

Proliferation Resistance and Physical Protection of Gen IV Reactor Systems **Robert A. Bari Brookhaven National Laboratory** May 23, 2018 Canadian Nuclear NATIONAL N C22 aboratories исследовательский центр "КУРЧАТОВСКИЙ ИНСТИТУТ" NPS

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.



International



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:

EDF shares plunge to an all-time low 4000 B Double of the state and the standard standard states of the satisfy the second states on the second states termine and the sub-structure law was not New or Wilson I an else in succession of the and the in other ways in the state of the NAMES OF TAXABLE PARTY. off-shift of factor from the shift of the second second the black three should be install second study. the other states of the second The next successful prime prime which the balance is a standard from the second standard the specific process of the plant of the ball of the second second second second second second second second se sectors of the sector sectors where the sector is not the sector of the These Persons interaction or Alline The second se Statistics and including delights and the second se and in particular while and the distance of Designed in the second line in such as the the party of the light of the party in warp in contrast in the of the sector the state and build or head. And in case of the second seco and the state of t puter who is thought it. States The supervision and stating index light statistics and summer of the local shape and so that Property and particular the rest is not in the second second second second THE R. LOW and the second and start and a subscription of the start of a still a finishing by the manufacture of the little statements of the state of the statements of the statement of the statem INTERNATION OF TAXABLE standing of the local in the section of the COMPANY OF THE OWNER.

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Toshiba's US unit hires bankruptcy lawyers

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Getting Safety Right, lessons learned...







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



- <u>Proliferation resistance</u> is that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, <u>by the host State</u> in order to acquire nuclear weapons or other nuclear explosive devices.
- <u>Physical protection</u> (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, <u>by sub-national entities and other</u> <u>non-host State</u> 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 <u>earliest</u> 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



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



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PR & PP Measures



PR Measures

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

Measures are mapped to specific metrics

PP Measures

- Probability of Adversary Success
- Consequences
- Physical Protection Resources



PR&PP Threat Considerations



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

System Response

- <u>Pathway analysis</u>: Intuitive way to describe & analyze proliferation, theft, or sabotage scenarios and to identify vulnerabilities
 3
- 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 GENT International (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 GE 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



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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 GEN International

GIF-002-00



A Technology Roadmap for Generation IV **Nuclear Energy Systems** December 2002



Ten Nations Preparing Today for Tomorrow's Energy Needs

Technology Roadmap, 2002

Generation III / III+ Generation I Generation II Generation IV Safe Secure Sustainable Competitive Versatile Big Rock Point, GE BWR Diablo Canyon, Westinghouse PWR Kashiwazaki. GE ABWR Olkiluoto 3 AREVA PWR Arriving - 2030 Early Large-scale Evolutionary Innovative designs prototypes power stations designs Calder Hall (GCR) Bruce (PHWR/CANDU) ABWR (GE-Hitachi; Toshiba EPR (AREVA NP PWR) GFR gas-cooled fast BWR) reactor **Douglas Point** Calvert Cliffs (PWR) ESBWB (GE-Hitachi BWR) ACR 1000 (PHWR/CANDU) LFR lead-cooled fast - Flamanville 1-2 (PWR) Small Modular Beactors (AECL CANDU PHWR) reactor · Dresden-1 (BWR) Fukushima II 1-4 (BWR) - B&W mPower PWR AP1000 (Westinghouse- MSR molten salt reactor · Fermi-1 (SFR) - Grand Gulf (BWR) - CNEA CAREM PWR Toshiba PWR) SFR sodium-cooled fast Kola 1-2 (PWR/VVER) Kalinin (PWR/VVER) - India DAE AHWR APR-1400 (KHNP PWR) reactor Peach Bottom 1 (HTGR) Kursk 1-4 (LWGR/RBMK) - KAERI SMART PWR APWR (Mitsubishi PWR) SCWR supercritical water- Shippingport (PWR) - Palo Verde (PWR) NuScale PWR cooled reactor Atmea-1 (Areva NP) OKBM KLT-405 PWR -Mitsubishi PWR) VHTR very high temperature reactor CANDU 6 (AECL PHWR) VVER-1200 (Gidropress PWR) 1950 1970 1990 2010 2030 2050 2070 2090

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 GE

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

System	Neutron Spectrum	Coolant	Possible Fuels	Refueling Mode	Fuel Cycle	Size (MWe)
VHTR	Thermal	Не	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?





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

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



Proliferation Resistance and Physical Protection Working Group (PRPPWG)

Bibliography Compiled by the PRPPWG

Final/Revision 0.4

PRPPWG Bibliograph

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





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 Juna 2019	Molten Salt Actinide Recycle and Transforming	
07 Julie 2018	System with and without Th-U support: MOSART	

Dr. Victor Ignatiev, Kurchatov Institute, Russia

30 July 2018Astrid – Lessons Learned

22 August 2018 BREST-300, Lead Cooled Fast Reactor

Dr. Frederic Varaine, CEA, France

Dr. Valery Rachkov, Institute of Power and Engineering, Russia