***Workshop on the Proliferation Resistance and Physical Protection Evaluation (PR&PP) Methodology for Generation IV Nuclear Energy Systems***

**University of California, Berkeley · Berkeley, California**
**November 4, 2015**

# GIF PR&PP Program Overview

*Presenter*: Robert Bari, Co-chair
GIF PR&PP Working Group

*Workshop on the Proliferation Resistance and Physical Protection Evaluation (PR&PP) Methodology for Generation IV Nuclear Energy Systems*
University of California, Berkeley · Berkeley, California · November 4, 2015

# Topics

- Goals and Objectives of Workshop
- Technology Goals for Generation IV
- Purpose of PR&PP evaluations in Generation IV
- Overview of PR&PP group and its activities

## Goals and Objectives of Workshop

- *Help workshop participants become more aware of the evaluation methodology and its application.*
- *Obtain feedback to improve implementation by workshop participants.*



## Technology Goals for Generation IV

- *Sustainable Nuclear Energy*
- *Competitive Nuclear Energy*
- *Safe and Reliable Systems*
- *Proliferation Resistance and Physical Protection*

# GIF Goals for PR&PP

***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.***



## *Purpose of PR&PP evaluations in Generation IV*

- **To introduce PR&PP features into the design process at the earliest possible stage of concept development**
- **Both the *intrinsic* (physical and engineering) and *extrinsic* (safeguards and institutional arrangements) characteristics can benefit from incorporating PR&PP risk reduction into considerations of the design**
- **While only the most general features of the design are known initially, PR&PP concepts can be applied to manage risk reduction**
- **As the design matures, increasing detail can be incorporated in the PR&PP evaluation model of the system: progressive refinement**

# Current Terms of Reference

- ***Advise*** *the PG and EG on PR&PP issues related to Gen IV nuclear energy systems*
- ***Maintain capability*** *to perform or direct PR&PP studies on request of GIF*
- ***Monitor*** *the integrity and quality of PR&PP evaluations for GIF (peer review on request)*
- ***Maintain configuration control*** *over the PR&PP methodology, its documentation and revisions*
- ***Strengthen the link*** *with Gen IV system designers, in particular with GIF SSCs*
- ***Promote and facilitate*** *early consideration of PR&PP in the development and design of Gen IV systems*
- ***Maintain cognizance*** *of related GIF activities, e.g., safety, economics*
- ***Maintain cognizance*** *of and interactions with non-GIF activities such as IAEA initiatives and specific national initiatives*
- ***Promote*** *PR&PP goals and broad acceptance of the PR&PP methodology*



# Some Important Definitions

- ***Proliferation resistance*** ***is that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by the host State in order to acquire nuclear weapons or other nuclear explosive devices.***
- ***Physical protection*** ***(robustness) is that characteristic of a nuclear energy system that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices, and the sabotage of facilities and transportation, by sub-national entities and other non-host State adversaries.***

# Assessment Paradigm

CHALLENGES → SYSTEM RESPONSE → OUTCOMES

*Threats* — *PR & PP* — *Assessment*

**Intrinsic**
- Technical Design Features

**Extrinsic (Safeguards/Protection)**
- Institutional Arrangements

Proliferation, theft and sabotage involve **competing actors**.
Important to recognize actors′ perspectives and the human interplay.



# Major Accomplishments

- ***The Methodology*: developed through a succession of revisions – currently in Revision 6 report**
- ***The "Case Study"* approach: an example (sodium-cooled) reactor system was chosen to develop and demonstrate the methodology – resulted in major report**
- ***Joint Efforts with six GIF design* areas (System Steering Committees or SSCs) - resulted in major report**

***All three reports can be obtained at:***

***https://www.gen-4.org/gif/jcms/c_9365/prpp***

## *Some Key Points*

- ***Fundamental differences between host-state proliferation threats and non-state adversary***
- ***Some advanced technologies can offer benefits against non-state threats—but not against host-state adversary***
- ***For Host State, safeguards and safeguardability essential, as well as controls on technology***
- ***Country context of paramount importance to determining proliferation risks associated with Host State***
- ***No such thing as "proliferation proof"—take great care in using term Proliferation Resistance***



## *Potential Future Applications for PR&PP Approach*

- ***Enhancing GIF Designs—begins with the designers***
- ***Enabling Safeguards by Design***
  - o ***Usability of analytical tools by designers and its safeguards team: critical to designers analyzing safeguardability***
- ***Proliferation and Security Concerns Should be Part of Future Global Fuel Cycle Architectures***
- ***PR&PP as a Quality Assurance Tool***
- ***Integration of Safeguards and Security with Safety and other Performance Objectives— challenge of how to do this well***
- ***Harmonize with related efforts (national and international)***
  ***e.g. IAEA/INPRO***

# Some Recent Activities

- Participated in GIF-INPRO meeting at IAEA HQ, March 2015
- GIF Symposium at ICONE23; PRPPWG participant in panel session, May 2015
- Participated in PG/EG meeting in Chiba, Japan May 2015
- Participated in GIF RSWG meeting in Petten, Netherlands, June, 2015



# Recent Activities (cont'd)

- PRPPWG paper presented at Global 2015, Paris, September 2015
- FAQ for PR&PP on GIF open website and now as a tri-fold handout
- Bibliography of PR&PP-related reports has been assembled and now on GIF open website
  - https://www.gen-4.org/gif/jcms/c_71068/prpp-bibliography

# Current PR&PP Activities

- 25th PRPPWG meeting: December 5-6, 2015,
  U.C. Berkeley, host
  -includes today's workshop
  - joint meeting with GIF safety group

- Progress report to GIF EG/PG, October 26-30, 2015, in St. Petersburg, Russia

- Interface meeting with IAEA/INPRO, March 2016



# PRPPWG Membership: Countries and Organizations

- Canada
- China
- Euratom
- France
- IAEA - Observer
- Japan
- NEA - Secretariat
- Republic of Korea
- Russia
- USA

# Overview of the Historical Origins of PR&PP

**Per F. Peterson**
**GIF PRPP Working Group**

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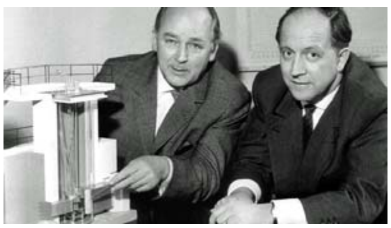
# Implications of Binding Energy: Fission

$$^{235}_{92}U + n \rightarrow {}^{137}_{55}Cs + {}^{97}_{37}Rb + 2n$$

energy balance $Q = 235(7.8\text{MeV}) - 137(8.5\text{MeV}) - 97(8.9\text{MeV})$

$= -200\text{MeV}$



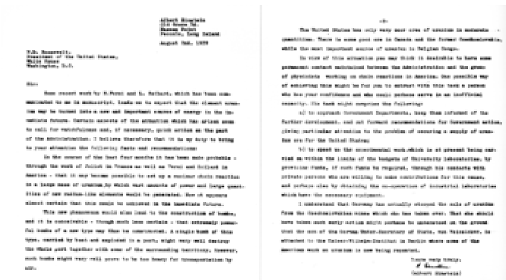
Otto Hahn and Fritz Strassman

Lise Meitner and Otto Frisch

December, 1938 – Hahn and Strassman detect barium in uranium irradiated with neutrons; with this information Meitner and Frisch articulate the theory for how uranium might fission and predict a large release of energy.

# Call to War

*Einstein letter to President Roosevelt: 1939*



*Alerts Roosevelt to potential power of nuclear fission chain reaction and that Germany may be pursuing weapons development. Suggests US government alignment with "group of physicists"*

*→ Birth of Manhattan Project*

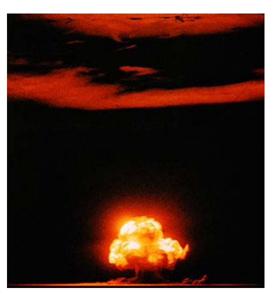


# Los Alamos to Alamogordo: 1942-45

*Oppenheimer leads Manhattan Project*

*Resulted in reactors, diffusion plants, and other nuclear technology devices,*

*...and culminated in Trinity Test at Alamogordo NM on July 16, 1945*



# Hiroshima and Nagasaki: War Ends

American GI standing in rubble of Hiroshima, November 1945

Aftermath of horrible tragedy: rebuilding of Japan (and Europe), proliferation of nuclear weapons and beginning of arms race, peaceful uses of nuclear energy

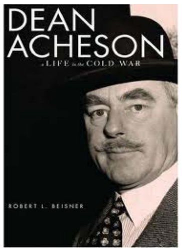


# Managing the Atom: 1946-53

Acheson-Lilienthal Report: 1946

Discussed possible methods for the international control of nuclear weapons and the avoidance of future nuclear war

→ Cold War

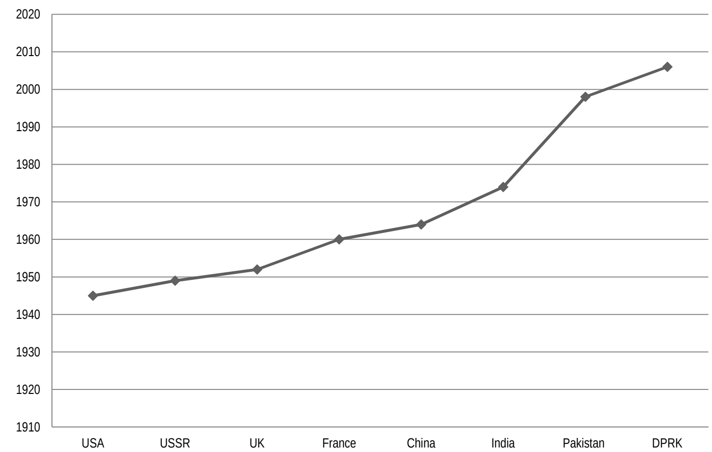



Eisenhower: Atoms for Peace: 1953

Nuclear science and technology to benefit mankind

→ Nuclear power plants

# Country vs. Year of First Nuclear Test




*"I am haunted by the feeling that by 1970, unless we are successful, there may be 10 nuclear powers instead of 4, and by 1975, 15 or 20." –John Kennedy, 1963*



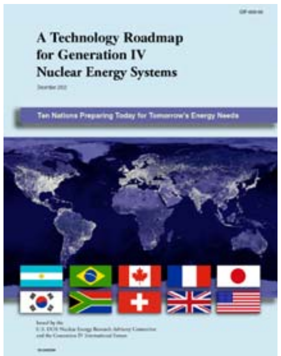
# Key events

- ***1957: Creation of the International Atomic Energy Agency***
  - ***Cold War; concerns about weapons proliferation***
- ***1970: Nuclear Nonproliferation Treaty enters into force***
  - ***Safeguards for civil nuclear facilities***
- ***1989: Fall of Berlin wall***
  - ***Concerns about loose nuclear materials***
- ***2001: 9/11 attack in U.S.***
  - ***Concerns about terrorist attacks on nuclear facilities***
- ***2002: Creation of Gen IV International Forum***
  - ***Goals include PR&PP***


IAEA, Vienna

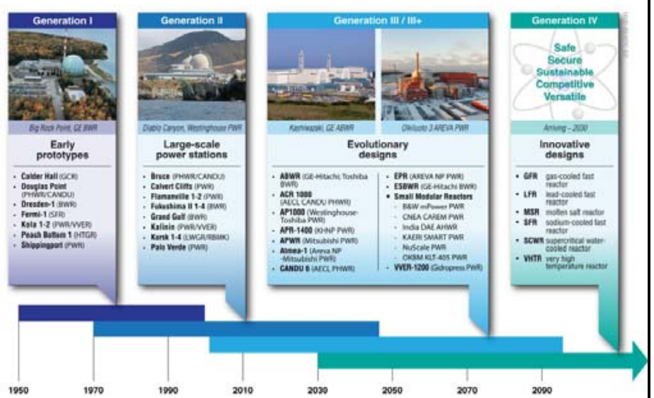
GEN IV International Forum

# Generation IV International Forum




Technology Roadmap, 2002

Generation IV Technology Timeline






GEN IV International Forum

# Generation IV Goals

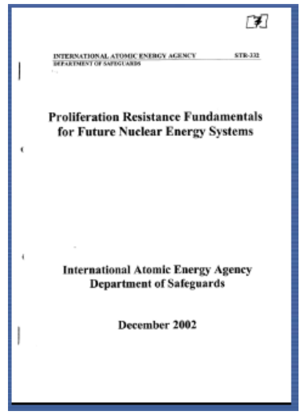
- ***Sustainability***
  - ***Long term fuel supply***
  - ***Minimize waste and long term stewardship burden***
- ***Safety & Reliability***
  - ***Very low likelihood and degree of core damage***
  - ***Eliminate need for offsite emergency response***
- ***Economics***
  - ***Life cycle cost advantage over other energy sources***
  - ***Financial risk comparable to other energy projects***
- ***Proliferation Resistance & Physical Protection***
  - ***Unattractive materials diversion pathway***
  - ***Enhanced physical protection against terrorism***

## Defining PR: The 2002 IAEA Como meeting

- ***Developed the currently accepted definition of "Proliferation Resistance":***

  ***"Characteristic of a nuclear system that impedes diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear explosive devices".***

  ***(Meeting in Como, Italy, December 2002)***


INTERNATIONAL ATOMIC ENERGY AGENCY STR-332
DEPARTMENT OF SAFEGUARDS

Proliferation Resistance Fundamentals for Future Nuclear Energy Systems

International Atomic Energy Agency
Department of Safeguards

December 2002



## Key PR&PP Working Group conclusion: Analysis of PR, PP, safety and reliability can use similar approaches

**ACCIDENT INITIATORS → SYSTEM RESPONSE → CONSEQUENCES**

**THREATS → SYSTEM RESPONSE → OUTCOMES**

- ***Safety and PR&PP should be considered from the earliest stages of design***
  - ***Flow diagrams: preliminary safety hazard and PR&PP target identification and categorization***
  - ***Physical arrangement: external events shielding, access control***
- ***Safety and PR&PP can be complementary (in some ways) and in conflict (in others)***
  - ***Design to maximize the complementary***

# PR&PP Methodology is synergistic with INPRO Methodology

- *International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)*
  - *Assessment checks for use of best practices*
  - *Has commonality with General Design Criteria for reactor safety*
- *Complements PR&PP scenario-based assessment*



# Some examples of synergy/conflict

- *Emergency response*
  - *Clear conflicts between safety and physical security (personnel access/egress)*
  - *Reactor passive safety systems and remote handling of nuclear materials helps mitigate this conflict*
- *Human performance*
  - *Clear synergies between safety, reliability, and physical security (background checks, access controls, tamper-evident tags and seals, two-man rules, supervisor observations)*
- *Quality Assurance (QA)*
  - *Clear synergies between safety, reliability, and international safeguards (supports effective Design Information Verification (DIV) for IAEA safeguards)*
- *Plant Probabilistic Risk Assessment (PRA)*
  - *Systematic identification of transient/accident initiating events and assessment of frequency*
  - *Clear synergies between safety, reliability, and international safeguards (assure that transients and accidents do not result in a false alarm (Type I error) and need for IAEA investigation)*

## The Safeguards Technical Objective

### IAEA INFCIRC 153 Para. 28

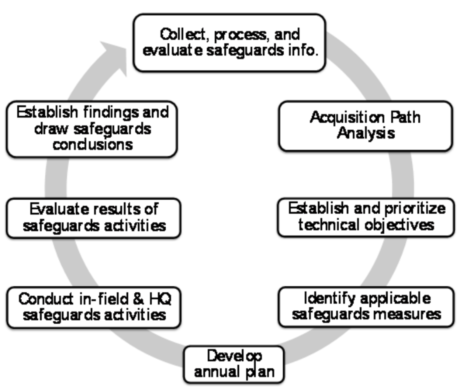
*... the **objective of safeguards** is the **timely detection** of **diversion of significant quantities** of **nuclear material** from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and **deterrence** of such diversion by the **risk of early detection**. …*

*NOTE:*

- ***Timeliness***
- ***Significant quantities***
- ***Deterrence by risk of early detection***



## The current IAEA State Level Concept (SLC) for nuclear safeguards




Adapted form Cooley, J. "IAEA State Level Concept." ESARDA Joint Meeting, November 2013 •

**State-Level Safeguards Objectives:**

A. Detect undeclared nuclear material or activities in the State
B. Detect undeclared production or processing of nuclear materials in declared facilities or locations outside facilities (LOFs)
C. Detect diversion of declared nuclear material in declared facilities or LOFs

# Physical Security Responsibilities

**IAEA INFCIRC 225 Rev. 5**

- ***"Each State carries the full responsibility for nuclear security. Specifically,***
  - ***to provide for the security of nuclear and other radioactive material and associated facilities and activities;***
  - ***to ensure the security of such material in use, storage or in transport;***
  - ***to combat illicit trafficking and the inadvertent movement of such material; and***
  - ***to be prepared to respond to a nuclear security event."***
- ***"The international community has agreed to strengthen the Convention on the Physical Protection of Nuclear Material, and it has cooperated with the IAEA in establishing nuclear security guidance.***

# *Overview of the PR&PP Methodology*

***Presenter*: Jeremy Whitlock, Co-chair**
***GIF PR&PP Working Group***

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# *Assessment Paradigm*

**CHALLENGES → SYSTEM RESPONSE → OUTCOMES**

***Threats*** ***PR & PP*** ***Assessment***

**Intrinsic**
- Technical Design Features

**Extrinsic (Safeguards/Protection)**
- Institutional Arrangements

Proliferation, theft and sabotage involve **competing actors**.
Important to recognize actors′ perspectives and the human interplay.

