GEN IV International Forum
Expertise | Collaboration | Excellence

Proliferation Resistance and Physical Protection (PR&PP) Evaluation Methodology in Support of PR&PP by Design for Fast Reactors and Associated Fuel Cycles

IAEA Technical Meeting on Proliferation Resistance of Fast Reactors and Associated Fuel Cycles
18-21 August 2025

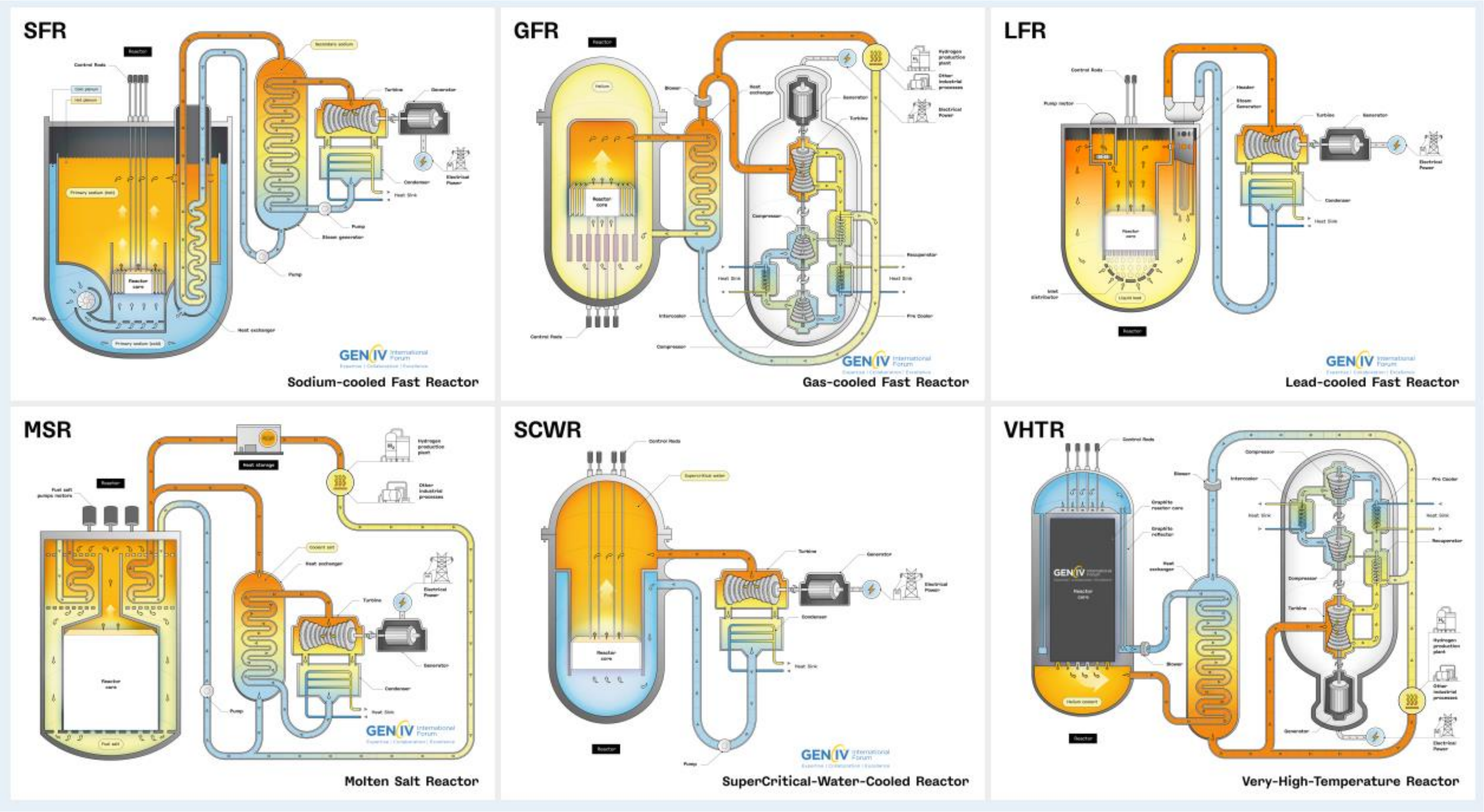
Bryan van der Ende
(Canadian Nuclear Laboratories)
on behalf of the Generation IV International Forum (GIF) Proliferation Resistance and Physical Protection Working Group (PRPPWG)

Presentation Outline

- Overview of the Generation IV International Forum (GIF) Proliferation Resistance and Physical Protection Working Group (PRPPWG)
- Motivation for the GIF PR&PP methodology
- Framework of the GIF PR&PP methodology
- Example Fast Sodium Cooled Reactor (ESFR) as a case study of the methodology
- How the GIF PR&PP methodology supports PR&PP by design of a nuclear energy system (NES)
- GIF PR&PP methodology in safety, security, safeguards (3S) interfaces

GEN IV International Forum

Generation IV International Forum



Technology goals for Gen-IV systems in 4 broad areas:

- Sustainability
- Economics
- Safety and Reliability
- Proliferation and Physical Protection (PR&PP)

https://www.gen-4.org/

GEN IV International Forum
Expertise | Collaboration | Excellence

GIF PR&PP Working Group (PRPPWG) Membership: Countries and Organization

- Canada
- China
- Euratom
- France
- IAEA - Observer
- Japan
- NEA - Secretariat
- Republic of Korea
- South Africa
- UK
- USA

- *Co-Chairs: G. Renda (EC-JRC Euratom), B. Cipiti (SNL-US), F. Nguyen (CEA-France)*
- *Technical secretary supporting PRPPWG: A. Ozeretzkosky (NEA)*

PRPPWG 35th meeting (Annual Meeting) at the JRC Ispra in February 2025

Introduction to the GIF PR&PP Methodology (PRPPEM)

Motivation for development of the methodology

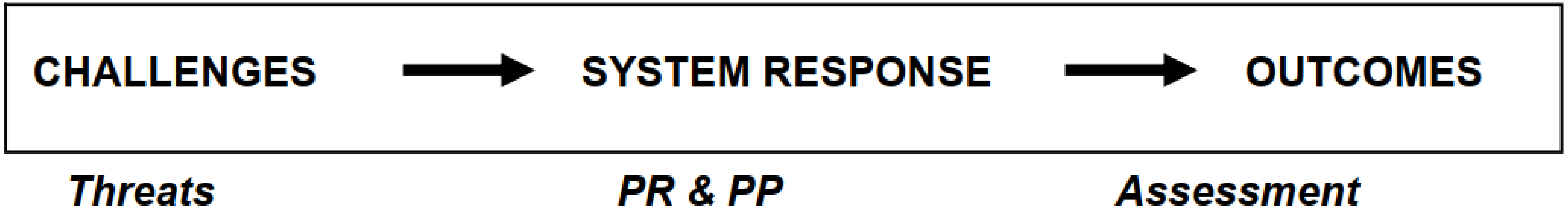
- The PRPPWG was established in 2002 to provide a methodology for the assessment of Gen-IV systems against Gen-IV Non-Proliferation and Physical Protection related goals:

Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials and provide increased physical protection against acts of terrorism.

- The methodology has been developed and refined over the years to stay in line with latest policy and technology evolutions in areas of PR&PP.
- The methodology is organized to allow evaluations to be performed at earliest system design stages, becoming more detailed and representative as design progresses.
- Application of the PR&PP methodology is intended for system designers, program policy makers, and external stakeholders.

