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GEN IV International Forum

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Proliferation Resistance and Physical Protection: Insights for GFR, SFR, LFR, SCWR, VHTR, and MSR

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PRPP Working Group Objectives

- Facilitate introduction of PRPP features into the design process at the earliest possible stage of concept development

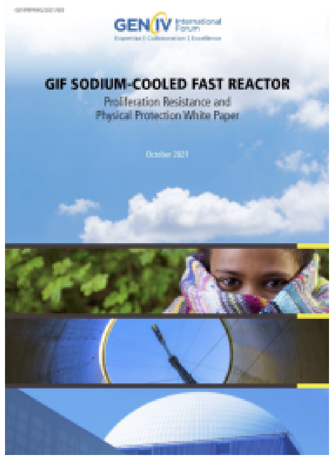
  → **PRPP by design**

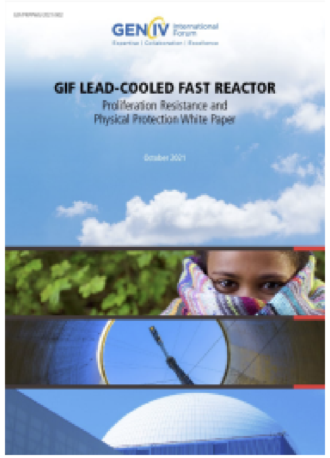
- Assure that PRPP results are an aid to informing decisions by policy makers in areas involving safety, economics, sustainability, and related institutional and legal issues
- The PRPP Working Group includes members from Canada, China, Euratom, France, IAEA, Japan, NEA, Republic of Korea, Russia, South Africa, UK, USA.

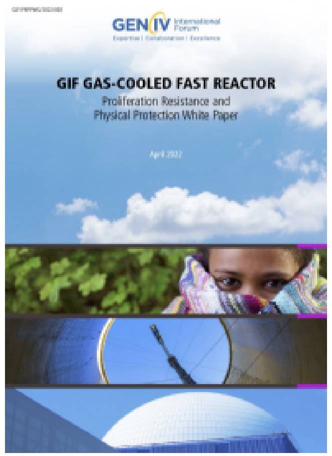
"*Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.*"

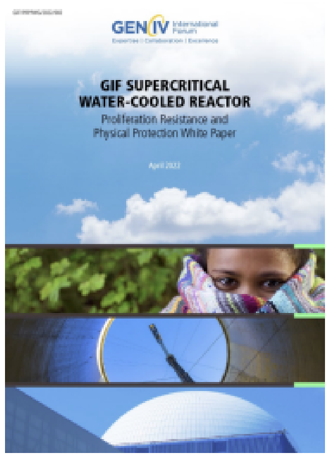
PRPPWG Resources for Industry

- PRPP white papers on the six Gen-IV reactor systems have been updated with four currently available publicly:
- A companion crosscut document is being finalized that discusses PR&PP considerations that crosscut all reactor designs.
- The technology-neutral methodology, developed through a succession of revisions, is currently in Revision 6 (Japanese and Korean translations)
- A “Case Study” approach (example sodium-cooled modular fast reactor system used to develop and demonstrate the methodology) resulted in a major report
- GIF Updated PRPP Bibliography









All current reports can be obtained at:
https://www.gen-4.org/gif/jcms/c_9365/prpp

PRPPWG Key Points

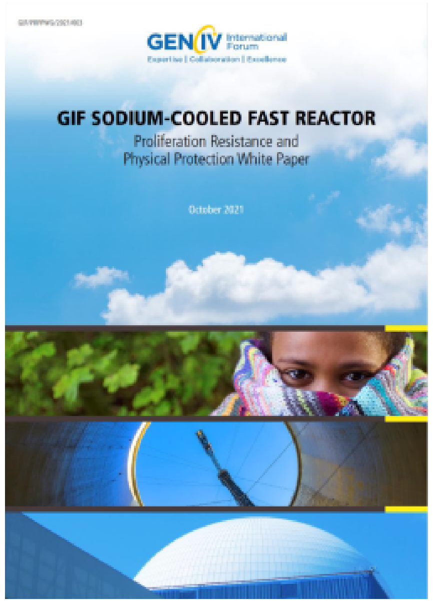
- PR&PP considers both intrinsic and extrinsic features.
- Intrinsic features of a particular system that may have PR challenges will likely require more robust extrinsic features (more monitoring, surveillance, or measurements).
  - Designers should take these facts into consideration since these tradeoffs will factor into plant economics.
- Designers are highly encouraged to consider multiple types of sabotage/theft scenarios early in the design process in order to develop robust, yet cost-effective PP designs.
  - Safety by Design is a key focus of most advanced reactor vendors, but enhanced safety systems do not necessarily equate to enhanced security. Vendors are encouraged to take an integrated approach to safety and security to more fully consider a range of adversary threats.
  - PP costs can play a significant role in overall economics—avoid costly retrofits by considering PP approaches early in the design process.

