Assessment of DUPIC Fuel Cycle using IAEA INPRO Methodology

Sandia National Laboratories
14th International Security Conference
April 4 ~ 6, 2005, Chantilly, VA

Myung Seung YANG*
Jin Kyung KIM**
Eckhard HASS**

*Korea Atomic Energy Research Institute
**International Atomic Energy Agency

Revised INPRO Methodology, PR Area
(IAEA TECDOC-1434 : 2004. 12.)

Basic Principles	User Requirements	Indicators	Variables
BPPR1 Proliferation resistance features and measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.	**URPR1.1** States' commitments, obligations and policies regarding non-proliferation should be adequate.	**IPR1.1.1** States' commitments, obligations and policies regarding non-proliferation.	**VPR1.1.1.1 ~ VPR1.1.1.14**
	URPR1.2 The attractiveness of nuclear material in an INS for a nuclear weapons programme should be low. This includes the attractiveness of undeclared nuclear material that could credibly be produced or processed in the INS.	**IPR1.2.1** Material Attractiveness.	**VPR1.1.2.1 ~ VPR1.1.2.5**
	URPR1.3 The diversion of nuclear material should be reasonably difficult and detectable. Diversion includes the use of an INS facility for the introduction, production or processing of undeclared nuclear material.	**IPR1.3.1** Difficulty and detectability of diversion.	**VPR1.1.3.1 ~ VPR1.1.3.9**
BPPR2 Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.	**URPR2.1** Innovative nuclear energy systems should incorporate multiple proliferation resistance features and measures.	**IPR2.1.1** The extent by which the INS is covered by multiple intrinsic features. "Extent" is the fraction of plausible acquisition paths. It is understood that each acquisition path is covered by appropriate verification measures.	
		IPR2.1.2 Robustness of barriers covering an acquisition path.	
	URPR2.2 The combination of intrinsic features and extrinsic measures, compatible with other design considerations, should be optimized (in the design/engineering phase) to provide cost-efficient proliferation resistance.	**IPR2.2.1** Cost to incorporate those intrinsic features and extrinsic measures, which are required to provide proliferation resistance.	
		IPR2.2.2 Verification approach with a level of extrinsic measures agreed to between the verification authority (e.g. IAEA, Regional safeguards organizations, etc.) and the State.	

Revised INPRO Methodology (1)

- **Revised INPRO Methodology : BP1 - UR1 - Indicator**

BPPR1: PR features and measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.	
URPR1.1: States' commitments, obligations and policies regarding non-proliferation should be adequate.	
IPR1.1.1: States' commitments, obligations and policies regarding non-proliferation.	**VPR1.1.1.1 : Safeguards agreements pursuant to the NPT** **VPR1.1.1.2 : Nuclear-weapons-free zone treaties** **VPR1.1.1.3 : Comprehensive IAEA safeguards agreements** **VPR1.1.1.4 : Additional protocols of IAEA agreements** **VPR1.1.1.5 : Export control policies** **VPR1.1.1.6 : Relevant international conventions** **VPR1.1.1.7 : Commercial, legal or institutional arrangements that control access to NM and NES** **VPR1.1.1.8 : Bi-lateral agreements for supply and return of nuclear material** **VPR1.1.1.9 : Bi-lateral agreements governing re-export of NES components** **VPR1.1.1.10 : Multi-lateral ownership, management or control of a NES** **VPR1.1.1.11 : Verification activities** **VPR1.1.1.12 : State or regional systems for accounting and control** **VPR1.1.1.13 : Safeguards approaches for the State's or regional safeguard system, capable of detecting diversion or undeclared production** **VPR1.1.1.14 : An effectiveness international response mechanism for violations**

Revised INPRO Methodology (2)

- **Revised INPRO Methodology : BP1 - UR2 - Indicator**

BP 1: PR features and measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.	
UR 1.2: The attractiveness of nuclear material in an INS for a nuclear weapons programme should be low.	
I 1.2.1: Material Attractiveness	**V 1.2.1.1: Isotope content** **V 1.2.1.2: Chemical form** **V 1.2.1.3: Radiation field** **V 1.2.1.4: Heat generation** **V 1.2.1.5: Spontaneous neutron generation rate**

Revised INPRO Methodology(3)

