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기술보고서

Proliferation Resistance: Acquisition/Diversion Pathway Analysis for the DUPIC Fuel Cycle

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1. Introduction

The INPRO proliferation resistance evaluation methodology provides both a framework for assessing proliferation resistance (PR), and guidance to improve the proliferation resistance of an innovative nuclear energy system (INS). It is based on the basic principle that proliferation resistance intrinsic features and extrinsic measures shall be implemented throughout the full life cycle of the INS to help ensure that INS will continue to be an unattractive means to acquire fissile material for a nuclear weapons program [1]. The methodology has five User Requirements, along with relevant Criteria, Indicators, Evaluation Parameters, etc.

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 have been established through the Korean case studies 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) still needs to be developed. In this regard, the INPRO Phase 2 Collaborative Project on "Proliferation Resistance: Acquisition/Diversion Pathway Analysis (PRADA)" was proposed by the Republic of Korea as a Collaborative Project Program (CPP) at the 10th INPRO Steering Committee Meeting held in Vienna in December 2006 [2].

The kick-off meeting of the INPRO Phase 2 Collaborative Project on PRADA was held in Vienna from 19-20 November 2007, and a follow-on consultancy meeting was held from 5-6 May 2008 [3]. At the consultancy meeting in May 2008, "Approaches for Selection of the Prospective Pathways," which could be used for the pathway analysis required to satisfy the requirements of UR4, were presented. A three-year project schedule (Table 1) was proposed, and the proliferation objectives to be used in the proposed case study of the PRADA project were discussed, including quality and quantity of nuclear materials for proliferation, proliferation time required to acquire or divert nuclear materials, and capability of a proliferant country. Another meeting was held in Vienna from 24 to 28 November 2008. At the meeting, a draft of this report was presented on the contents and comments were received later on. This report is the result of these discussions and modification and summarizes the work done during the first year of work.

Table 1: Three-year Project with 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											■	■

Table 2: Work Schedule for the First Year

Work Scope	1st Year											
	1/4			2/4			3/4			4/4		
Description of proliferation objectives	■	■	■									
Kick-off meeting (IAEA)												
Quality and quantity of NM for proliferation	■											
Proliferation time required to acquire or diversion of NM		■										
Capability of the proliferant countries			■									
Study of possible strategies of proliferation				■	■	■	■					
Undeclared removal of NM from process flow directly				■	■							
Undeclared removal of NM from process flow by modification or misuse of facility and technology						■	■					
Systematic approach for possible pathways								■	■	■	■	■
Derivation of analysis method for possible pathways								■	■			
Possible pathways for acquisition/diversion										■	■	
Recommendation of analysis method												■
Wrap-up of 1st year study												

One of the decisions taken during the presentation of the project and reinforced during the meetings, has been to develop the indicators and criteria for the evaluation of UR4 benefitting from the work done in the context of the Proliferation Resistance and Physical Working Group of the Generation IV International Forum (GIF) [5].

2. Threat Definition

According to the GIF, threat is identified by actor, objective, capability and strategy. In this study, the objective of the host State is to acquire nuclear material that could be used for nuclear explosive devices through concealed diversion of nuclear material from flows and inventories of the declared DUPIC fuel cycle facility. It was also assumed that the actor, i.e., proliferant State, is an industrialized non-weapon State that has indigenous uranium resources, physical control over the commercial nuclear energy system and materials being evaluated, declared facilities and materials that are subject to international safeguards, and signed Additional Protocol (AP). Table 3 summarizes the threat definition result.

3. Study on the Possible Strategies of the Host State

The DUPIC fuel cycle is comprised of several system elements including the DUPIC fuel fabrication facility, a CANDU reactor, spent fuel interim storage facility, a final repository. The proliferation target could be 1) material that can be diverted, 2) equipment and processes that can be misused to process undeclared nuclear materials, or 3) equipment and technology that can be replicated in an undeclared facility. In the case study, only the first, diversion of nuclear materials from the DUPIC facility is considered, although equipment and technologies in the DUPIC fuel cycle system may be misused to bypass the IAEA safeguards system. The host State may divert nuclear material from the DUPIC fuel cycle in an abrupt manner or in a protracted way depending upon the circumstances. The strategy that a proliferant State would use to manufacture nuclear weapons is shown in Figure 1: covertly acquire nuclear material from the DUPIC fuel cycle, process acquired material at the undeclared facilities, and fabricate nuclear weapons.

Table 3: 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 considered, but not modeled in this study.

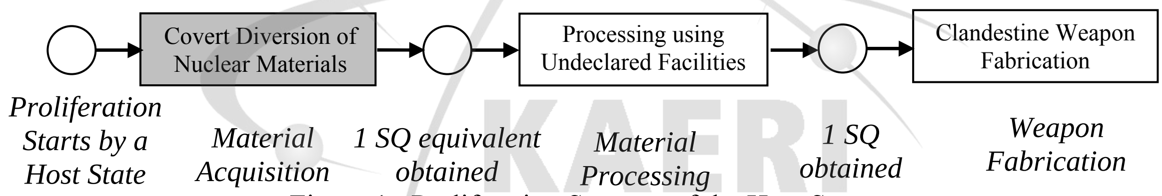

Figure 1: Proliferation Strategy of the Host State

4. Proposed Systematic Approach for Acquisition/Diversion Pathway Analysis

The acquisition/diversion pathway analysis of a nuclear energy system should ensure that all possible targets and pathways have been identified and analyzed. 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 analyzed in detail, through the identification of 1) potential diversion exit locations, 2) the physical and design barriers to removal of targets, 3) IAEA safeguards barriers in place which may include surveillance cameras, seals, neutron and gamma detectors, inventory key measuring points (KMP), and transfer KMPs. The pathway analysis should have reproducibility for its objectiveness and comprehensiveness. In this regard, a step-wise approach is proposed for the acquisition/diversion pathway analysis as presented in Figure 2 and described as follows:

