Proliferation Resistance and Physical Protection of Gen IV Reactor Systems

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Meet the presenter

Dr. Robert A. Bari is Scientific Advisor at Brookhaven National Laboratory and has over 40 years of experience in nuclear energy research. He has performed studies on safety, security and nonproliferation of advanced nuclear concepts. For 15 years Dr. Bari was co-chairman of the working group on proliferation resistance and physical protection of the Generation IV International Forum. He has served on the Board of Directors of the American Nuclear Society and as President of the International Association for Probabilistic Safety Assessment and Management. Dr. Bari was awarded the Theo J. "Tommy" Thompson Award in 2003 by the American Nuclear Society. In 2004, he received the Brookhaven National Laboratory Award for Outstanding Achievement in Science and Technology. Dr. Bari is a fellow of the American Nuclear Society and of the American Physical Society. He has participated in risk-based standards development for nuclear technologies for more than two decades. He has been a committee member of the U. S. National Academy of Sciences on Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of the U.S. Nuclear Plants. Dr. Bari also chaired a workshop of the U. S. National Academy of Sciences on safety and security culture held jointly between the U.S. and Brazil in 2014. He received his doctorate from Brandeis University (1970) and his bachelor's degree from Rutgers University (1965). He was awarded membership in the Phi Beta Kappa, Sigma Xi, and Sigma Pi Sigma honor societies.

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Prologue

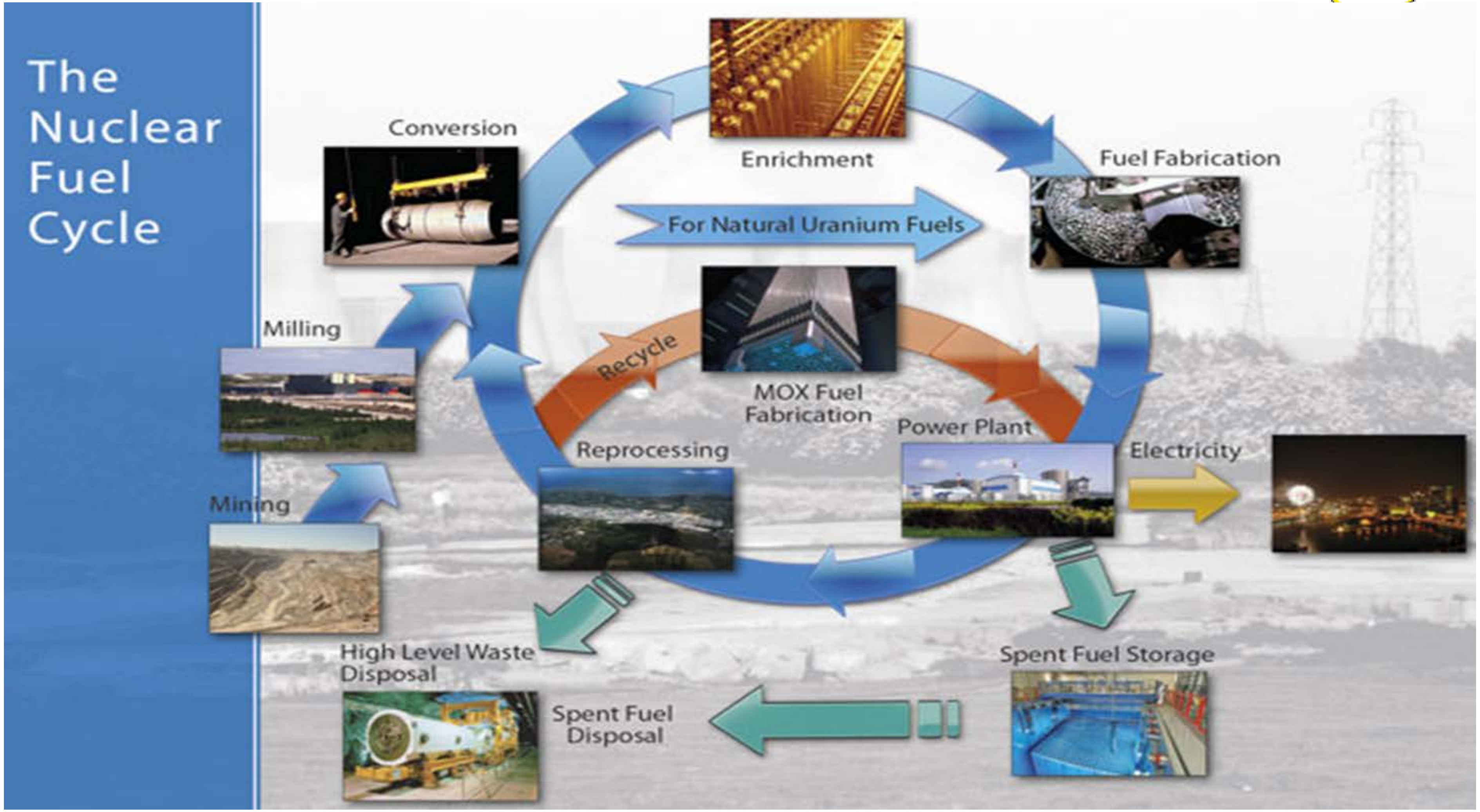
As we embark on the path to a growing number of nuclear power plants worldwide, it is important to consider…

Technology Goals for Generation IV

- Sustainable Nuclear Energy
- Economically Competitive Nuclear Energy
- Safe and Reliable Systems
- Proliferation Resistance and Physical Protection (PR&PP)

Getting Sustainability Right

Reliable Fuel Supply?