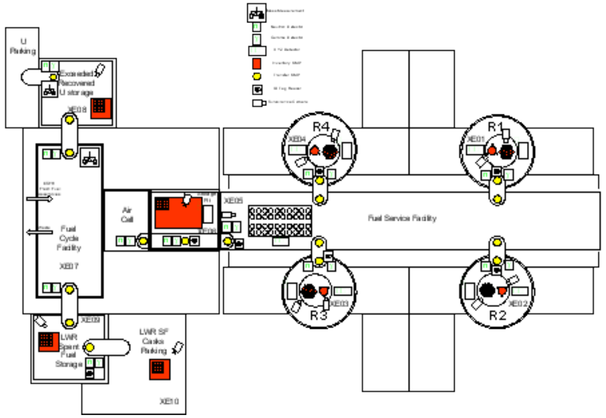
White Paper Content

Section	Type of Information Provided
1. Overview of Technology	Description of design options (major reactor parameters, core configuration, fuel form and composition, operating scheme and refueling mode, fresh/spent fuel storage and shipment, safety approach and vital equipment, physical layout and segregation of components, etc.)
2. Overview of Fuel Cycle(s)	High level description of the type(s) of fuel cycles that are unique to this GIF system and its major design options (recycle approach, technology, efficiency, and waste form(s)).
3. PR&PP Relevant System Elements and Potential Adversary Targets	For each design option, identification and description of the relevant system elements and their potential adversary targets, safeguards, and physical security approaches
4. Proliferation Resistance Features	Overview of the features of the system reference designs that create potential benefits or issues for each of the representative proliferation threats. Highlights the response of the system to the concealed diversion or production of material, the use of the system in a breakout strategy, and replication of the technology in clandestine facilities
5. Physical Protection Features	Overview of the elements of the system design that create potential benefits or issues for potential subnational threats, with discussion on the general categories of physical protection threats (theft of material for nuclear explosives or dispersal device and radiological sabotage)
6. PR&PP Issues, Concerns and Benefits	Reviews of the outstanding issues related to PR&PP for the concepts and their fuel cycles, the areas of known strength in the concept, and plans for integration and assessment of PR&PP for the concept.

SFR White Paper Key Conclusions

- Five reference designs: JSFR (compact loop), KALIMER-600 (pool configuration), ESFR (pool configuration), BN-1200 (pool configuration), AFR-100 (small modular).
- Little PR&PP variation was found between the different systems, and many PR&PP considerations were similar to any fast system.
- Fast systems generally have higher actinide content than large LWRs and smaller assemblies, but item accounting of assemblies can be applied easily.
- High radiation doses and operations under sodium (requiring specialized equipment) provide PR&PP advantages.
- The use of blankets could present a PR challenge, but extrinsic measures to detect blanket misuse/diversion scenarios are fairly mature.
- Sabotage scenarios need to consider attacking the sodium coolant, but all reference systems protect the sodium loops.





Example Sodium Fast Reactor (ESFR) PR&PP Case Study:

GIF PRPP Working Group, "PR&PP Evaluation: ESFR Full System Case Study," Final Report, GIF/PRPPWG/2009/002, Gen-IV International Forum, (October 2009).