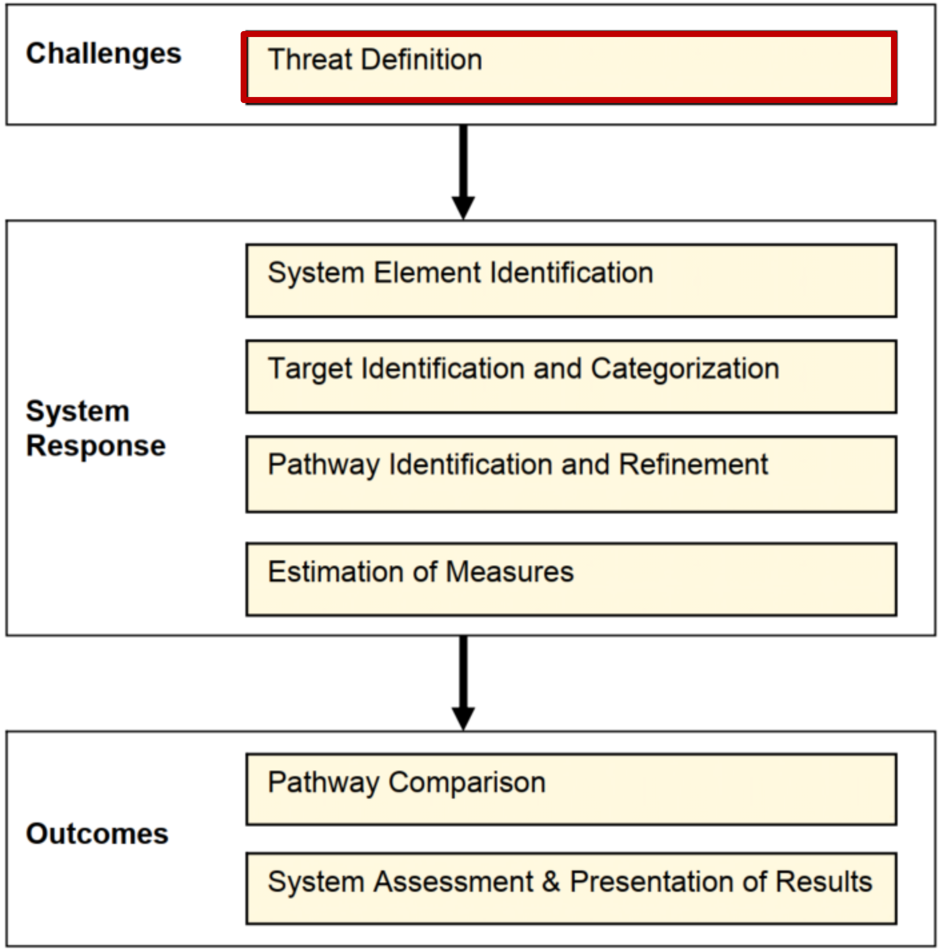
Basic Framework of the GIF PRPPEM

- The basic framework of the methodology follows a sequence:
  1. Define a set of challenges
  2. Analyze the system response to the challenges
  3. Assess the outcomes



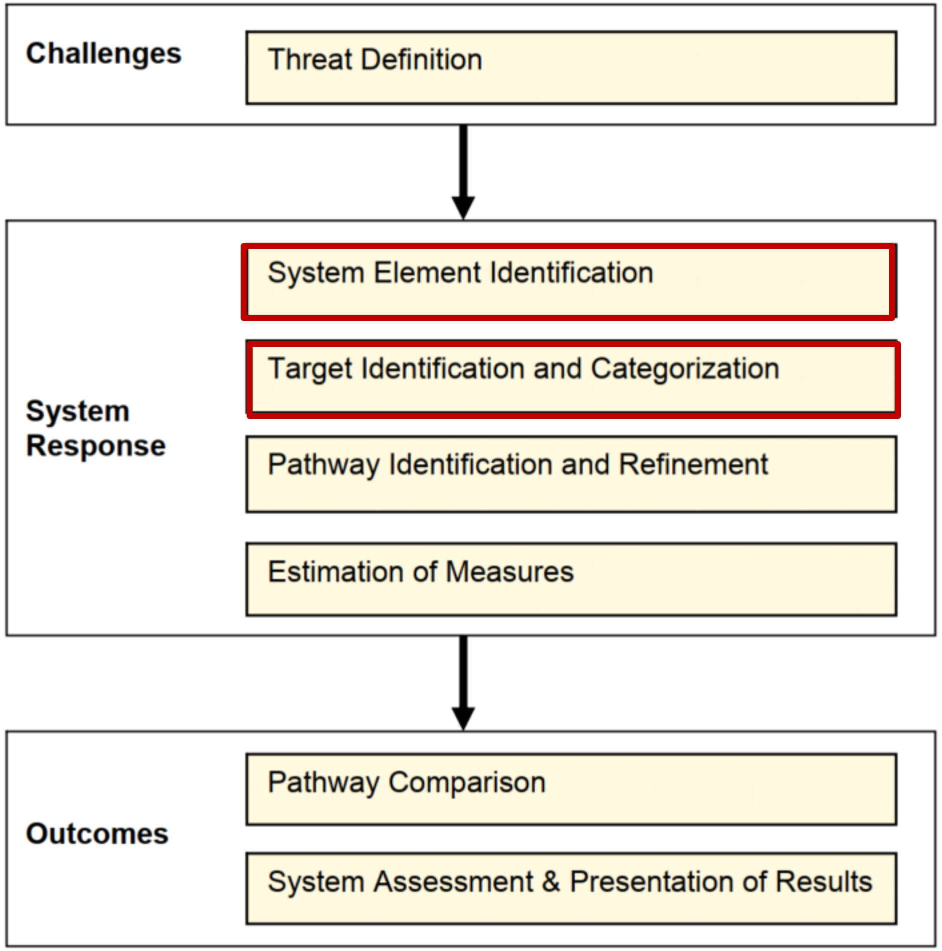
- Challenges include threats from States that are potential proliferators, as well sub-national adversaries.
- The response of each nuclear energy system will depend upon its technical intrinsic features and institutional extrinsic measures.
- Assessment of the outcomes is expressed in terms of a set of PR&PP measures.

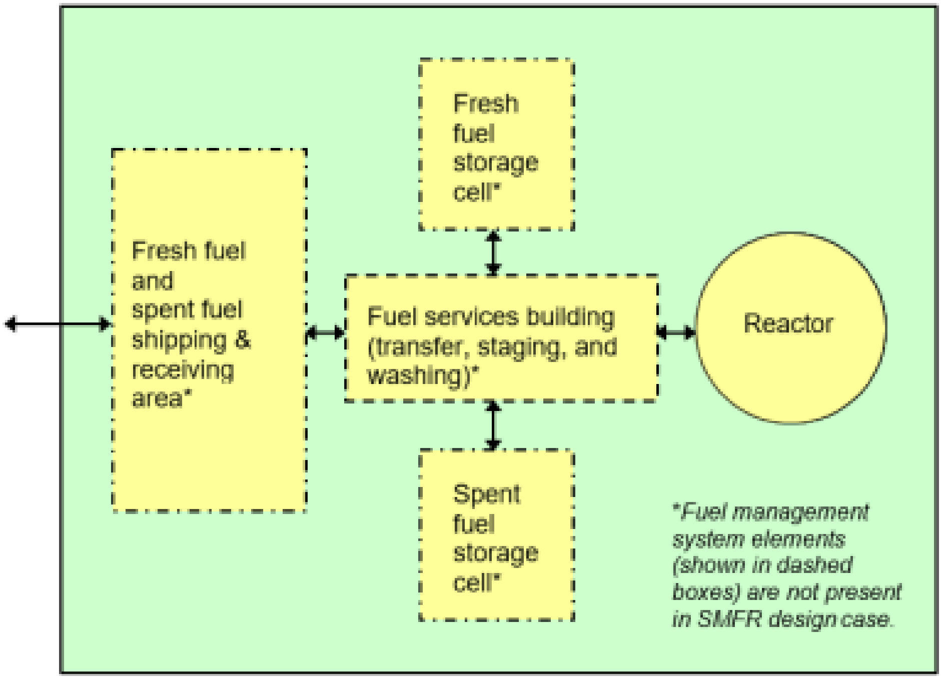
Expanded Framework of the GIF PRPPEM



	Proliferation Resistance	Physical Protection
Threat Space	• Host State with given capabilities • Acquisition of nuclear weapon(s) • 4 possible strategies (nuclear material (NM) diversion, facility misuse, breakout, and replication of technology in clandestine facilities)	• Sub-National Actor (insider, outsider, mix of both) with given capabilities • Sabotage, theft of NM or information • Various strategies