Waste Issues?

http://energy.sandia.gov/energy/nuclear-energy/advanced-nuclear-energy/nuclear-fuel-cycle-options-catalog

Getting Economics Right

From the popular press, we read:

Getting Safety Right, lessons learned…

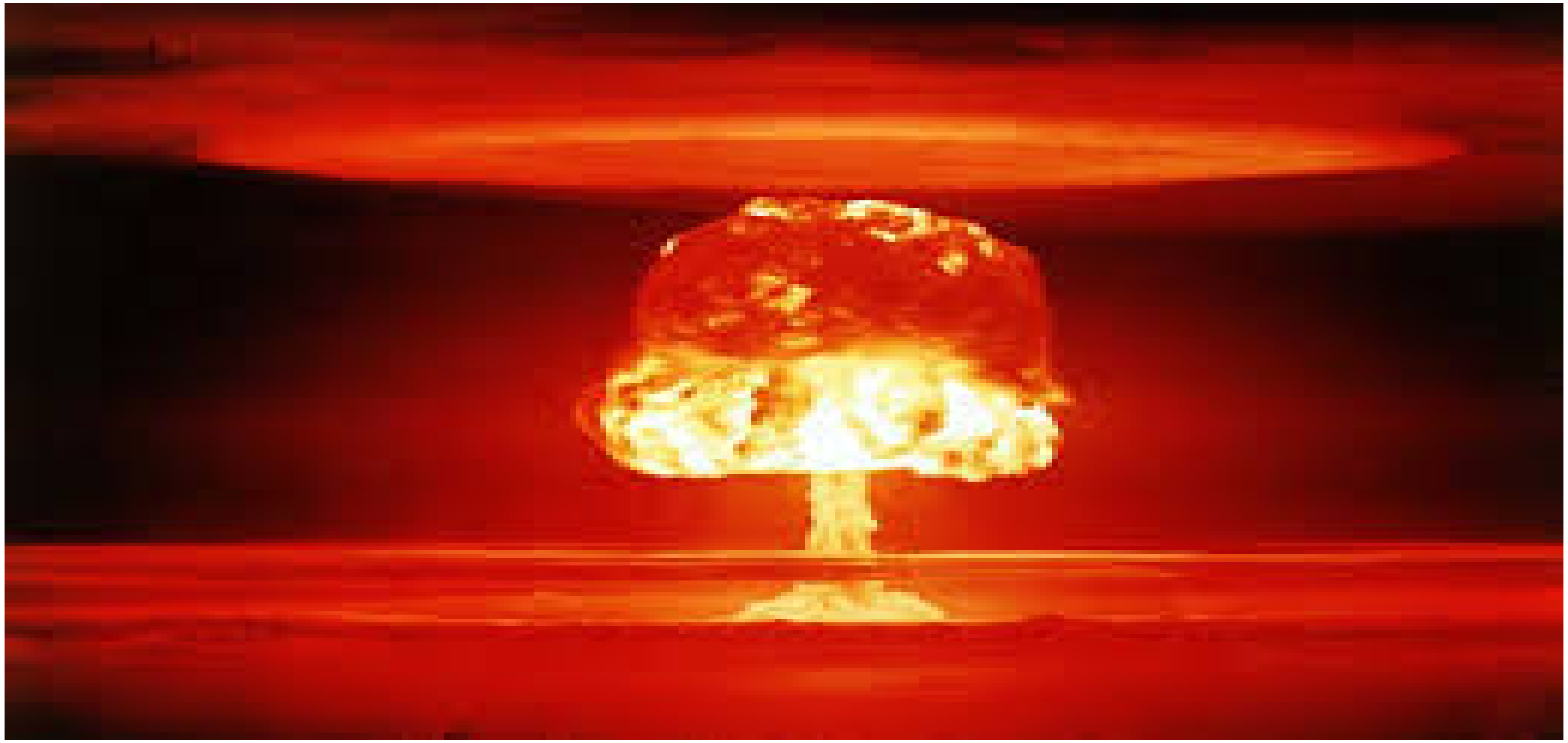
TMI

Chernobyl

Fukushima

Getting PR&PP Right,

must prevent



This Webinar

- PR&PP in Gen IV
- The PR&PP Methodology
- The Case Study
- Interactions with Gen IV Designers

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.

Distinction is important to articulate

PR & PP Working Group Charter

Develop and demonstrate a methodology for the systematic evaluation of Generation IV nuclear energy systems with respect to proliferation resistance (PR) and physical protection (PP)

(Seek consensus and harmony amongst GIF countries)

Major Tasks

- Characterize relevant proliferation and security threats
- Specify measures for expressing a system’s proliferation resistance and physical protection
- Develop a methodology to assess/quantify the measures

Work PR and PP together to build in coherence and to explore synergies and interfaces between them

PR&PP Group Major Products

- Methodology for PR&PP Evaluation
- Example Case Study
- Gen IV System Comparison Study
- Supporting Products:
  - PR&PP bibliography
  - PR&PP FAQ
- …and ongoing interactions with Gen IV designers

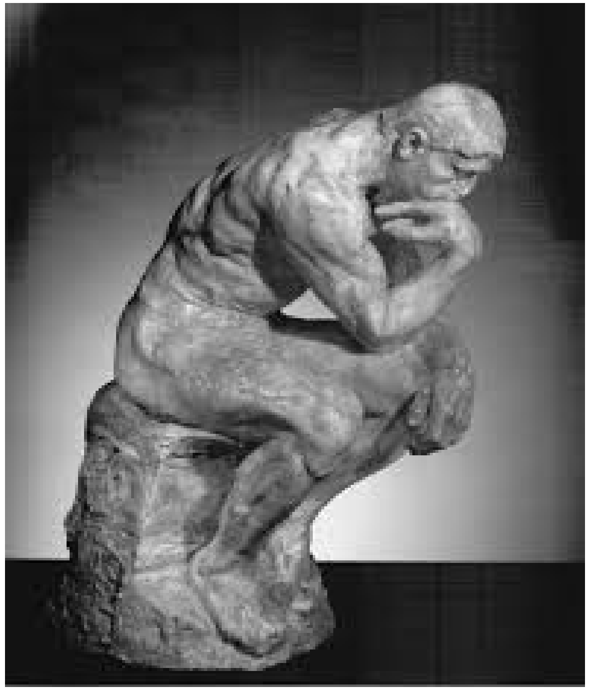
For reports see: https://www.gen-4.org/gif/jcms/c_9365/prpp