A. Define proliferation objectives and technical capabilities of the proliferant State;
B. Identify an Innovative Nuclear Energy System (INS) from which the host State may try to acquire proliferation target(s) and define any needed clandestine facility to process nuclear material;
C. Identify specific elements of INS;
D. Identify and categorize proliferation targets in the system such as
    - Nuclear material that can be diverted;

- Nuclear material, equipment and processes that can be misused to process undeclared nuclear material, or
- Equipment and technology that can replicated in an undeclared facility;

E. Analyze INS elements to identify plausible acquisition/diversion pathways
   - Decompose the system into sub-elements based on material balance areas, processes, or physical structure/layout of the system
   - Define operational states of the system and elements (normal operations, maintenance, repair, testing, steady state, transition to steady-state (start-up operation), transition phase, etc.) required for acquisition of the targets
   - Identify the different process steps in each sub-element

F. Qualitative acquisition/diversion pathway analysis
   - Identify and describe acquisition strategies/coarse pathways including concealment strategies for each target
   - Specify possible means of acquisition of the targets including diversion points
   - Identification of proliferation resistance intrinsic features and extrinsic measures
   - Perform qualitative pathway analysis
   - Examine multiplicity and robustness of barriers
   - Select subset of pathways for quantitative analysis

G. Detailed quantitative acquisition/diversion pathway analysis using logic trees. When done
   - Identify proliferation resistance intrinsic features and extrinsic measures
   - Examine multiplicity and evaluate robustness barriers

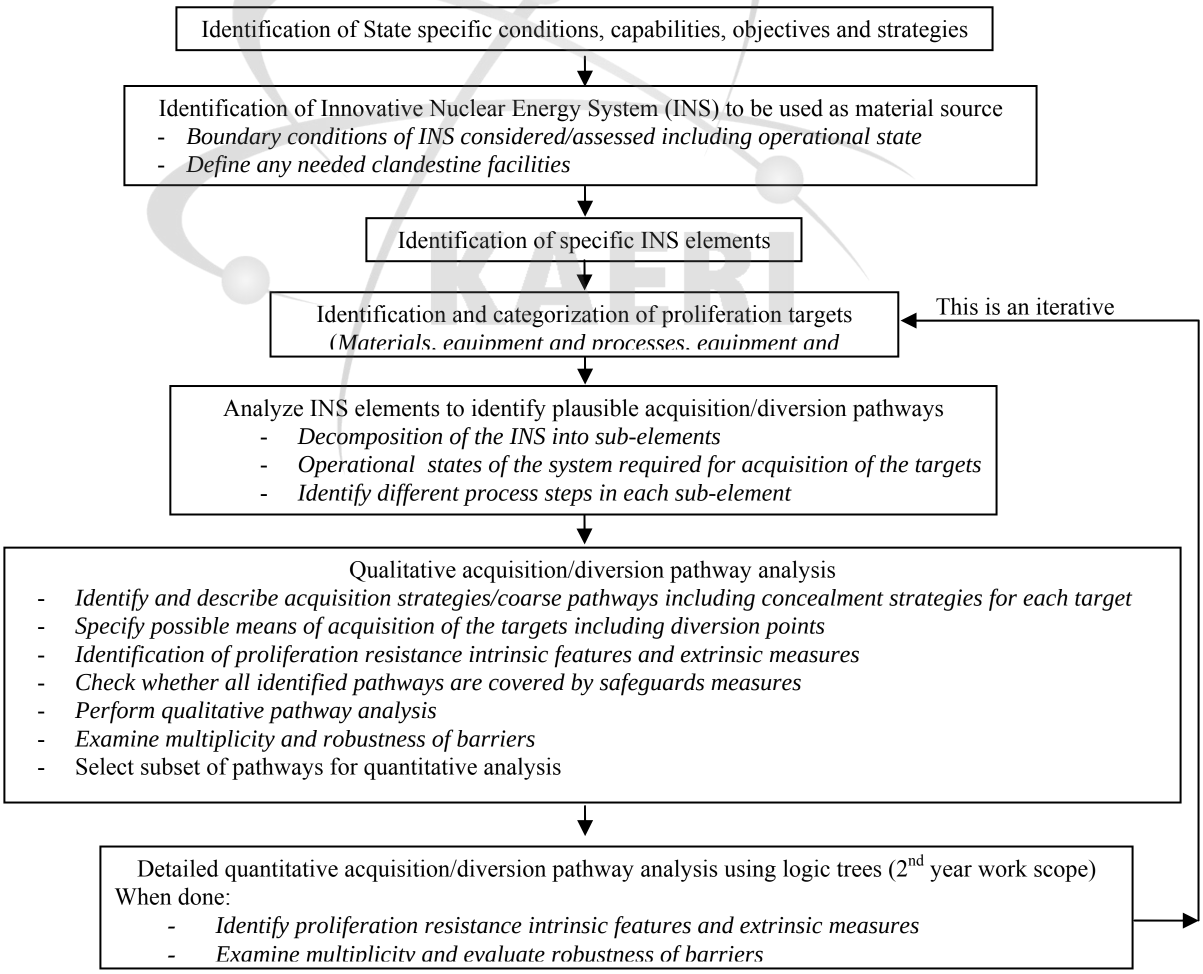

Figure 2: A Systematic Approach of Acquisition/Diversion Pathway Analysis

Once the nuclear material is acquired from the nuclear energy system, the nuclear material will be transported to the clandestine processing facility for the production of weapons-usable material.