## Evaluation Framework

**Challenges**
- Threat Definition

↓

**System Response**
- System Element Identification
- Target Identification and Categorization
- Pathway Identification and Refinement
- Estimation of Measures

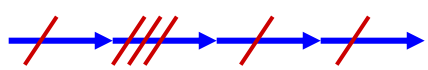
↓

**Outcomes**
- Pathway Comparison
- System Assessment & Presentation of Results



## Approach

- ***Pathway analysis: Intuitive way to describe & analyze proliferation, theft or sabotage scenarios***
- ***Pathways: Potential sequences of events followed by the proliferant state or adversary to achieve its objectives***
  - ***Along any pathway the proliferant state or adversary will encounter difficulties, barriers, or obstacles, all of which are collectively called "proliferation resistance" or "physical protection robustness"***



## Summary of PR & PP Threat Dimensions

| | Proliferation Resistance | Physical Protection |
|---|---|---|
| **Actor Type** | • Host State | • Outsider<br>• Outsider with insider<br>• Insider alone<br>• Above and non-Host State |
| **Actor Capabilities** | • Technical skills<br>• Resources (money and workforce)<br>• Uranium and Thorium resources<br>• Industrial capabilities<br>• Nuclear capabilities | • Knowledge<br>• Skills<br>• Weapons and tools<br>• Number of actors<br>• Dedication |
| **Objectives** (relevant to the nuclear fuel cycle) | Nuclear weapon(s):<br>• Number<br>• Reliability<br>• Ability to stockpile<br>• Deliverability<br>• Production rate | • Disruption of operations<br>• Radiological release<br>• Nuclear explosives<br>• Radiation Dispersal Device<br>• Information theft |
| **Strategies** | • Concealed diversion<br>• Overt diversion<br>• Concealed facility misuse<br>• Overt facility misuse<br>• Independent clandestine facility use | • Various modes of attack<br>• Various tactics |



## Summary

- ***The PR&PP Methodology is scenario based – systematic and comprehensive***
- ***Potential users: designers, program policy makers, national regulators, international agencies, and other stakeholders***
- ***Expertise needed: familiarity with PR&PP methodology, the system design, and the general requirements of non-proliferation (e.g. international safeguards) and physical protection. Can be a team-effort.***
- ***Can be applied at any time in the design process, and throughout the fuel cycle.***
- ***Technology (system) independent – e.g. can be applied to emerging SMR designs outside of GIF scope***

GEN IV International Forum

## *Summary (cont'd)*

- ***<u>Level of effort</u>: depends on user's needs, and stage of design – from a "pared-down" scoping study involving one expert, to a full-blown analysis involving a team***
- ***<u>Time needed</u>: Depending on type of application, from a few weeks to a year (for full analysis with multiple scenarios)***
- ***<u>Form of results</u>: Depends on user's needs and intended audience – can be qualitative, or detailed and highly quantitative***
- ***Complementary to other methodologies, eg. INPRO (INPRO assessments can assure that best practices have been considered, and adopted where appropriate, in system design. PR&PP assessments can assure that the system response to PRPP challenges will be acceptable.)***

# Major Elements of the PR&PP Methodology

*Presenters*: Per Peterson and Giacomo Cojazzi
GIF PR&PP Working Group

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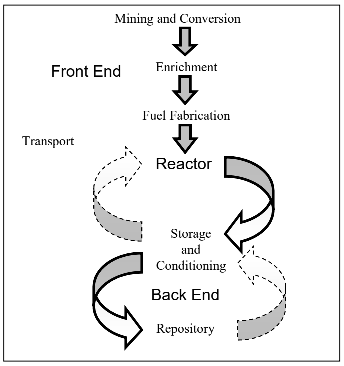
# System Element Identification

- ***Decomposes nuclear system into system elements to permit pathways analysis***
  - *Materials, facilities, processes, fuel cycle facilities, reactors, storage for fresh and spent fuel, nuclear research facilities, transportation links, etc.*
- ***Considers the location of operations and materials, their accessibility and characteristics, and elements such as***
  - *Material Balance Areas (MBAs),*
  - *Key Measurement Points (KMPs),*
  - *Safeguards and physical protection systems.*
- ***Identifies interfaces with other (nuclear) systems that are not part of the Gen IV system being evaluated.***




When detailed design information is not available, assumptions are documented and become a part of the system design bases

## Target Identification

**PR Target:**

1. *Nuclear material that can be diverted,*
2. *Equipment and process that can be misused to process undeclared nuclear materials, or*
3. *Equipment and technology that can be replicated in an undeclared facility.*

**PP Target**

1. *Nuclear material to be protected from theft,*
2. *Information to be protected from theft, or a*
3. *Set of equipment to be protected from sabotage.*

Outcome: Identify potential targets that:
1) designers should consider protecting, and with which
2) decision makers should be concerned.



## Pathway Identification and Refinement

- ***Pathways: Potential sequences of events/actions followed by the proliferant state or adversary to achieve its objective (proliferation, theft or sabotage). A pathway is composed of segments***
  - *Segment={Action, Target, System Element(s)}*
    - *Internal: Within the system being assessed*
    - *External: Outside of the system being assessed*
- ***Can be illustrated using: logic diagrams, event trees, adversary sequence diagrams, verbal descriptions, etc.***

# Estimation of Measures

Outcome: Results available from early in the design process based on available information.

*Progressive Approach*

- ***Initial coarse path analysis uses qualitative assessment of measures (Expert Judgement***
- ***Progressive refinement of me quantitative and sophisticate***
- ***Quantitative assessment***

Outcome: More detailed and comprehensive results with lower uncertainty available when more detailed evaluation is conducted using more detailed information.

***Some measures are estimated for:***

- ***individual segments then aggregated to estimate the value of the measure for each pathway***
  - ***e.g. Proliferation Time***
- ***a complete pathway, and are not meaningful on a segment basis.***
  - ***e.g. Consequences; Material Type***





# The PR Measures

- ***Proliferation resistance***
  - **Proliferation Technical Difficulty**
  - **Proliferation Cost**
  - **Proliferation Time**
  - **Fissile Material Type**
  - **Detection Probability**
  - **Detection Resource Efficiency**

Each measure represents major system characteristics that would be important impediments to the strategy of a proliferant nation (PR).

## The PP Measures

- *Physical protection*
  - **Probability of Adversary Success**
  - **Consequences**
  - **Physical Protection Resources**

Each measure represents major system characteristics that would be important impediments to the strategy of a non-host-state group attempting theft or sabotage (PP).



## Example Metrics and Estimated Measure Scales

| 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 |

*** Material Type Description**
**HEU** = high-enriched uranium, nominally 95% 235U;
**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 plutonium, nominally 5% 235U.

## Comparison of Material Categorization

| IAEA Category[1] | IAEA Verification Time[1] | IAEA Conversion Time[1] | PR&PP[2] | M&M[3] | DOE attractiveness level[4] |
|---|---|---|---|---|---|
| DIRECT USE (unirradiated) | 1 month | HEU, Pu, U233 metal (7-10 days) | VL (HEU) | WG-Pu, HEU>90% U236, U233 with U232<25 ppm | B |
| | | | L (WG-Pu) | Pu, Np, HEU>70% U236 U233 with U232>25 ppm | |
| | | HEU, Pu, U233 in unirradiated compounds (1 - 3 weeks) | M (RG-Pu) | HEU≥20% U236, Fresh TRU, Pu w/ Pu238 > 6% | C |
| (irradiated) | 3 months | HEU, Pu, U233 in irradiated compounds (1 - 3 months) | H (DB-Pu) | | |
| INDIRECT USE (unirradiated) | 1 year | U < 20% U236 and U233, Th (1 year) | VH (LEU) | Am+Cm, LEU<20% U236, Pu w/ Pu238 > 80%. | D |
| | | | | Cm, LEU<10% U236, HLW solution, | E |
| (irradiated) | | | | LEU<6% U236, NU, DU, Th | |

*Table 2.10,*
*GIF PRPP Methodology,*
*Rev. 6 (2011)*



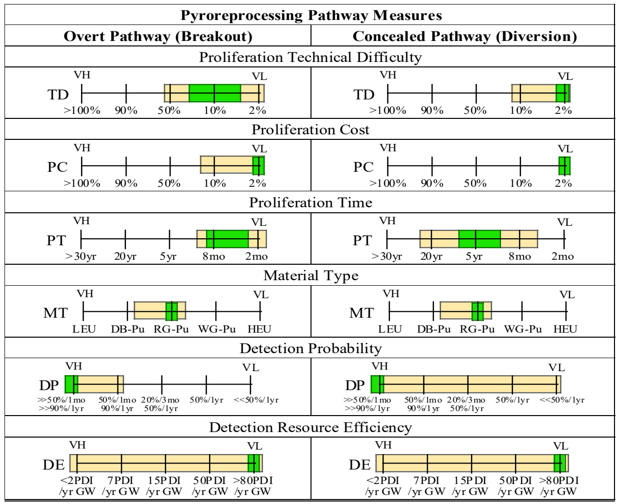
# *Pathway Comparison*

- ***Pathway analysis considers multiple pathways.***

**Key goals**

1. Identify the most important pathways, and feed back useful information to designers to reduce or eliminate these pathways as early as possible.
2. Allow program managers and policy makers to compare options for R&D, the deployment of fuel cycles, and the deployment of other elements of nuclear technology.

## Presentation of results: one example – a qualitative assessment comparison table






## Results tailored (in scope and timing) to meet end-user needs:

- ***SYSTEM DESIGNERS: detailed analysis (facility, target level), perhaps incomplete design as it evolves, to facilitate design decisions***
- ***POLICY MAKERS, EXTERNAL STAKEHOLDERS: high-level analysis (dominant, system-level pathways), to facilitate policy-level decisions, or high-level decisions between technology options***
- ***Different levels of detail tailored to suit end-user, but must remain transparently connected***
- ***In all cases must convey:***
  - ***credibility,***
  - ***accuracy,***
  - ***comprehensiveness (representative pathways, efficient frontier),***
  - ***level of uncertainty,***
  - ***sensitivity analysis, and***
  - ***insight gained from qualitative expert judgment***

## Conclusions

- ***Pathways provide an intuitive approach that promotes understanding and designer innovation***
- ***Analytical and capable of producing objective results***
- ***Facilitates assessment during the design process and throughout the full life cycle***
  - ***Assumptions are documented and become a part of the system design bases and functional requirements***
- ***Guides designers to develop systems that are more resistant to proliferation and robust against sabotage and theft***
- ***Provides information to program policy makers to aid in making decisions***

More detailed information describing the PR&PP methodology can be found in the PR&PP Methodology Report (Rev.6, 2011), www.gen-4.org/Technology/horizontal/PRPPEM.pdf

# PR&PP Case Study: ESFR System Description

*Presenters: Jean Cazalet and Ike Therios*
*GIF PR&PP Working Group*

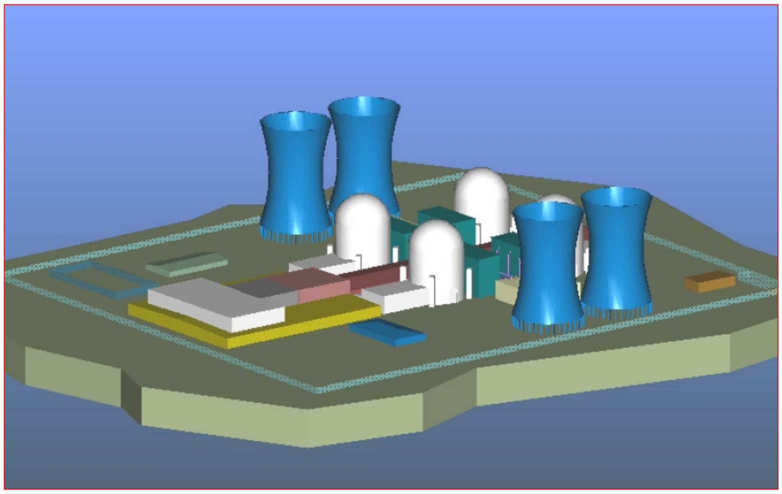
***Workshop on the Proliferation Resistance and Physical Protection Evaluation (PR&PP) Methodology for Generation IV Nuclear Energy Systems***
**University of California, Berkeley · Berkeley, California · November 4, 2015**

## Example Sodium Fast Reactor System

The baseline ESFR nuclear energy system is a hypothetical Generation IV system that includes, in a single site:

- The power plant(s) - 4 identical sodium fast reactors, based on the AFR-300, one of the concepts submitted to the Generation IV Roadmap.
- Staging area/subassembly washing station – a building located adjacent to the 4 reactor buildings used for fresh and spent fuel in transit and for washing spent fuel subassemblies before placing them in storage.
- Fuel Storage building – A facility to store (1) spent fuel discharged from the reactors waiting for processing, and (2) re-fabricated fuel waiting to be transferred to the reactors.
- Fuel Cycle Facility – A spent fuel processing facility based on dry recycling technology (pyroprocessing).
- LWR Spent Fuel Storage Facility – A facility to store LWR spent fuel assemblies that are used as a source of make up fissile material for the AFR-300 reactors.

# ESFR Nuclear Energy System Island

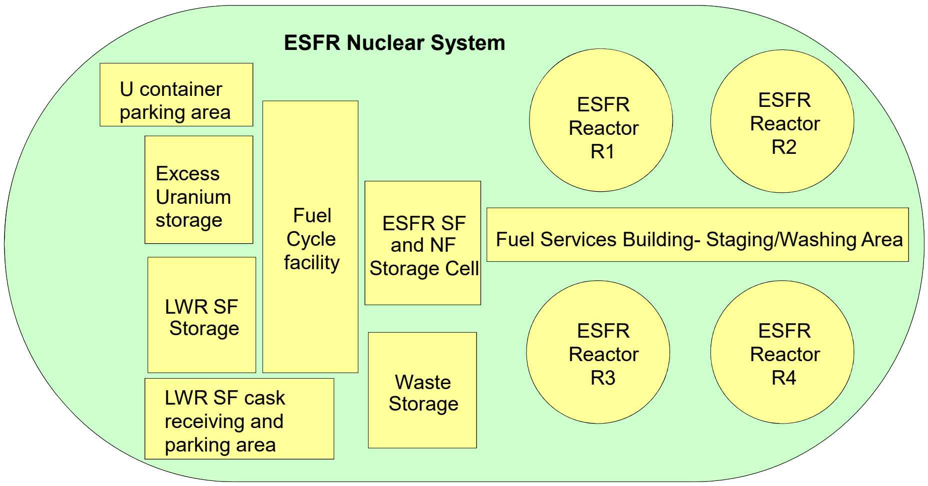




# Baseline ESFR System Assumptions

- The fast reactors are operated in a net transuranic (TRU) burning mode, so make-up fissile material must be brought to the site to re-fabricate new fast reactor fuel. The reactors are fueled with metal TRU fuel and are of pool-type.
- Spent fuel is stored in a storage basket inside the primary sodium tank for one refueling cycle.
- Passive safety characteristics (reactivity response, natural primary coolant circulation, passive decay heat removal) typical of recent sodium-cooled metal-fueled fast reactor designs are assumed.
- Make-up TRU fissile material is obtained from reprocessing LWR (PWR) spent fuel assemblies at the site's fuel cycle facility.
- Fresh fast reactor fuel is fabricated at the site's fuel cycle facility from recycled spent fast reactor fuel and make-up TRU from PWR.
- Capacities in the storage facilities and staging/washing area are the minimum required for continuous site operations.

# Baseline ESFR Nuclear System Elements

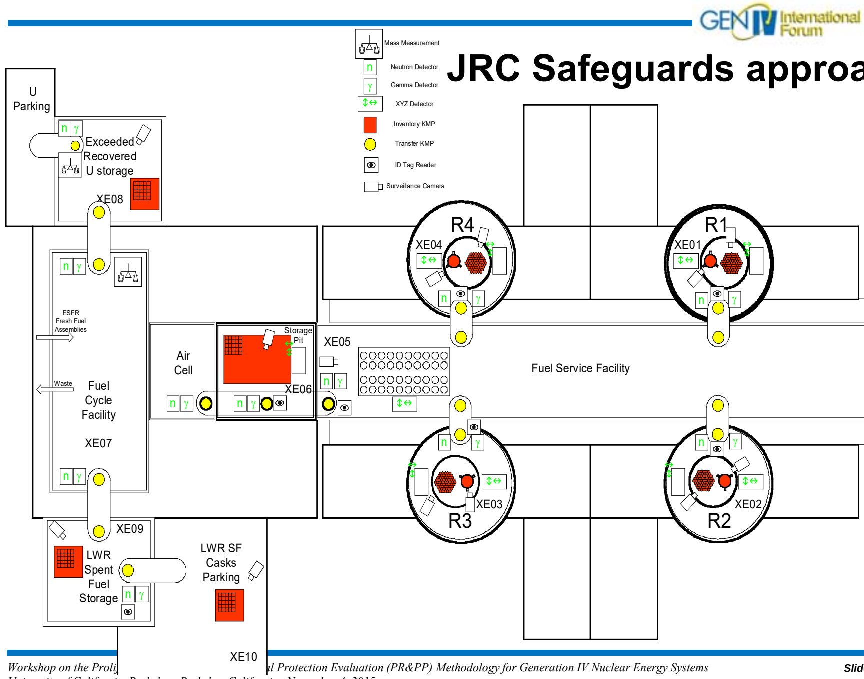





# ESFR System Safeguards and PPS

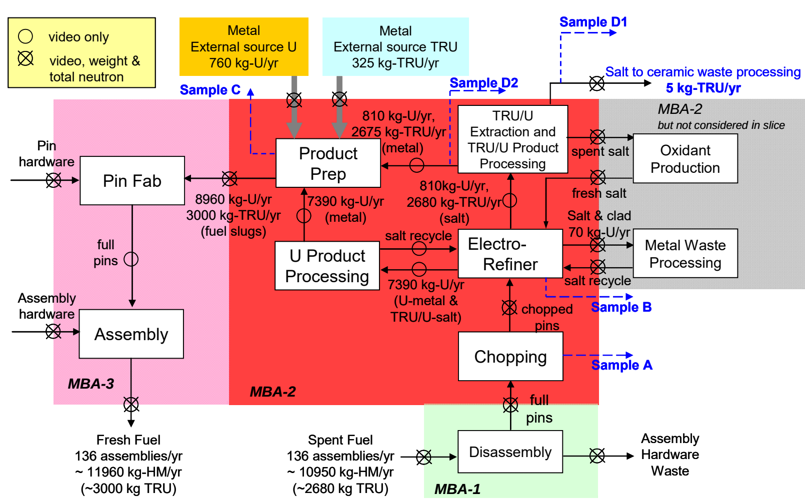
- Safeguards approach (including Material Balance Areas, and Key Measurement Points locations) for the reactor and fuel storage facilities developed by JRC
- Preliminary safeguards approach for the fuel cycle facility developed from contributions by LANL, AECL, INL, and ANL
- Time Based Interruption analysis of Physical Protection System (PPS) for ESFR developed by Sandia.