Value of PR&PP Evaluations for Future Designs

- Introduce PR&PP features into the design process at the earliest possible stage of concept development
- As the design matures, increasing detail can be incorporated in the PR&PP model of the system: progressive refinement
- PR&PP results can inform choices by policy makers

Evaluations should consider…

- Policy directions (to formulate questions)
- Adversary context for threat definition
  - Objectives
  - Capabilities
  - Strategies
- System design features relevant to PR&PP
- Fuel cycle architecture
- Safeguards and security contexts
- Reference (baseline) for comparison



PR&PP Methodology

CHALLENGES → SYSTEM RESPONSE → OUTCOMES

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

Intrinsic
- Physical & Technical Design Features

Extrinsic
- Institutional Arrangements

Proliferation, theft and sabotage involve **<u>competing</u> adversary and defender forces**. Important to recognize both perspectives and the human interplay.

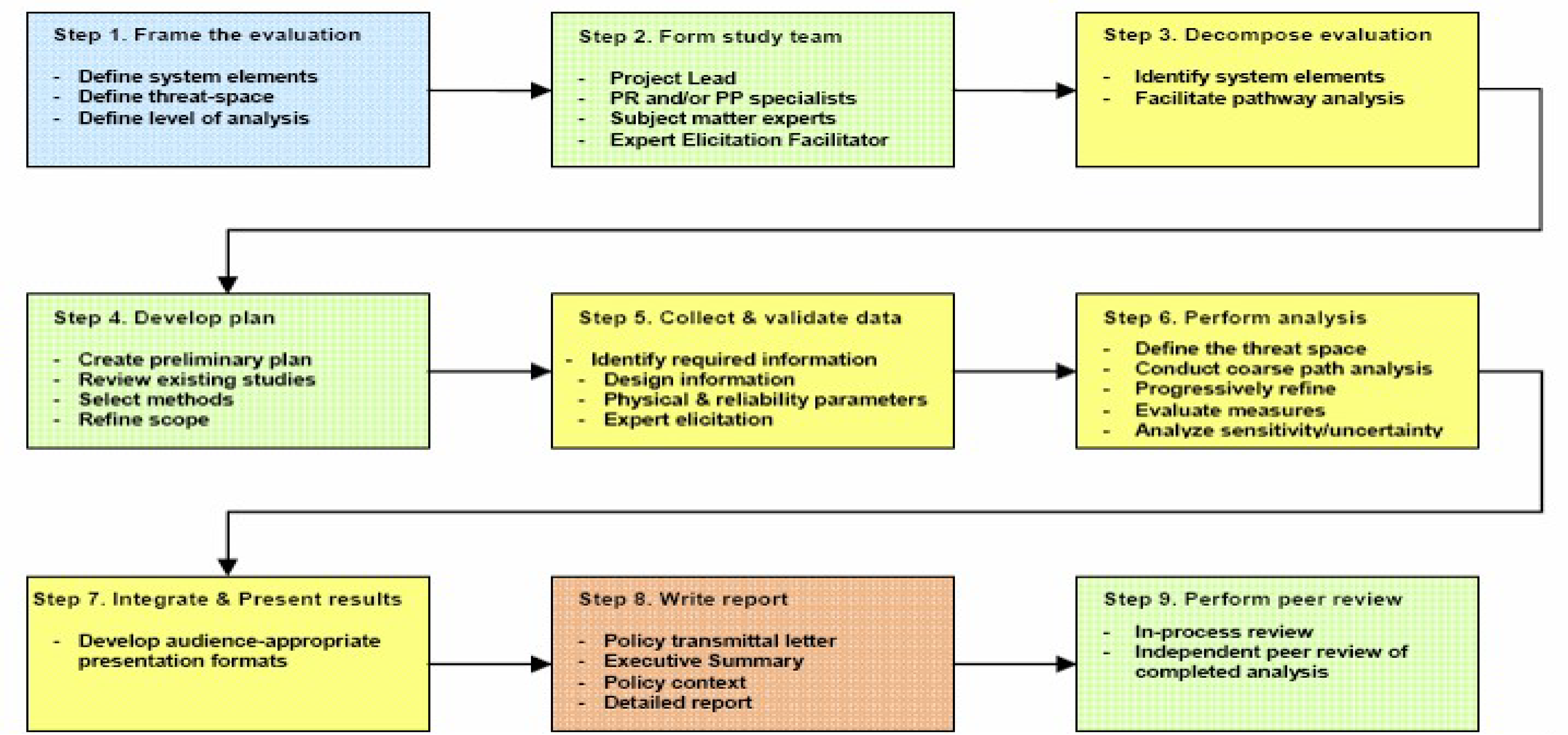
PR&PP Evaluation Framework

Challenges
- Threat Definition

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

Outcomes
- Pathway Comparison
- Assessment & Presentation of Results

Steps in the PR&PP Evaluation Process



GIF PRPP Methodology, Rev. 6 (2011), page 63

PR & PP Measures

PR Measures

- Proliferation Technical Difficulty
- Proliferation Time
- Proliferation Cost
- Detection Probability
- Fissile Material Type
- Detection Resources Efficiency

PP Measures

- Probability of Adversary Success
- Consequences
- Physical Protection Resources

