (*A case study is shown in Section 4.5*).

3) In addition to the general tables necessary to perform the requirements by UR1, UR2 and UR3, identify intrinsic PR features and extrinsic measures existing at each segment of the selected pathway, i.e. produce a table identifying proliferation barriers based on UR1, UR2 and UR3 for each of the plausible pathways (*A case study is shown in Table 15*).

4) Evaluate the multiplicity of barriers using expert judgment concerning whether the selected acquisition pathway is (or can be) covered by extrinsic measures at the facility/State level and intrinsic features compatible with other design requirements. The scale for evaluating indicator 4.1 on multiplicity could be the same as in the *INPRO PR Manual*: W (weak) for 'No multiple coverage' and S (strong) for 'Multiple coverage' as shown in Table 18.

5) If the answer is 'weak' (W), then identify and incorporate additional intrinsic features/extrinsic measures to enhance the PR with multiple coverage until the final answer is 'strong' (S).

6) Repeat the above procedure for all the plausible acquisition pathways until the acceptance limit is met for each of the plausible acquisition/diversion pathways.

With regard to lessons learned about improving the assessment tool, it should be noted that clear guidance should be given regarding how to assess substitution of dummy items. The proliferation concern is the diverted material, not the dummy items. The proper construction of dummy items is part of the diversion path.

### 4.6.2. Evaluation of robustness of proliferation barriers

The robustness of proliferation barriers in the context of INPRO PR methodology describes the effectiveness of acquisition pathway barriers. These are a measure of the difficulty of defeating proliferation barriers in terms of time and effort. Robustness is not a function of the number of barriers, or of their individual characteristics, but is an integrated value of the whole. For example, the difficulty in material handling, if not supplemented by safeguards measures, would have a very minor effect on the State level diversion compared to the diversion difficulty and detectability barriers.

TABLE 15: PARAMETERS FOR ASSESSMENT OF MULTIPLICITY OF PROLIFERATION BARRIERS AGAINST DIVERSION OF FRESH DUPIC FUEL

<table>
<tr><td colspan="6">Basic Principle: PR intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for INS to help ensure that INS will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.</td></tr>
<tr><td colspan="6">User requirement UR4: INS should incorporate multiple PR features and measures.</td></tr>
<tr><td rowspan="2">Indicators IN</td><td rowspan="2">Evaluation Parameter EP</td><td rowspan="2">Segment number and explanation</td><td colspan="3">INPRO User Requirements*</td></tr>
<tr><td>UR1 on State's Commitments</td><td>UR 2 on Material Attractiveness</td><td>UR 3 on Diversion Difficulty and Detectability (Safeguardability)</td></tr>
<tr><td colspan="6">Criteria 4.1 Defense in depth</td></tr>
<tr><td rowspan="3">IN 4.1:<br>The extent by which the INS is covered by multiple intrinsic features and measures</td><td rowspan="3">EP4.1:<br>All plausible acquisition paths are (can be) covered by extrinsic measures on the facility or State level and by intrinsic features which are compatible with other design requirements.*<br>(=AL4.1)</td><td>1. Segment-1: Bring in 49 dummy DUPIC fuel bundles (Cs-137 and Cf-252-implanted natural uranium fuel) in a storage basket (flask) into the storage pool through the flask loading area in the extension building.</td><td rowspan="3">1. State's commitments, obligations and policies established in accordance with international standards.<br>2. Institutional structural arrangements in support of PR have been considered accordingly on the basis of expert judgment.</td><td>1. Material quality barrier: Cs-137 and Cf-252 implanted dummy DUPIC fuel has a high radiation and spontaneous neutron field so that it requires heavy shielding, but facility is built to mitigate that issue<br>2. Material quantity barrier: 49 dummy bundles are required to replace 1 SQ fresh DUPIC fuel.</td><td>1. Amenability for C/S barrier: Surveillance camera in the extension building monitors the use of transport flask and bridge crane to move the flask.<br>2. Amenability for C/S and Detectability barriers: Monitoring on the transport flask monitors any nuclear material inside the flask.</td></tr>
<tr><td>2. Segment-2: Put the fuel storage basket with dummy fuel on the workstation at the bottom of the fuel storage pool through the basket welding station in the storage pool area.</td><td>1. Material quality barrier: Dose rate of dummy and fresh DUPIC fuel bundles (~150 mSv/hr).</td><td>1. Amenability for C/S barrier: Surveillance camera in the storage pool area monitors the use of basket welding station.<br>2. Amenability for C/S barrier: CCTV in the hot cell of the welding station monitors any activity in the drying hot cell.</td></tr>
<tr><td>3. Segment-3: Transport 3 trays of fresh DUPIC fuel bundles to the underwater workstation</td><td>1. Material quality barrier: dose rate of fresh DUPIC fuel bundles (~150 mSv/hr)<br>2. Material quantity barrier: a bridge crane needed to move fuel bundles.</td><td>1. Amenability for C/S barrier: Surveillance cameras monitor movement of the fuel tray lifter (bridge crane).</td></tr>
</table>