## JRC Safeguards approach






## Fuel cycle facility preliminary Safeguards approach



## ESFR Design Variations

- Slightly larger core (1000 MWth vs. 800 MWth) with:
  - conversion ratio similar to baseline case (DV0)
  - lower conversion ratio to result in a deep burner case requiring fuel with higher Pu enrichment (DV1)
  - higher conversion ratio to result in a break-even core without any blankets (DV2)
  - even higher conversion ratio to result in a breeder case using both external and internal U blankets (DV3)

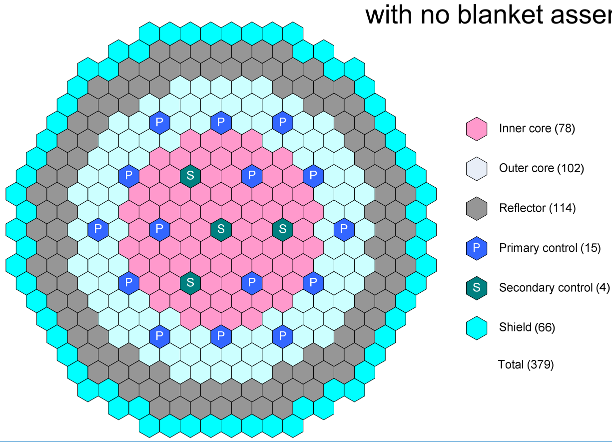


## Key Core Performance Parameters of Various Conversion Ratio Cores

| | Baseline ESFR | Design Variation 0 | Design Variation 1 | Design Variation 2 | Design Variation 3 |
|---|---|---|---|---|---|
| | Baseline 800 MWt TRU CR = 0.64 | Reference 1000 MWt TRU CR = 0.73 | 1000 MWt TRU CR = 0.22 | 1000 MWt TRU CR = 1.00 No Blankets | 1000 MWt TRU CR = 1.12 Radial & Internal Blankets |
| Nominal Electric Power, MWe | 300 | 350 | 350 | 350 | 350 |
| Thermal Power, MWt | 800 | 1000 | 1000 | 1000 | 1000 |
| Fuel composition (core / blanket) | Metallic U-TRU-10Zr / - | Metallic U-TRU-10Zr / - | Metallic U-TRU-20Zr / - | Metallic U-TRU-10Zr / - | Metallic U-TRU-10Zr / U-Zr |
| Cycle length, months | 12 | 12 | 6.6 | 12 | 12 |
| Capacity factor | 85% | 90% | 90% | 90% | 90% |
| Number of assemblies (core / blanket) | 102 / - | 180 / - | 180 / - | 180 / - | 108 / 72 |
| Number of batches (core / internal / radial) | 3 / - / - | 4 / - / - | 8 / - / - | 4 / - / - | 4 / 4 / 6 |
| Residence time, days (core / internal / radial) | 930/ - / - | 1300/ - / - | 1445/ - / - | 1300/ - / - | 1300/1300/1970 |
| Pins per assembly (core / internal / radial) | 271 / - / - | 271 / - / - | 324 / - / - | 271 / - / - | 271 / 127 / 127 |
| Structural pins per assembly | 0 | 0 | 7 | 0 | 0 |
| Average TRU enrichment, % | 24.9 | 22.1 | 58.5 | 14.4 | 19.3 |
| Fissile/TRU conversion ratio | 0.8 / 0.64 | 0.84 / 0.73 | 0.55 / 0.22 | 0.99 / 1.00 | 1.07 / 1.12 |
| HM/TRU inventory at BOEC, MT | 9.0 / 2.2 | 13.2 / 2.9 | 6.9 / 3.9 | 18.5 / 2.8 | 20.5 / 2.5 |
| Discharge burnup (ave/peak), MWd/kg | 80 / ? | 93 / 138 | 185 / 278 | 67 / 103 | 92 /146 |
| TRU consumption rate, kg/year | 80 | 81.6 | 241.3 | -1.2 (gain) | -33.2 (gain) |

# Design Variations Radial Core Layout

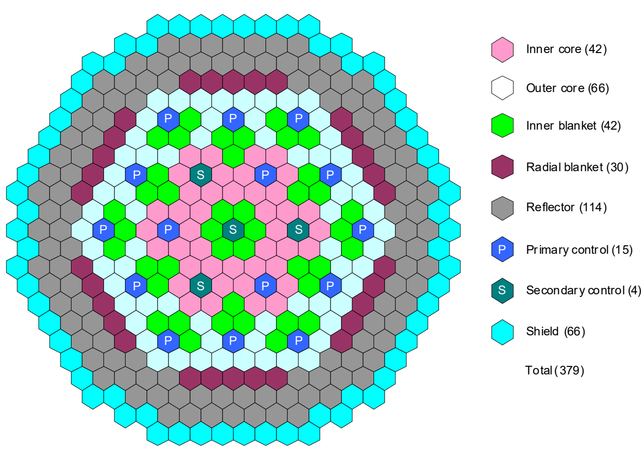
- Design Variation 0: 1000 MWth Core with TRU CR=0.73;
- Design Variation 1: 1000 MWth Core with TRU CR=0.22;
- Design Variation 2: 1000 MWth Core with TRU CR=1.00, with no blanket assemblies






# Design Variations Radial Core Layout

- Design Variation 3: 1000 MWth Core with TRU CR=1.12, with Internal and Radial Blankets

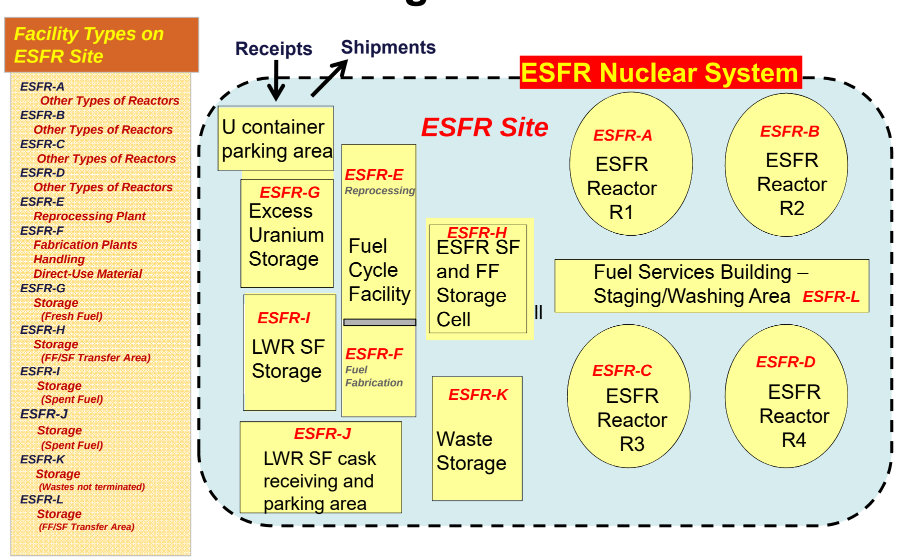


# ESFR Site Facilities: Safeguards Categories

- "Other Types of Reactors" – 4 SFRs
- "Storage"
  - Storage for 1) SFR SF 2) FF (TRU)
  - LWR SF Storage – source for fissile material
  - Staging area / FA washing station – SF, FF for SFRs
- "Reprocessing" – Reprocessing facility
- "Fabrication Plants Handling Direct Use Material"
  - Fast Reactor Fuel from LWR SF recycled SFR fuel
  - Fresh TRU fuel (direct use material)



# ESFR Safeguards Context



## ESFR Safeguards Concerns: Conversion II

- Material is reprocessed “bulk” material
- Converted to form suitable for fuel fabrication
  - TRU / predominately Pu – for TRU fresh fuel
- Diversion pathways / strategies:
  - Divert material and convert for Pu explosive device




## ESFR Safeguards Concerns: Fuel Fabrication

- Material starts as “bulk”
  - Natural U / Reprocessed U / TRU
- Fabricated into fuel = “item form”
  - TRU fuel – fuel for Burner reactors – SFR
- Diversion pathways / strategies:
  - Fuel diverted for clandestine Pu production reactor
  - Fuel diverted for clandestine enrichment LEU stock
  - TRU fuel - divert to Conv II facility for nuclear explosives

## ESFR Safeguards Concerns: Reactors

- Material starts as "item" form
- Burned in reactors – exits in "item" form
  - TRU fuel – unirradiated direct use material
  - Core Fuel/Spent Fuel is always irradiated direct use material
- Diversion pathways / strategies
  - Spent Fuel and secret targets diverted for Pu reprocessing
  - Fuel diverted for clandestine enrichment LEU stock
  - Fresh TRU fuel-divert to Conv II facility for nuclear explosives



## ESFR Safeguards Concerns: Reprocessing

- Material starts as "item" form
- Reprocessed into "bulk" U and TRU (ESFR)
  - Reprocessing of U and TRU from FPs
  - Form of product – U and TRU
  - Separated material goes to Conv II facility for preparation into:
    - Material for fuel
    - Material for explosive
- Diversion pathways / strategies
  - Spent Fuel and secret targets diverted for Pu reprocessing
  - Fuel diverted for clandestine enrichment LEU stock
  - Fresh TRU fuel-divert to Conv II facility for nuclear explosives

## ESFR Safeguards Concerns: SF Management

- Spent Fuel material starts/stays in "item" form
- Stored until…
  - Disposed in repository – Once-through fuel / wastes from ESFR
  - Sent to reprocessing – ESFR
- Diversion pathways/ strategies
  - Spent Fuel and secret targets in casks diverted for Pu reprocessing
  - Future Pu "mine"



## IAEA Safeguards Measures

- ***INFCIRC/153 SGs - Material Control and Accountancy***
  - ***Auditing of records and reports – "The Books"***
  - ***Verification of material accountancy – NDA and DA***
  - ***Containment and Surveillance***
    - ***Seals***
    - ***Surveillance – cameras/radiation detectors***
- ***AP – Nuclear Fuel Cycle Analysis of State***
  - ***Undeclared activities***
    - ***Environmental Sampling (ES)***
  - ***Undeclared facilities***
    - ***ES, satellite photo analysis, open source analysis***
  - ***Direction of nuclear program – peaceful?/military?***

## ESFR International Safeguards Summary

- IAEA safeguards missions at ESFR
  - Complex site – multiple nuclear fuel cycle facilities
  - Contains direct-use material and means to extract it
  - Application of CSA or AP with broader conclusion
  - Site and Sector Approaches



## Threat Space and Scenarios Considered

- Host State Threat
  - Concealed diversion of nuclear material from an ESFR facility
  - Concealed misuse to produce weapons-usable material in an ESFR facility
  - "Break-out" and overt misuse or diversion from an ESFR facility
- Sub-national Threat
  - Theft of nuclear material from an ESFR facility
  - Sabotage of ESFR facility system elements

# Clarification / Questions

## Overview of the ESFR Case Study

***Presenter*: Robert Bari**
***GIF PR&PP Working Group***

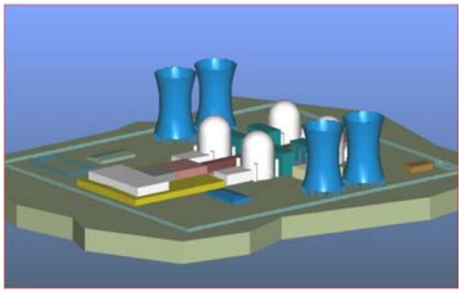
*Workshop on the Proliferation Resistance and Physical Protection Evaluation (PR&PP) Methodology for Generation IV Nuclear Energy Systems*
**University of California, Berkeley · Berkeley, California · November 4, 2015**

## PR&PP Case Study Background

- *The PR&PP Evaluation Methodology was developed with the aid of a series of studies that considered a hypothetical "Example Sodium Fast Reactor" (ESFR) nuclear energy system*
- *Further progress required a more comprehensive evaluation of a complete reactor/fuel cycle system*
  - *to gain practical experience within the application process*
  - *to discern the needs for further methodology development and presentation of results*
  - *to confirm the usefulness and usability of the evaluation methodology*
  - *to demonstrate that designers can obtain practical guidance through application of the methodology*
  - *to demonstrate the capability to apply the PR&PP evaluation framework at different levels of detail, corresponding to different efforts and resources.*
- *For these reasons, the PR&PP Working Group undertook a two-year Case Study.*

# ESFR studies objectives

1. Exercise the GIF PR&PP Methodology for a complete Gen-IV reactor/fuel cycle system
2. Demonstrate, via the comparison of different design options, that the Methodology can generate meaningful results
   - For designers
   - For decision makers
3. Provide examples of PR&PP evaluations for future users
   - Facilitate transition to other studies
   - Facilitate other ongoing efforts (e.g., INPRO)





# Lessons learned at scoping level

- Each PR&PP assessment should start with a Qualitative Analysis allowing scoping of the study, of the assumed threats and identification of targets, system elements etc.
  – need to include detailed guidance for qualitative analyses in methodology
- Role of experts is essential
  – need for PR and PP experts and expert elicitation techniques
- Qualitative analysis offers valuable results at preliminary design level. Can directly address TD, PT, PC, MT. DE and especially DP are harder to quantify

# Subgroup sessions for this Workshop

- *Use the ESFR as the example system to further elucidate the application of the methodology*
- *Encourage workshop participants to interact with working group members on specific applications of the methodology*
- *Develop lessons-learned from this exercise for methodology improvement and communication*



# Subgroup sessions

- *Subgroup sessions by Threat/Strategy scenarios*
  - *Host-State / Concealed Diversion and/or Misuse (Facilitators: G. Cojazzi, R. Bari, K. Hori)*
  - *Host-State / Overt Diversion and/or Misuse (Facilitators: J. Whitlock, J. Pilat)*
  - *Sub-national group / Theft & Sabotage (Facilitator: J. Cazalet, P. Peterson)*
- *Topics for each subgroup to discuss, using hand out reference materials*
  - *Review the threat definition*
  - *Identify ESFR system elements and targets*
  - *Identify representative pathway*
  - *Estimate measures for representative pathway*
  - *Compare and discuss pathways for the ESFR baseline design*

## Previous Lessons Learned from the ESFR Case Study

***Presenter*: Robert Bari**
***GIF PR&PP Working Group***

***Workshop on the Proliferation Resistance and Physical Protection Evaluation (PR&PP) Methodology for Generation IV Nuclear Energy Systems***
**University of California, Berkeley · Berkeley, California · November 4, 2015**

## Lessons learned at scoping level-recap

- ***Each PR&PP assessment should start with a Qualitative Analysis allowing scoping of the study, of the assumed threats and identification of targets, system elements etc.***
  - ***need to include detailed guidance for qualitative analyses in methodology***
- ***Role of experts is essential***
  - ***need for PR and PP experts and expert elicitation techniques***
- ***Qualitative analysis offers valuable results at preliminary design level. Can directly address TD, PT, PC, MT. DE and especially DP are harder to quantify***

## Proliferation resistance lessons (1)

- ***Completeness in diversion pathways can be ensured***
  - ***consideration of every target for the specific threats under consideration***
  - ***systematically searching for plausible scenarios that could implement the potential proliferant Host State's strategies to divert the target material.***
- ***A set of diversion pathway segments can be developed and the proliferation resistance measures for each pathway can be determined.***
- ***Methodology can compare and distinguish the proliferation resistance of different design choices. Methodology can provide useful information to authorities, officials, and designers.***



## Proliferation resistance lessons (2)

- ***Misuse, for achieving weapons-usable fissile material, is a complex process,***
  - ***not a single action on a single piece of equipment***
  - ***an integrated exploitation of various assets and system elements.***
- ***Given a proliferation strategy some measures are likely to dominate over the others, and within a measure some segments will dominate the overall pathway estimate.***
- ***Breakout is a modifying strategy within the Diversion and Misuse threats and takes various forms that depend upon intent and aggressiveness, and ultimately the proliferation time assumed by a proliferant state.***

## Proliferation resistance lessons (3)

- ***Qualitative analysis can***
  - *produce traceable, accountable, and dependable results*
  - *produce useful results to system designers even when detailed information is largely missing (e.g., to provide functional requirements)*
  - *identify small differences in the rationale and in the measure estimates*



## Physical protection lessons (1)

- ***For theft scenarios, multiple target and pathways exist; however, the most attractive target materials appeared to be located in a few target areas***

- ***For radiological sabotage scenarios five primary attack strategies should be considered:***
  - *loss of cooling,*
  - *reactivity,*
  - *direct attack,*
  - *fire/chemical, and*
  - *other forms of attack.*

## Physical protection lessons (2)

- ***For theft and sabotage scenarios where early detection probability was low, the response force time had the greatest impact on adversary success.***
- ***For theft and sabotage scenarios where early detection probability was high, probability of adversary success decreased rapidly as response times decreased.***



## Indicated improvements to methodology

- ***Proliferation Resistance***
  - ***practical use of some measures needs further investigation***
  - ***metrics might need some additional investigation***
- ***Physical Protection***
  - ***closer examination of the qualitative methods and the grouping of qualitative values for coarse pathway assessment***
  - ***include more systematic consideration of the response force deployment strategy***

*Subgroup session: Host-State Concealed Diversion*

*Subgroup Session Facilitators: Robert Bari and Giacomo G.M. Cojazzi*
*GIF PRPP Working Group*

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**University of California, Berkeley · Berkeley, California· November 4, 2015**

# *Goals for session*

- *Review the ESFR threat definition*
  - *Focus subgroup discussion on threat of diversion of nuclear material*
- *Identify ESFR system elements and diversion targets*
- *Identify a representative pathway*
- *Estimate PR measures for representative diversion pathway*
- *Discuss diversion pathways for the ESFR case study*

# PR&PP Evaluation Framework

**Challenges**
- Threat Definition

↓

**System Response**
- System Element Identification
- Target Identification and Categorization
- Pathway Identification and Refinement
- Estimation of Measures

↓

**Outcomes**
- Pathway Comparison
- System Assessment & Presentation of Results



# Proliferation Resistance Measures and Metrics

| Measures and Metrics | Metric Scales Bins (Median) | Proliferation Resistance |
|---|---|---|
| **Proliferation Technical Difficulty (TD)** Example metric: Probability of 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 resources for military capabilities | 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 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, RGPu, DB-Pu, LEU); interpolation based on material attributes | HEU | Very Low |
| | WG-Pu | Low |
| | RG-Pu | Medium |
| | DB-Pu | High |
| | LEU | Very High |
| **Detection Probability (DP)** Example metric: Cumulative detection probability | A | Very Low |
| | B | Low |
| | C | Medium |
| | D | High |
| | E | 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 |

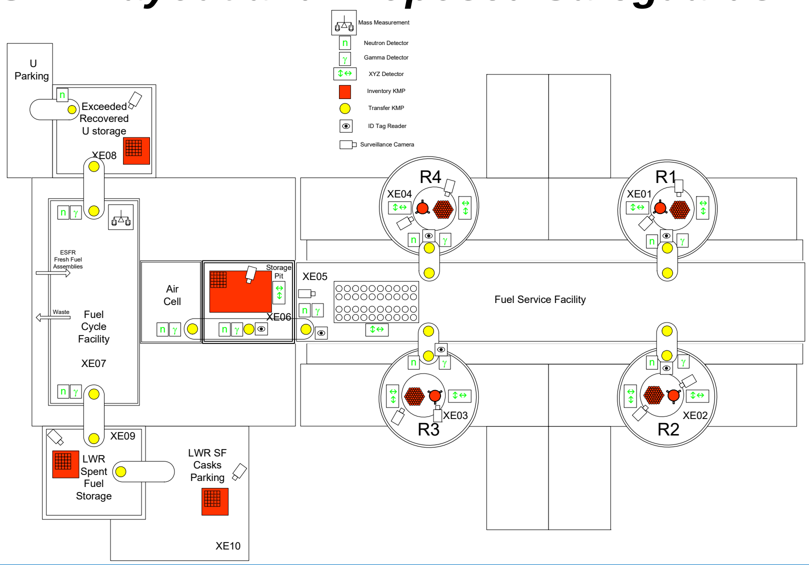
**Material Type Description**

**HEU** = high-enriched uranium, nominally 95% 235U;
**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% 235U.

**Detection Probability**

A - Significantly lower cumulative detection probability than the IAEA detection probability and timeliness goal for depleted, natural, and LEU uranium.
B - 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of depleted, natural, and LEU uranium).
C - 20% in 3 months, 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of spent fuel/irradiated material).
D - 50% in 1 month, 90% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity HEU/separated Pu).
E - Significantly greater cumulative detection probability than the IAEA detection probability and timeliness goal for HEU/separated Pu.