Measures are mapped to specific metrics

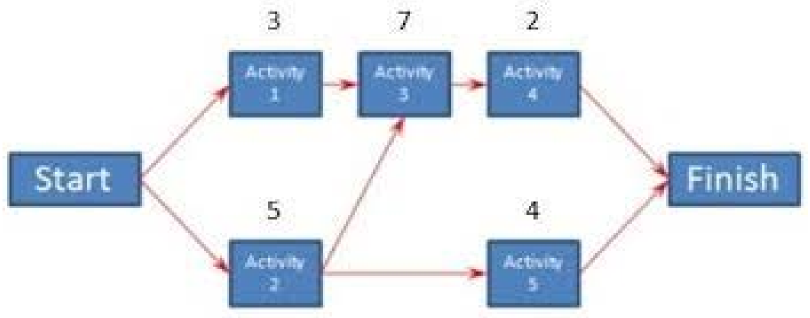
See: https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/gif_prppem_rev6_final.pdf

PR&PP Threat Considerations

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

System Response

- Pathway analysis: Intuitive way to describe & analyze proliferation, theft, or sabotage scenarios and to identify vulnerabilities



- Segmentation & decomposition, then re-aggregation
- Pathways: Potential sequences of events followed by the proliferator or adversary to achieve its objectives
  - Along any pathway the proliferant state or adversary will encounter various difficulties, barriers, or obstacles, all of which are collectively called “proliferation resistance” or “physical protection robustness”
- Considers time-dependent aspects and uncertainty

Similarities/Differences

Proliferation Resistance

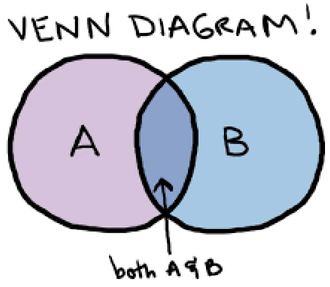
- Host state is adversary
- Threats are
  - Diversion
  - Misuse
  - Breakout
- International Safeguards
- Slow moving events

  (not always)
- International implications

Physical Protection

- Sub-national is adversary
- Threats are
  - Material Theft
  - Information Theft
  - Sabotage
- Security/Safeguards
- Fast moving events

  (sometimes)
- Regional implications



For PR: Safeguardability

- Because the probability of detection of a malevolent act by a proliferator is difficult to quantify, for new systems still in the design phase, the notion of Safeguardability has been introduced:
  - Safeguardability is defined as the ease with which a system can be effectively [and efficiently] put under international safeguards.
  - “Safeguardability” is a property of the whole nuclear system and is estimated for targets on the basis of characteristics related to the involved nuclear material, process implementation, and facility design.

Safeguards for Future Reactors…some considerations

- Accountancy tools and measures may need to be modified for non-conventional fuel types.
- New fuel loading schemes may present novel accountancy challenges.
- Accessibility to the nuclear material:
  - is facility operated continuously,
  - how facility is refueled,
  - location and mobility of facility,
  - existence and locations of other nuclear facilities

Safeguards for Future Reactors (cont’d)

- Fuel leasing or supply arrangements that avoid on-site storage of fresh and/or used fuel.
- Access issues for both inspectorate and the adversary.
- Remote monitoring by: Operator / State / IAEA communication

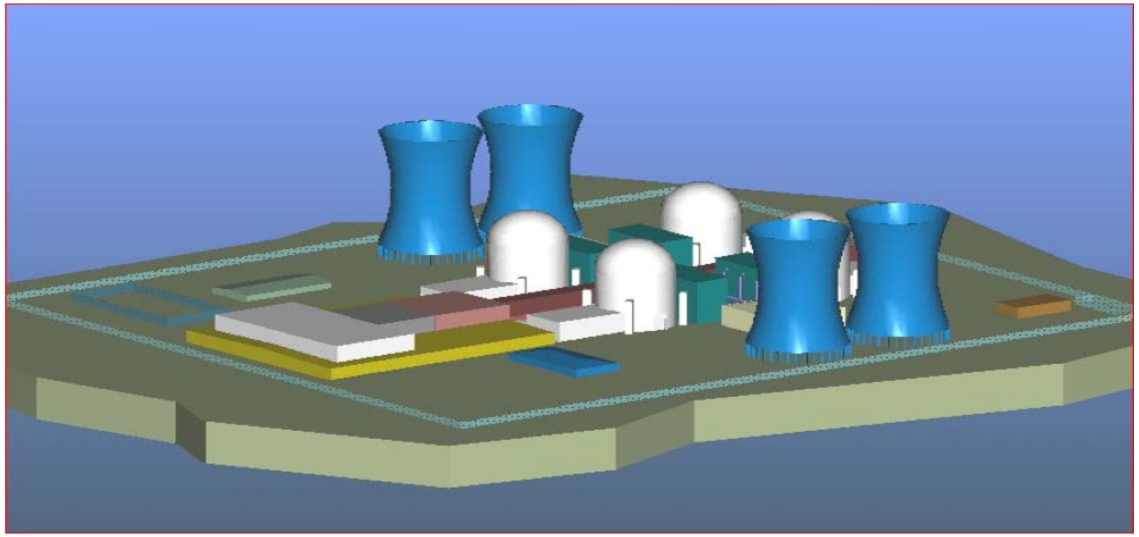
Safeguards for Future Reactors (cont'd)

- Will there be a different approach to physical protection and how might that affect the safeguards tools?
- Will the site or nearby sites have more or less ancillary equipment like hot cells, pin replacement capability, fuel storage, or nuclear research activities?
- Will the containment features be shared by multiple units; will there be underground containment?