In the next section, very coarse pathways of covert diversion of nuclear materials in the DUPIC fuel cycle are described based on the proposed approach. The next step, quantitative pathway analysis, will be carried out in the second year of the project, based on the discussion of the consultative meeting in November 2008.

5. Coarse Acquisition/Diversion Pathway Analysis for a DUPIC Fuel Cycle

A. Definition of proliferation objectives and technical capabilities of the host State

As described in Section 2, the proliferation objective of the host State is to acquire at least 1 SQ of nuclear material from the DUPIC fuel cycle that could be used for nuclear explosive devices and the technical capabilities of the host State are summarized in Table 3.

B. Definition of a nuclear energy system, the DUPIC fuel cycle, including any needed clandestine facility

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 [6]. 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 OREOX treatment for pelletizing and then re-fabricate 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 are the Korean Yonggwang Nuclear Station Unit 1&2's 17x17 standard PWR spent fuel assemblies with a minimum 10 years of cooling time after discharge from the reactor with 35,000 MWD/MTU of final burn-up.

In the case study, a conceptual DUPIC fuel fabrication facility with a throughput of 400 MTHM/yr is postulated as shown in Figure 3. The facility is assumed to meet international requirements for safety and security, as well as all IAEA requirements for nuclear material safeguards under the Comprehensive Safeguards Agreement of the IAEA (INFCIRC/153) [7] and Additional Protocol (INFCIRC/540) [8].

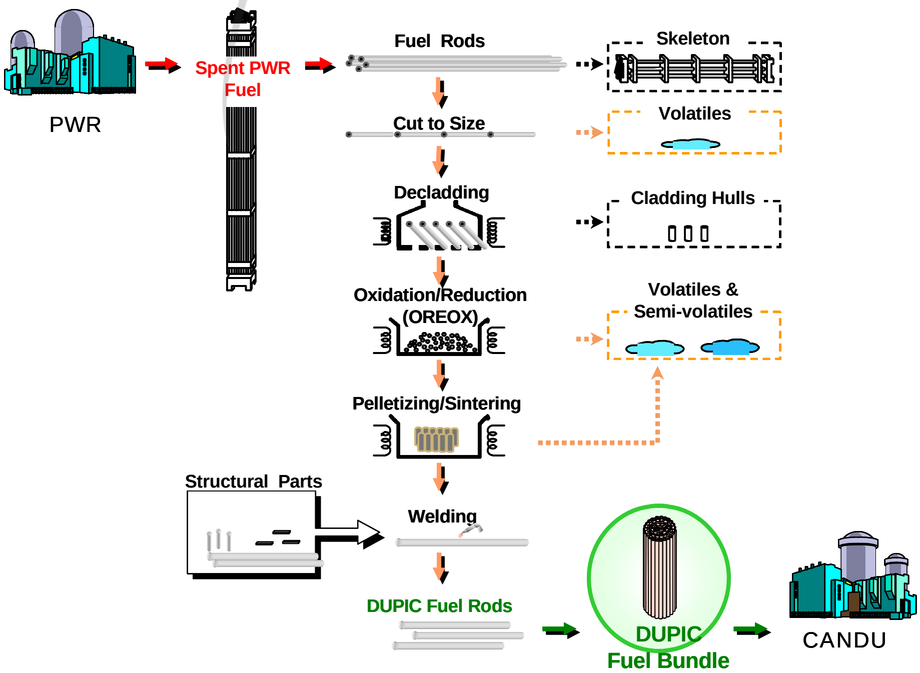

Figure 3: DUPIC Fuel Fabrication Process

It is also assumed that this facility has allowances for normal process systems startup and shutdown times, 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. Run-outs will be performed at the completion of each production campaign to meet international safeguards requirements, and cleanouts will also be performed several times per year which will require some time to complete.

The Wolsong CANDU Power Plant (Unit 1) was selected as the reference plant for the PRADA case study. A site visit was made to the plant in July 2008 to examine the IAEA safeguards system in a CANDU reactor, and identify possible routes of covert diversion of DUPIC fuel bundles. Table 4 shows technical specifications of Wolsong Unit 1, and Figure 4 shows the IAEA safeguards scheme in place.