# ESFR Layout and Proposed Safeguards

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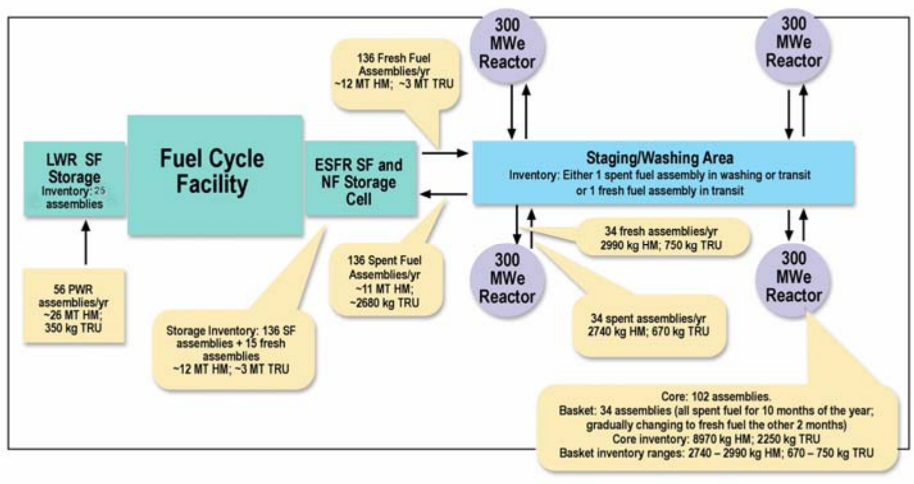
Slide 5

# Baseline ESFR System Material Flows

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Slide 6

# Discussion: Threat Definition

| | Range of Possibility | Threat Characteristics Relevant to Diversion Analysis limited by current scope |
|---|---|---|
| Actor Type | Host State | Host State |
| Actor Capabilities | Wide range of technical skills, resources (money, Workforce), U & Th resources), industrial capabilities, Nuclear capabilities | Capabilities of industrial nation |
| Objectives | Wide range of nuclear weapon aspirations: Number, reliability, ability to stockpile, Deliverability, production rate | 1 SQ |
| Strategies | • Concealed diversion<br>• Concealed facility misuse<br>• Overt facility misuse<br>• Clandestine facilities alone | Concealed removal of material from the normal, monitored ESFR process |

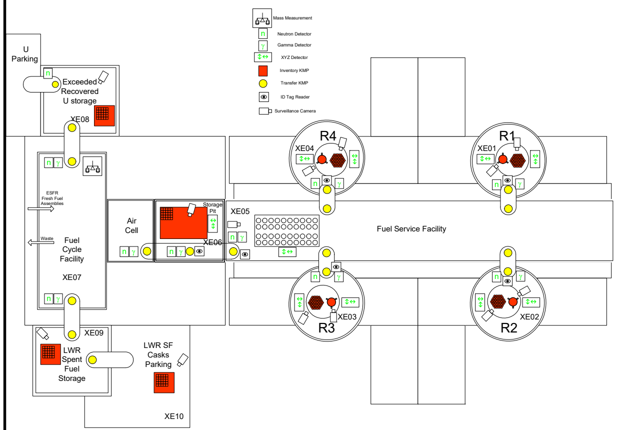


# Threat definition used in Case Study

| Actor Type | | Host State |
|---|---|---|
| Actor Capabilities | *Technical skills* | Advanced, with strong know-how in all relevant scientific and technological fields |
| | *Resources* | Sufficiently high to pose no limitations |
| | *Uranium and Thorium Resources* | Not present |
| | *Industrial capabilities* | Advanced industrial State |
| | *Nuclear capabilities* | Electricity production via the operation of advanced sodium cooled fast reactors, with next generation back-end solution. |
| Objectives | *No. of nuclear weapons devices (NWD)* | 1 |
| | *Reliability of NWD* | Any |
| | *Ability to stockpile* | Sufficient for short term stocking (around 10 years) |
| | *Deliverability* | Compatible with modern multi-role fighter jets |
| | *Production rate* | Only one device is planned |

GEN IV International Forum

# *Discussion: System Elements Identification (diversion)*




***Definition: "collection of facilities inside the identified nuclear energy system (NES) where nuclear material diversion/acquisition and/or processing, as well as theft or radiological sabotage could take place"***



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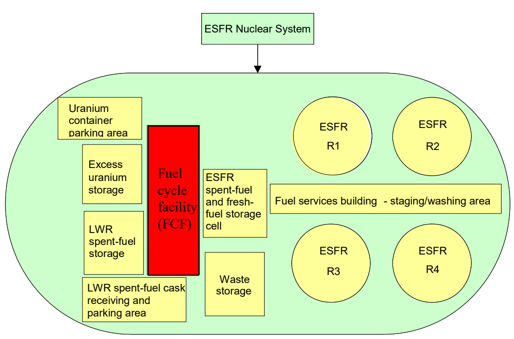
# *System Elements identified in Case Study*




## *System Elements*

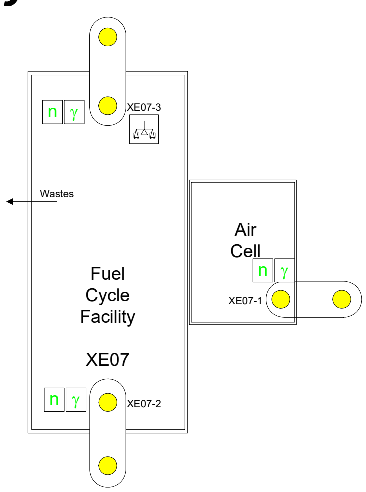
- ***XE01 – Reactor #1 (Rx1)***
- ***XE02 – Reactor #2 (Rx2)***
- ***XE03 – Reactor #3 (Rx3)***
- ***XE04 – Reactor #4 (Rx4)***
- ***XE05 – Fuel Service Facility (FSF)***
- ***XE06 – ESFR SF & NF Storage Cell (ESFR-fuel)***
- ***XE07 – Fuel Cycle Facility (FCF)***
- ***XE08 – Exceeded Recovered U Storage (XU)***
- ***XE09 – LWR Spent Fuel Storage (LWR-SF)***
- ***XE10 - LWR SF Casks Parking (Cask)***

# Questions to be kept in mind:

- How attractive is the material in this fuel cycle to potential proliferators for the use in a weapons program?
- If material suitable for use in nuclear explosives is produced or used, how difficult would it be to access the material?
- How transparent will the nuclear energy system be when it is deployed?
- Is the facility designed and operated in such a manner that all plausible acquisition paths are covered by intrinsic features or can be effectively covered by safeguards measures?



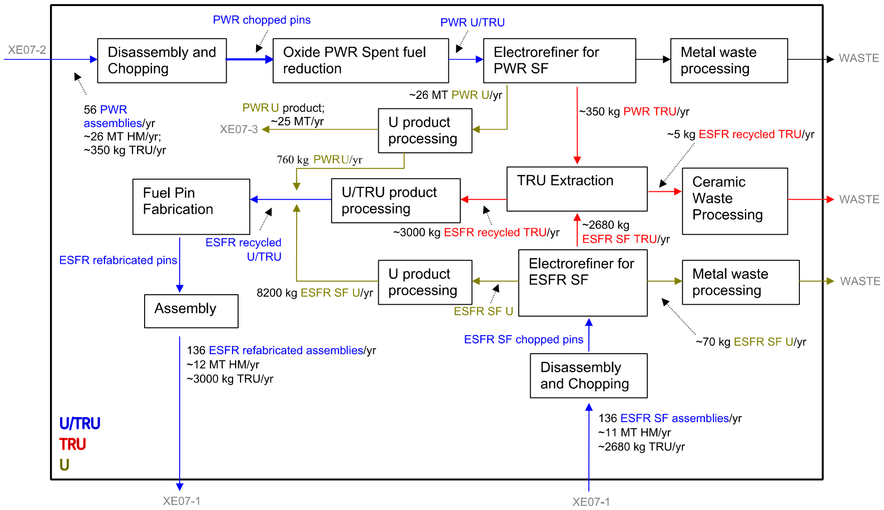
# Discussion: Target Identification for System Element XE07 – FCF




### Definition

***"nuclear material that can be diverted** or equipment/processes that can be misused **to process undeclared nuclear materials or can be replicated in an undeclared facility"***

# *Discussion:* Targets identification for System Element XE07-FCF






# *Discussion:* Target identification for System Element XE07 - FCF

- ***PWR assemblies***
- ***PWR chopped pins***
- ***PWR U/TRU***
- ***ESFR SF assemblies***
- ***ESFR chopped pins***
- ***ESFR recycled U/TRU***
- ***ESFR refab. Pins***
- ***ESFR refab. assemblies***

- ***PWR TRU***
- ***ESFR SF TRU (T3)***
- ***ESFR recycled TRU (T4)***

- ***PWR U***
- ***ESFR SF U***

# Discussion: Diversion Qualitative Pathways identification

1. Identification of potential diversion points from the system element.
2. Identification of target material type that could be diverted from the system element through these diversion points.
3. Identification of potential opportunities for misuse.



# Selected Targets identified in Case Study

System Element XE-07 Target Analysis Example

| Diversion points (Exits) | Target ID | Target Description | Target Material Character | Potential Diversion Containers | Container Transition | Normal Container Material | Process | Operational state | Safeguards |
|---|---|---|---|---|---|---|---|---|---|
| WASTE | T3 | TRU metal from electro-refiner process. | TRU metal (80% Pu) | Waste container | Transit – between XE-07 and outside | Normal operating waste. | Transfer of waste | Normal operation | Mass measurement. Inventory. Gamma detector? Neutron detector? |
| WASTE | T4 | Waste containing TRU metal from electro-refiner process. | TRU metal (80% Pu) | Waste container | Transit – between XE-07 and outside | Normal operating waste. | Transfer of waste | Normal operation | Mass measurement. Inventory. Gamma detector? Neutron detector? |

## Pathway Analysis

- Stages of a proliferation pathway:

Acquisition ➔ Processing ➔ Fabrication

In this Diversion Pathway PR assessment
- Material Acquisition steps evaluated in detail
- Material Processing stage evaluated at high level
- Weapon Fabrication not considered



## Discussion: Diversion Qualitative Pathways identification

1. Examine every potential target
   - ✓ Specify the material characteristics of the target
2. Identify the possible physical mechanisms that could be used to remove the material
3. Identify the physical and design barriers to removal
4. Identify the safeguards measures that monitor each physical mechanism
5. Hypothesize ways to defeat the safeguards
6. Layout pathways for removal of each target
7. Perform a coarse qualitative estimation of the measures

## *Diversion Pathway identified in Case Study*

Protracted diversion process:

***Proliferator puts TRU material (T3) in waste container in fuel cycle facility (XE-07) and transports out through waste portal.***

- Must compromise the neutron and gamma detectors (if they exist), surveillance cameras and compromise material records.
- Requires a separate facility to polish the waste and extract the TRU.
- The amount of TRU diverted per batch needs to be small enough to deceive nuclear safeguards NM accountancy



## *Discussion: AP Measures estimation*

| | Value | Acquisition Segment | Processing Segment |
|---|---|---|---|
| Proliferation Technical Difficulty | | How difficult is it to transfer out the material? | How difficult it is to separate the wanted material? |
| Proliferation Cost | | How expensive it is to divert the material? | How expensive it is to process the material (infrastructure, processing) |
| Proliferation Time | | How long it takes to transfer out all the material? | How long it takes to set up the necessary infrastructure and process the material? |
| Detection Probability | | How easy it is to detect the diversion activity by foreseen safeguards? | How easy it is to detect the processing activity by nuclear safeguards? |
| Fissile Material Type | | What type of material is being diverted? | What type of material will be obtained after separation? What's its suitability in a nuclear explosive? |
| Detection Resource Efficiency | | How much would it cost to safeguard the pathway segment? | How much would it cost to safeguards the pathway segment? |

## Pathway Analysis in Case Study

| | T3-XE-07-1 | | |
|---|---|---|---|
| | **Value** | **Acquisition Segment** | **Processing Segment** |
| Proliferation Technical Difficulty | Low | TRU metal in waste container. | Most processing done, need only hot cell with chemical processing capability |
| Proliferation Cost | Very low | Little or no special equipment required | Much smaller facility needed for processing TRU |
| Proliferation Time | Medium (less than five years) | Dependent on the amount and of TRU taken and how often put into Waste containers | May not need as much time to construct as a reprocessing facility |
| Detection Probability | Medium | TRU in waste container may be able to be moved undetected | Detection probability of processing facility not considered |
| Fissile Material Type | Medium | TRU already processed and cleaned up | weapons usable but not optimum |
| Detection Resource Efficiency | High | This is part of a multi-reactor facility, would have extensive safeguards | This would be a function of the cost of the international intelligence community and will be difficult to determine |



## Diversion Pathway identified in Case Study

Protracted diversion process:

***Proliferator collects normal TRU via waste container and sends to clandestine facility.***

- Requires a separate facility to polish the waste and extract the TRU.
- The amount of TRU diverted per batch needs to be small enough to deceive nuclear safeguards NM accountancy

## Pathway Analysis in Case Study

| | T4-XE-07-1 | | |
|---|---|---|---|
| | Value | Acquisition Segment | Processing Segment |
| Proliferation Technical Difficulty | Low | No material accountability on waste once it exits facility | Low concentration of TRU means that processing must be efficient to extract what is there. Misuse scenario could have higher concentration. |
| Proliferation Cost | Low | Little cost since plans are for waste to be removed to disposal site | Hot cell and chemical processing of metal |
| Proliferation Time | Medium (less than five years) | Dependent on the amount of TRU in waste | Construction of chemical processing facility is not difficult given availability of equipment |
| Detection Probability | Very low | Once waste is out, no safeguards. Some TRU is expected in Waste. If misuse is involved more TRU may be put into waste so may be more easily detected | Detection probability of processing facility not considered |
| Fissile Material Type | Medium | TRU is desirable but waste needs to be cleaned up | Weapons usable but not optimum |
| Detection Resource Efficiency | High | This is part of a multi-reactor facility, would have extensive safeguards | This would be a function of the cost of the international intelligence community and will be difficult to determine |



## References


- ***PR&PP Expert Group, PR&PP Evaluation ESFR Full System Case Study Status Report, October 2009, for external release, & Appendixes, Published on web May 2010.***

- ***Zentner, M.D., Coles, G.A., Therios, I., A Qualitative Assessment of Diversion Scenarios for an Example sodium Fast Reactor using the Generation IV PR&PP Methodology, Nuclear Technology, 179, pp. 70-75, July 2012.***

## Diversion Targets and Pathways Summary

- Diversion subgroup selected five targets for analysis
  - TRU metal from electrorefiner processing
  - Waste containing TRU metal from electrorefiner cleanout
  - Cask of LWR fuel assemblies
  - LWR spent fuel assembly
  - Recycled uranium metal
- Generated a total of 10 pathways
- Performed a coarse estimation of the measures for each diversion pathway (for the reference configuration, CR=0.73 )
  - Addressing the entire pathway as a whole
- Effects of conversion ratio variations were reviewed but not analyzed in detail
  - Variations judged to have minor impact on the outcome, limited mainly to the isotopic composition of the TRU targets

## Applying the GIF PR&PP Methodology for a qualitative analysis of a misuse scenario

*Subgroup Session Facilitators: Giacomo G.M. Cojazzi and Robert Bari*
*GIF PR&PP Working Group*

*Misuse sub-group: G.G.M. Cojazzi, G. Renda, J.S. Choi, J. Hassberger*

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**University of California, Berkeley · Berkeley, California· November 4, 2015**

# Overview

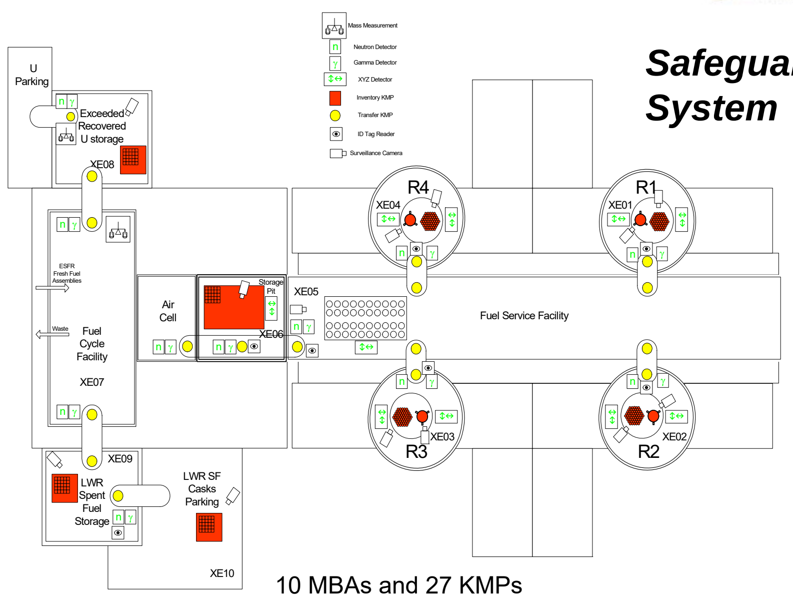
- *ESFR & Safeguards*
- *Threat definition*
- *Approach to System Response*
  - *System Elements Identification*
  - *Targets identification*
  - *Pathway identification*
  - *Estimation of Measure: Baseline, DV0, DV1*
- *Lessons learned & conclusions*

# ESFR Baseline and Design Variations (ANL)

| | Baseline ESFR | Design Variation 0 | Design Variation 1 |
|---|---|---|---|
| | 800 $MW_{th}$ TRU CR = 0.64 | 1000 $MW_{th}$ TRU CR = 0.73 | 1000 $MW_{th}$ TRU CR = 0.22 |
| Nominal Electric Power, $MW_e$ | 300 | 350 | 350 |
| Thermal Power, $MW_{th}$ | 800 | 1000 | 1000 |
| Fuel composition (core / blanket) | Metallic U-TRU-10Zr / - | Metallic U-TRU-10Zr / - | Metallic U-TRU-20Zr / - |
| Cycle length, months | 12 | 12 | 6.6 |
| Capacity factor | 85% | 90% | 90% |
| Number of assemblies (core / blanket) | 102 / - | 180 / - | 180 / - |
| Number of batches (core / internal / radial) | 3 / - / - | 4 / - / - | 8 / - / - |
| Residence time, days (core / internal / radial) | 930/ - / - | 1300/ - / - | 1445/ - / - |
| Pins per assembly (core / internal / radial) | 271 / - / - | 271 / - / - | 324 / - / - |
| Structural pins per assembly | 0 | 0 | 7 |
| Average TRU enrichment, % | 24.9 | 22.1 | 58.5 |
| Fissile/TRU conversion ratio | 0.8 / 0.64 | 0.84 / 0.73 | 0.55 / 0.22 |
| HM/TRU inventory at BOEC, MT | 9.0 / 2.2 | 13.2 / 2.9 | 6.9 / 3.9 |
| Discharge burnup (ave/peak), MWd/kg | 80 / ? | 93 / 138 | 185 / 278 |
| TRU consumption rate, kg/year | 80 | 81.6 | 241.3 |