Expanded Framework of the GIF PRPPEM



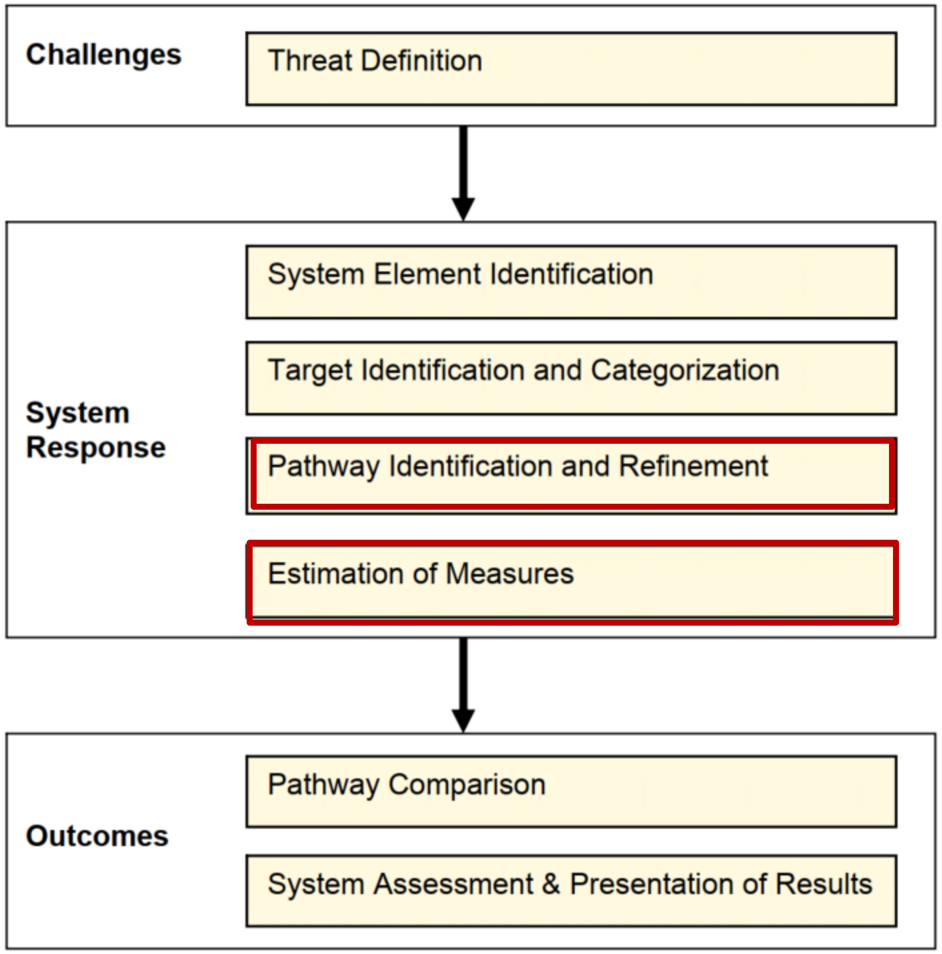


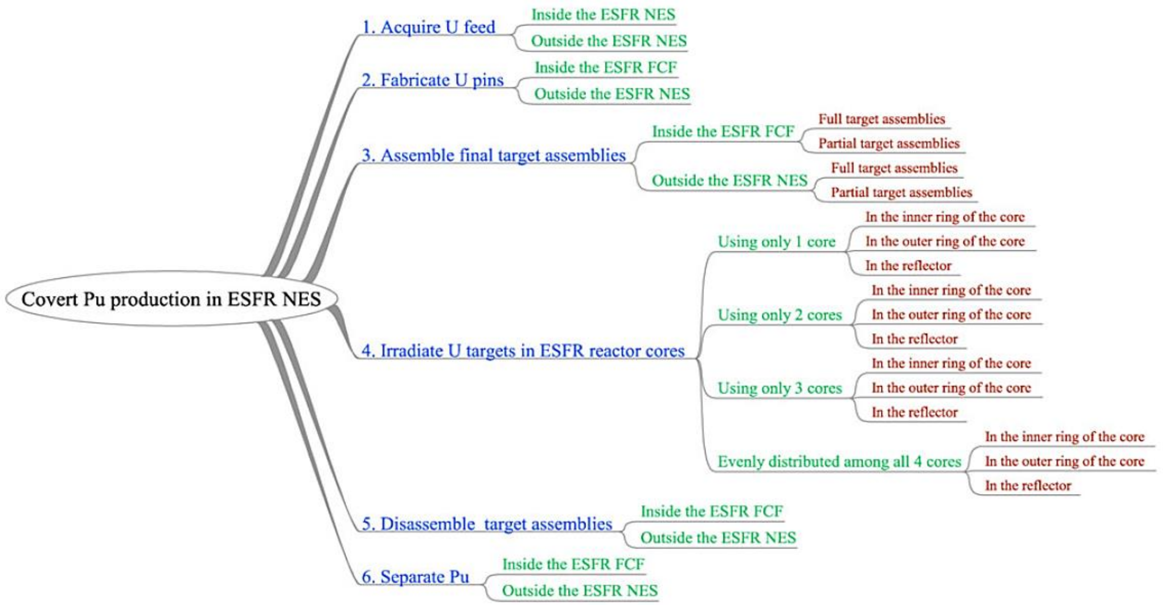
GIF Sodium-Cooled Fast Reactor Proliferation Resistance and Physical Protection White Paper, 2021.

	Proliferation Resistance	Physical Protection
Targets	• NM to be diverted • Equipment/process to be misused • Equipment/technology to replicate clandestinely	• NM to be protected from theft • Information to be protected from theft • Equipment to be protected from sabotage

GEN IV International Forum

Expanded Framework of the GIF PRPPEM





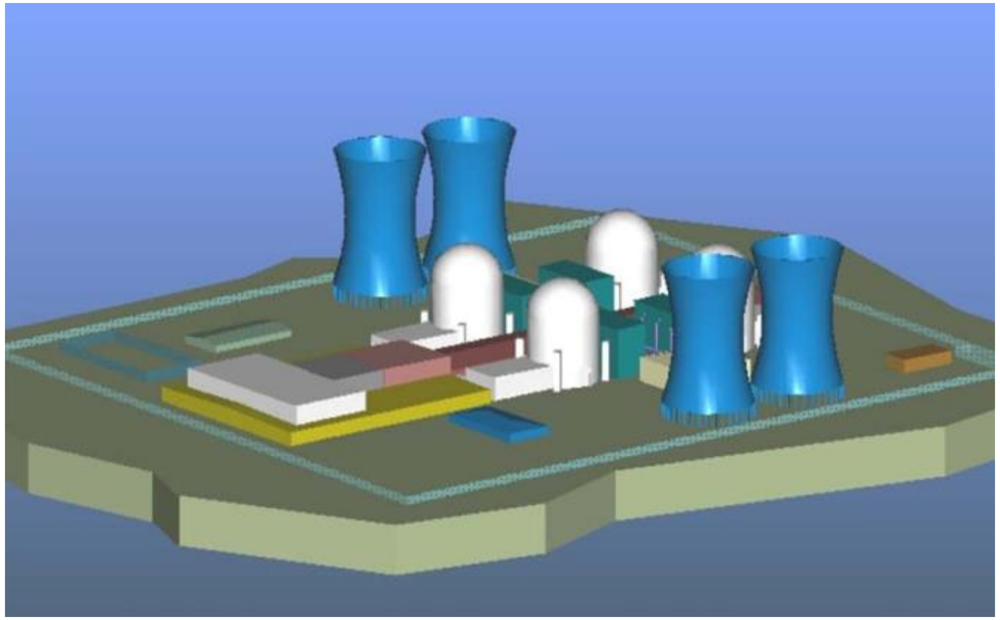
	Proliferation Resistance	Physical Protection
PR&PP Measures	• Proliferation Technical Difficulty • Proliferation Cost • Proliferation Time • Fissile Material Type • Detection Probability • Detection Resources Efficiency	• Probability of Adversary Success • Consequence • Physical Protection Resources

GEN IV International Forum
Expertise | Collaboration | Excellence

Some History of the Development of the PRPPEM

- The PR&PP evaluation methodology was developed with the aid of a sequence of studies:
  1. Initial development study in 2004.
  2. Demonstration study in 2005 to 2006.
  3. Follow-up two-year case study applying the methodology to all PR&PP aspects of a full Gen-IV nuclear energy system (NES).