Table 4: Technical Specifications of Wolsong Unit 1

Reactor parameters	CANDU	
- Electric power (MWe)	713	
- Thermal efficiency (%)	33	
- Thermal power (MWt)	2,161	
- Specific power (MWt/ton U)	25.5	
- Load factor	0.9	
- Cycle length (Full Power Day)	-	
- No. of fuel assemblies or bundles per core	4,560	
- Loading per core (tU)	84.7	
	Characteristic Parameters	
	CANDU with NU fuel	CANDU with DUPIC fuel
Reactor		
- Loading per core (t U or t HM)	84.7	84.7
- Annual fuel requirement (tU or tHM)	94.63	46.09
Fuel		
- Initial enrichment	Nat. U	Spent PWR fuel
- No. of fuel rods per assembly	37	43
- Discharge burnup (MWd/kgHM)	7.5	15.4
Normalization of Fuel		
- Required fuel amount for 1 GWe-yr (tU or tHM)	132.73	64.64

A conceptual spent fuel interim dry storage facility with silos is postulated. The spent DUPIC fuel bundles will be stored at the CANDU power station for sometime 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; that is, 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 a clay-based buffer material within each borehole. Each disposal room is backfilled with clay-based backfill materials, and the room entrance is sealed when all of the boreholes have been filled.

C. Definition of any needed clandestine facility to process nuclear material

It is assumed that the host State has designed and constructed a clandestine reprocessing facility for recovery of plutonium from the diverted fuel.

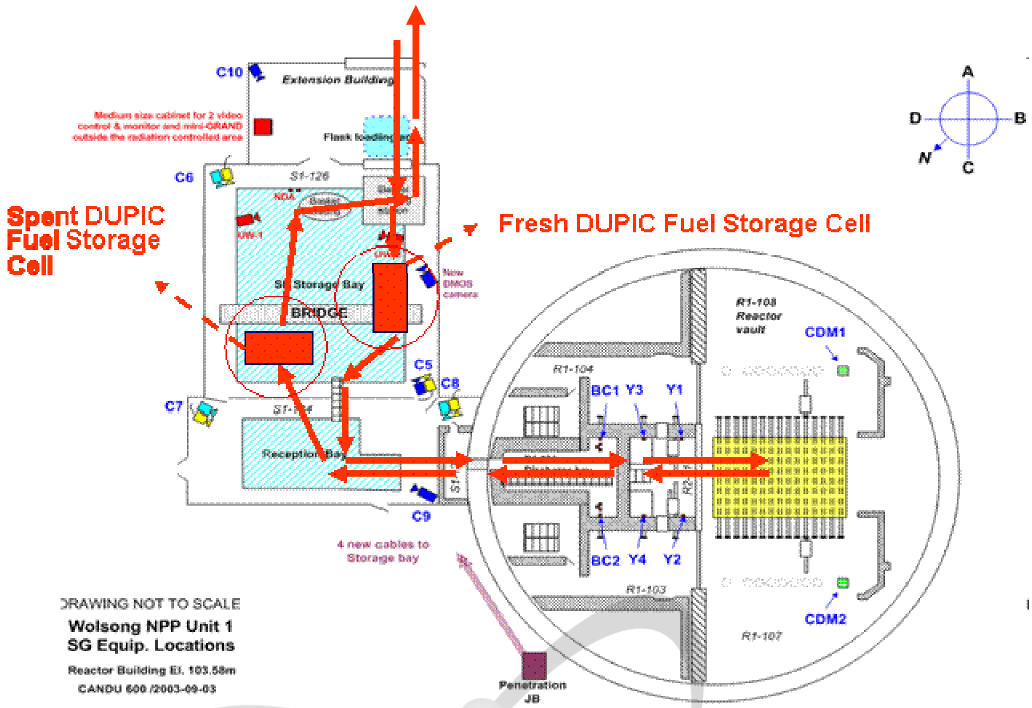

Figure 4: IAEA Safeguards System and Flow of DUPIC Fuel Bundles in a CANDU Reactor

D. Identification of proliferation targets in specific INS elements of the DUPIC fuel cycle

The international safeguards detection goal is to detect one significant quantity (SQ) of nuclear material with a certain detection probability within a given time. Table 5 shows the significant quantity for different target materials as defined in the IAEA safeguards Glossary [9].

In the DUPIC fuel cycle, target materials are uranium and reactor grade plutonium contained with minor actinides in spent PWR fuel rods/pellets, nuclear materials during the DUPIC fuel fabrication processes, fresh DUPIC fuel bundles fabricated at the DUPIC fuel fabrication facility, and spent DUPIC fuel bundles discharged from the CANDU reactor core. Diverted uranium could be used for undeclared enrichment in a clandestine enrichment facility, however this acquisition path is not considered in this study because uranium in the DUPIC fuel cycle is below the enrichment level of LEU and is not suitable for production of weapons-usable material.

Table 5: Safeguards Significant Quantities for Target Materials (1 SQ) [9]

	Material	1 SQ
Direct use nuclear material	Pu (containing less than 80% ^{238}Pu)	8kg Pu
	^{233}U	8kg ^{233}U
	HEU (^{235}U≥ 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 tones

Table 6 shows the plutonium isotopic vector for spent PWR fuel and in fresh and spent elements of the DUPIC fuel cycle. The amount of spent PWR fuel required for 1 SQ of 8kg plutonium is 866.74 kg, whereas the number of fuel bundles (17.64 kg HM/bundle) required for 1 SQ are 49 for fresh and 54 for spent DUPIC fuel bundles, respectively.

Table 6: Isotopic Vector in PWR Spent Fuel and DUPIC Fuels

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	**8.893E+03**		**8.89E+03**		**7.96E+03**	

E. Analysis of the DUPIC Fuel Cycle System for Coarse Pathway Analysis

To identify potential diversion points, the DUPIC fuel cycle system was decomposed into several elements: DUPIC fuel fabrication facility, CANDU power plant, interim dry storage, and permanent disposal repository, as shown in Figure 5. Potential diversion can occur; (1) during transport of nuclear materials (spent PWR fuel assemblies, fresh and spent DUPIC fuel bundles) 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 7 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 means identified, potential safeguards barriers considered to derive diversion strategies that the host State could use to divert nuclear materials.