CASE STUDY: EXAMPLE SODIUM FAST REACTOR (ESFR)

Case Study Objectives

- Demonstrate the Methodology for an entire system
- Confirm applicability at different levels of design detail
- Provide examples of PR&PP evaluations for future users of the Methodology
- Determine the needs for further methodology development



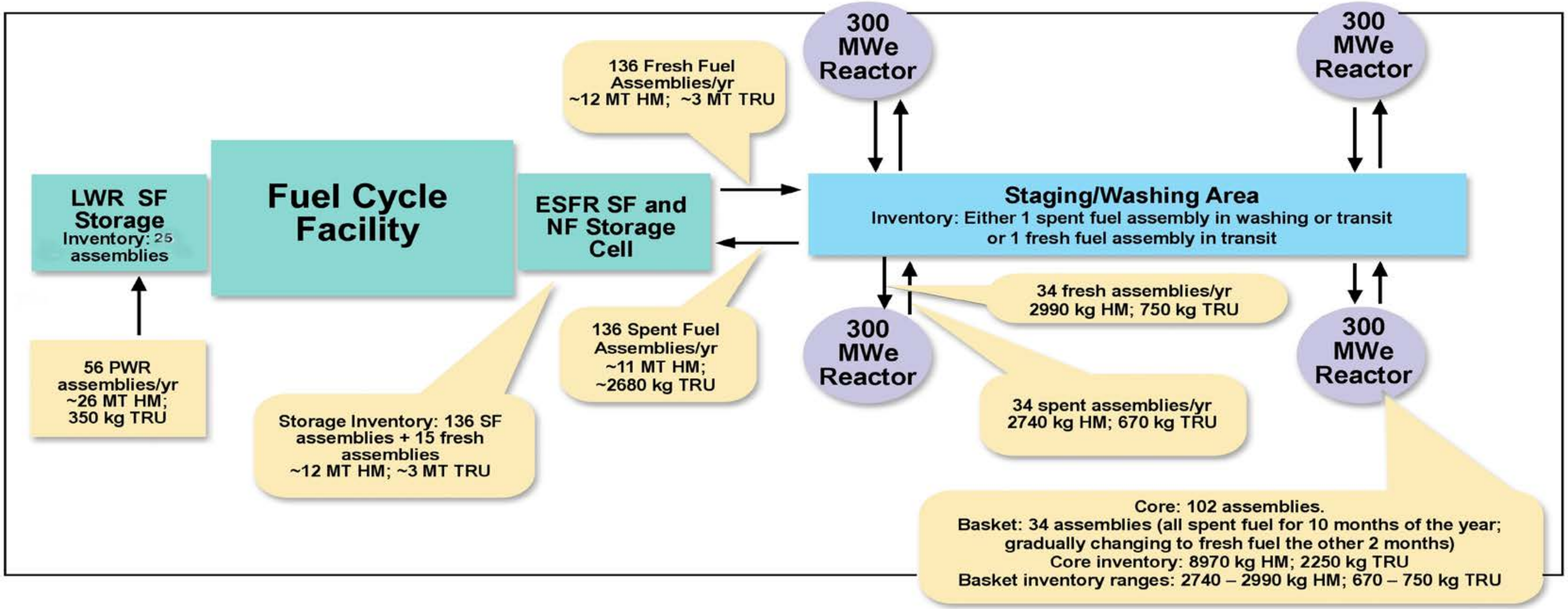
ESFR Case Study Scope

Concealed diversion of material

Concealed misuse of the facility

Breakout and overt diversion or misuse

Theft of weapons-usable material or sabotage of facility system elements.



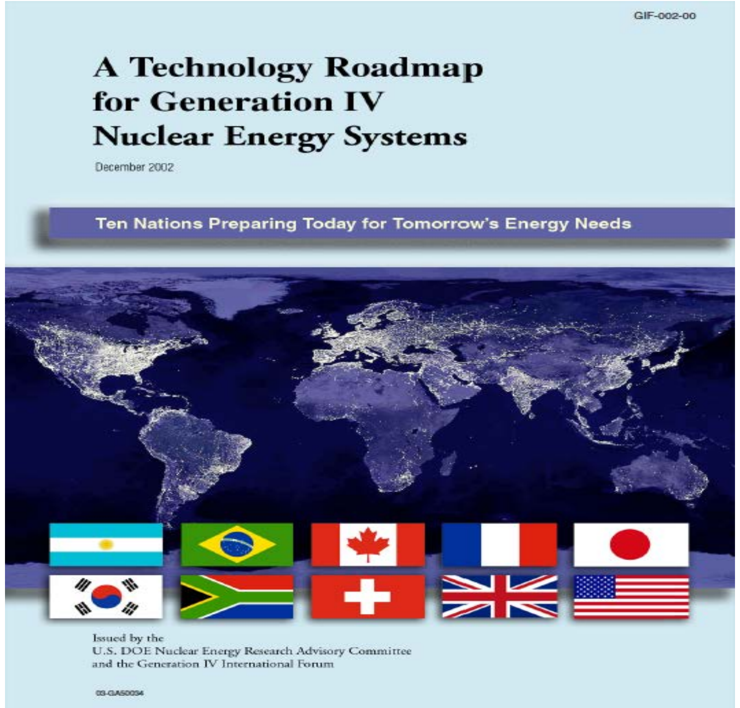
Methodology Lessons Learned

- Methodology can be applied during the conceptual stage of system development and design
- Completeness in identifying attractive targets and pathways is important
  - They can be systematically identified, and plausible scenarios can be described
- Assessment frequently requires assumptions about the system and its safeguards/protection
  - These assumptions provide the basis for functional requirements and design bases documentation for the system
- Assessment requires considerable technical expertise on system design and operation, as well as on safeguards and physical protection measures
- Greater standardization of the methodology and its use is needed
- Specific insights obtained for both PR and PP-related design considerations