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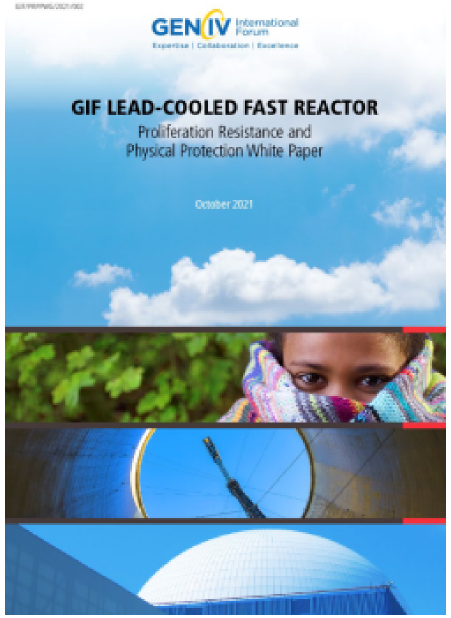
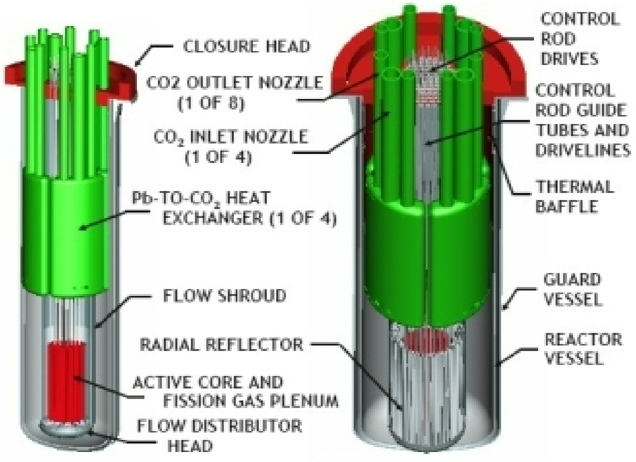
LFR White Paper Key Conclusions

- Three reference designs: ELFR, BREST-OD-300, SSTAR
- Closed fuel cycle assumed; Pu fuel containing minor actinides is utilized to avoid generating pure Pu streams.
- No enrichment required which provides a PR advantage.
- Pin removal on-site not possible for ELFR design, and SSTAR uses a lifetime sealed core. Difficult to access cores and high automation provide PR&PP advantages.
- The inert lead coolant and low pressure system help to minimize risks of sabotage threats.



SSTAR (one of three reference systems):

J. J. Sienicki, A. Moisseytsev, D. C. Wade and A. Nikiforova, "Status of development of the Small Secure Transportable Autonomous reactor (SSTAR) for Worldwide Sustainable Nuclear Energy Supply," in *Proceedings of the International Congress on Advances in Nuclear Power Plants (ICAPP)*, Nice (F), 2007.



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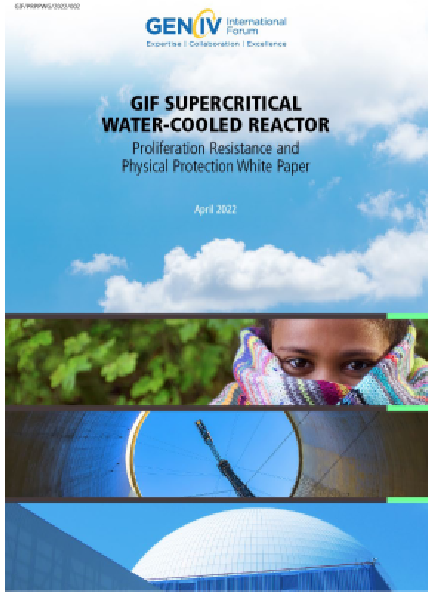
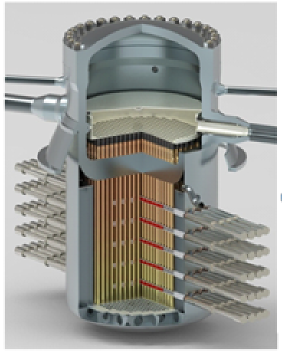
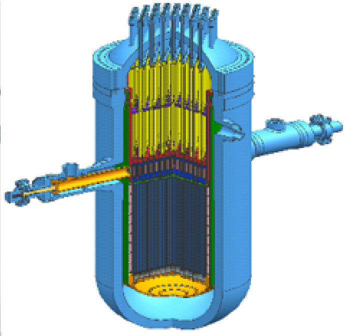
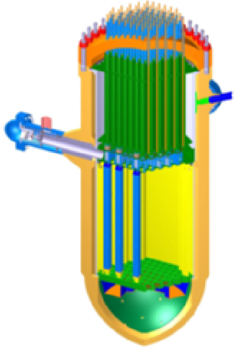
SCWR White Paper Key Conclusions