# Safeguards System




10 MBAs and 27 KMPs

## Selected PR Threat for the misuse strategy

| | | |
|---|---|---|
| **Actor Type** | | Host State |
| **Actor Capabilities** | *Technical skills* | Advanced, with strong know-how in all relevant scientific and technological fields |
| | *Resources* | Sufficiently high to pose no limitations |
| | *Uranium and Thorium Resources* | Not present |
| | *Industrial capabilities* | Advanced industrial State |
| | *Nuclear capabilities* | Electricity production via the operation of advanced sodium cooled fast reactors, with next generation back-end solution. |
| **Objectives** | *No. of nuclear weapons devices (NWD)* | 1 |
| | *Reliability of NWD* | Any |
| | *Ability to stockpile* | Sufficient for short term stocking (around 10 years) |
| | *Deliverability* | Compatible with modern multi-role fighter jets |
| | *Production rate* | Only one device is planned |

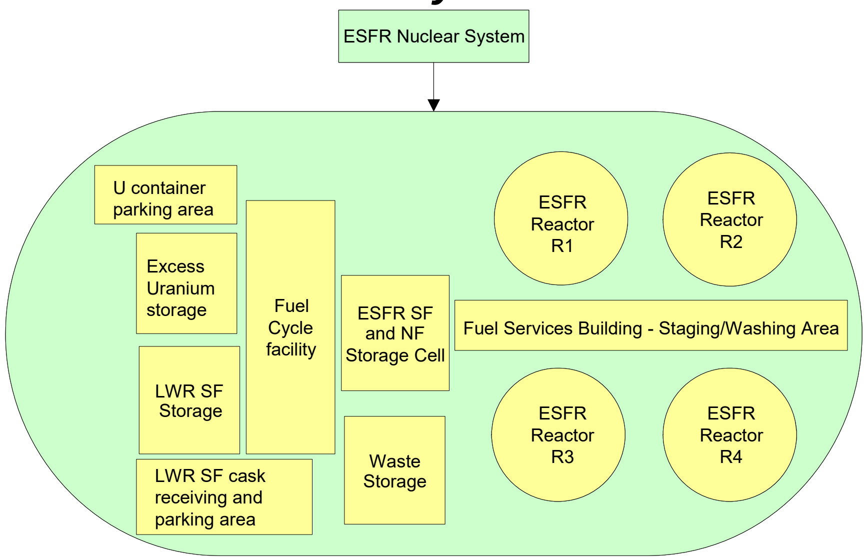


## Qualitative Approach to System Response

*No attempt to be exhaustive rather try to select a challenging pathway, emphasis on the methodological aspects.*

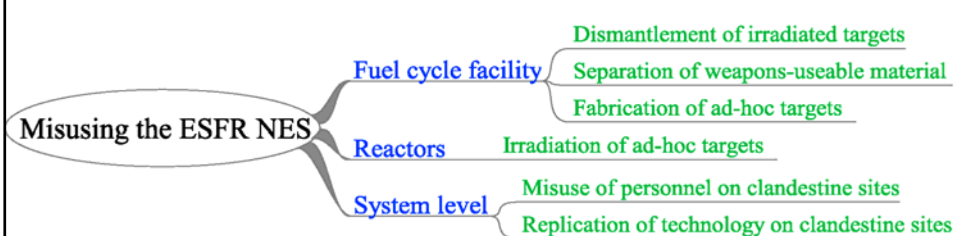
1. *Screen/analyze system elements and targets and selection of targets.*
2. *Brainstorming for identification of "best" pathway and its coarse characterization and breaking down in segments.*
3. *Characterization of pathway segments up to the needed level of detail (iterative process), including Identification of needed concealment actions.*
4. *For each segment formulation of relevant questions (identification of the required evidence) for supporting the estimation of measures (PT, PC, MT, DP, DE).*
5. *Measures estimation providing replies to the identified questions capturing the evidence*
6. *Notional aggregation of segments measures.*

# ESFR Nuclear System Elements





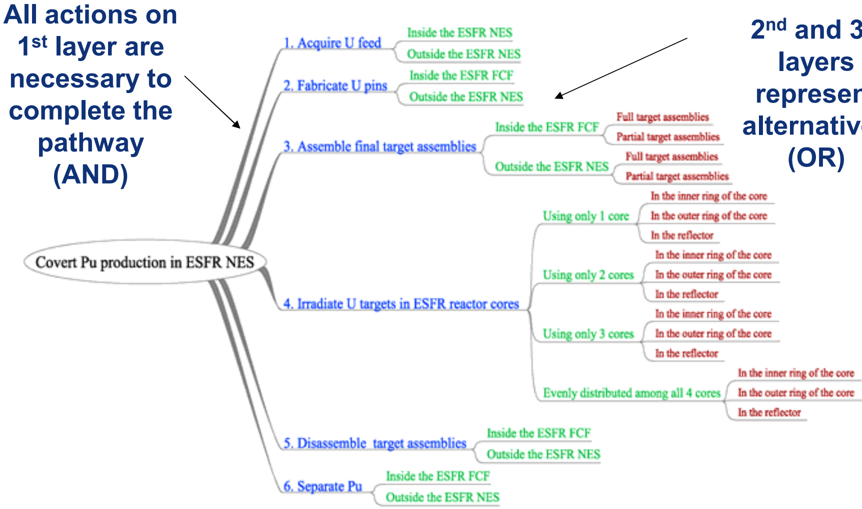

# ESFR Illustrative Misuse Targets



## ESFR Illustrative Misuse Segments identification

All actions on $1^{st}$ layer are necessary to complete the pathway (AND)

$2^{nd}$ and $3^{rd}$ layers represent alternatives (OR)




**The figure embeds up to 5184 misuse pathways…**

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*Slide 9*

## Brainstorming for identification of "best" pathway

- *Assuming proliferators point of view:*
- *Look for ways to achieve better than available Pu (MT)*
- *Fulfill objectives overcoming Technical Difficulties (TD) without being detected (DP), -> concealment is needed*
- *Try to minimize interaction with safeguards measures e.g. follow Routine Operations, maximize clandestine external segments*
- *Proliferation  Time (PT) is not a critical issue..*
- *Proliferation Cost (PC) is not a critical issue..*
- *DE is irrelevant for the proliferator..*

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*Slide 10*

# Assumptions for selecting a Representative Misuse Pathway (Baseline)

a) All transfers/movements inside the facility follow standard procedures and schedules for minimising the perturbation of normal operations and therefore for minimising the likelihood of detection. Irradiation time is hence fixed in 12 months.

b) For introducing nuclear material inside the ESFR site and diverting it, the proliferator will use the existing openings, as e.g. maintenance accesses.

c) The uranium pins are fabricated outside the ESFR site for minimising the activities performed in a safeguarded area, and therefore minimising the likelihood of detection.

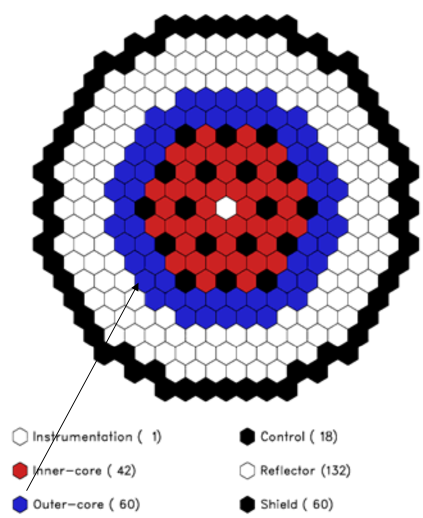
d) According to data provided by ANL, in order to get one significant quantity of Pu in a twelve months irradiation period, between 5.2 and 11.5 full target assemblies are needed. As in each assembly there are 271 pins, a total of 271 x 5.2 =1410 to 271 x 11.5 =3117 target pins are needed. They are supposed to be inserted in 10 assemblies made up by standard and target pins in order to minimize the detection capability of the radiation monitors and the disturbances in the design neutron flux. Weapons Grade Pu could be obtained.

e) The target assemblies are evenly distributed among the four reactor cores available onsite to minimize the number of suspicious movements within the same core.

f) The location for irradiation has been identified in the **outer ring of the core** to match overall core flux, without causing safety problem or arousing suspicion.



# Baseline core



# The Selected ESFR Misuse Pathway (Baseline)

1. Host state acquires outside natural uranium (or depleted uranium (DU) if available).
2. Host state prepares target uranium pins outside the ESFR site.
3. (Host state introduces target pins into the ESFR site and then into the FCF).
4. Host state assembles ESFR final target fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins using the FCF.
5. (Host state transfers target assemblies from FCF to in vessel storage baskets).
6. (Host state loads target assemblies into outer-ring of the 4 reactors cores during refuelling).
7. Host State irradiates target assemblies for 12 months in the outer ring of the core.
8. (Host state unloads target assemblies out of reactor cores into in-vessel storage baskets, during subsequent refuelling, and leaves them there for cooling).
9. (Host state transfers target assemblies out of in vessel storage baskets to FCF).
10. Host state disassembles target assemblies and recovers target pins at the FCF (then transfers target pins out of ESFR FCF to clandestine facility).
11. Host state separates Pu at a clandestine facility.



# ESFR Misuse Pathway measure estimation process

a) The pathway segmentation and description has been developed up to the level needed to generate meaningful measures estimates.

b) For each of the segments, questions supporting the measures estimation have been developed.

c) On the basis of the replies to the questions, estimates for each of the segment measures are derived.

d) An attempt to aggregate the estimates for each measure over the whole pathway is done.

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# Example of Questions to be answered for Pathway Measures' Estimation

| Segment | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Action | Host state acquires natural uranium (or depleted uranium (DU) if available) | Host state prepares dummy uranium pins outside the ESFR site | Host state introduces dummy pins into the ESFR site and then into the FCF | Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins |
| Proliferation Technical Difficulty (TD) | a) How difficult to find the necessary amount of uranium without being detected?<br>b) How much is it difficult to perform the shipment? | How difficult:<br>a) to build a clandestine facility b) to train the people and to run it<br>c) to deliver the expected output at a sufficient quality? | a) How difficult to introduce the pins via the maintenance routes?<br>b) How much is it difficult to conceal the action? | a) How difficult to assemble the dummy assemblies?<br>b) How much is it difficult to conceal the action? |

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# Example of Replies to Questions (Baseline)

| **Segment** | **3** | **4** |
|---|---|---|
| **Action** | **Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF** | **Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins** |
| **TD** | **a) Host state controls all access to the FCF, it would not be difficult to introduce dummy elements into the ESFR and FCF.**<br>**b) Once inside the FCF, the dummy elements are bag-into the assembly station as tool sets (i.e., several bag-in operations may be required)** | **a) The action involves substitution of radioactive pins with the dummy ones. The level of radioactivity will pose serious health hazards to the personnel performing the action. 154 pins per day are transferred in for fabrication. Substitution of pins at such a frequency without perturbing the overall process is not easy. Accessibility of the site for personnel is not completely clear.**<br>**b) The difficulty of tampering with the camera depends on the logic with which the camera works. Might span form a simple in front of the lens tampering to more complicate action.** |

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## Metrics, Estimations and Qualitative PR Qualifiers

- For all segments and for all measures, metrics and values estimation have been provided
- Binning and qualifiers follow table 2.5 of PR&PP rev. 5 Methodology Report
- Other metrics for DE has been explored
  - DE. On segment: How much does it cost to cover the segment?
- For all segments and for all measures PR is expressed as Very-Low, Low, Medium, High, Very High -> notional aggregation
- Uncertainties are taken into account



## Design Measures Estimates (Baseline, DV0, DV1)

| Segment | PR(TD) | PR(PT) | PR(PC) | PR(MT) | PR(DP) | PR(DE) |
|---|---|---|---|---|---|---|
| 1 Host state acquires natural uranium (or depleted uranium (DU) if available) | Very low to low | Very low to medium | Very low | NA | Very low | Low |
| 2 Host state prepares dummy uranium pins outside the ESFR site | Very low to low | Low | Very low | NA | Very low | Low |
| 3 Host state introduces dummy pins into the ESFR site and then into the fuel assembly station of the FCF | Very low | Very low to low | Very low | NA | Very low | Very high |
| 4 Host state assembles ESFR dummy fresh fuel assemblies made up by uranium target pins and standard ESFR fresh fuels pins | Medium | Very low | Very low | NA | Low to high | Very high |
| 5 Host state transfers dummy assemblies from FCF to in vessel storage baskets | Very low | Low | Very low | NA | Very low | Medium |
| 6 Host state loads dummy assemblies into outer-ring of reactors core (during refuelling) | Very low | Very low | Very low | NA | Very low | Very High |
| 7 Host State irradiates dummy assemblies for 12 months m (6.6 months for DV1) | Very low | Low | Very low | NA | Very low | Very High |
| 8 Host state unloads dummy assemblies out of reactors core into in-vessel storage baskets (during subsequent refuelling) and leaves them there for cooling | Very low to medium | Medium | Very low | NA | Low to medium | High to very high |
| 9 Host state transfers dummy assemblies out of in vessel storage baskets to FCF | Very low | Medium | Very low | NA | Very low | Medium |
| 10 Host state recovers dummy pins at the FCF and transfers dummy pins out of ESFR FCF to clandestine facility | Medium | Very low | Very low | NA | Low to high | High to very high |
| 11 Host state recovers Pu at a clandestine facility | Low | Very low to medium | Very low | Low (WG Pu) | Very low to low | Low |
| Global (notional aggregation) | Medium | Medium | Very low | Low (WG Pu) | Low to high | Low to high |

## Conclusions on the system (Baseline, DV0, DV1)

- *The illustrative ESFR qualitative analysis highlighted that 1 SQ of WG Pu (MT) might be covertly produced in the standard irradiation period, however such an attempt would involve challenges difficult to overcome.*
- *TD is mainly driven by boundary conditions imposed by safeguards, especially in FCF (Segments 4 and 10), and*
- *PT is dominated by the choice of following standard operation schedule. Both measures are strongly influenced by the choice of a covert strategy, imposing all reasonable efforts to minimize detection by the international community.*
- *Due to the considered Safeguards approach, DP is dominated by FCF segments, in particular by segments 4 and 10.*
- *In view of the analysis outcomes, it has been possible to notice that the postulated safeguards approach could be improved in terms of coverage and robustness with inexpensive modifications, e.g. more control on maintenance accesses (segment 3) and foreseeing comparison of “finger prints” of different assemblies (segments 5, 6, 9). ->This would increase technical difficulty and would decrease uncertainty on DP estimate*



## Conclusions on the Methodology 1/2

- *The application of the methodology during this case study confirmed that the high-level framework as in the Rev.5 Report is a good and robust one.*
- *The exercise investigated a practical way of applying it at qualitative level in traceable way, leading to accountable and dependable results.*
- *The analysis of a misuse strategy put in evidence how in such scenarios proliferation pathways are likely to involve more than one misuse target at a time, making their identification not entirely straightforward.*
- *It is not a single action on a single piece of equipment, but rather an integrated exploitation of various assets and system elements*

# Conclusions on the methodology 2/2

- *The proposed qualitative application of the methodology is able to spot even small differences in the overall scenario (the experts can pinpoint also variations that would not influence the final estimates of the measures), but the scales adopted are not suited for capturing these subtle differences. (In this case, however, we think that the proliferation resistance of baseline design, DV0 and DV1 is comparable, and therefore a more discriminating set of scales wouldn't have been needed).*

- *Some aspects of the application of the methodology have been identified:*
  - *Optimal use of some measures and metrics (MT and DE).*
  - *The example metrics illustrated in the report should be considered as a staring point: (especially those of PC and DE).*
  - *Given a proliferation strategy some measures are likely to dominate over the others, and within a measure some segments will, in their turn, result to dominate the overall estimate.*



# References

- PR&PP Expert Group, PR&PP Evaluation ESFR Full System Case Study Status Report, October 2009, for external release, & Appendixes, Published on web May 2010. http://www.gen-4.org/Technology/horizontal/documents/PRPP_CSReport_and_Appendices_2009_10-29.pdf

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# Clarification / Questions

*Subgroup session: Host State Overt Diversion and/or Misuse*

***Subgroup Session Facilitators**: Jeremy Whitlock and Joe Pilat*
*GIF PR&PP Working Group*

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# Goals for session

- Discuss breakout as a "strategy modifier"
- Review the ESFR threat definition
– Focus subgroup discussion on threat of breakout and overt diversion of nuclear material

- Identify ESFR system elements and diversion targets
- Identify representative pathways for different breakout strategies
- Estimate PR measures for representative diversion pathways and breakout strategies
- Discuss breakout pathways for the ESFR

# PR&PP Evaluation Framework

**Challenges**
- Threat Definition

**System Response**
- System Element Identification
- Target Identification and Categorization
- Pathway Identification and Refinement
- Estimation of Measures

**Outcomes**
- Pathway Comparison
- System Assessment & Presentation of Results



# Proliferation Resistance Measures and Metrics

| Measures and Metrics | Metric Scales Bins (Median) | Proliferation Resistance |
|---|---|---|
| **Proliferation Technical Difficulty (TD)** Example metric: Probability of 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 resources for military capabilities | 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 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, RGPu, DB-Pu, LEU); interpolation based on material attributes | HEU | Very Low |
| | WG-Pu | Low |
| | RG-Pu | Medium |
| | DB-Pu | High |
| | LEU | Very High |
| **Detection Probability (DP)** Example metric: Cumulative detection probability | A | Very Low |
| | B | Low |
| | C | Medium |
| | D | High |
| | E | 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 |

**Material Type Description**

**HEU** = high-enriched uranium, nominally 95% 235U;
**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% 235U.

**Detection Probability**

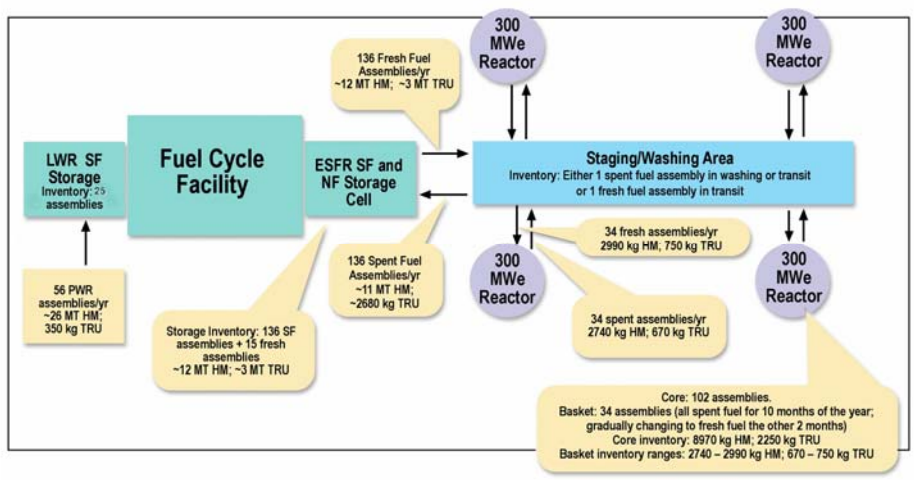
A - Significantly lower cumulative detection probability than the IAEA detection probability and timeliness goal for depleted, natural, and LEU uranium.
B - 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of depleted, natural, and LEU uranium).
C - 20% in 3 months, 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of spent fuel/irradiated material).
D - 50% in 1 month, 90% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity HEU/separated Pu).
E - Significantly greater cumulative detection probability than the IAEA detection probability and timeliness goal for HEU/separated Pu.