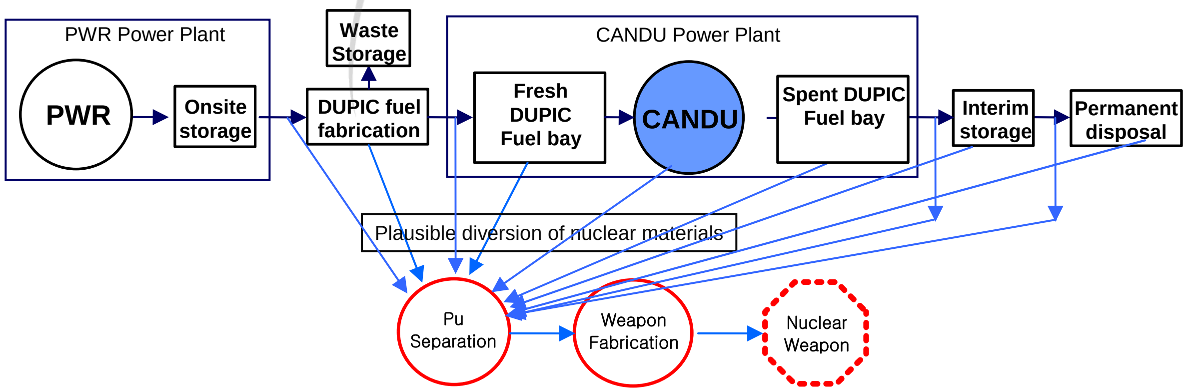

Figure 5: Material Flow in the DUPIC Fuel Cycle

The strategies that the host State would develop to bypass IAEA safeguards system in the diversion of nuclear materials are also presumed 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. Concerning the means of removal of nuclear material from systems elements, the host State may use internal containers or external shielded containers to remove nuclear materials out of the DUPIC fuel fabrication facility. In such cases the host State would have to introduce in advance or at the same time dummy materials into the facility so as to cheat the safeguards system, etc.

Table 7: Diversion Targets and Possible Diversion Points at the DUPIC Fuel Cycle

Diversion targets	Possible diversion points
1. Spent PWR fuel assemblies	1. During transport of spent PWR fuel assemblies from onsite storage at PWR reactor to the DUPIC fuel fabrication facility
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) 8. Transport from DUPIC facility to CANDU power plant 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 11. Spent DUPIC fuel storage racks of the CANDU power plant 12. Transport from CANDU plant to the Interim Dry Storage 13. Interim Dry Storage 14. Transport from Interim Storage to Permanent Disposal Repository 15. Permanent Disposal Repository

1) Transport of spent PWR fuel assemblies from the onsite storage at the PWR station to the DUPIC fuel fabrication facility

The spent PWR fuel assemblies at the PWR onsite 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 the 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 kgHM per an assembly) contain one SQ of plutonium. However, the spent PWR transport casks are not deemed viable targets for covert diversion under normal operation, although it is not impossible.

Table 8: Pathway Analysis Worksheet for the Transport of Spent PWR Fuel to the DUPIC Fuel Fabrication Facility

Target ID	Target description	Diversion point	Diversion means or device	Intrinsic features	Safeguards scheme	A or P	Pathway Description	Proliferator actions
1	Spent fuel assemblies in transport casks	During marine transportation	Transport casks		Escorted transport, item counting	A	Diversion during marine transport	1) Fake a collision at sea 2) Declare the loss of spent fuel transport casks (boat – sunk) 3) Sink dummy transport casks instead of real transport casks

2) DUPIC fuel fabrication facility

The DUPIC fuel fabrication facility is a complete fuel recycling plant that covers all functions and equipment for processing spent PWR fuel and converting it to CANDU DUPIC fuel. It employs only thermal and mechanical processes which recover fissile material remaining in spent PWR fuel for CANDU 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. The facility shall also have provisions for emergency power generation and related equipment for sustaining essential plant operation and safe plant shutdown procedures. 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 which meet IAEA requirements is designed and installed in the DUPIC fuel fabrication facility in order to safeguard the nuclear materials, and includes surveillance cameras, seals, neutron and gamma detectors, inventory key measuring points (KMPs), transfer KMPs, etc. Three material balance areas are defined based on the needs of safeguards as shown in Figure 6.

- MBA-1: The spent PWR fuel assemblies are disassembled into spent fuel rods.
- MBA-2: Spent fuel rods are cut into pieces, de-cladded, and sent through the thermo-mechanical OREOX processing to produces UO_2 powder. The powder is then pelletized after sintering, and fuel rod and DUPIC fuel bundles are fabricated.
- MBA-3: Fresh DUPIC fuel bundles are stored in the maintenance room for transport to the CANDU reactor.

Physical protection systems are also assumed to be integrated with MC&A systems to provide a balanced safeguards and security system. In the MBA-2, there are several operational states: normal operations, maintenance, repair, and testing, and only normal operational phase is considered in the analysis.