PRPPWG/SSCs Interactions & Workshops

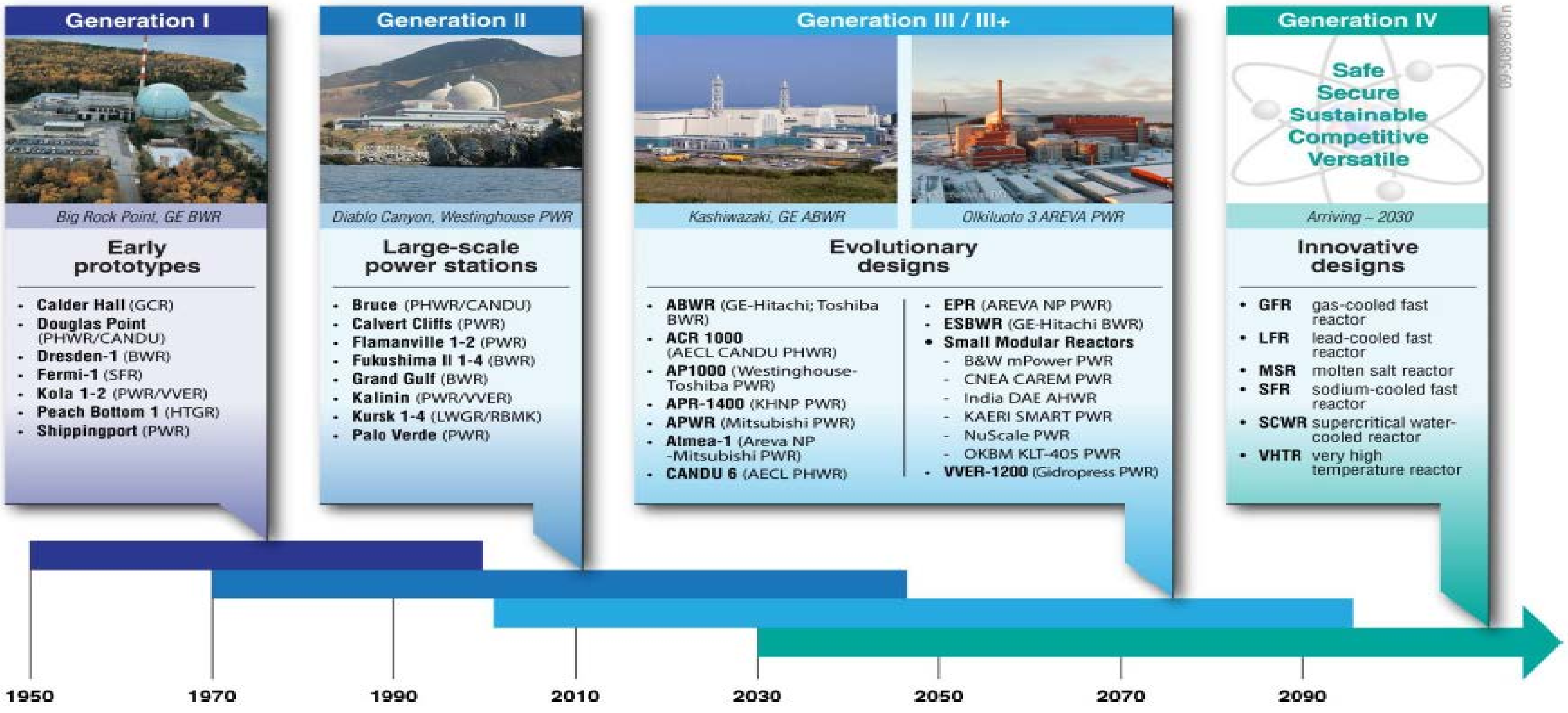
- Near term objectives:
  - Focus methodology efforts toward system development needs
  - Generate insights concerning design and operating features to enhance PR&PP performance of Gen IV systems
- Longer term objectives:
  - Establish beneficial PR&PP-related design and operation principles and practices
- Supporting objectives:
  - Establish a working relationship between experts in the PR&PP WG and GIF system designers
  - Increase SSC/designers' familiarity with the capabilities and limitations of the PR&PP methodology
  - Identify techniques and procedures to enhance effective application of PR&PP methodology
- Workshops USA (2005), Italy (2006, 2010), Japan (2007, 2011), RoK (2008), Russia (2012), France (2014), Berkeley (2015), RoK (2016), France (2017)