| | | | | | |
|---|---|---|---|---|---|
| | | 4. Segment-4: on the underwater workstation, replace the dummy DUPIC fuel in the storage basket with the fresh DUPIC fuel bundles using a fuel lifting tool. | | 1. **Material quality barrier:** special equipment (fuel lifting tool) needed. | 1. **Amenability for C/S and detectability barriers:** Surveillance cameras monitor the movement of fuels.<br>2. **Amenability for C/S barrier:** Surveillance cameras monitor the use of fuel lifting tool.<br>3. **Detectability barrier:** NDA equipment monitors the movement of fuel. |
| | | 5. Segment-5: Transport 3 trays of dummy DUPIC fuel bundles back to the fresh DUPIC fuel bay. | | 1. **Material quality barrier**: dose rate of fresh DUPIC fuel bundles (~150 mSv/hr)<br>2. **Material quantity barrier:** A bridge crane needed. | 1. **Amenability for C/S barrier:** Surveillance cameras monitor movement of the fuel tray lifter. |
| | | 6. Segment-6: Take the loaded storage basket from the pool area to the extension building through the basket welding station. | | 1. **Material quality and quantity barriers**: dose rate of fresh DUPIC fuel bundles (~150 mSv/hr) and 49 fuel bundles requires heavy shielded container | 1. **Amenability for C/S barrier:** CCTV in the hot cell of the welding station monitors any basket movement in the drying hot cell.<br>2. **Detectability barrier:** Monitoring on the transport flask monitors any fuel basket in the flask.<br>3. **Surveillance camera** monitors movement of the transport flask. |
| | | 7. Segment-7: Transport the loaded storage basket from the extension building to the outside parking lot using a heavy-duty truck | | 1. **Material quantity barrier**: The flask containing a storage basket loaded with dummy DUPIC fuel requires a crane to transport.<br>2. **Material quantity barrier**: A heavy duty truck needs to be used. | 1. **Amenability for C/S barrier:** Surveillance camera in the extension building monitors movement of a transport flask and a heavy duty truck. |

* It should be noted that not all the barriers are relevant for the detailed pathway considered.

TABLE 16: EVALUATION OF USER REQUIREMENT 4 – CR 4.1 (MULTIPLICITY)

<table>
<tr><td colspan="6">Basic Principle: PR intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for INS to help ensure that INS will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.</td></tr>
<tr><td colspan="6">User requirement UR4: INS should incorporate multiple PR features and measures.</td></tr>
<tr><td colspan="6">CR4.1 Defence in depth</td></tr>
<tr><td rowspan="2">Indicators<br>IN</td><td rowspan="2" colspan="2">Evaluation Parameter<br>EP</td><td colspan="2">Evaluation Scale</td><td rowspan="2">Acceptance Limit<br>AL</td></tr>
<tr><td>W</td><td>S</td></tr>
<tr><td rowspan="2">IN 4.1:<br>The extent to which the INS is covered by multiple intrinsic features and measures</td><td rowspan="2">EP4.1:<br>Analysis of each plausible acquisition pathway</td><td>Multiple coverage by extrinsic measures on the facility (UR3) and State level (UR1)</td><td>No</td><td>Yes</td><td rowspan="2">AL4.1: According to expert judgment, all plausible acquisition paths* are (can be) covered by extrinsic measures on the facility and State level and by intrinsic features which are compatible with other design requirements.</td></tr>
<tr><td>Multiple coverage by intrinsic features which are compatible with other design requirements (UR2)</td><td>No</td><td>Yes</td></tr>
</table>

* Note: for this example, only 1 of the paths has been assessed to test the methodology.