The spent PWR fuel rods extracted from the fuel assembly after disassembling in MBA-1 are not considered as a material for potential diversion because the undetected removal of fuel rods inside the cladding tubes is extremely unlikely in consideration of the exit locations as well as the physical and design barriers to removal of targets, including safeguards barriers. Nuclear materials for potential diversion from MBA-2 of the DUPIC fuel fabrication facility are: (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. In MBA-2, physical inventory taking (PIV) using destructive assay and weighing is carried out at each key measuring point, 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 materials such as spent PWR fuel pellets after decladding, DUPIC powder feed stock for sintering after OREOX process, sintered DUPIC fuel pellets before welding which can be diverted using internal or external shielded containers, could use dummy fuel materials introduced in advance into the MBA-2.

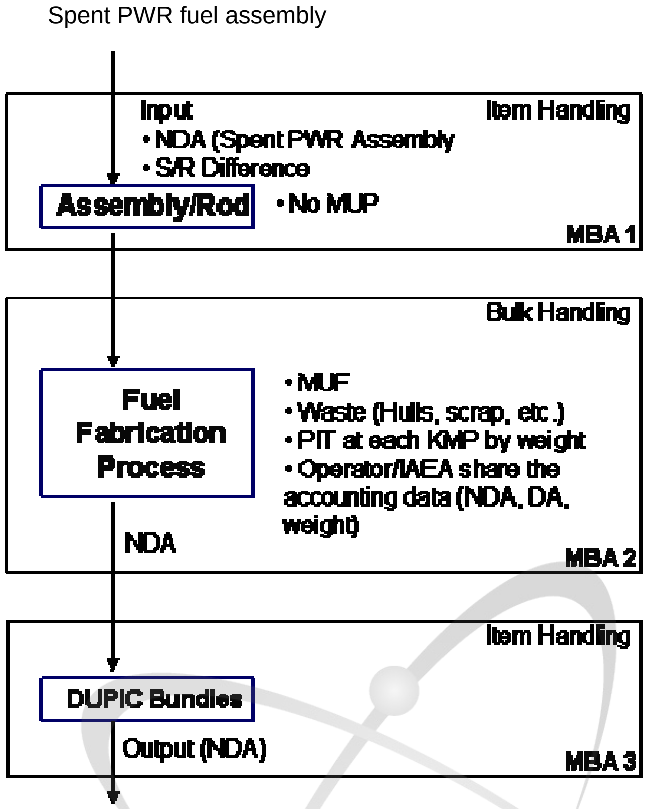

Figure 6: Nuclear Material Accounting Scheme of a CANDU Fuel Fabrication Facility

Finally, the fresh DUPIC fuel bundles assembled in MBA-2 will be non-destructively tested for welding quality, dimensions 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 the item counting for inventory verification, the 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 9 shows pathway analysis worksheet for the DUPIC fuel fabrication facility.

Table 9: Pathway Analysis Worksheet for the DUPIC Fuel Fabrication Facility

Target ID	Target description	Diversion point	Diversion means or device	Intrinsic features	Safeguards scheme	A or P	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 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 2) Discard hulls as waste 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 2) Remove the real pellets in cladding hull baskets to the parking lot outside of the facility
			External shielded containers				-Use dummy pellets - Declare MUF to divert real fuel pellets in external shielded containers	1) Introduce dummy fuel pellets into MBA-2 2) Declare MUF 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 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 2) Insert dummy fuel pellets into the cladding tubes 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 by defeating the IAEA safeguards system 2) Replace real fuel elements with dummy ones 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 2) Fool or disable the IAEA cameras 3) Replace a fresh DUPIC fuel basket with slightly enriched fresh CANDU fuel imbedded with radiation source such as 252Cf 4) Compromise the inventory measurement records with dummy fuels

3) Transport of fresh DUPIC fuel bundles from the DUPIC fuel fabrication facility to the CANDU power station

The transport of fresh DUPIC fuel bundles from the DUPIC fuel fabrication facility to the CANDU power station will be done via licensed truck transport casks and by sea. The fuel will then be transferred to the fresh DUPIC fuel storage racks in the spent fuel storage pool at the reactor building. As is the case with the transportation of spent PWR fuel assemblies, fresh DUPIC fuel bundles in storage containers are not deemed viable for protracted covert diversion under normal operation. Therefore, the host State must fake an accident to divert nuclear material by replacing real containers with dummy fuel bundle containers.

Table 10: Pathway Analysis Worksheet for the Transport of DUPIC Fuel Bundles from the DUPIC Fuel Fabrication Facility to the CANDU Power Station

Target ID	Target description	Diversion point	Diversion means of devices	Intrinsic features	Safeguards scheme	A or P	Pathway Description	Proliferator actions
7	Fresh DUPIC fuel bundles in transport basket containers	During transportation	Transport basket containers		Escorted transport, item counting		- Diversion during transport	1) Fake a collision at sea 2) Declare the sinking of the boat with DUPIC fuel bundle transport basket containers at the bottom of the sea 3) Replace the recovered transport basket containers with dummy fuel basket containers 4) Compromise the inventory with dummy fuel basket containers

4) CANDU Power Plant

Only the 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 equipments in the CANDU reactor are shown in Figure 4.

During normal operation, eight DUPIC fuel bundles per day go through remote visual inspection 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 fueling 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 the 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 refueling or inspection. As the new fuel bundles are loaded, the burnt fuel bundles are automatically discharged from the core and transferred to discharge bay. The spent fuel is then inspected for failure and 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. There is no need for the operator or any other person to physically handle a fuel bundle.