# Breakout not a stand-alone strategy

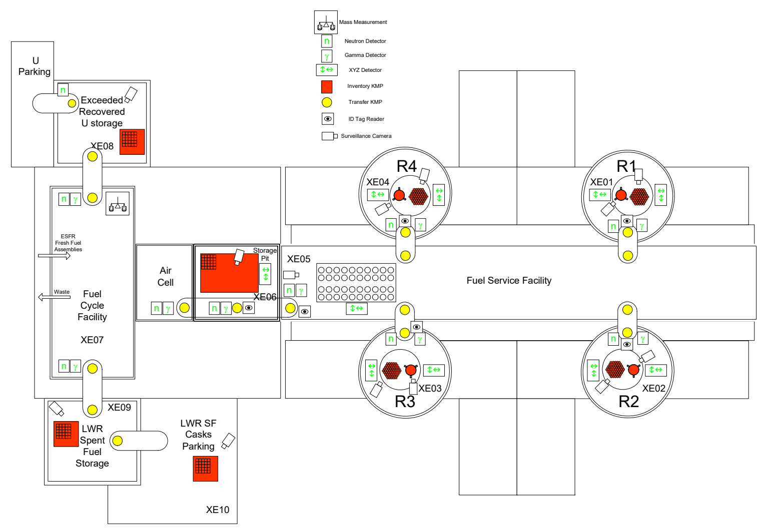
- ***"End game" for Misuse or Diversion strategies***
- ***"Strategy modifier": nature of Breakout itself will shape the Misuse or Diversion threat via Proliferation Time (pre- or post-Breakout), and therefore complexity available***
- ***Goal of ESFR Breakout analysis has therefore been to focus on Proliferation Time (pre- or post-Breakout)***



# Baseline ESFR System Material Flows



# ESFR Layout and Proposed Safeguards






# Discussion: Threat Definition

| | Range of Possibility | Threat Characteristics Relevant to Diversion Analysis limited by current scope |
|---|---|---|
| **Actor Type** | **Host State** | **Host State** |
| **Actor Capabilities** | Wide range of technical skills, resources (money, workforce, U & Th), industrial capability, nuclear capability | Capabilities of industrial nation |
| **Objectives** | Wide range of nuclear weapon aspirations: Number, reliability, ability to stockpile, Deliverability, production rate | 1 SQ |
| **Strategies** | • Concealed diversion<br>• Concealed facility misuse<br>• Overt facility misuse<br>• Clandestine facilities alone | Concealed or **overt removal** of material from the normal, monitored ESFR process |

## Threat definition used in Case Study

| Actor Type | | Host State |
|---|---|---|
| Actor Capabilities | *Technical skills* | Advanced, with strong know-how in all relevant scientific and technological fields |
| | *Resources* | Sufficiently high to pose no limitations |
| | *Uranium and Thorium Resources* | Not present |
| | *Industrial capabilities* | Advanced industrial State |
| | *Nuclear capabilities* | Electricity production via the operation of advanced sodium cooled fast reactors, with next generation back-end solution. |
| Objectives | *No. of nuclear weapons devices (NWD)* | 1 |
| | *Reliability of NWD* | Any |
| | *Ability to stockpile* | Sufficient for short term stocking (around 10 years) |
| | *Deliverability* | Compatible with modern multi-role fighter jets |
| | *Production rate* | Only one device is planned |



## Discussion: Breakout Targets

1. *Diversion of stockpiled ESFR fresh fuel – Pu separation from spent LEU in a clandestinely developed PUREX facility (utilizing either the full pin length or just the lower-burnup ends of the pins)*
2. *Misuse of facility to irradiate fertile material in-core*
3. *Misuse of facility to irradiate fertile material in storage basket*
4. *Misuse of facility to extract high Pu-purity TRU in FCF*

## *Pathway Analysis*

- Stages of a proliferation pathway:

Acquisition ➔ Processing ➔ Fabrication

In this Overt Diversion Pathway PR assessment

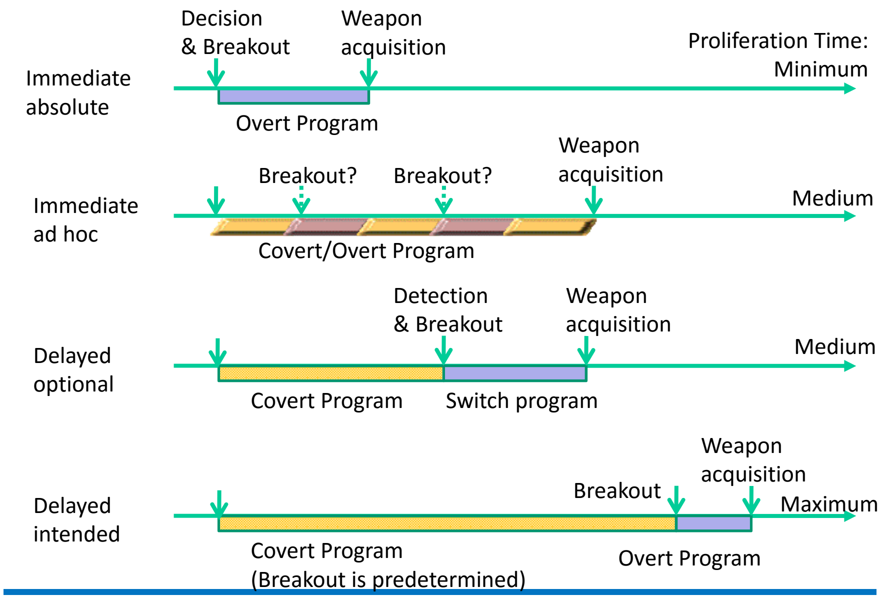
- Material Acquisition steps evaluated in detail
- Material Processing stage evaluated at high level
- Weapon Fabrication not considered



## *Discussion: Breakout "Strategies"*

1. *Immediate, absolute breakout (proliferant state decides to break out and immediately acts upon decision): minimum time, minimum complexity available to proliferation activities*
2. *Immediate, ad hoc breakout (proliferant state "effectively" breaks out though actions, without explicitly breaking out): medium time, medium complexity available to proliferation activities*
3. *Delayed, optional breakout (proliferant state covertly misuses or diverts, with acceptance of the detection risk and intention to break out if/when detection occurs): medium time, medium complexity available to proliferation activities*
4. *Delayed, intended breakout (proliferant state covertly misuses or diverts, with acceptance of the detection risk and a predetermined schedule for breakout and overt activity – the "load the gun" scenario): maximum time, maximum complexity available to proliferation activities*

Breakout Strategies considered in Case Study






# *Breakout "Strategies"*

- *The category of breakout chosen by a proliferant state is significantly affected by political factors (foreign relations agenda of state, probability [timing and extent] of external intervention after breakout, external dependence of proliferant state's supply chain, etc.).*
- *These factors, although of interest, must be excluded from ESFR PR&PP analysis*
- *HOWEVER, one can still explore how PR&PP measures affect factors that benefit a Breakout strategy (pre- and post-breakout) …*

## Factors Benefiting Breakout and Measures that Address These

| Phase | Breakout Factor | PRPP Measure |
|---|---|---|
| Pre-Breakout | Low probability of detection of diversion/misuse | · Detection probability<br>· Detection resource efficiency |
| | Low scrutiny of collateral clandestine activities to reduce time for subsequent overt activities | · Detection probability (Additional Protocol)<br>· Detection resource efficiency<br>· Proliferation time<br>· Technical difficulty (need to start technical development in pre-breakout phase) |
| | Low scrutiny/interference of supply chain to acquire needed equipment and materials | · Detection probability (Additional Protocol?)<br>· Technical difficulty (need to import equipment, vs. domestic development)<br>· Proliferation cost |



## Factors Benefiting Breakout and Measures that Address These (Cont'd…)

| | | |
|---|---|---|
| Post-Breakout | Available time/speed of development | · Technical difficulty<br>· Proliferation time<br>· Material type |
| | Available inventory and material type | · Detection probability (addresses build-up of NM inventory during pre-breakout stage)<br>· Material type |
| | Technology for weaponization | · Technical difficulty<br>· Material type<br>· Detection probability (addresses build-up of necessary technology during pre-breakout phase) |
| | Knowledge for weaponization | · Technical difficulty<br>· Material type<br>· Detection probability (addresses build-up of necessary expertise during pre-breakout phase) |
| | Physical barriers to external intervention | · Transparency of facilities *<br>· Robustness of facilities * |
| | Political barriers to external intervention | · Foreign relations (will and ability to intervene) *<br>· Response time and capability * |

* These measures not included in PRPP methodology

## *Discussion:* Dependence of Target Attractiveness on Breakout Strategy

| Target [2] | Breakout Strategy [4] (decreasing Proliferation Time, and thus available complexity) → | | | | | |
|---|---|---|---|---|---|---|
| | Delayed intended[1] | Delayed optional[1] | Immediate *ad hoc*[3] | Immediate absolute | MT | PT, TD |
| *Diversion:* U-TRU from LEU • full pin length | Medium | Medium | High | High | High | High |
| *Diversion:* U-TRU from LEU • top & bottom sections | High | High | High | High | Low | Low |
| *Misuse:* U-TRU from undeclared irradiation of targets in core | High | High | Medium | Very low | Low | High |
| *Misuse:* U-TRU from undeclared irradiation of targets in storage baskets | High | High | Low | Very low | Low | High |
| *Misuse:* FCF to produce high Pu-purity U-TRU | High | Medium | Low | Very low | High | High |
| Design Variation: breeder, *Diversion* – inner blanket | High | Medium | Low | Very low | High | High |

Notes:
1. If detected – select least time path between continuing at max rate or taking TRU directly from TRU extraction
2. Requires PUREX processing, assumed in a clandestine off-site location
3. Plan is to continue, assuming "acceptable" international reaction
4. Abrogation pathways would take all SQs possible; usually more than 1



## *Insights from Study of Breakout Threat*

- *Until point of Breakout, safeguards, supplier-group controls, national intelligence agencies, and technical means will play a role in detecting the intent to break out. Detection Probability and Efficiency are important measures during this period, but play no role after breakout*
- *Most attractive Breakout strategy is non-intuitive: depends on political factors not included in PR&PP analysis (e.g. Material Type measure may not have same impact, as political gains may be met with faster weaponization using lower-grade material)*
- *A key issue in assessing the breakout pathways is the definition of the proliferant state's strategy around detection, and how the state's aversion to detection risk changes as it progresses closer to the end of the pathway. Such "dynamic strategy" considerations add another level of complexity to the analysis.*

## Subgroup session: Subnational group / Theft


Subgroup Session Facilitators: Jean Cazalet and Per Peterson

GIF PR&PP Working Group


*Workshop on the Proliferation Resistance and Physical Protection Evaluation (PR&PP) Methodology for Generation IV Nuclear Energy Systems*
**University of California, Berkeley · Berkeley, California · November 4, 2015**

# Goals for session

- Review the ESFR threat definition
  - Focus subgroup discussion on threat of theft of material
  - Bonus problems: theft of information and radiological sabotage
- Identify ESFR system elements and theft targets
- Identify a representative pathway
- Estimate PP measures for representative theft pathway
  - Focus on Probability of Adversary Success metric, using Adversary Sequence Diagram
- Discuss theft pathway for the ESFR

## PR&PP Evaluation Framework

**Challenges**
- Threat Definition

↓

**System Response**
- System Element Identification
- Target Identification and Categorization
- Pathway Identification and Refinement
- Estimation of Measures

↓

**Outcomes**
- Pathway Comparison
- System Assessment & Presentation of Results



## Physical Protection Robustness Measures

| Measure | Definition |
|---|---|
| Probability of Adversary Success (PAS) | Probability that an adversary will successfully complete the action described by a pathway and generate a consequence. |
| Consequences (C) | The effects resulting from successful completion of the adversary's intended action described by a pathway. |
| Physical Protection Resources (PPR) | The staffing, capabilities, and costs (for both infrastructure and operations) required to provide a given level of physical protection robustness and the sensitivity of these resources to changes in the threat sophistication and capabilities. |

*From GIF PR&PP WG, "Evaluation Methodology for Proliferation Resistance and Physical Protection of Gen IV Nuclear Energy Systems", rev. 6*

## PP Measures & 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)**<br>Nominal value | $60 \geq t_d > 30$<br>45 | $30 \geq t_d > 10$<br>20 | $10 \geq t_d > 1$<br>5.5 | $1 \geq t_d = 0$<br>0.5 |
| **Response Time, $t_r$ (minutes)**<br>Nominal value | $1 \geq t_r = 0$<br>0.5 | $10m \geq t_r > 1m$<br>5.5 | $30m \geq t_r > 10m$<br>20 | $60m \geq t_r > 30m$<br>45m |
| **Measures** | **Range/Value** | | | |
| | **High** | **Medium** | **Low** | **Nil** |
| **Probability of Adversary Success, PAS**<br>Nominal value | $1 > P_s \geq 0.8$<br>0.9 | $0.8 > P_s \geq 0.5$<br>0.65 | $0.5 > P_s \geq 0.1$<br>0.3 | $0.1 > P_s = 0$<br>0.05 |
| **PP Resources, PPR (% Operating Cost)**<br>Nominal value | >10%<br>10 | 10%>%>5%<br>5 | 5%>%>0%<br>1 | 0<br>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 |

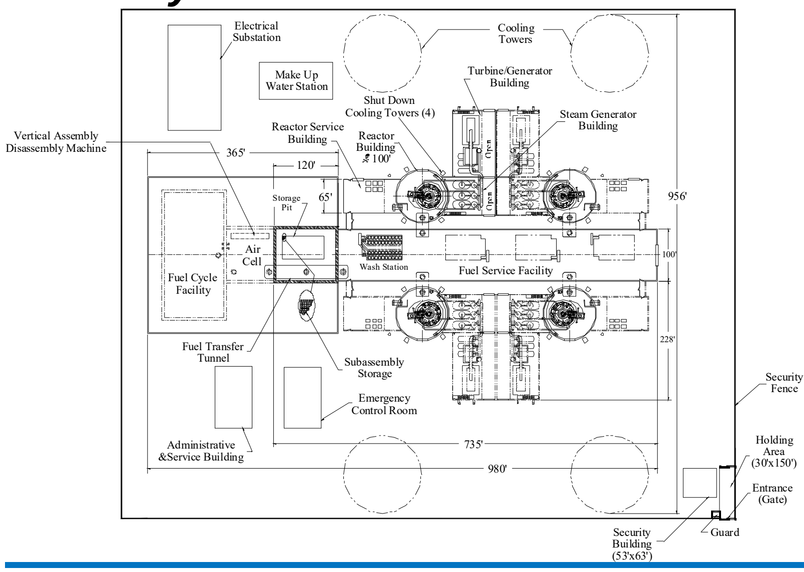
- ***Probability of Interruption, $P_I = f(P_d, t_d, t_r)$;***
- ***Assume PAS = 1 – $P_I$ for <u>coarse</u> pathway for conceptual facilities***



# Some useful Definitions

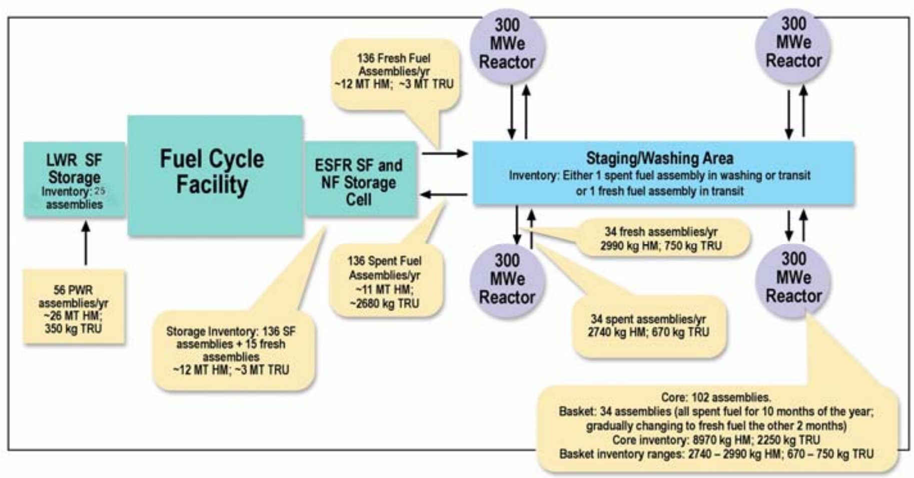
| Term | Definition |
|---|---|
| Adversary delay | The time required by the PP actor to overcome intrinsic barriers to accessing and disabling a vital equipment target set (sabotage) or to removing materials (theft). |
| Consequence generation | A PP pathway stage, considering the sequence of events following target exploitation that result in radiological release, damage, or disruption.. |
| Design Basis Threat | "The attributes and characteristics of potential insider and/or external adversaries, who might attempt unauthorized removal or sabotage, against which a physical protection system is designed and evaluated." (INFCIRC/225/Rev.5) |
| Equipment target set | Minimum set of equipment that must be disabled to successfully sabotage a facility or to gain access to a theft target. |
| Protected area | A restricted access area in a nuclear facility protected by security fences and intrusion detection systems, typically with access portals to detect the introduction of weapons or explosives. |
| Target access | A PP pathway stage considering the activities carried out to gain access to a target or an equipment target set. |
| Target exploitation | A PP pathway stage considering the activities carried out to remove a theft target from a facility or transportation system or to damage an equipment target set. |
| Vital area | Location in a nuclear facility containing equipment, systems, or devices or nuclear/radioactive material the sabotage of which could directly or indirectly lead to unacceptable radiological consequences. |

## ESFR Layout






## Baseline ESFR System Material Flows



# Physical Protection Features

***"Nuclear facilities also have PP systems that restrict access to and prevent theft of nuclear materials. Both intrinsic features and extrinsic measures are required to protect the material, because, without any extrinsic PP measures, all materials become vulnerable to theft by terrorist groups. The design of PP systems for material protection, control, and accounting has significant overlap with the design for effective implementation of international safeguards, safety, and reliability." (Case Study, p. 25)***