A State proliferator would have unrestricted access to the entire nuclear facility and the equipment designed for handling nuclear material. Therefore, the robustness of proliferation barriers is defined in PRADA as a combination of the barriers described in UR1, UR2 and UR3, and is measured by determining whether the safeguards goals can be met. However, it should not be construed as implying that proliferation using a system and its material for which the safeguards goals can be met is impossible (i.e. the system is proliferation-proof).

The diversion difficulty and detectability required in UR3 (safeguardability) is based on the effectiveness and efficiency (timeliness) of the IAEA safeguards system framework established under UR1. Successful evaluation of the robustness of barriers identified in UR4 requires sufficient information on the process and design information of the INS, which will become available for an INS only as its design progresses. Based on the above rationale, the proposed approach to evaluate Indicator 4.2 concerning the robustness of proliferation barriers along the plausible acquisition/diversion pathway is as follows:

1) Evaluate the effectiveness of each proliferation barrier identified by Criteria 4.1 on multiplicity for each segment of the selected plausible pathway.
2) Evaluate the robustness of multiple barriers along the selected pathway using expert judgment as to whether the robustness of the barriers would be sufficient to meet the IAEA safeguards goals. The scale for evaluating indicator 4.2 on robustness could be: W (weak) for ‘No (safeguards goals cannot be met on all acquisition paths)’ and S (strong) for ‘Yes (safeguards goals can be met on all acquisition paths)’ as shown in Table 17.
3) If the answer is W, then identify and incorporate additional intrinsic features/extrinsic measures to provide or improve the PR until the final answer is S.
4) Repeat the above procedure for all the other plausible acquisition pathways until the acceptance limit is met for each of the plausible pathways.

TABLE 17: EVALUATION OF USER REQUIREMENT 4 – CR 4.2 (ROBUSTNESS)

<table>
<tr><td colspan="5">Basic Principle: PR intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for INS to help ensure that INS will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.</td></tr>
<tr><td colspan="5">User requirement UR4: INS should incorporate multiple PR features and measures.</td></tr>
<tr><td colspan="5">CR4.2 Robustness of barriers</td></tr>
<tr><td rowspan="2">Indicators<br>IN</td><td rowspan="2">Evaluation Parameter<br>EP</td><td colspan="2">Evaluation Scale</td><td rowspan="2">Acceptance Limit<br>AL</td></tr>
<tr><td>W</td><td>S</td></tr>
<tr><td>IN4.2: Robustness of barriers covering each acquisition path*</td><td>EP4.2: IAEA safeguards goals (time and quantity) can be met</td><td>No</td><td>Yes</td><td>AL4.2: Robustness is sufficient based on expert judgment</td></tr>
</table>

* Note: for this example, only 1 of the paths has been assessed to test the methodology.

## 4.7. EVALUATION OF USER REQUIREMENT 5 ON OPTIMIZATION OF DESIGN

The cost of incorporating additional intrinsic features and extrinsic measures into an INS that are required by UR4 to provide or improve PR could be excessively high. Therefore, UR4 leads to User Requirement 5, optimization of the combination of intrinsic features and extrinsic measures in the design/engineering phase to provide cost-efficient PR.

The main concern in UR4 is to demonstrate the robustness of barriers and relate this to the State capability through the optimization of the robustness of proliferation. Therefore, the assessment procedure and metrics to evaluate UR5, optimization of combination of PR features and measures, would be as follows:

1) Evaluate whether PR has been taken into account as early as possible in the design and development of the INS.
2) Optimize costs of the combination of intrinsic features and extrinsic measures which are to be incorporated to provide or improve PR and to support the implementation of safeguards.
3) Confirm whether a verification approach with a level of extrinsic measures can be designed and agreed on between the verification authority and the State.