It is not deemed possible to divert nuclear material from inside of the CANDU reactor building during normal operation. Therefore, potential diversion materials in a CANDU power plant are (1) fresh DUPIC fuel bundles on the fresh fuel storage racks, (2) failed DUPIC fuel bundles in the reception bay, and (3) spent DUPIC fuel bundles on the spent DUPIC fuel storage racks in the spent fuel pool. The failed fuel bundles are defined as the fuel that has short residence time in the reactor channel due to damage, or fuel discharged before reaching 75% of expected burn-up.

Because the physical form of the fuel bundles does not change before and after the 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 measure the inventory of DUPIC fuel, including failed fuel in the reception bay, by the item counting. The IAEA safeguards scheme for a CANDU reactor include advance facility information, containment and surveillance measures, core discharge monitors (CDM), bundle counters (BC), and surveillance in remote data transmission and in an unattended mode. An unattended monitoring scheme (UMS) is also implemented for spent fuel transfers from the fuel storage bay to dry storage.

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 fuels. Therefore, dummy fuel bundles could be used to replace fresh and/or spent DUPIC fuel bundles for diversion. That is, the fresh DUPIC fuel bundles could be replaced with slightly enriched CANDU fuel embedded with a radiation source like ^{252}Cf. 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 fueling machine and system. During either normal or abnormal operation, there is no way that fuel bundles are repositioned without using the fueling machine. Passage to the reactor building is through the equipment door with a lock 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.

Table 11: Pathway Analysis Worksheet for the CANDU Power Station

Target ID	Target description	Diversion point	Diversion means or devices	Intrinsic features	Safeguards scheme	P or A	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 slightly enriched fresh CANDU fuel imbedded with radiation source	1) Fool or disable the IAEA cameras 2) Replace fresh DUPIC fuel baskets with the baskets of slightly enriched fresh CANDU fuel bundles 3) Compromise the inventory measurement records with dummy fuels bundles 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 2) Replace failed DUPIC fuel bundle containers with dummy fuel bundle containers 3) Compromise the inventory measurement records with dummy fuel bundles 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 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 3) Compromise the inventory measurement records with dummy fuels 4) Use heavy truck and trailer to move basket containers

5) Transport of spent DUPIC fuel bundles from the CANDU power station to an AFR interim storage

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

Table 12: Pathway Analysis Worksheet for the Transport of Spent DUPIC Fuel Bundles from the CANDU Power Station to an AFR Interim Storage Facility

Target ID	Target description	Diversion point	Diversion means or devices	Intrinsic features	Safeguards scheme	A or P	Proliferator actions	Pathway Description
8	spent DUPIC fuel bundles	During marine transportation	Transport basket containers		Escorted transport, item counting		-Fake an accident at sea	1) Fake a collision of boats at sea 2) Declare loss of spent fuel transport basket containers 3) Replace the recovered fuel bundle basket containers with dummy fuel basket containers 4) Compromise the inventory measurement records with dummy fuel bundle baskets

6) Analysis of an AFR dry storage facility

As the transport basket containers arrive at the AFR 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 similar safeguards barriers as the onsite 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 onsite dry storage facility (e.g., MACSTOR/KN-400) of the CANDU power station.

Table 13: Pathway Analysis Worksheet for the AFR Dry Storage Facility

Target ID	Target description	Diversion point	Diversion means or devices	Intrinsic features	Safeguards scheme	A or P	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 2) Use heavy truck and trailer to move basket containers 3) Compromise the inventory measurement records with dummy fuels

7) Transport from an interim dry storage to the permanent disposal repository

Table 14: Pathway Analysis Worksheet for Transport of Spent DUPIC Fuel Bundles from the Interim Storage to the Permanent Disposal Repository

Target ID	Target description	Diversion point	Diversion device	Intrinsic features	Safeguards scheme	A or P	Pathway Description	Proliferator actions
8	spent DUPIC fuel bundles	During transport using a licensed truck	Transport basket containers		Escorted transport, item counting		-Use dummy fuel bundles in storage baskets	1) Fake an accident during the road transportation 2) Replace the fuel bundle transport basket containers with dummy fuel bundle basket containers 3) Compromise the safeguards system with dummy fuel bundle basket containers

8) Permanent disposal repository

The reference disposal repository consists of two parts: a surface facility and an underground facility assumed to be 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 they are transported 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 the clay-based buffer material within each borehole. Each disposal room is backfilled with clay-based backfill materials, and the room entrance is sealed when all of the boreholes have been filled.

The permanent disposal repository is an item-counting facility and therefore MUF should be zero. The plutonium content of the spent DUPIC fuels is ~0.7 wt% and the chemical form of the fuel is oxide. During operation, the history of the spent DUPIC fuel and their containers are continuously traced. The containment/surveillance equipment in all the entrance and exit areas of the disposal facility are installed and material flow are monitored. It is extremely difficult to contact the nuclear material directly during the disposal activities and also difficult to refurbish the packaging and disposal facility for diversion and to install diversion equipment in the disposal facility. But the radiation field gradually becomes lower with time and after hundreds of years, the radiation field will no longer exist. In addition, diversion after the disclosure of the repository will not be plausible because tunneling work on the surface will easily be detected. Therefore, only diversion during normal operation is considered in this case study.