- These studies used an Example Sodium Fast Reactor (ESFR).
  - Hypothetical NES with 4 pool-type sodium-cooled fast reactors (SFRs) co-located with dry fuel storage and pyrochemical spent fuel cycle facility (FCF).
  - SFRs are a more mature Gen-IV technology with sufficient information available.



Full ESFR Case Study

- Full ESFR case study performed in 2007-2008 was a comprehensive assessment of the entire ESFR reactor and fuel cycle system.
  - Final report was issued publicly in 2009.

- Case study objectives:
  - Demonstrate the methodology for an entire fuel cycle system.
  - Confirm applicability of the methodology at different levels of design detail.
  - Provide examples of PR&PP evaluations for future users of the methodology.
  - Identify areas for further development in the methodology.

GIF/PRPPWG/2009/002

PR&PP Evaluation:
ESFR Full System Case Study
Final Report

October, 2009

Prepared by:

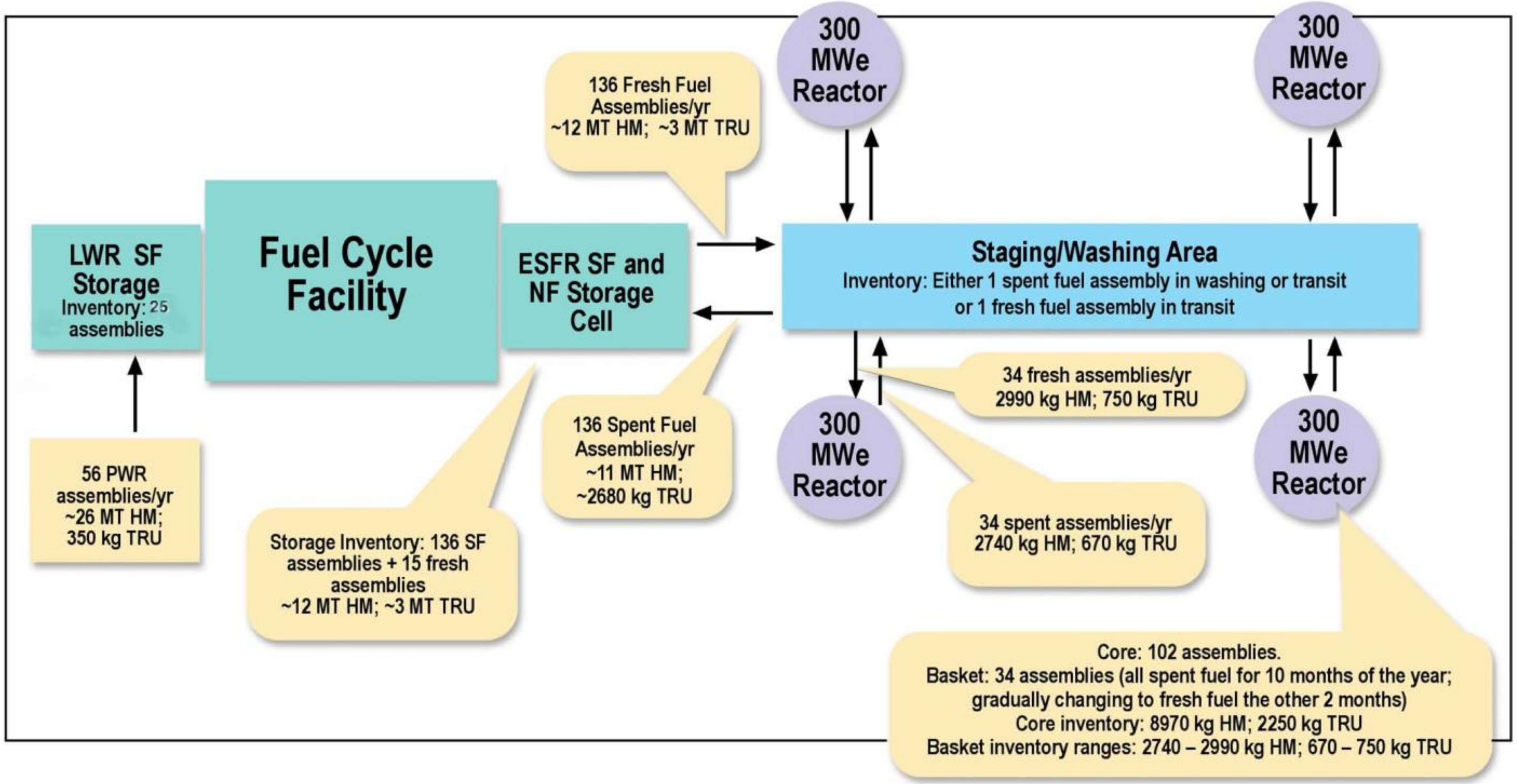
GEN IV International Forum

Proliferation Resistance and Physical Protection Evaluation Methodology Working Group

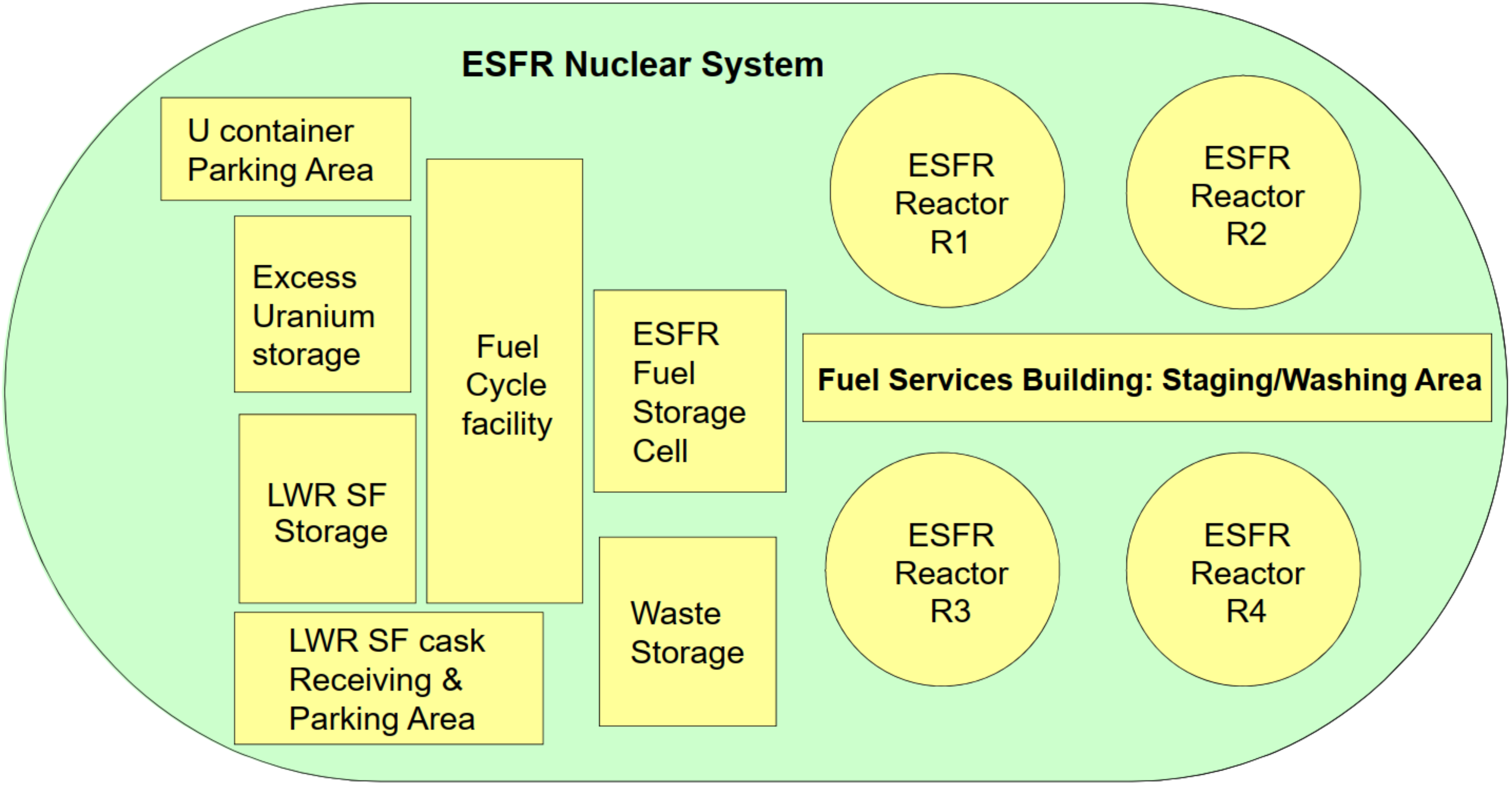
ESFR Case Study: Overview of Analysis Approach