# 5. INTERACTION WITH THE PROLIFERATION RESISTANCE & PHYSICAL PROTECTION WORKING GROUP (PR&PP WG) OF GENERATION IV INTERNATIONAL FORUM (GIF)

The GIF PR&PP [5] and INPRO PR methodologies developed by international teams are the two most widely accepted methodologies, and the necessity to harmonize them has been acknowledged by their technology developers and potential users [12]. The GIF PR&PP methodology considers a nuclear energy system primarily from the standpoint of the designer of the system and identifies proliferation challenges, system responses, and outcomes, while the INPRO Methodology adopts the standpoint primarily of nuclear energy system users. Both approaches endorse the need for PR considerations to be taken into account as early as possible in the design and development of a nuclear energy system. Figure 12 shows the interaction between the INPRO and GIF PR methodologies.

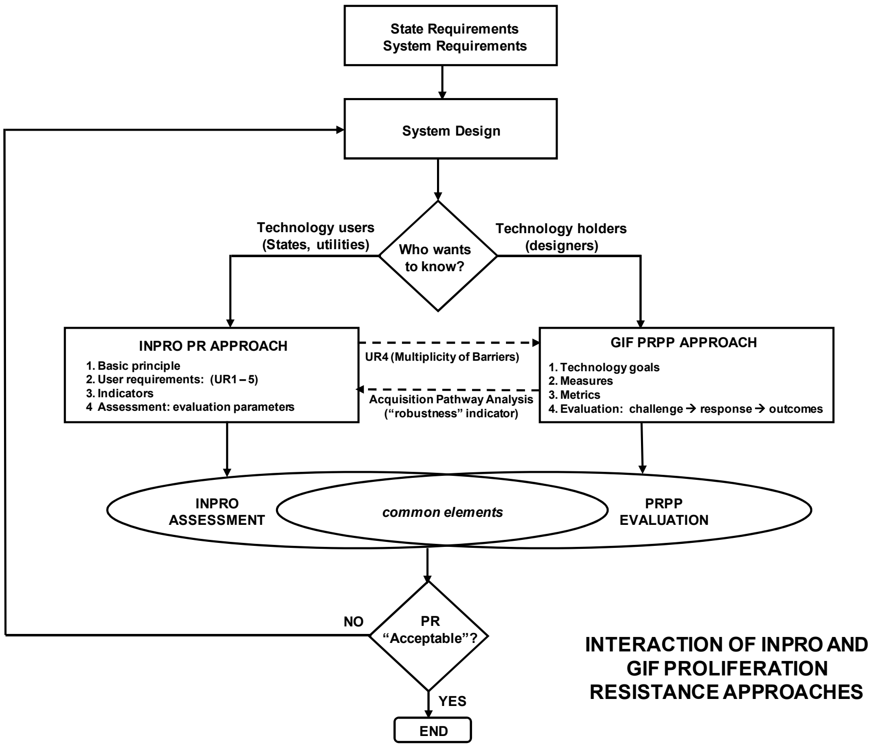



*FIG. 12. Interaction of INPRO and GIF PR&PP methodologies.*

Both methodologies share certain similarities, beginning with a common definition of PR, and have a hierarchical analytical structure, with PR principles, high-level evaluation factors and multiple measures or requirements related to each high-level factor. Both methodologies incorporate institutional and policy context for the system under consideration. INPRO takes into account a State's non-proliferation commitments and agreements in one of its user requirements. In the GIF approach, however, these commitments are treated implicitly when estimating the GIF detection probability measure. The GIF methodology lends itself to comparing the PR of alternative nuclear energy systems. GIF separates a system into components (system elements) and performs a pathway analysis, providing the basis for a PR evaluation. Neither approach aggregates results into a single numerical value or grade, so that strengths and weaknesses under each of the main evaluation criteria are explicitly considered.

There are several notable differences between the two methodologies. The INPRO approach is focused on the potential contribution of declared facilities to proliferation, and excludes the analysis of clandestine facilities, including those that might be needed to complete a proliferation pathway or breakout scenario in which a facility is overtly misused for proliferation purposes. The GIF PR&PP methodology considers both declared and undeclared facilities and activities, and also misuse following breakout, to complete the proliferation pathway from acquisition and processing of material to fabrication of a nuclear explosive device. INPRO examines the whole system, sets explicit user requirements, and asks how the system meets these requirements.