- **Revised INPRO Methodology : BP1 - UR3 - Indicator**

BPPR1: PR features and measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.	
URPR1.3: The diversion of nuclear material should be reasonably difficult and detectable.	
IPR1.3.1: Difficulty and detectability of diversion	**VPR1.3.1.1: Complexity of, and time required for modifications necessary to use a civilian INS for a weapons production facility** **VPR1.3.1.2: Bulk and mass** **VPR1.3.1.3: Skills, expertise and knowledge required to divert or produce NM and convert it to weapons useable form** **VPR1.3.1.4: Time required to divert or produce NM and convert it to weapons useable form** **VPR1.3.1.5: Design features that limit access to NM** **VPR1.3.1.6: Material stocks and flows** **VPR1.3.1.7: Diversion detectability** **VPR1.3.1.8: Effectiveness of prevention of diversion of NM** **VPR1.3.1.9: Difficulty to modify fuel cycle facilities and process for undeclared production**

Revised INPRO Methodology (4)

- **Revised INPRO Methodology : BP2 - UR1 - Indicators**

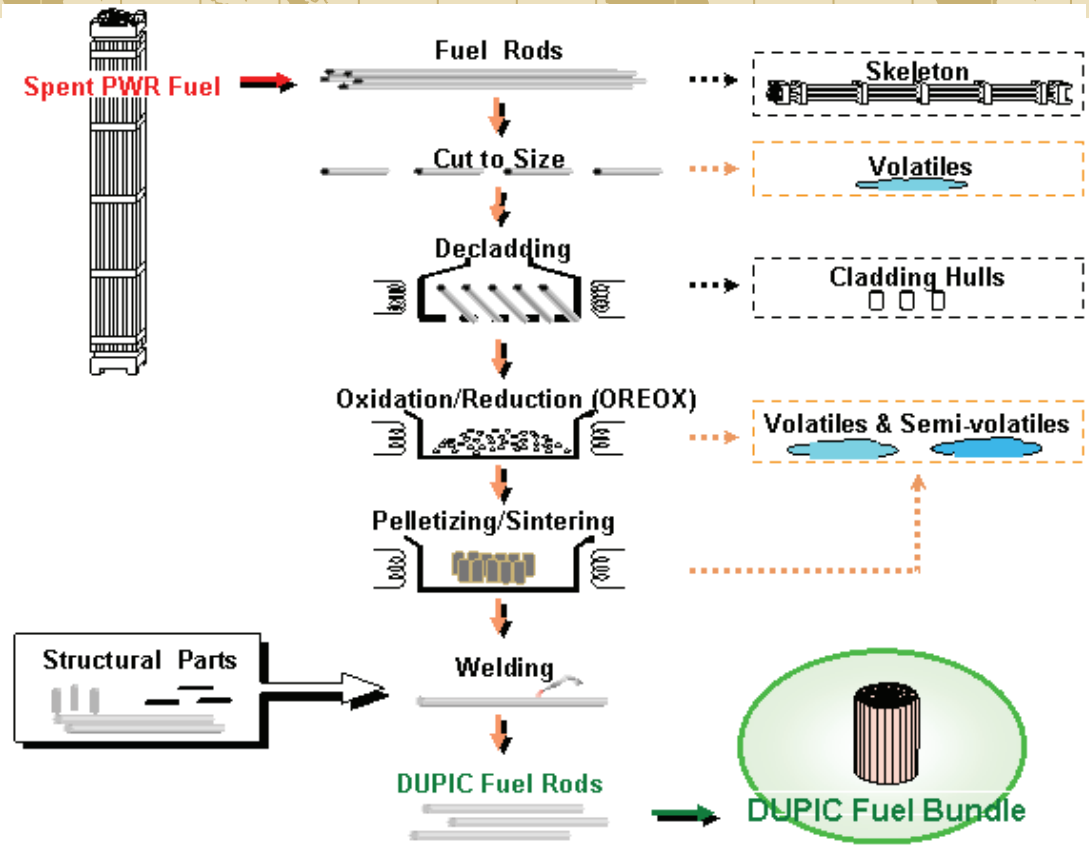
BP 2: Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.	
UR 2.1: Innovative nuclear energy systems should incorporate multiple PR features and measures.	
I 2.1.1: The extent by which the INS is covered by multiple intrinsic features.	**•Define multiple intrinsic features •Determine Acceptance Limits**
I 2.1.2: Robustness of barriers covering an acquisition path.	**•Define acquisition path of NM •Determine Acceptance Limits**

Revised INPRO Methodology (5)

- **Revised INPRO Methodology : BP2 - UR2 - Indicators**

BP 2: Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.	
UR 2.2: The combination of intrinsic features and extrinsic measures should be optimized to provide cost-efficient PR.	
I 2.2.1: Cost to incorporate those intrinsic features and extrinsic measures, which are required to provide PR.	**•Incremental costs for intrinsic features and extrinsic measures •Determine Acceptance Limits**
I 2.2.2: Verification approach with a level of extrinsic measures agreed to between the verification authority and the State.	**•Determine Acceptance Limits**