- ESFR design, operation and safeguards/protection information was compiled.
- Three proliferation resistance (PR) and one physical protection (PP) "threat scenarios" were defined for system evaluation.
- Four working subgroups were formed, each focused on a threat scenario.
  - Identified possible "targets" and "pathways" for each threat scenario.
  - Selected a few targets and pathways for analysis based on their attractiveness to the adversary.
  - Characterized ESFR system PR&PP performance/response by estimating PR&PP measures for these targets and pathways.

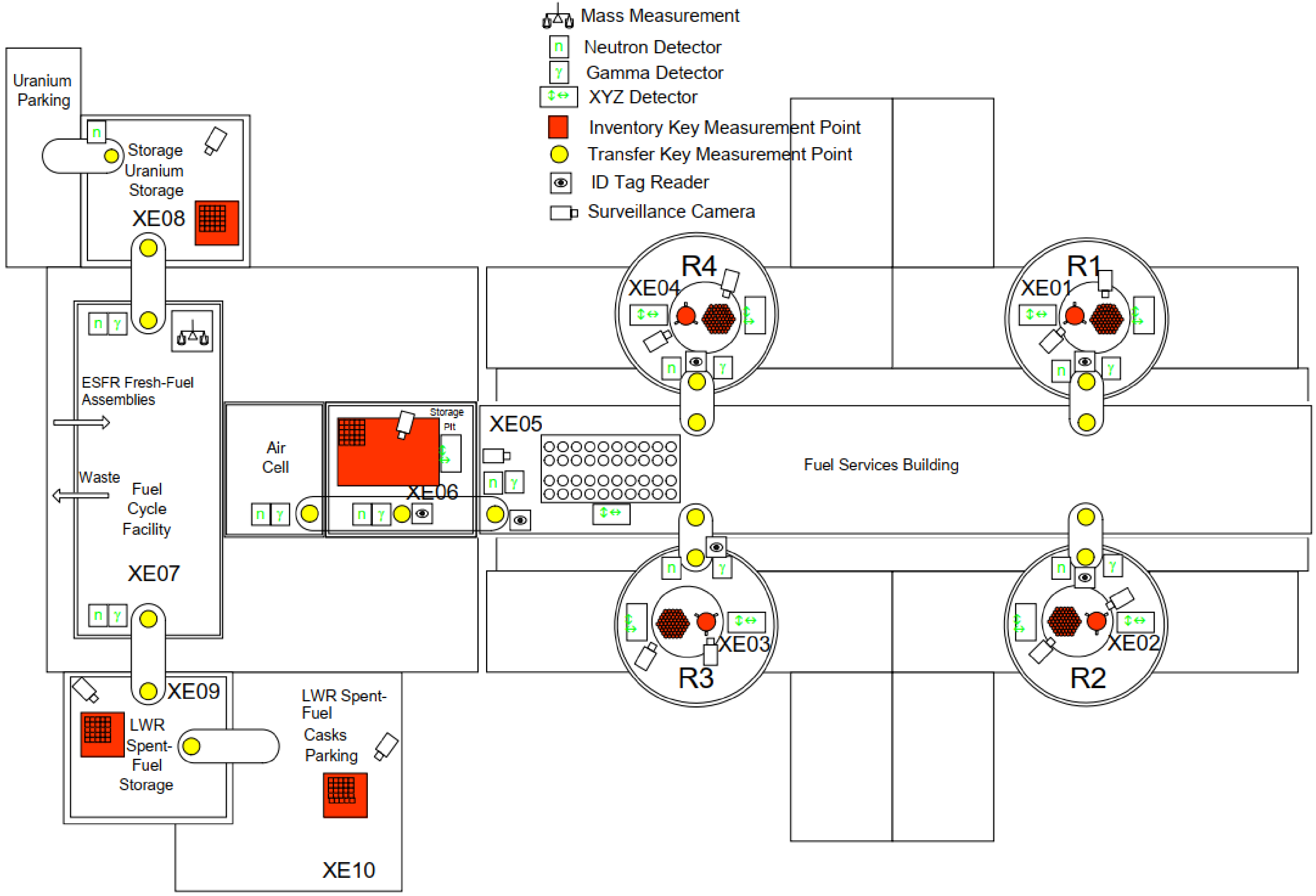
ESFR Case Study: Baseline System Material Flows



ESFR Case Study: Nuclear System Elements

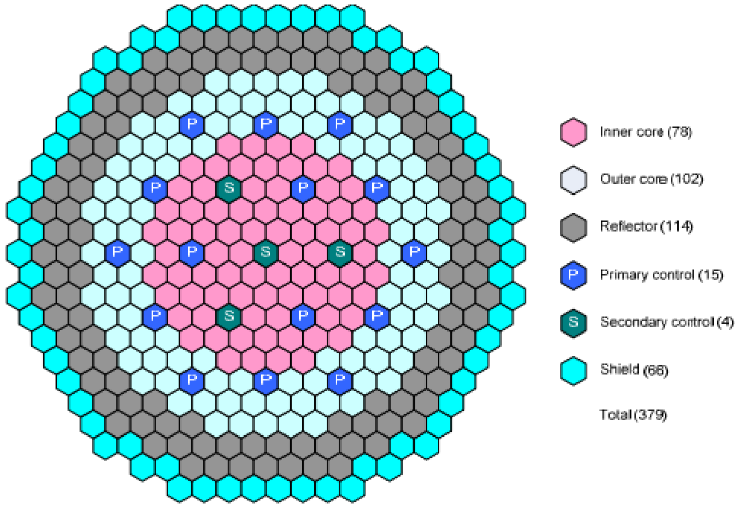


ESFR Case Study: Safeguards System

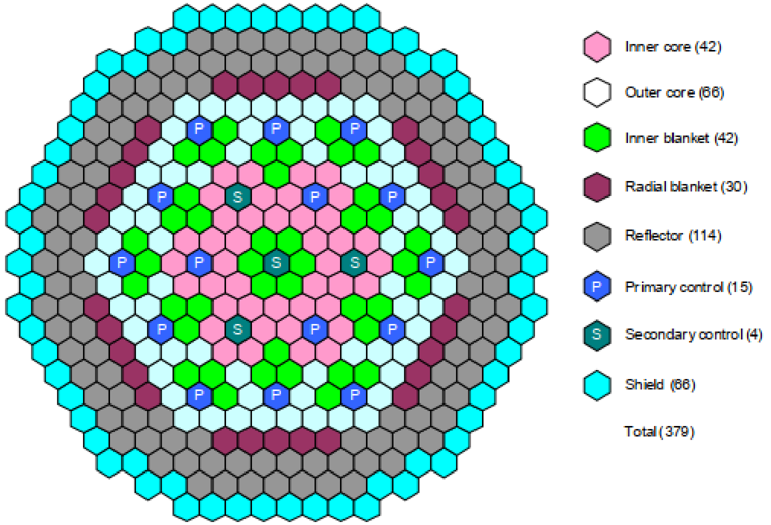


ESFR System Variations: 1000 MWth Capacity, 180 assemblies

- Variation 0: Conversion ratio (CR) for transuranic actinides (TRU) = 0.73 (22.1% TRU enrichment)
- Variation 1: Lower CR (0.22) requiring fuel of higher enrichment (58.5% TRU enrichment)
- Variation 2: Higher CR (1.00) representing a break-even core without fertile blankets (14.4% TRU enrichment)