Table 15: Pathway Analysis Worksheet for the Permanent Disposal Repository

Target ID	Target description	Diversion point	Diversion means or devices	Intrinsic features	Safeguards scheme	A or P	Pathway Description	Proliferator actions
8	Spent DUPIC fuel bundles in sealed containers	Temporary storage areas or disposal vaults	External transport basket containers		Seals, cameras		- use dummy fuel bundles	1) Fool or disable the IAEA cameras 2) Use heavy truck and trailer to move basket containers 3) Compromise the inventory measurement records with dummy fuel bundles

F. Description of coarse acquisition/diversion from the DUPIC fuel cycle

Potential diversion possibilities listed in Table 7 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. Additional acquisition/diversion pathways can further be identified at the interim storage facility and the repository if so recommended by the meeting.

6. Conclusions

Very coarse material diversion pathways were identified for the DUPIC fuel cycle. The approach proposed in this study was reviewed and discussed at the consultative meeting in November 2008 for its appropriateness and comprehensiveness. Although the diversion of nuclear material in the fresh DUPIC fuel storage location was selected in the Terms of Reference of the project for the evaluation of pathway for the acquisition/diversion analysis, the meeting recommended to consider other options. Therefore, in the first step of the second stage of the project (December 2008 ~ November 2009), detailed pathway analysis will be performed for selected diversion pathways based on sufficient design and process information on the DUPIC fuel cycle system.

In the second step, logic trees (event trees) will be developed for selected pathways for follow-on analysis using fault tree analysis technique, or other methods such as expert elicitation or probabilistic analysis techniques. At the final step, each segment of the pathway will be evaluated in terms of the material characteristics, technical availability, safeguardability, quality and quantity of the material, etc. as specified in the UR 1, 2 and 3 of the INPRO methodology.

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서 지 정 보 양 식

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제목 / 부제	DUPIC 핵연료주기시스템의 핵확산저항성평가를 위한 전용경로분석

연구책임자 및 부서명	고원일 (핵연료주기 시스템분석연구)
연 구 자	장 홍 래, 고 원 일, 송대용, 이호희, 권은하, 정창준, 김 호 동

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위탁연구기관		계약번호	

초록(300 단어 내외)

IAEA 주관 하에 혁신원자력시스템의 핵확산저항성 평가방법론이 개발되어 왔다. 그러나 다섯 가지 평가인자중에 4 번째인 핵확산방벽의 다중성 및 견고성에 대한 평가방법은 아직 개발단계에 있다. 이를 평가하기 위해서는 원자력시스템에서의 핵물질 전용경로 분석이 선결조건이기 때문에 이 연구에서는 DUPIC fuel cycle 을 이용하여 개발된 핵물질 획득을 위한 전용경로를 확인하고 분석할 수 있는 체계적인 방법론에 대해 기술하고 있다. 첫 단계로, 핵물질의 양 및 질, 핵물질 획득 시간, 그리고 핵확산 가능국가의 능력들, 핵확산의 목적에 대해 검토가 이루어졌으며, 두 번째 단계에서는 핵확산 가능국가가 채택할 수 있는 전용 전략, 즉 핵연료주기 시설에서 핵물질을 비밀리에 전용하기 위한 기술적인 전략 및 전용된 물질을 핵무기로 변환시키기 위한 추가 단계 등이 검토되었다. 그리고, 이를 바탕으로 전체 핵연료주기 시설에서 핵물질전용 가능경로를 확인하고 분석할 수 있는 체계적인 방법론을 개발하였으며, 그 결과를 기술하였다. 그리고, DUPIC 핵연료주기에서 확인 된 전용경로 및 개발된 전용경로 확인 및 분석방법론에 대한 적절성 및 포괄성이 IAEA 전문가 회의에서 확인되었다.

주제명 키워드 (10 단어 내외)

핵확산저항성, INPRO, DUPIC 핵연료주기, DUPIC 핵연료제조시설, 전용경로분석, IAEA 안전조치, 사용후핵연료

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Abstract (About 300 Words)

Within the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), a methodology for evaluating proliferation resistance (INPRO PR methodology) has been developed. However, it remains to develop the methodology to evaluate User Requirements (UR) 4 regarding multiplicity and robustness of barriers against proliferation – *innovative nuclear energy systems should incorporate multiple proliferation resistance features and measures*. Since this requires an acquisition/diversion pathway analysis, this report describes a systematic approach developed for the identification and analysis of pathways for the acquisition of weapons-useable nuclear material using the DUPIC fuel cycle system. At the first step, the objectives of the proliferation were identified, including the quality and quantity of the material, the time required to acquire the material for the proliferation, the capability of the potential proliferant country, etc. At the second step, the possible strategies, which the potential proliferant country could adopt, were identified: undeclared removal of nuclear material from the fuel cycle facilities; and further treatment of the diverted nuclear materials needed to acquire weapons-useable materials. At the final step, a systematic approach to select the plausible pathways for the acquisition/diversion of nuclear material during the whole fuel cycle has been developed. The coarse material diversion pathways for the DUPIC fuel cycle and the approach developed was reviewed and discussed at the experts meeting at the IAEA for its appropriateness and comprehensiveness.

Subject Keywords (About 10 Words)

INPRO, proliferation resistance, DUPIC fuel cycle, DUPIC fuel fabrication facility, acquisition/ diversion pathway, IAEA safeguards, PWR spent fuel