Generation IV International Forum

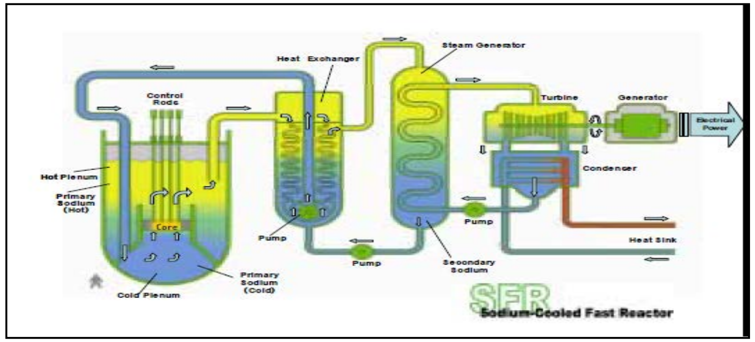


Technology Roadmap, 2002

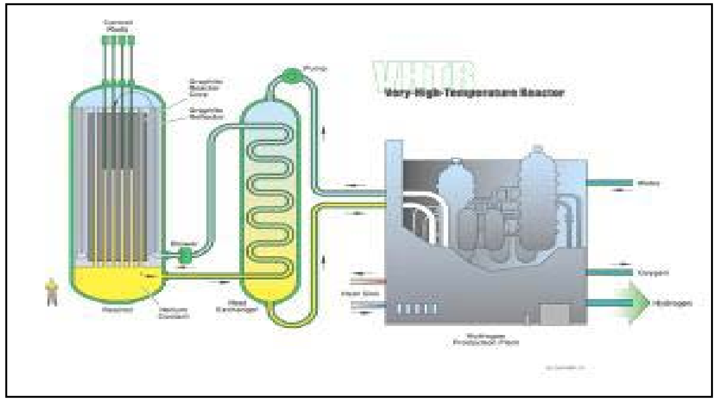
Generation IV Technology Timeline



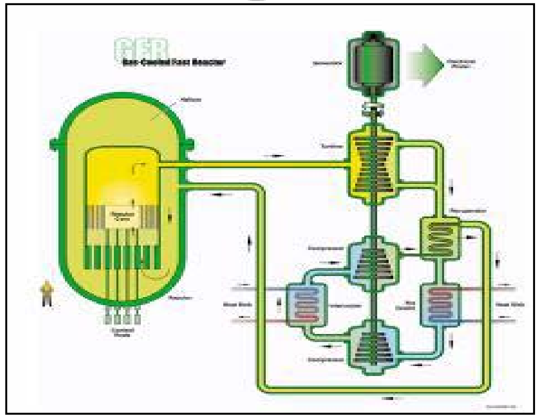
Six Gen-IV Systems



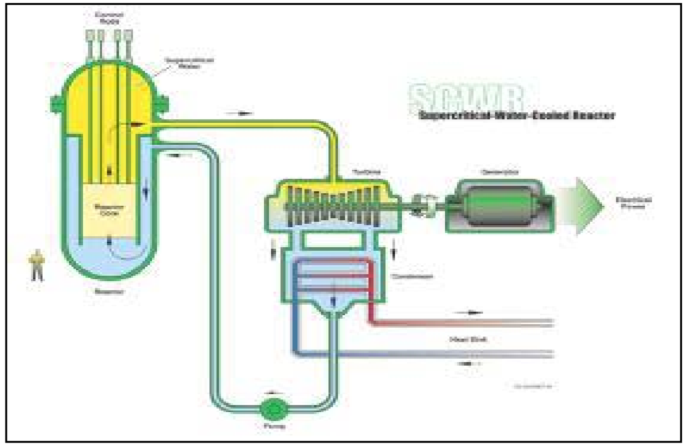
Sodium-cooled Fast Reactor (SFR)



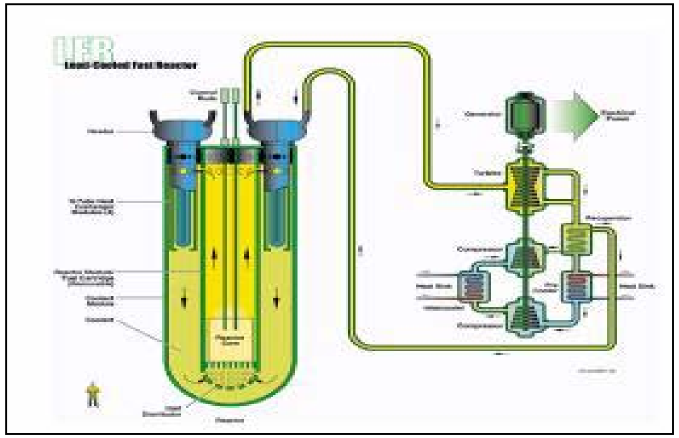
Very High Temperature Reactor (VHTR)



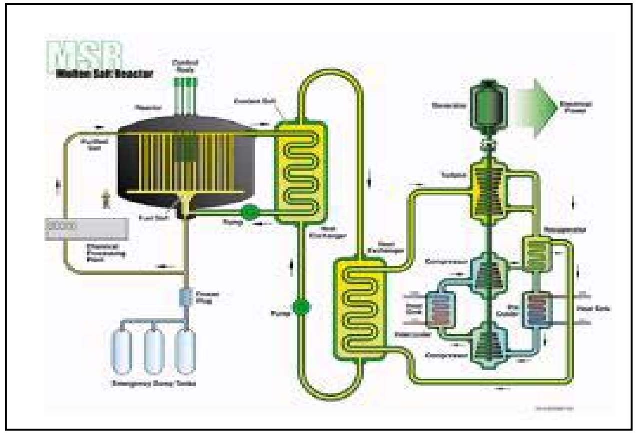
Gas-cooled Fast Reactor (GFR)



Supercritical Water-cooled Reactor (SCWR)



Lead-cooled Fast Reactor (LFR)



Molten Salt Reactor (MSR)

Six GEN IV Nuclear Energy Systems

http://www.gen-4.org/PDFs/GIF-2009-Annual-Report.pdf

GEN IV International Forum℠

System	Neutron Spectrum	Coolant	Possible Fuels	Refueling Mode	Fuel Cycle	Size (MWe)
VHTR	Thermal	He	Prismatic/Pebble LEU, Pu, TRU, U-233,Th/U, MOX	On-site; Offline batch / Online continuous	Open	250-300
SFR	Fast	Na	Convert vs. Breed Metal U-TRU and MOX TRU bearing	On-Site; Offline batch / Offline full core (Off-site)	Closed	50-150 300-1500 600-1500
SCWR	Thermal/ Fast	H2O	Once-through [LEU (UO2)] vs. recycle (U/Pu or Th/U MOX)	On-site; Offline batch / Online continuous SMR with 30 year core life	Open/ Closed	300-700 1000-1500
GFR	Fast	He	Breeding gain Pu isotopics (RG vs. Deep Burn) MA fertile blankets RepU/DU with Pu Fuel mixes	On-site; Offline batch	Closed	1200
LFR	Fast	Pb	Breeder/burner Actinide recycling MOX and TRU fuels	On-site; Offline batch / Offline full core (Offsite)	Closed	10-100 300-1200 600-1000
MSR	Thermal/ Fast	Fluoride salts	Breeder vs. Burner Fertile blankets U-233 vs. Pu (TRU) initial core	On-site; Online continuous	Closed	1000

PRPPWG/SSC Interactions: Report*

- Abstract
- Executive Summary
- Part I: General Overview
- Introduction
  - Objectives
  - Scope
- How the report was produced
  - Workshops
  - Production of White Papers
  - Drafting of the report
- Crosscutting Topics
  - *Fuel Type*
  - *Coolant, moderator*
  - *Refueling modes*
  - *Fuel cycle architectures*
  - *Safeguards topics*
  - *Other GIF crosscuts*
- Conclusion
  - Summary
  - Next steps
- Part II: System White Papers

System white papers TOC:

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

**Report was issued in 2011; updated study currently underway*

What will designers and analysts actually do?