# Discussion: Threat Definition

| | Proliferation Resistance | Physical Protection |
|---|---|---|
| **Actor Type** | • Host State | • Outsider<br>• Outsider with insider<br>• Insider alone<br>• Above and non-Host State |
| **Actor Capabilities** | • Technical skills<br>• Resources (money and workforce)<br>• Uranium and Thorium resources<br>• Industrial capabilities<br>• Nuclear capabilities | • Knowledge<br>• Skills<br>• Weapons and tools<br>• Number of actors<br>• Dedication |
| **Objectives** (relevant to the nuclear fuel cycle) | Nuclear weapon(s):<br>• Number<br>• Reliability<br>• Ability to stockpile<br>• Deliverability<br>• Production rate | • Disruption of operations<br>• Radiological release<br>• Nuclear explosives<br>• Radiation Dispersal Device<br>• Information theft |
| **Strategies** | • Concealed diversion<br>• Overt diversion<br>• Concealed facility misuse<br>• Overt facility misuse<br>• Independent clandestine facility use | • Various modes of attack<br>• Various tactics |

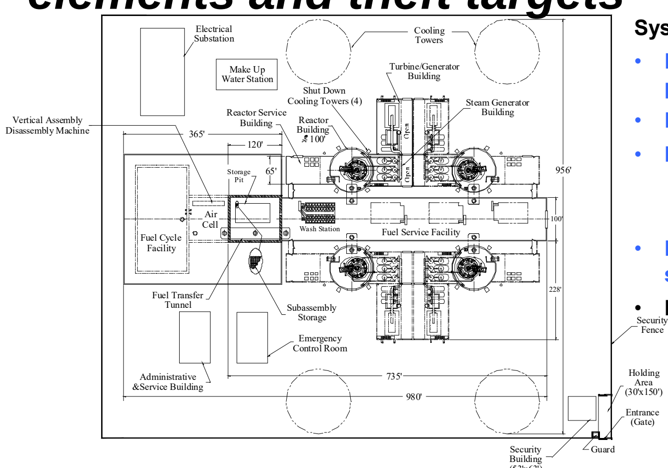
- ***Discuss potential threat definitions for theft of nuclear material for use in nuclear explosives***

## Threat definition used in Case Study

- **Actor Type: Military trained assault force**
- **Actor Capabilities:**
  - Knowledge – knowledge of plant layout and PP basic design, sufficient knowledge of plant processes to understand targets of opportunity
  - Skills – ability to design assault equipment to penetrate barriers, training in using assault weapons,
  - Weapons and tools – assault weapons, specialized explosive ordinance, armored vehicles
  - Numbers of actors – 12 outsiders and 1 insider
  - Dedication – Military Objective oriented
- **Objective: Theft of items from the ESFR facility in sufficient quantity to obtain 1 SQ of nuclear weapon material.**
- **Strategy: Surprise assault on ESFR facility directed at material storage areas.**



## Discussion: Identify system elements and theft targets




**System Elements (Pg. 49):**

- LWR spent-fuel cask parking area
- LWR spent-fuel storage
- Fuel cycle facility
  - Air cell (hot cell)
  - Inert hot cell
- Fuel services building staging/washing area
- Reactors

- **Discuss potential ESFR targets for theft of nuclear material for use in nuclear explosives**

## Target used in Case Study

*"For the purpose of demonstrating the methodology, the adversary pathway identified in Figure D.4-10 [for Theft of TRU/Uranium Product (in Process Cell) was] analyzed qualitatively. This particular pathway was selected because the U/TRU slugs represent the stage of the electrochemical process where the material is in a readily portable form (solid metallic slugs), and the TRU concentration is high compared to potentially downblended fuel – i.e. this is a relatively attractive target for theft."*



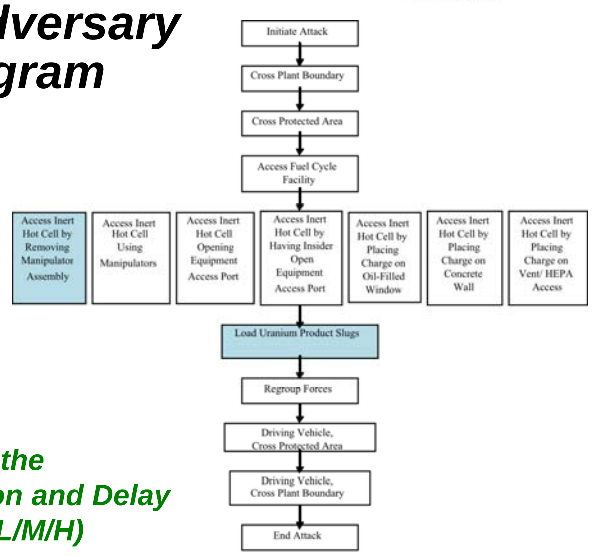
## Barriers to theft of material (from Case Study, pg. 18)

- *Intrinsic characteristics of the materials themselves*
  - *mass, bulk, and radiation levels*
- *Intrinsic characteristics of the locations where the materials are stored and handled*
  - *vaults, hot cells, transfer casks, equipment rooms, and other controlled locations*
- *Extrinsic measures associated with PP system design to*
  - *detect, delay, and neutralize adversaries*
  - *control the effects of insider actions (alarms, motion sensors, armed security forces, access control systems, locks, and seals).*

# *Case study* adversary sequence diagram

*"To succeed, the adversary must cross the site and PIDAS boundaries, access the FCF, access the inert hot cell, collect uranium/TRU slugs, and the escape the site. The consequence of adversary success is the theft of 1 SQ or more of fissile material." (pg. 50)*

- ***Discussion: What are the Probability of Detection and Delay Time for each task? (L/M/H)***




**Case Study:** Figure 6.4. Adversary Sequence Diagram for Theft of TRU/Uranium Product (in Process Cell)



# To Validate Qualitative Analysis, the Case Study also used EASI v200

| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | |
| 2–5 | | | ***Estimate of Adversary Sequence Interruption*** | Probability of Guard Communication | | Force Time (in Mean | Standard Deviation | | |
| 5 | | | | 1 | | 150 | 15 | | |
| 6 | | **Theft of TRU/Uranium Product Slugs Pathway 5a** | | | | | | | |
| 7–8 | | Task | Description | P(Detection) | Location | Delays (in Seconds): Mean: | Standard Deviation | Rt | |
| 9 | | 1 | Initiate Attack | 0.5 | M | 30 | 3 | 6210 | |
| 10 | | 2 | Cross Plant Boundary | 0.5 | M | 30 | 3 | 6180 | |
| 11 | | 3 | Cross Protected Area | 0.85 | M | 1200 | 120 | 6150 | |
| 12 | | 4 | Access Fuel Cycle Facility | 0.95 | M | 2700 | 270 | 4950 | |
| 13 | | 5 | Access Inert Hot Cell by Removing Manipulator Assembly | 0.95 | M | 1200 | 120 | 2250 | |
| 14 | | 6 | Load TRU/Uranium Product Slugs | 0.5 | M | 330 | 33 | 1050 | |
| 15 | | 7 | Regroup Forces | 0.1 | M | 30 | 3 | 720 | |
| 16 | | 8 | Cross Protected Area | 0.1 | M | 330 | 33 | 690 | |
| 17 | | 9 | Cross Plant Boundary | 0.1 | M | 330 | 33 | 360 | Critical Detection Point |
| 18 | | 10 | End Attack | 0.1 | M | 30 | 3 | 30 | |
| 19 | | 11 | | | | | 0 | 0 | |
| 31 | | | | | | 6210 | | | |
| 32 | | | Probability of Interruption: | 1.00 | | | | | |

**Example EASI v200 output**

# Case Study: PD & Delay

***Multiple insights:***

- *"Construction of the [FCF] building as a hardened structure will reduce the probability of adversary success dramatically…"*
- *"An insider has the greatest ability to increase the adversary's overall probability of success. If the insider can pre-open doors or hot cell access ports…"*
- *"The next greatest weakness in accepting the hot cells as secure rooms is the presence of the windows and adversary access to the manipulators…"*

| Task | PD[1] | Delay | Assessment Description |
|---|---|---|---|
| 1-Initiate attack | Low | No | The militarily trained force is assumed to achieve both strategic and tactical surprise. |
| 2-Cross plant boundary | Low | No | The outer boundary is typically a simple fence and or vehicle barrier. Note that they will be detected by various sensors at this point. |
| 3-Cross protected area | Medium | Medium | The PIDAS boundary is a set of fences, vehicle barriers, and sensors. A trained group will readily be able to cross this but not without detection. At this point, defensive forces are moving in and engaging the adversary. |
| 4-Access FCF | High | High | When the sensors alarm, the building will be locked down. The adversaries will have to force (probably via explosives) their way in. If the insider's task is to be inside the building, the insider can defeat the locks and open a door. This step must be performed while under fire. If the building is hardened, multiple breaching charges (while under fire) will be required. |
| 5-Access inert hot cell by removing manipulator assembly | High | Medium | This step is very time intensive, and thus is unlikely to be completed. |
| 6-Load uranium product slugs | Low | Low | The adversaries must be equipped with self-contained breathing equipment. Any adversary loading fuel slugs is not available to engage the defensive forces. The adversary is in a restrictive location, and the defensive forces are already aware. However, the adversaries inside the cell are expected to be alone. |
| 7-Regroup forces | N/A[2] | No | Regrouping must occur under fire, through known access points (the opened door), and in a known location (within the PIDAS). |
| 8-Driving vehicle, cross protected area | N/A | Low | Complete defensive force response (including heavier weapons and armored vehicles) will have arrived by this point. Vehicles will be placed under heavy fire to disable them as an avenue of escape. Dismounted adversaries have to cross the PIDAS while under fire. |
| 9-Driving vehicle, cross plant boundary | N/A | Low | Because the defensive forces will be converging on the adversaries, is it assumed that successful escape from the PIDAS constitutes a breakout. Accordingly it is easier to then continue on through the plant boundary. |
| 10-End attack | N/A | No | Only the adversary gets to decide when to quit. |



# Further discussion

- ***Probability of Adversary Success (PAS) for theft of TRU/uranium slugs of can be made low***
- ***Consequences***
  - ***After successful theft, significant work still required to fabricate a nuclear explosive, but less than for irradiated fuel***
- ***Physical Protection Resources***
  - ***Onsite handling of material (no transportation) in hot cells reduces Physical Protection Resources needed to provide a low PAS***
  - ***Overall guard force size likely determined by protection of facility from radiological sabotage (not theft of material)***

# Previous Lessons Learned from the ESFR Case Study

Presenter: Robert Bari
GIF PR&PP Working Group

Workshop on the Proliferation Resistance and Physical Protection Evaluation (PR&PP) Methodology for Generation IV Nuclear Energy Systems
University of California, Berkeley · Berkeley, California · November 4, 2015

## Lessons learned at scoping level-recap

- *Each PR&PP assessment should start with a Qualitative Analysis allowing scoping of the study, of the assumed threats and identification of targets, system elements etc.*
  - *need to include detailed guidance for qualitative analyses in methodology*
- *Role of experts is essential*
  - *need for PR and PP experts and expert elicitation techniques*
- *Qualitative analysis offers valuable results at preliminary design level. Can directly address TD, PT, PC, MT. DE and especially DP are harder to quantify*

## Proliferation resistance lessons (1)

- ***Completeness in diversion pathways can be ensured***
  - ***consideration of every target for the specific threats under consideration***
  - ***systematically searching for plausible scenarios that could implement the potential proliferant Host State's strategies to divert the target material.***
- ***A set of diversion pathway segments can be developed and the proliferation resistance measures for each pathway can be determined.***
- ***Methodology can compare and distinguish the proliferation resistance of different design choices. Methodology can provide useful information to authorities, officials, and designers.***



## Proliferation resistance lessons (2)

- ***Misuse, for achieving weapons-usable fissile material, is a complex process,***
  - ***not a single action on a single piece of equipment***
  - ***an integrated exploitation of various assets and system elements.***
- ***Given a proliferation strategy some measures are likely to dominate over the others, and within a measure some segments will dominate the overall pathway estimate.***
- ***Breakout is a modifying strategy within the Diversion and Misuse threats and takes various forms that depend upon intent and aggressiveness, and ultimately the proliferation time assumed by a proliferant state.***

## Proliferation resistance lessons (3)

- ***Qualitative analysis can***
  - ***produce traceable, accountable, and dependable results***
  - ***produce useful results to system designers even when detailed information is largely missing (e.g., to provide functional requirements)***
  - ***identify small differences in the rationale and in the measure estimates***



## Physical protection lessons (1)

- ***For theft scenarios, multiple target and pathways exist; however, the most attractive target materials appeared to be located in a few target areas***

- ***For radiological sabotage scenarios five primary attack strategies should be considered:***
  - ***loss of cooling,***
  - ***reactivity,***
  - ***direct attack,***
  - ***fire/chemical, and***
  - ***other forms of attack.***

## Physical protection lessons (2)

- ***For theft and sabotage scenarios where early detection probability was low, the response force time had the greatest impact on adversary success.***
- ***For theft and sabotage scenarios where early detection probability was high, probability of adversary success decreased rapidly as response times decreased.***



## Indicated improvements to methodology

- ***Proliferation Resistance***
  - ***practical use of some measures needs further investigation***
  - ***metrics might need some additional investigation***
- ***Physical Protection***
  - ***closer examination of the qualitative methods and the grouping of qualitative values for coarse pathway assessment***
  - ***include more systematic consideration of the response force deployment strategy***

# Selected examples of application of PR&PP outside GIF

*Presenter*: Giacomo G.M. Cojazzi
GIF PR&PP Working Group

*Workshop on the Proliferation Resistance and Physical Protection Evaluation (PR&PP) Methodology for Generation IV Nuclear Energy Systems*
**University of California, Berkeley · Berkeley, California · November 4, 2015**

# PR&PP Implementation Activities Within National Programs

- USA
  - Comparison of alternative fuel separation technologies (relative to PUREX)
    - COEX, UREX, pyroprocessing
    - Primarily improvements regarding non-state actors
    - Potential measurement challenges for large bulk facilities
  - Multi-laboratory assessment of reactor designs
    - SFR, HTGR, HWR, LWR
  - SMR Princeton study
    - Gen II vs SMR (LWR and fast-spectrum)

## PR&PP Implementation Activities Within National Programs (cont'd)

- **Canada**
  - *Pre-licensing assessment of two advanced CANDU designs (ACR-1000 and EC6)*
  - *"Pared-down" PRPP approach, incorporating designer, SSAC and IAEA*
  - *Design improvements identified*



## PR&PP Implementation Activities Within National Programs (cont'd)

- **Japan**
  - *Evaluation of the methodology (JAEA and U. Bologna)*
  - *Comparison of SFR and LWR (presented at 2014 IAEA SG Symposium)*
  - *Important to consider PR measures in a particular order*
  - *Difficulty incorporating impact of Additional Protocol*
  - *Facilitated a better understanding of PR, and how the methodology can help meet researchers' needs*

# PR&PP Implementation Activities Within National Programs (cont'd)

- *Europe*
  - *"Collaborative Project for a European Sodium Fast Reactor" (CP-ESFR): study of impact of alternative core design options (another pared-down PRPP application)*
  - *MYRRHA (Belgium) – accelerator-driven research reactor: comparison with existing high flux test reactor and study of impact of alternative design variations.*



# PR&PP bibliography

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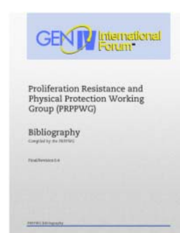

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- *J. Whitlock et al., Status of the Gen-IV Proliferation Resistance and Physical Protection (PRPP) Evaluation Methodology, Symposium on International Safeguards: Linking Strategy, Implementation and People. IAEA, Vienna, 20-24 October 2014.*
- *J. Cazalet et al., Status of the Gen-IV Proliferation Resistance and Physical Protection (PRPP) Evaluation Methodology, Symposium on International Safeguards, GLOBAL 2015, 21st International Conference & Exhibition: Nuclear Fuel Cycle For a Low-Carbon Future, Paris, September 21-24, 2015.*
- *GIF PRPP, Bibliography of the GIF PRPPWG, Final/Revision 0.4 (08/21/2014)*


# Proliferation Resistance considerations in the framework of the European Sodium Fast Reactor Collaborative Project

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*Work done while at JRC-ITC

Workshop on the PR&PP Evaluation Methodology

University of Berkeley, CA, USA
November 4, 2015

## Content


- The CP-ESFR project, overview
- CP-ESFR PR Evaluation: Objective & Approach
- CP-ESFR PR relevant design feature and PR qualitative considerations:

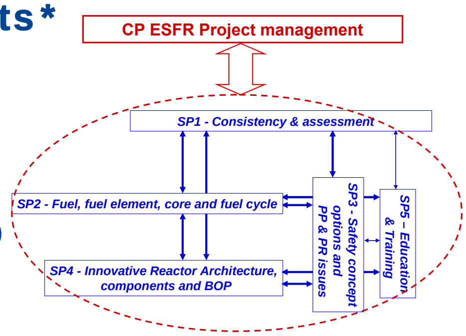
  System elements, targets, response to threats
- Hints on other studies: Material type, diversion analyses and safeguards/safeguardability considerations
- Conclusions

## Collaborative Project for European Sodium Fast Reactor


- Collaborative Project on **European Sodium Cooled Fast Reactor** (2009-2012). 7th EURATOM Programme.
- Contribute to establish a "***sound scientific and technical basis for the European Sodium fast Reactor***, *in order to accelerate practical developments for the* ***safe management of long-lived radioactive waste, to enhance the safety performance, resource efficiency and cost-effectiveness of nuclear energy***…"
- 26 project partners, CEA coordinator. JRC: ITU (Lead) and IET.
- Total estimated eligible project costs: ~11.4 M€ (5.8 M€ requested FP7 contribution)



## CP-ESFR sub-projects*




- SP0: Management
- SP1: Consistency and assessment (cross-cut)
- SP2: Fuel, fuel element, core & fuel cycle (oxide, carbide)
- SP3: Safety concept options and PR&PP issues (cross-cut)
- SP4: Innovative Reactor Architecture, components and BOP
- SP5: Education & training (cross-cut)

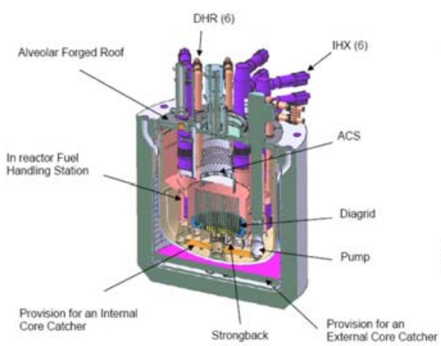
* The Collaborative Project on European Sodium Fast Reactor (CP ESFR), G.L. Fiorini, FISA 2009, Seventh European Commission conference on Euratom research and training in reactor systems, 22-24 June 2009, Prague, Czech Republic

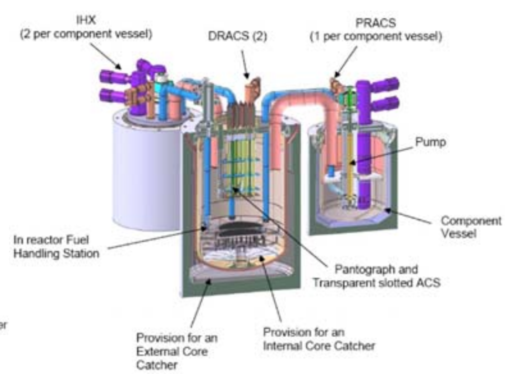
## CP-ESFR focus

- Two reactor concepts: pool vs. loop design
- Two fuel options: Oxide vs. Carbide fuel
- Possibility for Minor Actinide (MA) management (both homogeneous and heterogeneous cases), investigated for oxide fuel
- Reference cores (working horses) and optimization studies
- Blanket/no-blanket options



## CP-ESFR Working Horses Type Options (AREVA)*




**Pool Concept** **Loop Concept**

* The Collaborative Project on European Sodium Fast Reactor (CP ESFR), G.L. Fiorini, FISA 2009, Seventh European Commission conference on Euratom research and training in reactor systems, 22-24 June 2009, Prague, Czech Republic

## CP-ESFR PR requirements & activities

- No need of for full PR analysis;
- Consider GIF PR&PP work as Subsumed Framework;
- Consider IAEA INPRO PR work; UR2 (MT attractiveness) used for MT studies;
- Collect from project reports PR relevant design information according to GIF SSC-PR&PP white paper template and issue qualitative PR considerations by consensus among partners;
- Additional studies: Material type studies, diversion analyses and safeguards/safeguardability considerations.