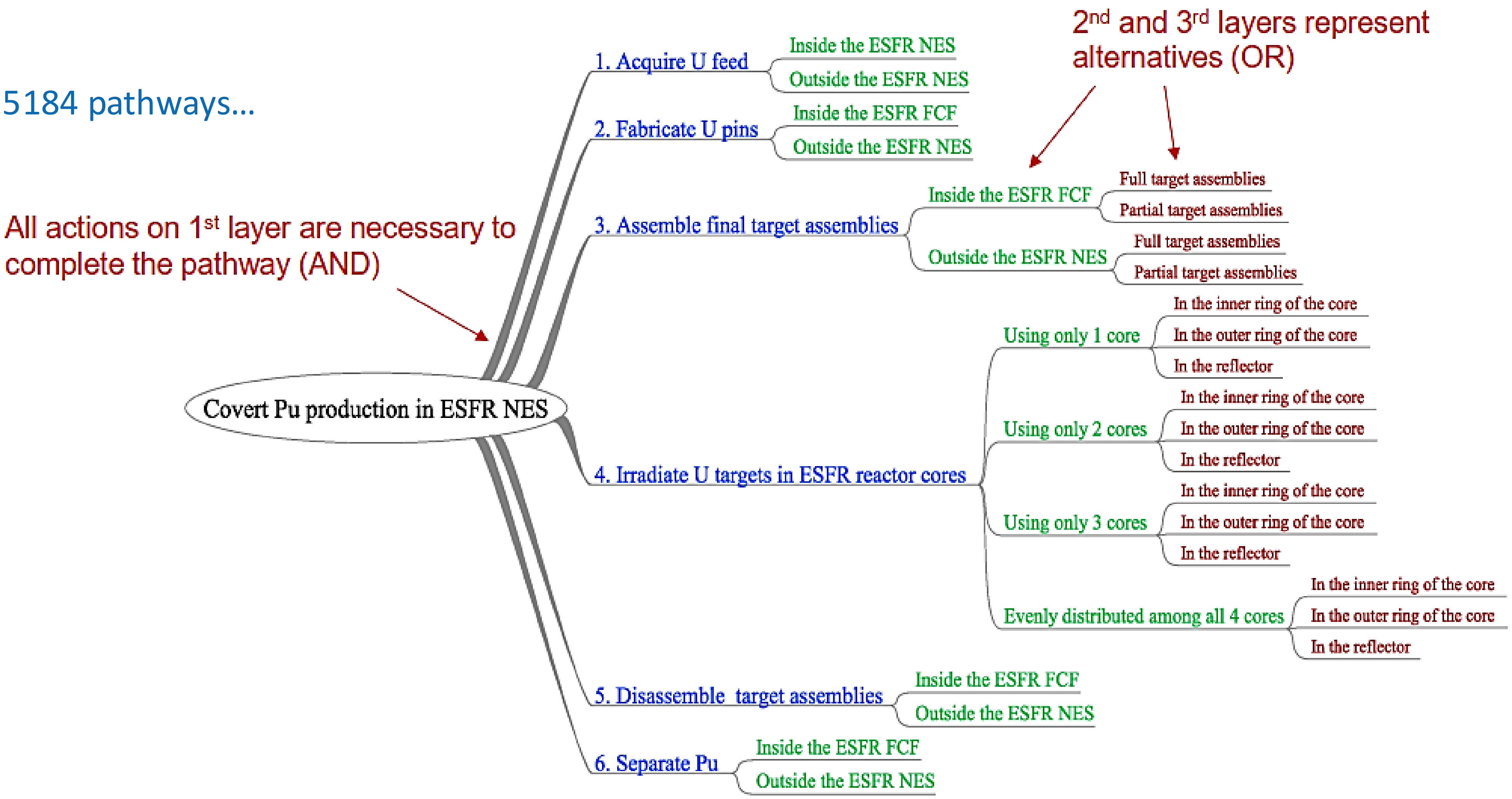


- Variation 3: Yet higher CR (1.12) representing a breeding core with internal and external U blankets



ESFR Case Study: Example Pathways Identification

This figure embeds 5184 pathways…



ESFR Case Study: Threat Scenarios

Proliferation Resistance	Physical Protection
Adversary: Host state in control of the ESFR facility	**Adversary**: Military trained sub-national/terrorist group (12 outsiders and 1 insider)
Objective: To obtain at least one significant quantity (SQ) of plutonium for at least one nuclear weapon	**Objective**: Theft of one SQ of nuclear weapon material ➢ Radiological sabotage also considered
Capabilities: Typical of a developed industrial nation	**Capabilities**: ➢ Knowledge of plant layout, basic PP features, and theft targets of opportunity ➢ Ability to acquire and use assault equipment and weapons, including specialized explosives and armored vehicles
Strategies: ➢ Concealed diversion of nuclear material from ESFR ➢ Concealed misuse of ESFR to produce weapons-usable material ➢ Break-out and overt misuse or diversion	**Strategies:** Surprise assault on ESFR material and storage areas

ESFR Case Study: Representative Case Study Results

Threat Scenario	Diversion		Misuse	
	Reference ESFR Diversion Pathway 1	Reference ESFR Diversion Pathway 2	Reference ESFR, CR=0.73 Misuse Pathway 1	ESFR Variation 1, CR=0.22 Misuse Pathway 1
Pathway Description	Diversion of TRU/U ingot material using a new fuel assembly hardware container and transporting it out of the FCF through the assembly hardware portal.	Diversion of TRU/U ingot material using recovered uranium container and transporting it out through recycled U container portal.	Irradiation of ad-hoc U targets in reactor(s) and Pu recovery in a clandestine reprocessing facility.	Irradiation of ad-hoc U targets in reactor(s) and Pu recovery in a clandestine reprocessing facility.
Technical Difficulty (TD)	Low	Low	Medium	Medium
Proliferation Time (PT)	Medium	Medium	Medium	Medium
Proliferation Cost (PC)	Very Low	Very Low	Very Low	Very Low
Material Type (MT)	Medium (RG Pu)	Medium (RG Pu)	Low (WG Pu)	Low (WG Pu)
Detection Probability (DP)	Medium	High	Low to High	Low to High
Detection Resource Efficiency (DE)	High	High	Low to High	Low to High

ESFR Case Study: Methodology Lessons Learned

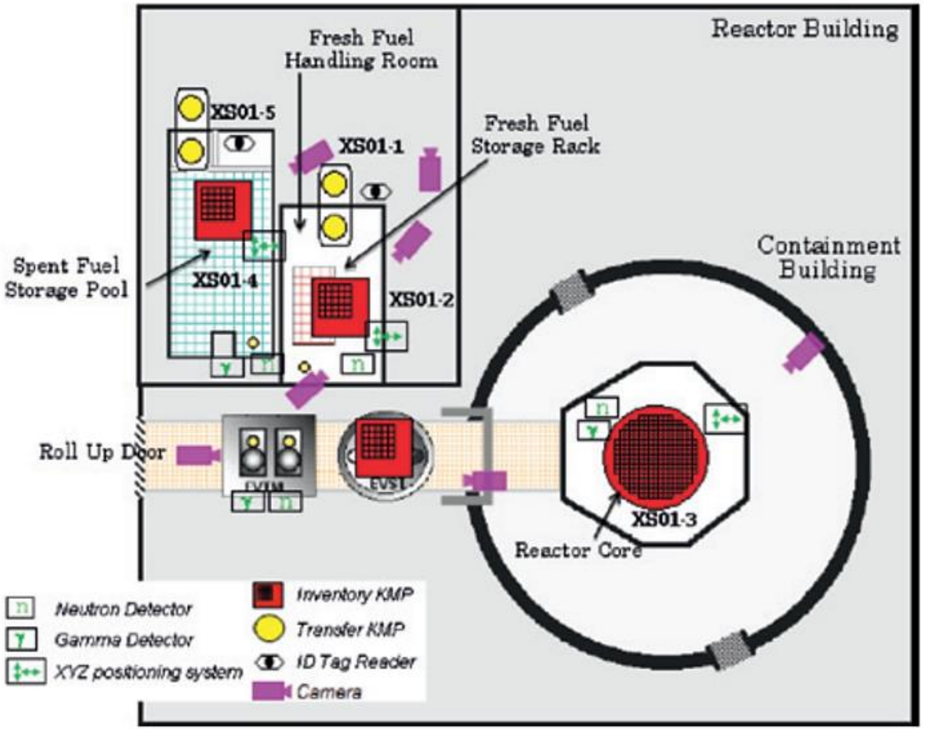
- The PR&PP methodology provides systematic treatment of PR and PP threat spaces at all design stages.
  - Qualitative analysis is insightful, even when detailed design information is missing or incomplete.
- Multi-disciplinary expert elicitations should be used to achieve consistency in the analysis.
  - Provides required technical expertise on system design and operation.
- Completeness in identifying attractive targets and pathways can be achieved.
  - Reasonable assumptions must be made about the system design and required safeguards and physical protection approaches.
- In practice, there can be a lot of pathways to consider, wherein one should focus on a subset of representative pathways.