DUPIC Fuel Fabrication Process



Benefits

- Inherent Proliferation-resistant process owing to no separation of sensitive nuclear material
- Minimization of process waste through a dry thermal/mechanical process

Technical Challenges

- Development of remote fuel fabrication and QA/QC technology

DUPIC Evaluation Example (Intrinsic Features)

Variables	Evaluation Parameters	Evaluation Scale of Acceptance Limit				
		U	W	M	S	V
Isotope content	^{239}Pu/Pu (wt%)	> 93	80 ~ 93	70~80	60~70	< 60
	^{235}U/U (wt%)	> 90	50 ~ 90	20~50	5~20	< 5
	^{232}Ucontam. for ^{233}U (ppm)	> 1	1 ~ 100	100~4000	4000-~7000	< 7000
Chemical form	Chemical form	Pure Pu metal	PuO_2, PuN	Fresh MOX	Spent fuel	Spent fuel with high burnup
Radiation field	Dose (rem/hr)	< 1	1~15	15~100	100~1000	> 1000
Bulk and mass	Mass (kg)	<10	10~100	100~500	500~1000	> 1000
	Size (cm)	< 10	10~40	40~100	100~300	> 300
Heat generation	^{238}Pu/Pu (wt%)	< 0.1	0.1~1	1~10	10~80	> 80
Spontaneous neutron generation rate	(^{240}Pu+ ^{242}Pu) /Pu (wt%)	< 1	1~10	10~20	20~50	> 50
Detectable radiation	Detectability	No reliably signature	No reliably signature	Moderately detected by active means	Reliably detected by active means	Easily detected by passive means
Diversion detectability	MUF Kg Pu or ^{233}U Kg ^{235}Uwith LEU kg ^{235}Uwith HEU tonTh	> 16 > 50 > 150 > 40	8~16 25~50 37~75 20~40	4~8 25~12 18~37 10~20	2~4 7~6 9~18 5~10	< 2 < 6 < 9 < 5
Effectiveness of prevention of diversion of nuclear material	Environment	Open	Open	Glove box, concrete, or metal	Shielded hot cell	Geological media
Difficulty to modify fuel cycle facilities and process for undeclared production	Degree of difficulty	Very easy	Easy	Difficult	Very difficult	Absolutely impossible

U: Unacceptable, W: Weak, M: Moderate, S: Strong, V: Very Strong

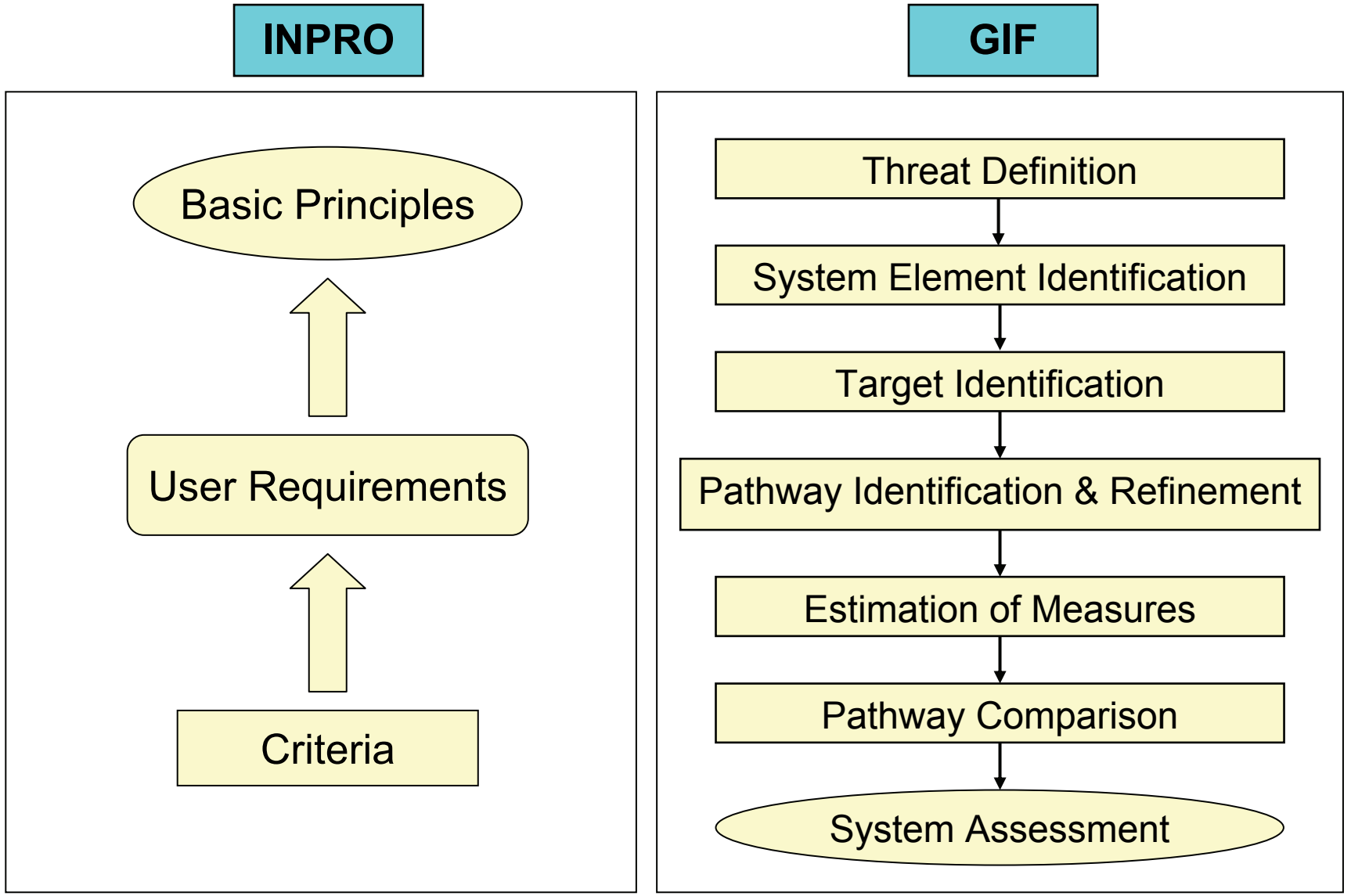
DUPIC Evaluation Example (Extrinsic Measures)