## GIF SSC-PR&PP study on GEN IV systems

Ref. GIF-SSC-PRPP

- Cross cutting issues
- White papers prepared jointly by SSC and PR&PP for VHTR, MSR, SCWR, LFR, GFR and SFR.

1. Overview of Technology;
2. Overview of Fuel Cycle;
3. PR&PP Relevant System Elements and Potential Adversary Targets;
4. Proliferation Resistance Features:
   a) Concealed diversion or production of material;
   b) Breakout; and
   c) Production in clandestine facilities;
5. Physical Protection Features:
   a) Theft of material for nuclear explosives and
   b) Radiological sabotage;
6. PR&PP Issues, Concerns and Benefits.

**SFR PRPPWG white paper structure was used for the PR relevant description of ESFR**

# Context and Description of Task 3.2.5

**SP3-WP2**: Implementation of a whole set of “defence-in-depth” levels with the corresponding provisions, and identification of incidents/accidents which are representative for design basis and Design Extension Conditions.

**Task 3.2.5**: PR Considerations: Provide a proposal for an approach to make nuclear proliferation resistance considerations on a Sodium Fast Reactor design

**Task Partners: JRC-ITU, AREVA, EDF, ENEA**



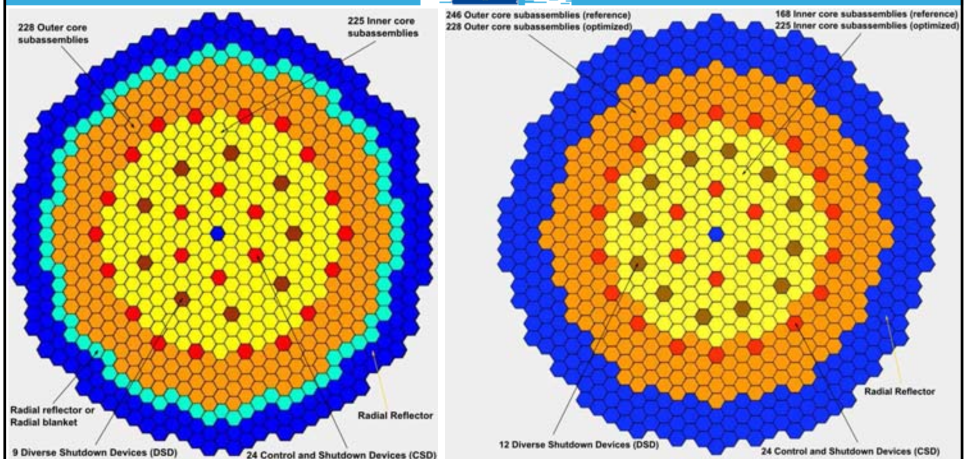
# GIF SSC-PR&PP SFR vs. CP-ESFR

**Ref. GIF-SSC-PRPP**

| | SFR Design Concepts in GIF | | | ESFR Both Loop and Pool type | |
|---|---|---|---|---|---|
| Design Parameters | JSFR (Loop) | KALIMER (Pool) | SMFR | Oxide | Carbide |
| Power Rating, MWe | 1,500 | 600 | 50 | 1500 | |
| Thermal Power, MWt | 3,570 | 1,525 | 125 | 3600 | |
| Plant Efficiency, % | 42 | 42 | ~38 | 42 | |
| Cycle length, years | 1.5–2.2 | 1.5 | 30 | 2050 EFPD | 1600 EFPD |
| Fuel reload batch, batches | 4 | 4 | 1 | 5 | 3 |
| Core Diameter, m | 5.1 | 3.5 | 1.75 | 4.72 | 4.10 |
| Core Height, m | 1.0 | 0.8 | 1.0 | 1.0 | 0.8 |
| Fuel Type | MOX (TRU bearing) | Metal (U-TRU-10%Zr Alloy) | Metal (U-TRU-10%Zr Alloy), | $(U,Pu)O_2$ | (U,Pu)C |
| Pu enrichment (Pu/HM), % | 13.8 | 24.9 | 15.0 | 14.05-16.35 | 17.80-24.50 |
| Burn-up, GWd/t | 150 | 79 | ~87 | 100 | 144 |
| Breeding ratio | 1.0–1.2 | 1.0 | 1.0 | - | - |

# ESFR Core Options (CEA)

Ref. CP-ESFR




**Oxide Core** **Carbide Core**

Fresh fuel Pu vector (Reactor Grade)

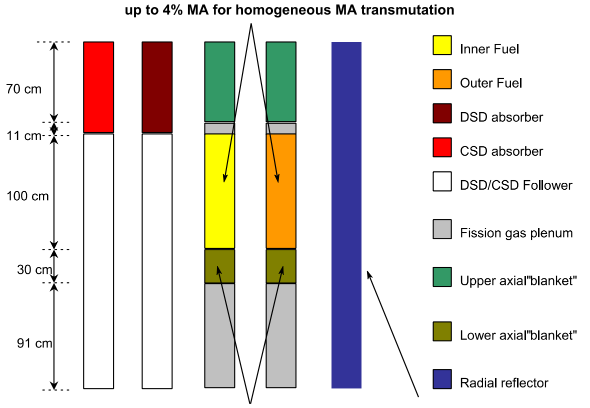
| Pu Isotope | $^{238}$Pu | $^{239}$Pu | $^{240}$Pu | $^{241}$Pu | $^{242}$Pu |
|---|---|---|---|---|---|
| % w | 3.60 | 47.76 | 29.89 | 8.29 | 10.46 |



Ref. CP-ESFR

# The axial cross-section (R-Z) of the oxide core inner and outer FAs

Oxide cores' inner and and outer fuel active areas can host up to 4% MA for homogeneous MA transmutation




| MA Isotope | MA % w |
|---|---|
| $^{237}$Np | 16.86 |
| $^{241}$Am | 60.62 |
| $^{242m}$Am | 0.24 |
| $^{243}$Am | 15.70 |
| $^{242}$Cm | 0.02 |
| $^{243}$Cm | 0.07 |
| $^{244}$Cm | 5.14 |
| $^{245}$Cm | 1.26 |
| $^{246}$Cm | 0.09 |

Optimized cores foresee a fertile DU blanket in the lower axial "blanket" part of the FA

Oxide cores' radial reflector can be partially replaced by fertile radial blanket assemblies hosting up to 20% MA for MA heterogeneous transmutation

# Oxide vs. Carbide cores (reference case)

## Oxide Core

- Bigger core
- Bigger FA size
- Lower Pu enrichment
- Larger number of FAs
- Lower power density
- Lower average burnup
- Longer Fuel residence time
- More batches
- Lower number of FA movements in the same period

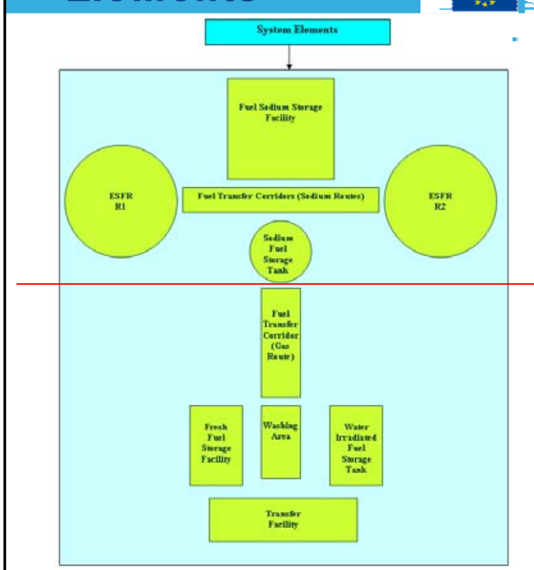
## Carbide Core

- Smaller core
- Smaller FA size
- Higher Pu enrichment
- Lower number of FAs
- Higher power density
- Higher average burnup
- Shorter Fuel residence time
- Fewer batches
- Higher number of FA movements in the same period

**Both oxide and carbide fresh FA contain more than one SQ* of Pu**



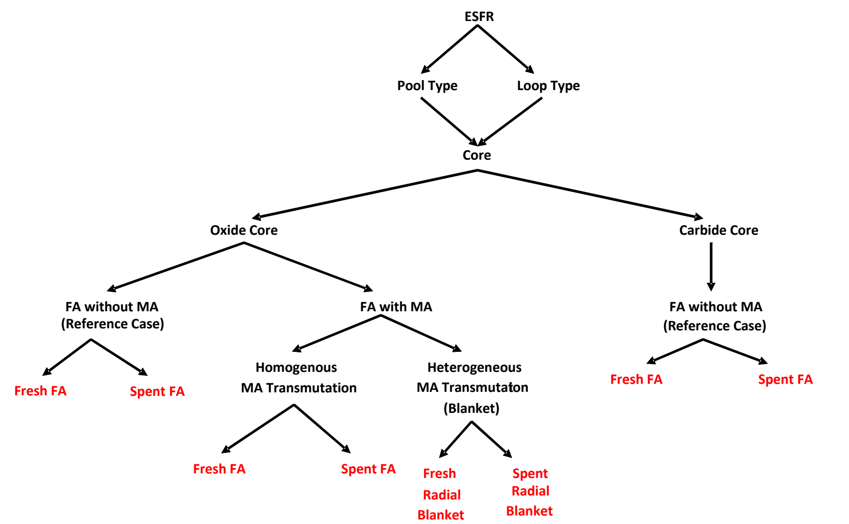
# ESFR System Elements




- ..where nuclear material diversion acquisition and or processing ..could take place.
- System elements of Loop and Pool types are mostly same.
- The types of the reactors (R1 and R2) and in vessel fuel handling (IVFH) systems are different in the pool and loop types.
- IVFH different solutions (Pool: DLCM+FACM; Pantograph arm for loop..)

## Reference cores
## Diversion targets

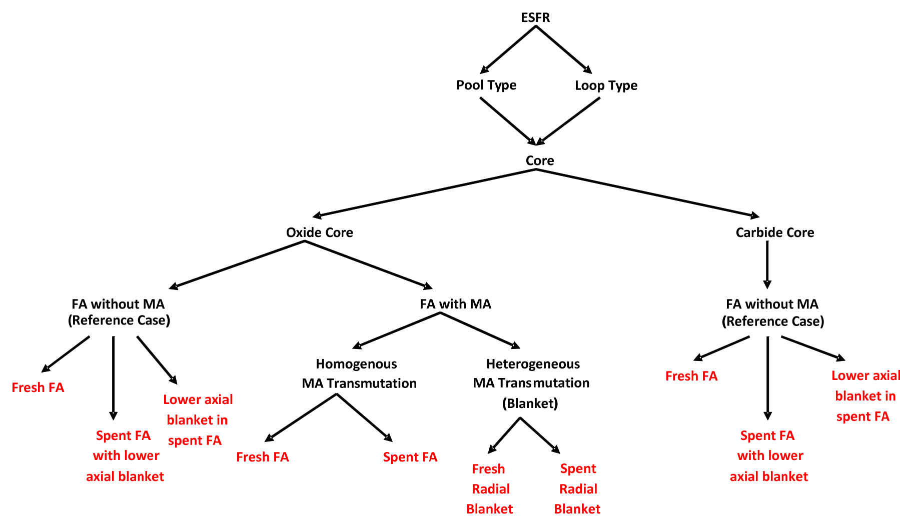
Ref. CP-ESFR






## Optimised cores
## Diversion targets

Ref. CP-ESFR



## Diversion targets

Ref. CP-ESFR

| Core | Case | Target | SQ |
|---|---|---|---|
| Working Horses | Oxide Core | Fresh Fuel Assembly | 3.45 |
| | | Spent Fuel Assembly | 5.01 |
| | Carbide Core | Fresh Fuel Assembly | 2.90 |
| | | Spent Fuel Assembly | 3.70 |
| | Oxide Core with 4% MA in FA | Fresh Fuel Assembly | 3.45 |
| | | Spent Fuel Assembly | 5.26 |
| | Oxide Core with 20 % MA in Radial Blanket | Spent Blanket Assembly | 0.83 |
| Optimized Cores | Oxide Core | Fresh Fuel Assembly | 3.52 |
| | | Spent Fuel Assembly | 4.34 |
| | | Axial Blanket Part in Spent Fuel Assembly | 0.13 |
| | Carbide Core | Fresh Fuel Assembly | 2.57 |
| | | Spent Fuel Assembly | 3.18 |
| | | Axial Blanket Part in Spent Fuel Assembly | 0.11 |
| | Oxide Core with 4% MA in FA | Fresh Fuel Assembly | 3.52 |
| | | Spent Fuel Assembly | 3.82 |
| | Oxide Core with 15 % MA in Radial Blanket | Spent Blanket Assembly | 1.07 |
| | Oxide Core with 20 % MA in Radial Blanket | Spent Blanket Assembly | 1.68 |



## PR ESFR: other studies

- Material type considerations on PR diversion Targets for oxide and carbide reference and optimised cores (Kessler 2008, B. Pellaud 2002, N. Inoue et al. 2010, INPRO-PR, Bathke et al. 2009).
- Coarse pathway analysis, diversion points identification, safeguards coverage.
- Safeguardability and SBD considerations for loop and pool options. 2 Notional safeguards schemes investigated with definition of MBAs, KMPs.

## PR-Concealed Diversion

### Reference cores, both pool an loop types

- Each oxide core fresh fuel assembly contains an average of 27.6 kg of Pu (3.45 SQs)
- Each carbide core's fresh fuel assembly contains an average of 23.2 kg of Pu (2.9 SQs)
- In both fresh and spent fuel, Pu will be always of Reactor Grade quality.

### With Minor Actinides, oxide only

- MA bearing fresh fuel (homogeneous MA transmutation) has a higher radiation emission, making the handling of the fuel assemblies more complicate. This higher radiological barrier might increase proliferation resistance. However the presence of MA can affect its detectability as well.
- Due to the presence of MA in fertile radial blankets (heterogeneous MA transmutation) the resulting Pu will be of RG quality (more than 30% Pu 238).

### For optimized cores, both oxide and carbide

- Lower axial blanket in fresh fuel (made of depleted uranium), when irradiated, will result in weapon grade Pu, but the diversion of several assemblies will be needed for acquiring a SQ (8 for oxide, 10 for carbide).



## PR Concealed production of nuclear material

**Reference cores, both pool an loop types**

- There are multiple possibilities for misusing a system, yielding to several pathways. (different for quantity and quality of material).
- The weaker pathways with respect to PR should be identified and analyzed in detail and related safeguards requirements should be defined.
- Generally a misuse strategy has the objective to produce a better-than-available fissile material quality (in this case weapon-grade plutonium).
- Undeclared fissile material production by irradiating fertile material in inner, outer and blanket regions of the ESFR reference core might be a potentially attractive strategy.

**For optimized cores, both oxide and carbide**

- Weapon grade Pu is already present in the case of optimized cores, due to lower axial blankets: this was considered in diversion, (several axial blankets are needed for a SQ..).
- Trying to misuse the optimized reactor core a) to obtain bigger quantity of high-quality material or b) to end up with e.g. a single element containing one or more significant quantities might represent potentially attractive scenarios.

Main challenge for a proliferator for both scenarios will remain to avoid detection by safeguards, specific techniques might be needed.

## PR Breakout

- A large quantity of material will be available, but only RG grade Pu and not weapon-grade Pu, i.e. less than ideal for a weapon programme.
- The only exception being the lower axial blanket material present in the optimized cores
- According to IAEA, the conversion time for MOX fuel is of the order of 1-3 weeks.
- The major concern posed by a breakout scenario would be the production capability of Pu of any desired quality, and the key parameter to assess would be the proliferation time.

## PR Production in clandestine facilities

- As highlighted by other literature studies (SSC-PR&PP, WP), the sodium fast reactor technology does not seem the most suitable one to be replicated in a clandestine facility.
- The intrinsic difficulties connected with the presence of sodium, together with the overkilling dimensions of a fully-fledged commercial power reactor makes the ESFR a very unlikely candidate for clandestine replication.



## Conclusions (1/2)

- CP-ESFR R&D project explored different reactor and core solutions.
- From a PR point of view the two working horses options (pool or loop) are equivalent, provided that they are considered with the same core configuration, i.e. oxide (with or without MA) or carbide.

- The main common features are the following:
  - Use of reactor grade Pu as feed;
  - High fuel burn-up;
  - Possibility of including Minor Actinides (MA) in the fuel for MA management (Homogeneus vs. Heterogeneous);
  - The presence of MA in radial blanket, where present, will result in RG-Pu with a high percentage of $^{238}$Pu;
  - The lower axial blankets of both optimised cores contain WG-Pu;

- Safeguards will be fundamental for all options.

## Conclusions (2/2)

- A full scope PR evaluation was not in the objectives of the project.
- Any PR activity needs to start with the identification of PR relevant plant information.
- The PR&PP white paper template, provides a disciplined framework for collecting the PR relevant plant information.
- Filling the template allows as well to perform a qualitative PR evaluation.
- At the same time this allows to identify areas needing additional investigations i.a. MT specific studies on all the different core alternatives.
- Limited scope diversion analysis can build on the collected information.
- This can constitute in a nut shell a preliminary high level PR evaluation.
- This can give a high level global picture of a system PR.



## Acknowledgments

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