Interaction between the GIF and INPRO methodologies is intended to identify common metrics (GIF) and evaluation parameters (INPRO) to be used in both methodologies to determine the PR of a nuclear energy system as part of a proliferation pathway. Both approaches recognize the concept of barriers to proliferation, but implement the concept differently. Figure 13 shows the comparison of metrics and evaluation parameters used in the GIF and INPRO PR evaluation methodologies, respectively.

Both methodologies recognize that the degree of PR results from a combination of factors, including technical design features, operational modalities, institutional arrangements and safeguards measures [6], and treat PR as a function of extrinsic measures (e.g. safeguards) and intrinsic features (e.g. material attractiveness, etc.). In particular, effective international safeguards are an essential component of PR, and PR should not be viewed as a substitute for the highest standards of international safeguards, or for other non-proliferation tools such as effective export controls.

In the INPRO Methodology, the robustness of proliferation barriers is the effectiveness of acquisition pathway barriers, and is a combination of (a) safeguardability (UR-3) augmented by sufficient safeguards to achieve the IAEA's safeguards goals, and (b) technical difficulty based on the attractiveness of material and technology (UR-2). 'Technical difficulty' consists of first, the utility for use in nuclear explosives after any required conversion, and second, the difficulty of material handling and the availability and difficulty of different processes needed to produce weapon-usable material after diversion/misuse.

The technical difficulty of barriers in the GIF PR&PP approach shown in Figure 13 represents the probability of failing to achieve the proliferation goal. This evaluation will be subject to expert judgment, as determined by following GIF PR&PP evaluation methodology. As described in the previous section, the INPRO assessment methodology needs information from the results of such analyses, performed jointly by a technology developer (supplier), safeguards experts, and experts in PR. These analyses can be done by the GIF PR methodology analysing the system response to challenges.

In the GIF PR&PP methodology, a pathway analysis is performed to identify acquisition scenarios that a State could pursue to obtain nuclear weapons by taking advantage of its peaceful nuclear material and facilities. In order to develop the appropriate methods to evaluate the multiplicity and robustness of proliferation barriers for INPRO, the GIF pathway concept has been applied to the DUPIC fuel cycle to identify and analyse the acquisition/diversion pathway for nuclear material. This demonstrates the possibility of merging both methodologies into one holistic approach.

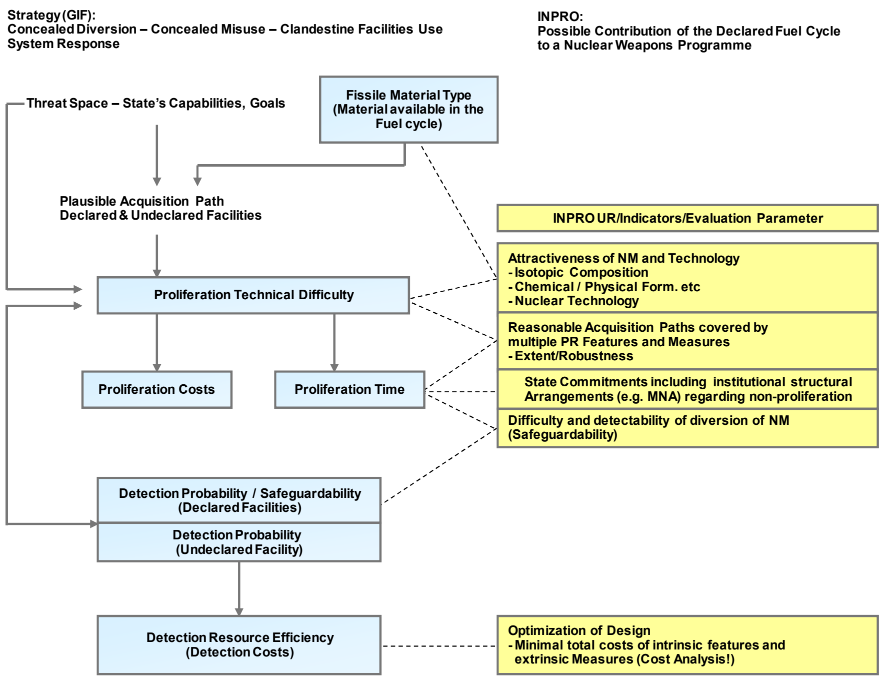



*FIG. 13. Dependencies of measures in GIF PR evaluation methodology and their relation to INPRO user requirements/indicators.*