PRPPEM Supports PR & PP by Design

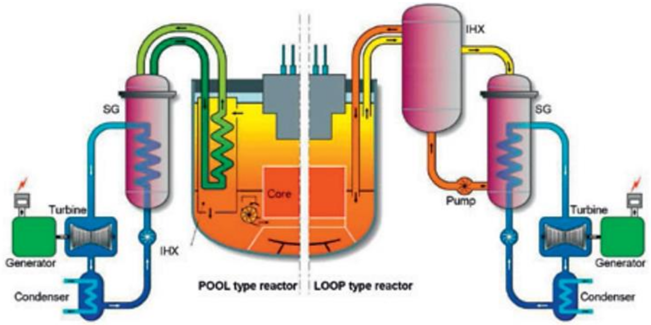
- PR methodology provides a structural approach to assessing the value of intrinsic features and extrinsic measures to the proliferation resistance of a nuclear energy system (NES) facility.
  - Evaluate and compare proposed safeguards approaches to reveal potential weaknesses in each approach.
  - Safeguards authorities and inspectorates are concerned about the safeguardability of a NES facility.
  - NES designers, producers, and vendors are responsible to ensure the design conforms to safeguards requirements in a cost-effective manner – from earliest design stages.
  - The GIF ESFR case study considered design variations and their effect in a misuse scenario: identified small differences in measure estimates.
- On the PP side, the ESFR study revealed strategies for achieving a consistent level of protection for the NES facility against local threats.
  - Showed how to enhance intrinsic impediments in the facility design to theft and sabotage.

GEN IV International Forum

PRPPEM in Past Safeguards-by-Design Studies

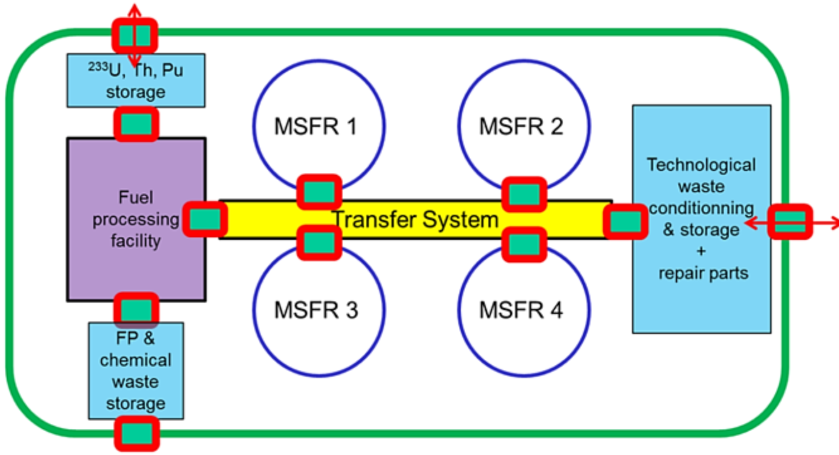


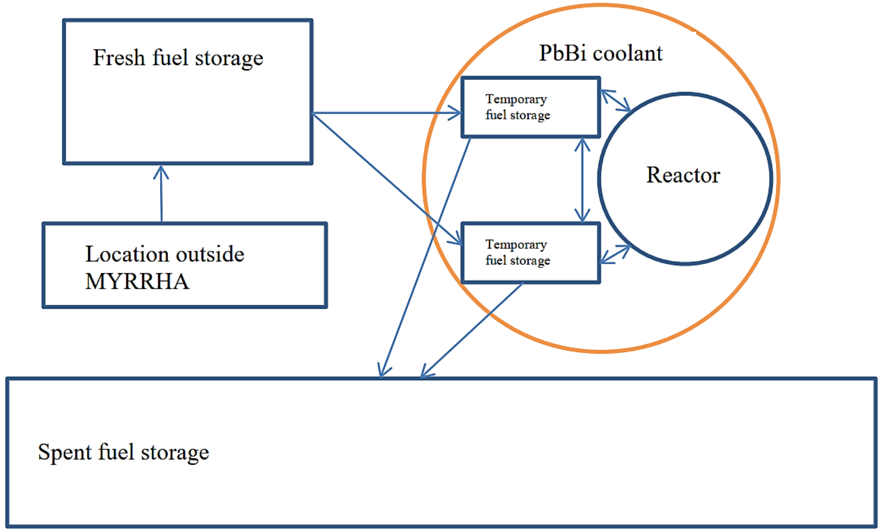
SFR based on Japanese Sodium Fast Reactor layout
Rossi, ESARDA Bulletin, 52 (2015) 98-113



European Sodium-Cooled Fast Reactor
Renda, Alim, Cojazzi, ESARDA Bulletin, 52 (2015) 124-143

Molten Salt Fast Reactor
Allibert et al., EPJ Nucl. Sci. Tech. 6, 5 (2020)