Variables	Evaluation Parameter	Evaluation Scale of Acceptance Limits				
		U	W	M	S	V
Non-proliferation related treaties and convention	NPT	No	No		Yes	Yes
	NW-free zone treaties	No	No		Yes	Yes
	CTBT	No	No		Yes	Yes
Export control	Export control policies	No	No		Yes	Yes
	Bilateral arrangements for supply and return of nuclear fuel	No	No		Yes	Yes
	Bilateral agreements governing re-export of NES components	No	No		Yes	Yes
Commercial, legal or institutional arrangements that control access to NM and NES	Multi-national ownership	No	No		Yes	Yes
	Management or control of a NES	U	W	M	S	V
Safeguards agreements, verification and response	Safeguards agreements pursuant to the NPT	No	No		Yes	Yes
	State or regional systems for accounting and control	No	No		Yes	Yes
	Safeguards approaches for the State's or regional safeguard systems	U	W	M	S	V
	An effective international response mechanism for violations	U	W	M	S	V

Aggregation Example of PR Assessment

System Element (Fabrication)	Basic Principle	User Requirement	Indicator	Evaluation Results of Variables				
				U	W	M	S	V
Step Fabrication (M)	BP1 (M)	UR1.1 (S)	I1.1.1 (V)					O
			I1.1.2 (V)					O
			I1.1.3 (S)				O	
			I1.1.4 (S)				O	
			I1.1.5 (V)					O
		UR1.2 (M)	I1.2.1 (V)					O
			I1.2.2 (S)				O	
			I1.2.3 (M)			O		
			I1.2.4 (M)			O		
			I1.2.5 (V)					O
		UR1.3 (S)	I1.3.1 (S)				O	
			I1.3.2 (S)				O	
			I1.3.3 (S)				O	
			I1.3.4 (S)				O	
			I1.3.5 (S)				O	
	BP2 (S)	UR2.1 (S)	I2.1.1 (S)				O	
			I2.1.2 (S)				O	
		UR2.2 (S)	I2.2.1 (S)				O	
			I2.2.2 (S)				O	