# 6. SUMMARY AND CONCLUSIONS

The objective of PRADA was to further develop a documented approach for performing proliferation resistance assessments using the INPRO Methodology and, where appropriate, also elements and tools of the GIF PR&PP Methodology. In this context, a systematic approach for the identification and analysis of acquisition/diversion pathways of nuclear material was developed and applied to a CANDU reactor in the DUPIC fuel cycle. Procedures for determining and analysing plausible acquisition pathways were developed and tested, however not all plausible pathways were assessed. It was concluded that not all evaluation parameters are relevant for detailed pathways, such as those considered in this study. Furthermore it was concluded that additional guidance and detail would be useful in the documentation for the INPRO Methodology.

Multiplicity of barriers was demonstrated using a proliferation barrier analysis. It was shown that barriers against PR specified in UR1, UR2, and UR3 are not independent, and that in addition the strength of barriers against proliferation might depend on State capabilities. The degree of PR results from a combination of factors, including technical design features, operational modalities, institutional arrangements and safeguards measures [6]. The effectiveness of barriers to proliferation can be categorized as: (1) technical difficulty in making weapons (as a State level concern, not related to a specific facility), (2) barriers representing the difficulty in handling and processing material (both at the State and at the facility level), and (3) barriers leading to difficulty/detectability and safeguardability (at a specific facility-related pathway level). Therefore, there are three levels of PR indicators in the INPRO PR assessment: State level, INS level and facility level, including facility-specific pathways. The indicators also have a hierarchical relationship in terms of applicability, as shown in Figure 14.

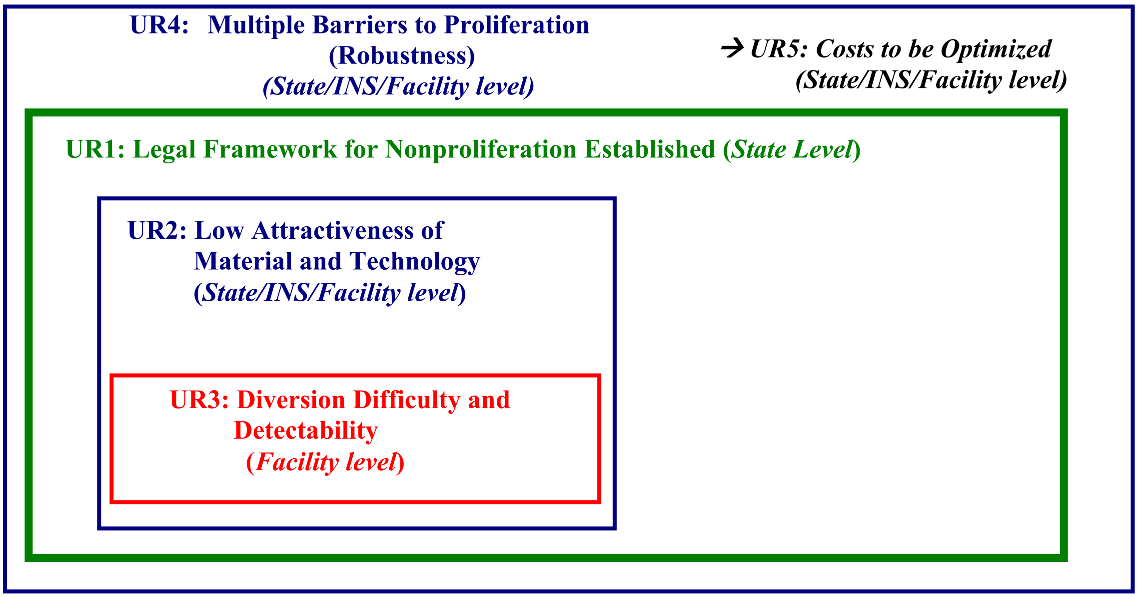



*FIG. 14: Three levels of proliferation barriers, and hierarchy of user requirements.*