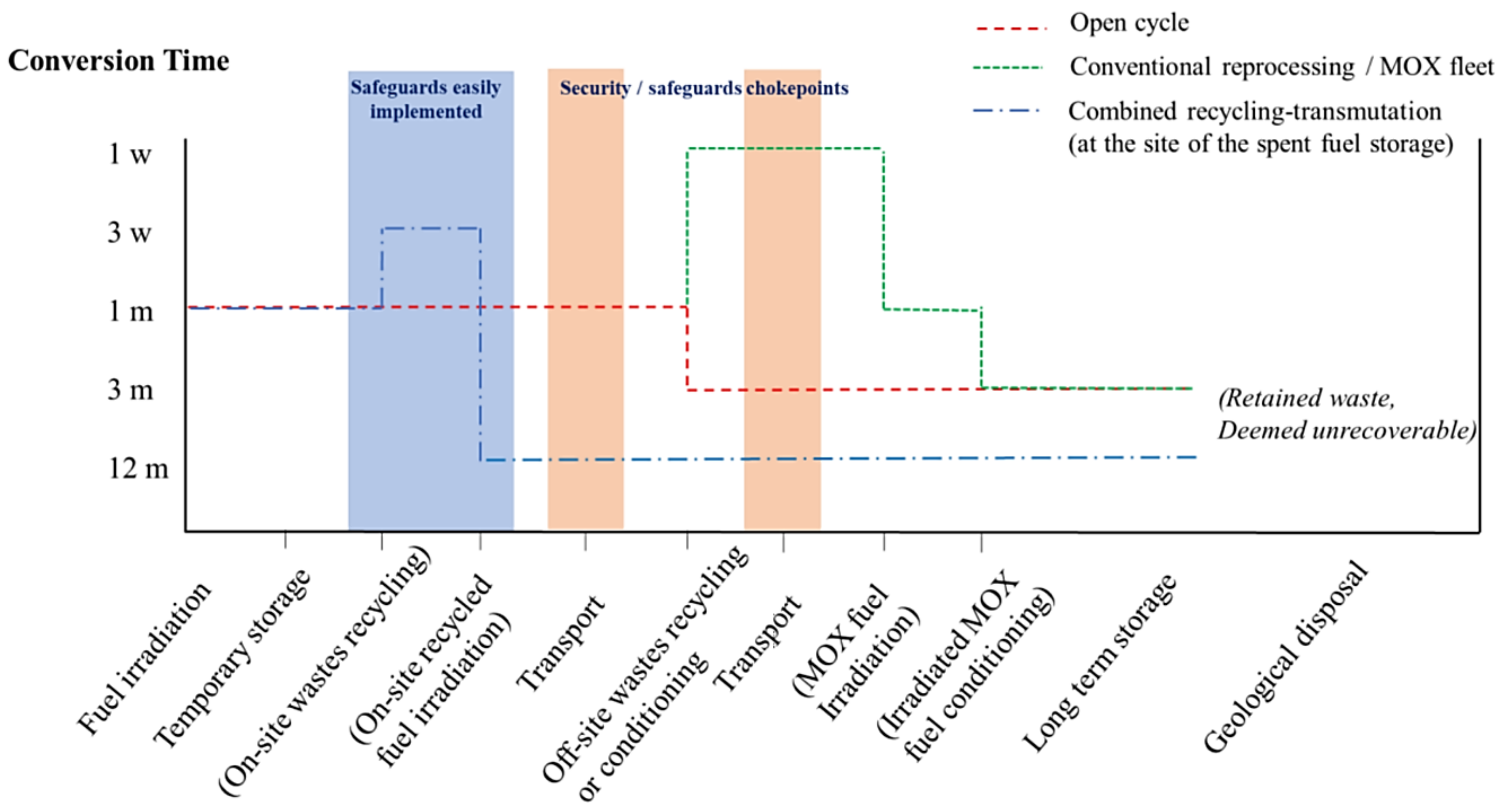




MYRRHA
Van der Meer, Borella, Rossa, INMM 2011 Annual Meeting

GEN IV International Forum
Expertise | Collaboration | Excellence

Further Fast Reactor Application Opportunities



O. Gregoire, Non-Proliferation and Safeguards by Design Considerations in the WATSS Recycling Process
2023 Annual Conference of the Canadian Nuclear Society

- Different categories of proliferation resistance intrinsic design features in GIF PR&PP white papers have helped identify non-proliferation assurance provisions for Moltex SSR-W and WATSS facility.
- These provisions increase proliferation time relative to an open cycle.
- The GIF PR&PP methodology can play a role in further stages of the safeguards by design process.

PRPPEM in 3S Interfaces

- The optimization of the performance of an NES requires integrated consideration of multiple design goals: sustainability, safety and reliability (S&R), PR&PP, economics.
- Design approaches motivated by each of the goal areas may be compatible or in conflict.
- There exists close coupling between S&R and PR&PP that deserves further attention.
  - ➢ Each of these areas has their own methods and concepts, which can be synergistic or conflicting in their interfaces with each other.
- Further work can include:
  - ➢ Shared development and testing of potentially common elements of their respective evaluation methodologies, to enhance mutual consistency and facilitate cooperative application.
  - ➢ Target cooperative application and testing of the respective methodologies with the aim of demonstrating their application for assessment and optimization of Gen-IV NES designs.

Conclusions

- From the onset of its development, the GIF PR&PP evaluation methodology used the case study of a notional example fast reactor design.
- The methodology has since been applied in a number of safeguards-by-design studies of fast reactors.
  - ➢ The methodology is recognized as a comprehensive technology-neutral platform for supporting PR&PP evaluations of various NES design types.
- There are still further opportunities for its application in the design process of future advanced reactor designs, as well as in the consideration of 3S interfaces in NES facilities.

Back-up Slides

GEN IV International Forum

PR Measures and Metrics

Measures and Metrics	Estimated Measure Value Bins (Median)	Proliferation Resistance Qualitative Descriptor[b]
Proliferation Resistance Measures Determined by Intrinsic Features		
Proliferation Technical Difficulty (TD) Example metric: Probability of segment/pathway failure from inherent technical difficulty considering threat capabilities	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-95% (90%)	High
	95-100% (98%)	Very High
Proliferation Cost (PC) Example metric: Fraction of national military budget required to execute the proliferation segment/pathway, amortized on an annual basis over the Proliferation Time	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-100% (90%)	High
	>100% (>100%)	Very High
Proliferation Time (PT) Example metric: Total time to complete segment/pathway, starting with the first action taken to initiate the pathway	0-3 mon (2 mon)	Very Low
	3 mon-1 yr (8 mon)	Low
	1-10 yr (5 yr)	Medium
	10 yr-30 yr (20 yr)	High
	>30 yr (>30 yr)	Very High
Fissile Material Type (MT) Example metric: Dimensionless ranked categories (HEU, WG-Pu, RG-Pu, DB-Pu, LEU)[a]; interpolation based on material attributes (reflecting the preference for using the material and not it's usability in a nuclear explosive device)	HEU	Very Low
	WG-Pu	Low
	RG-Pu	Medium
	DB-Pu	High
	LEU	Very High

Measures and Metrics	Estimated Measure Value Bins (Median)	Proliferation Resistance Qualitative Descriptor[b]
Proliferation Resistance Measures Determined by Extrinsic Measures and Intrinsic Features		
Detection Probability (DP) Example metric: Probability that safeguards will detect the execution of a diversion or misuse segment /pathway	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-95% (90%)	High
	95-100% (98%)	Very High
Detection Resource Efficiency (DE) Example metric: GW(e) years of capacity supported (or other normalization variable) per Person Days of Inspection (PDI) (or inspection $)	<0.01 (0.005 GWyr/PDI)	Very Low
	0.01-0.04 (0.02 GWyr/PDI)	Low
	0.04-0.1 (0.07 GWyr/PDI)	Medium
	0.1-0.3 (0.2 GWyr/PDI)	High
	>0.3 (1.0 GWyr/PDI)	Very High

[a] HEU = high-enriched uranium, nominally 95% ^{235}U;
WG-Pu = weapons-grade plutonium, nominally 94% fissile Pu isotopes;
RG-Pu = reactor-grade plutonium, nominally 70% fissile Pu isotopes;
DB-Pu = deep burn plutonium, nominally 43% fissile Pu isotopes;
LEU = low-enriched uranium, nominally 5% ^{235}U.

[b] These qualitative descriptors are indicative of the relative value of an estimated measure for comparison against competing pathways, and should not be misinterpreted as value judgments of a given pathway or technology with respect to proliferation resistance itself.

PP Measures and Metrics

Metrics	Range/Value			
	High	Medium	Low	Nil
Probability of Detection, P_d	$1 > P_d \geq 0.9$	$0.9 > P_d \geq 0.8$	$0.8 > P_d \geq 0.2$	$0.2 > P_d = 0$
	0.95	0.85	0.5	0.1
Delay Time, t_d (minutes) Nominal value	$60 \geq t_d > 30$ 45	$30 \geq t_d > 10$ 20	$10 \geq t_d > 1$ 5.5	$1 \geq t_d = 0$ 0.5
Response Time, t_r (minutes) Nominal value	$1 \geq t_r = 0$ 0.5	10m $\geq t_r >$ 1m 5.5	30m $\geq t_r >$ 10m 20	60m $\geq t_r >$ 30m 45m
Measures	**Range/Value**			
	High	**Medium**	**Low**	**Nil**
Probability of Adversary Success, PAS Nominal value	$1 > P_s \geq 0.8$ 0.9	$0.8 > P_s \geq 0.5$ 0.65	$0.5 > P_s \geq 0.1$ 0.3	$0.1 > P_s = 0$ 0.05
PP Resources, PPR (% Operating Cost) Nominal value	>10% 10	10%>%>5% 5	5%>%>0% 1	0 0
Consequences, C_t (SNM Theft)	1 SQ of unirradiated or irradiated direct use material	1 SQ of unirradiated indirect use material	1 SQ of irradiated indirect use material	Unsuccessful theft

- Probability of Interruption, $P_I = f(P_d, t_d, t_r)$;
- Assume PAS = 1 – P_I for <u>coarse</u> pathway for conceptual facilities

GEN IV International Forum
Expertise | Collaboration | Excellence