- Need a multidisciplinary team
  - Designers
  - Safety
  - Safeguards
  - Security
  - Analysts
  - Other?

- Develop plants models at block diagram level
- Proceed through progressive refinement to more detailed designs and models (update, iterate)
- Interactions with regulators, IAEA, as appropriate

FAQ on PR&PP

https://www.gen-4.org/gif/jcms/c_44998/faq-on-proliferation-resistance-and-physical-protection

1. What is the Proliferation Resistance and Physical Protection (PR&PP) evaluation approach?
2. Why was the PR&PP methodology developed?
3. What is the level of effort needed to perform a PR&PP evaluation?
4. What is the time needed to perform a PR&PP evaluation?
5. What is the form of the results?
6. Who would use the results?
7. What is the expertise needed to perform an evaluation?
8. How does a PR&PP evaluation differ from an IAEA INPRO evaluation of proliferation resistance?
9. What is the relation between PR&PP and IAEA safeguards?
10. Does PR&PP apply to national or sub-national actors?
11. How does a PR&PP evaluation relate to a safety and reliability evaluation?
12. At what stage of an evaluation should a PR&PP evaluation be performed?
13. To what type of systems does a PR&PP evaluation apply?
14. Are there other methodologies for performing similar evaluations?
15. Will the PR&PP methodology be updated or is it in final form?
16. What are benefits to performing PR&PP analysis early in the design process?
17. Where can I find more information?


The Generation IV International Forum (GIF) is a co-operative international endeavour which was set up to carry out the research and development needed to establish the feasibility and performance capabilities of the next generation nuclear energy systems.

For more information, consult www.gen-4.org

15. Will the PR&PP methodology be updated or is it in final form?

The methodology is ready for use, currently as Revision 6. It will receive updates as feedback is received on implementation, and as the field of knowledge in non-proliferation and physical protection evolves.

16. What are the benefits from performing PR&PP analyses early in the design process?

Benefits include synergies with safety and economics, reduction of risk for schedule slippage, efficiencies in implementing PR&PP-related system design components, guidance on design decisions with maximum flexibility to early design stage.

Generation IV International Forum

Where can I find more information?

The PR&PP Evaluation Methodology report is available online at www.gen-4.org/Technology/horizontal/proliferation.htm.

The Nuclear Technology journal has several articles on the methodology and provides examples of its application, Vol. 179, pgs. 1-96, July 2012.

www.gen-4.org

Generation IV International Forum

PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION

(PR&PP FAQs)

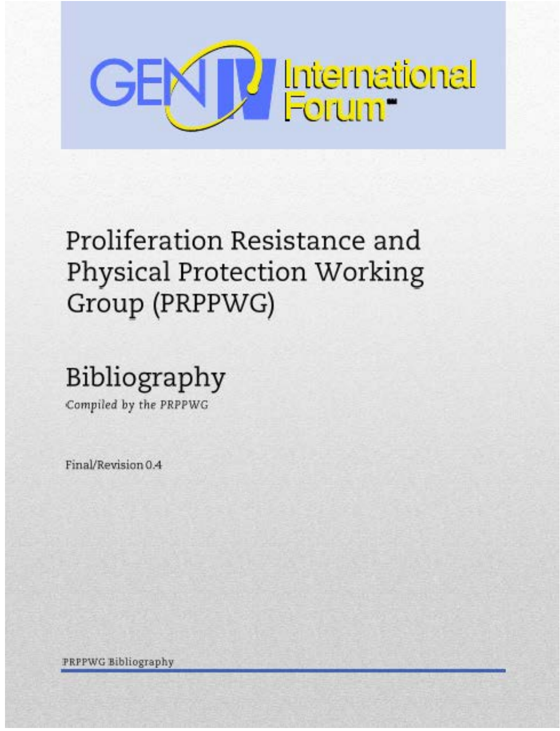
frequently asked QUESTIONS

www.gen-4.org

PR&PP Bibliography

Table of Contents

Section1	Official GIF PRPPWG reports and deliverables (and their translation in non-English languages)
Section 2	Official/collective GIF PRPPWG articles and papers on the PR&PP Methodology and its applications
Section 3	Papers and articles authored by GIF PRPPWG members (from one institution) and non-members on the PR&PP Methodology and its applications
Section 4	Papers and articles authored by individual GIF PRPPWG members and non-members on PR&PP related topics
App. A	Selected IAEA and IAEA-INPRO publications referencing the PR&PP Methodology


Proliferation Resistance and Physical Protection Working Group (PRPPWG)

Bibliography

Compiled by the PRPPWG

Final/Revision 0.4

PRPPWG Bibliography

https://www.gen-4.org/gif/upload/docs/application/pdf/2015-02/gif_prppwg_bibliography_final.pdf

PR&PP Participants

- Canada
- China
- Euratom
- France
- International Atomic Energy Agency (observer)
- Japan
- Nuclear Energy Agency (secretariat)
- Republic of Korea
- Russian Federation
- South Africa
- United Kingdom (not currently active)
- United States

…with acknowledgments to all in this truly international effort!

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

Final Notes

It is the **insight** gained from the disciplined process of performing the evaluation that is of value, and not just the bottom line results.

Seek benefits of PR&PP evaluations **early** in the design of nuclear energy systems

The PR&PP evaluation process is not a one-stop check-list exercise…it is a **journey** (throughout the full life-cycle)

Upcoming Webinars

07 June 2018	Molten Salt Actinide Recycle and Transforming System with and without Th-U support: MOSART	Dr. Victor Ignatiev, Kurchatov Institute, Russia
30 July 2018	Astrid – Lessons Learned	Dr. Frederic Varaine, CEA, France
22 August 2018	BREST-300, Lead Cooled Fast Reactor	Dr. Valery Rachkov, Institute of Power and Engineering, Russia