Compliance with User Requirement 1 (UR1), *State's commitments, obligations and policies regarding non-proliferation and its implementation*, has considerable impact on PR of an INS. On the one hand, it demonstrates a State's compliance with non-proliferation commitments and, on the other hand, it establishes the tools to detect non-compliance at the State and INS/facility levels. UR1 has two criteria (CR): legal framework (CR1.1) and institutional structural arrangements (CR1.2) at the State level. CR1.1 asks the State to establish a sufficient legal framework addressing international non-proliferation, i.e. ensuring the adequacy of the States' commitment, obligations and policies regarding non-proliferation, and CR1.2 determines if the implementation is adequate to meet international standards in the non-proliferation regime. It also addresses the capability of the IAEA to detect undeclared nuclear material and activities

User Requirement 2 (UR2) states that the INS should have low attractiveness of nuclear material and technology for use in a nuclear weapons programme. This User Requirement refers to key proliferation barriers related to material and technology characteristics at all three levels of evaluation. The role of the INPRO assessor is to determine whether an INS has achieved a level of attractiveness that is acceptably low by assessing the corresponding criteria. The attractiveness of nuclear material is determined by two intrinsic features, the conversion time and the total mass needed to achieve 1 SQ. The attractiveness of nuclear material increases with shorter conversion time of the acquired material and with smaller mass of material needed to form 1 SQ.

Currently UR2 is presented in a table that describes the proliferation target material in the system, regardless of the level of evaluation (State/INS/facility), but not a specific proliferation target material for specific pathways. The assessment table should provide a means for identifying the target being described in a pathway, and therefore an additional column could be added: *Not applicable to pathway or level of assessment*. The proliferator's strategy will determine the level of detail. Therefore, the tables should reflect the impact of State capabilities on the strength of proliferation barriers to address the different assessment levels. The table should be self-documenting. This process could be performed at higher level in the early design phases, with updates as the design matures.

User Requirement 3 (UR3) stipulates reasonable difficulty and detectability of diversion of nuclear material, and is to be addressed by the technology holder (developer) at the facility level. UR3 must be seen in the context of UR1, which provides the necessary framework to implement safeguards. The evaluation parameters of UR3 have, in principle, similar issues as those of UR2, and the results in the assessment matrix table should be related to a specific acquisition pathway and material. All assessments concerning barriers and diversion difficulty should be related to proliferator actions. The equipment, C/S measures, etc. involved should be addressed in the evaluation of User Requirement 3 for specific acquisition pathways, and therefore, this UR is associated with 'Safeguards by Design'.

Attractiveness of nuclear material and nuclear technology in an INS for a weapons programme (UR2) and the detectability and difficulty of diversion of nuclear material (UR3) are not independent parameters. Attractiveness of an INS (or a component thereof) decreases with an increase in detectability/difficulty of diversion of nuclear material. Indicators (barriers against proliferation) defined under UR2 that might be weak at a facility level can paradoxically increase; for example, material with a high radiation field could be a proliferation target at the facility level, but its radiation field could increase the detectability of unrecorded movements of nuclear material. Therefore, some of the characteristics of nuclear material and technology discussed in UR2 are also relevant for UR3.

Robustness was determined not to be a function of the number of barriers or of their individual characteristics but an integrated function of the whole. User Requirement (UR4) evaluates the multiplicity and robustness of barriers and is correlated with User Requirement (UR5) concerning the cost and optimization of PR features and measures, as shown in Figure 14. The robustness of proliferation barriers as defined in PRADA is measured by determining if, and how, the international safeguards goals can be met. 'Robustness' does not guarantee that proliferation using an INS and its material is impossible (i.e. that the system is 'proliferation proof').

This leads to the question, *why encourage States, designers and operators to make nuclear material and technologies reasonably unattractive, if the value of PR is determined by the ability to meet the safeguards goals*? The INPRO *Proliferation Resistance Basic Principle* states in part: "Proliferation resistance intrinsic features and extrinsic measures shall be implemented…. to help ensure that INS will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme…" [1]. Whether or not an INS is an 'unattractive means' depends, ultimately, on the risk of early detection, on proliferation time, and proliferation cost.