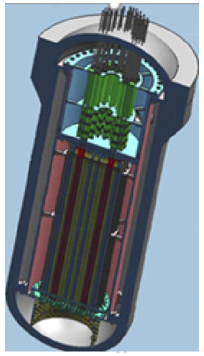
- Eight design tracks considered: HPLWR (Euratom), Super FR & Super LWR (Japan), CSR1000 (thermal and mixed spectra; China), SCWR (Canada), VVER-SCP-600 & VVER-SKD (Russia)
- There is little PR&PP difference in SCWR designs as compared to existing large LWRs, for which safeguards and security are well-established.
- All reference systems (both pressure vessel and pressure tube designs) utilize batch refueling (not continuous).
- Newer fuels utilize HALEU, so have slightly higher attractiveness. Pu breeding in fast or mixed spectrum systems is a possibility, but would be contained in assemblies mixed with minor actinides and fission products.
- PP features are very similar to large LWRs.




Canada's Pressure-Tube Type SCWR Core Concept

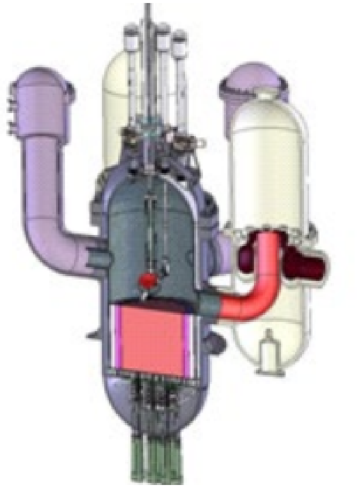

China's Pressure-Vessel Type SCWR Core Concept

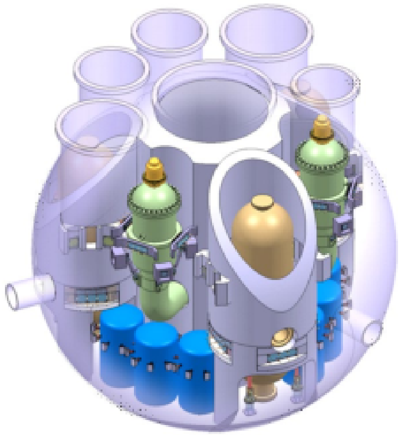

EU's Pressure-Vessel Type SCWR Core Concept


Japan's Pressure-Vessel Type SCWR Core Concept

GFR White Paper Key Conclusions

- One design track considered: 2400MWt GFR reference design, but other designs like ALLEGRO and EM2 are discussed.
- System assumes a closed fuel cycle, fuel contains Pu with minor actinides.
- Fuel pins are not separated from fuel assemblies on site.
- Pre-stressed concrete containment building and bunker-like spent fuel storage pool provides robust protection.
- Inert coolant gas and refractory fuel can sustain very high temperatures.
- High radiation levels for both fresh and spent fuel hinder theft.