Comparison of Evaluation Framework INPRO vs. GEN-IV

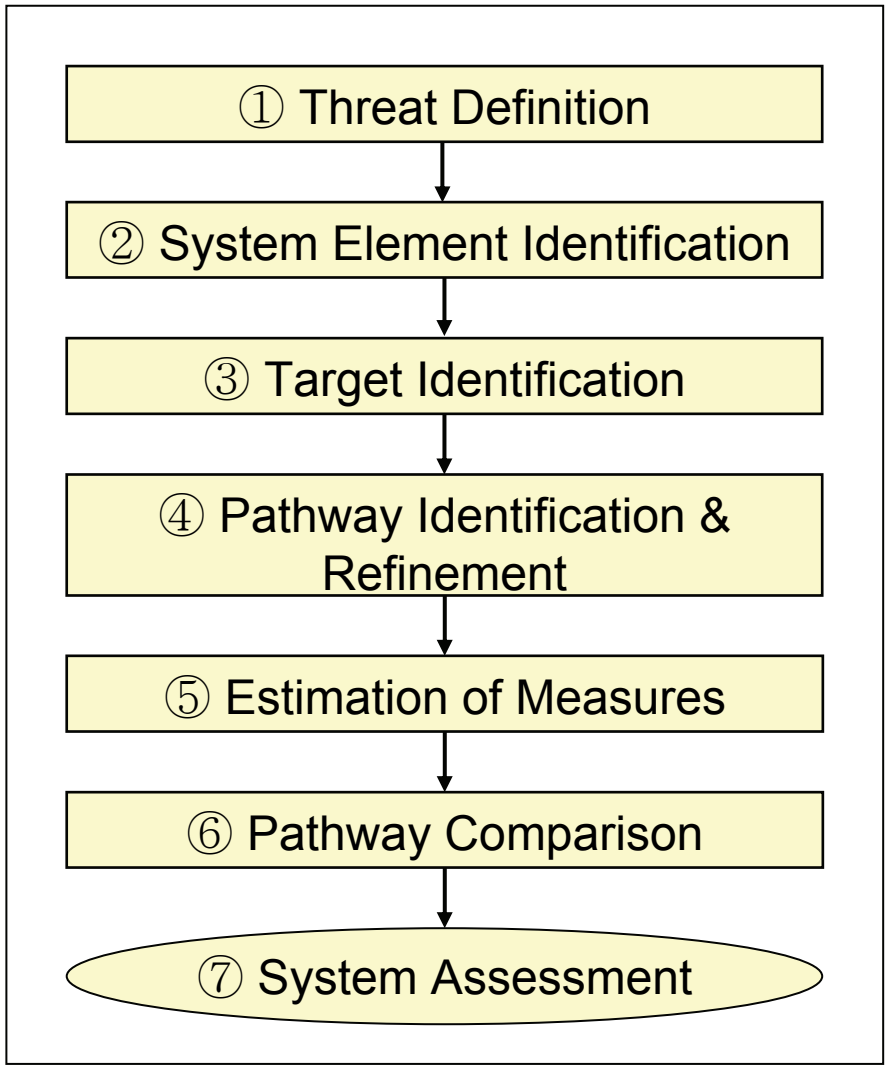


GEN-IV Six Measures for PR

- **Proliferation Technical Difficulty**
  - Inherent sources of difficulty that increase the technical sophistication and materials handling capabilities required to overcome the multiple barriers to materials acquisition by diversion or undeclared production, processing to directly usable form, and fabrication of nuclear explosives
- **Proliferation Resources**
  - Economic and manpower investment required to overcome the multiple technical barriers to proliferation including the use of existing or new facilities
- **Proliferation Time**
  - Minimum time required to overcome the multiple barriers to proliferation

    (i.e., The total time planned by the State for the project)
- **Fissile Material Quality and Quantity**
  - The total quantity or rate at which potentially weapons-usable material with specified characteristics can be acquired by the State and the degree to which the quality of the material affects its utility for use in nuclear explosives
- **Detection Time**
  - The time following the initiation of diversion or undeclared production, for detection resources to detect irregularities and to provide adequate confirmation that diversion or undeclared production has occurred or is occurring
- **Detection Resources**
  - Manpower, technology and funding required to apply international safeguards

GEN-IV Evaluation Framework



① - Capability : NNWS with commercial nuclear operation without enrichment or reprocessing facility

- Objective : 5 weapons, 20 kT yield, 50% reliability, 1 T weight

- Strategy : Material diversion, Facility misuse

② SF storage/ Fuel cycle facility/Fuel storage/ Reactor/ Waste storage

③ Target : Material of processes to be protected from PR threat

④ - EX 1 : Diversion of SF assembly

- EX 2 : Irradiation of U target in reactor

- Complete Pathway : Acquisition, Processing, Fabrication

⑤ 6 PR measures of path segment

⑥ Aggregate the measure values for pathway

⑦ Refine the paths and gauge for the measures

Summary

- Quantitative assessment methodology for proliferation resistance of nuclear system are under development
  - IAEA INPRO Methodology
  - GEN-IV PR&PP Expert Group