The INPRO assessment methodology needs information from the results of a more quantitative analyses performed jointly by a technology developer (supplier), safeguards experts, and experts in PR. These can be performed by the GIF PR&PP methodology when analysing the system response to challenges. Accordingly, the GIF pathway concept was applied to a CANDU reactor in the DUPIC fuel cycle to identify and analyse nuclear material acquisition/diversion pathways; i.e. it was used to evaluate the multiplicity and robustness of proliferation barriers (UR4). This demonstrates the possibility of merging both methodologies to form one holistic approach.

Finally, the PRADA study identified a number of areas for possible improvement in the INPRO PR Manual, for instance: (1) a better explanation of the rationale for acceptance limits, (2) a reformatting of the evaluation tables to improve clarity, and (3) a restructuring of the evaluation tables to provide needed details to the user.

# REFERENCES


[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual – Proliferation Resistance, Volume 5 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles(INPRO), IAEA-TECDOC-1575, IAEA Vienna (2007).

[2] YANG, M.S., Korea National Case Study on DUPIC Fuel Cycle, Korea Atomic Energy Research Institute (June 2004).

[3] YANG, M.S., and PARK, J.H., Korean Assessment of the Proliferation Resistance on the Whole Fuel Cycle of DUPIC, Korea Atomic Energy Research Institute (May 2006).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Terms of Reference for the INPRO Collaborative Project, Proliferation Resistance: Acquisition/Diversion Pathway Analysis, IAEA, Vienna (5 May 2008).

[5] GENERATION IV INTERNATIONAL FORUM PR&PP EXPERT GROUP, Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems, Revision 5, GIF/PRPPEG/2006/005, (30 September 2006).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Proliferation Resistance Fundamentals for Future Nuclear Energy Systems, IAEA STR-332, IAEA Department of Safeguards, IAEA, Vienna (2002).

[7] KO, W.I., CHOI, H.B., and YANG, M.S., Cost Evaluation of a Commercial-Scale DUPIC Fuel Fabrication Facility (Part II) – Preliminary Conceptual Design, KAERI/TR-1373/99 (Rev.1), Korea Atomic Energy Research Institute (2005).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, The Structure and Content of Agreements between the Agency and States required in connection with the Treaty on the Non-proliferation of Nuclear Weapons, INFCIRC/153 (Corrected) (June 1972)

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Model Protocol Additional to the Agreement(s) between States and the International Atomic Energy Agency for the Application of Safeguards, INFCIRC/540 (Corrected), Vienna (September 1997)

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Design Measures to Facilitate Implementation of Safeguards at Future Water Cooled Nuclear Power Plants, TRS-392, IAEA, Vienna (1998).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safeguards Glossary 2001 Edition, International Nuclear Verification Series No.3, IAEA, Vienna (June 2002).

[12] POMEROY, G., et al., Approaches to Evaluation of Proliferation Resistance of Nuclear energy Systems, Proceedings of INMM 49$^{th}$ Annual Meeting, Nashville, TN (2008).

# ABBREVIATIONS

| | |
|---|---|
| CANDU | Canada Deuterium Uranium |
| CCTV | closed circuit television |
| C/S | containment and surveillance |
| DA | destructive analysis |
| DIV | design information verification |
| DUPIC | direct use of spent PWR fuel in CANDU reactors |
| EJ | expert judgment |
| GIF | Generation IV International Forum |
| INPRO | International Project on Innovative Nuclear Reactors and Fuel Cycles |
| INS | innovative nuclear energy system |
| KMP | key measurement point |
| MBA | material balance area |
| MC&A | material control and accountancy |
| MTHM | metric ton heavy metal |
| MUF | material unaccounted for |
| NDA | non-destructive assay |
| NES | nuclear energy system |
| NM | nuclear material |
| NPT | Non-Proliferation Treaty |
| NRTA | near real time accountancy |
| NWFZ | nuclear weapon free zone |
| OREOX | oxidation and reduction of oxide fuel |
| PP | physical protection |
| PR | proliferation resistance |
| PRADA | Proliferation Resistance: Acquisition/Diversion Pathway Analysis |
| PR&PP | Proliferation Resistance and Physical Protection (GIF) |
| PWR | pressurized water reactor |
| RSAC | regional system of accounting for and control of nuclear material |
| SQ | significant quantity |
| SSAC | State’s system of accounting for and control of nuclear material |
| UR | user requirement |

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