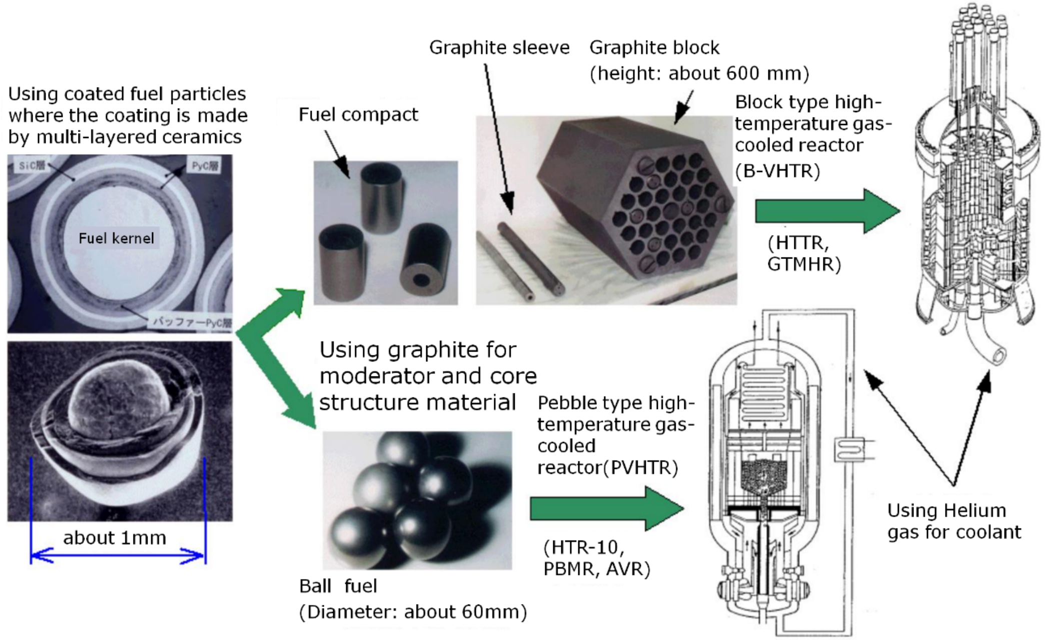
2400 MWt GFR Reference System

VHTR White Paper Key Conclusions

- Both pebble and prismatic concepts are considered that use TRISO fuel, which is robust to high temperatures.
- The high dilution factor of the fuel along with the lack of maturity for industrial reprocessing provides a PR advantage.
- Prismatic designs can benefit from item accounting of fuel assemblies, while pebble designs have additional safeguards considerations requiring more monitoring/measurements. A PR advantage is that it takes 50,000-100,000 pebbles to acquire an IAEA significant quantity.
- Large quantities of pebbles are a PP advantage from a theft standpoint, but vendors need to consider sabotage of spent pebbles.

*White Paper should be available in the next 1-2 months

Prismatic vs. Pebble Fuel Designs:



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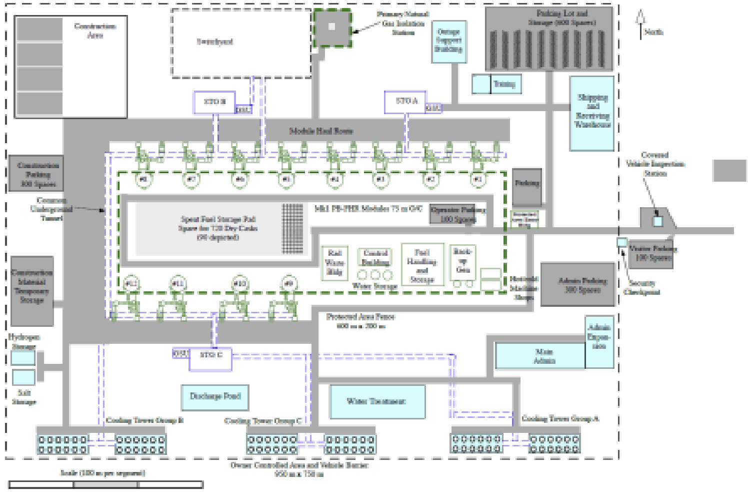
MSR White Paper Key Conclusions

- Three design classes considered: Liquid-fueled with integrated salt processing (MSFR), solid-fueled with salt coolant (Mk1 PB-FHR), liquid-fueled without integrated salt processing (IMSR).
- Liquid-fueled designs with on-site fission product removal will have more PR challenges in that they resemble bulk handling facilities—more extrinsic measures needed.
- Liquid-fueled designs without fission product removal are designed to replace the salt or core every 7-8 years, which adds complexity to the fuel cycle.
- Solid fueled designs that use molten salt as the coolant will have PR&PP features similar to the VHTR.
- The high radiation field, rather dilute actinide content, and remote handling are a barrier to theft.
- The low-pressure, chemically inert coolant mitigates radiological risks in sabotage scenarios.

*White Paper should be available in the next year

K1 PB-FHR Example Site Layout:



Companion Crosscut Report

- The crosscut report discusses additional PR&PP considerations that crosscut all reactor types.
- Of the 12 topical areas covered, some include differences across reactor types while others have the same implications for all reactors.
- Expected to be complete in the next month.

Crosscutting Reactor Design Aspects:

- Fuel type
- Coolant, moderator
- Refueling modes
- Small modular and microreactor options

Fuel Cycle and Grid Compatibility

- Fuel cycle architecture
- Life cycle
- Flexibility

Common Interfaces

- Safeguards topics
- Cyber threat
- Operational transparency
- Safety interfaces
- Economics

Crosscut Report: Key Conclusions (1/4)

- Fuel Type: Larger items are more difficult to steal but contain more fissionable material per item. Smaller items may be easier to divert but require more items to obtain an SQ. Pebble and molten salt fuel introduce bulk accountancy challenges. Oxide and metallic fuels have established reprocessing technologies, while reprocessing of TRISO fuels has not been demonstrated on a large scale. Material attractiveness: fresh fuel and irradiated blanket assemblies with potentially fertile seeds are more attractive than spent fuel with higher burnups.

- Coolant/Moderator: The opacity of the coolant affects the ability to visually verify fuel assemblies while in the reactor. Highly accessible systems makes safeguards inspections easier; less accessible systems may have a proliferation resistance advantage. Chemical reactivity, retention of fission products, and ease of dispersal needs consideration for proper protection of the plant against sabotage.

- Refueling Modes: With batch refueling, misuse is more limited because even one batch produces enough burnup to lower the material attractiveness. Continuous refueling could provide more opportunities to remove low-burnup fuel. Molten salt reactors have unique PR aspects particularly if on-line processing is utilized because of the potential for separating actinides. Long-lived, sealed cores will have limited movement of material, but physical verification of fuel inventory in a timely manner should be considered.

Crosscut Report: Key Conclusions (2/4)

- Small Modular and Microreactor Options: Modular deployment of reactors could increase safeguards burden if refueling is occurring regularly. Small reactor operators need to reduce security staffing on site to improve economics. Single batch cores and sealed cores which could provide a proliferation resistance advantage. Deployment of either small or micro reactors in remote locations, transportable or floating reactors, and automated or remote operations pose new PR&PP challenges.

- Fuel Cycle Architecture: While fuel fabrication is common to all designs, enrichment, reprocessing, and storage needs can vary considerably dependent upon the fuel cycle. Co-location of reactors and fuel cycle facilities: reduced transport of nuclear material is an advantage, but more nuclear material targets on site may be a disadvantage.

- Life Cycle: The IAEA provides guidance on the application of safeguards through the full life cycle of a nuclear plant, from design through decommissioning. PR&PP should consider the full life cycle of the reactor.

Crosscut Report: Key Conclusions (3/4)

- Flexibility: Flexibility of plant operations, whether for load following or non-electric sources of energy, will likely have little effect on PR&PP. The use of more reactors around the world for different purposes will place additional burden on the IAEA for safeguards. Siting reactors near population centers (which would be desirable for heat production) could raise additional physical protection challenges.

- Safeguards Topics: Revolutionary reactor designs can benefit from Safeguards by Design (SBD) activities based on present LWR safeguards. Safeguards inspection planning and implementation historically used could work for evolutionary designs. Revolutionary reactor or novel designs will have unique issues such as accessibility for inspectors and safeguards instruments for fuels (e.g., for nuclear material accounting), higher radiation environments, visibility issues, and time spans for core accessibility (longer operating cores without refueling).

- Cyber Threat: Four key areas for consideration in managing cyber threats: cyber risk management includes prioritizing digital assets by level of importance and risk, secure architectures involve the technology and systems utilized, operational transparency relates to international safeguards and the requirement for data authentication, and assurance of the supply chain helps prevent introduction of malicious hardware or software. The cyber-physical interface will be of increasing importance in the future threat space.

Crosscut Report: Key Conclusions (4/4)

- Operational Transparency: Increasing automation presents an opportunity for monitoring process flows in a facility in a manner transparent to operators and relevant regulatory bodies on the lookout for diversion or misuse of nuclear material. Fundamental to this operational transparency framework is the need for sharing of data in a secured and authenticated manner and in an environment that ensures trust between the involved parties. Greater operational transparency could better support safeguards and increase proliferation resistance.

- Safety Interface: Advanced reactors present new opportunities for the integration of safeguards, security, and safety (3S). The coupling between safety and security is needed to fully understand sabotage and theft threats to nuclear plants. Enhanced safety systems can sometimes, but not always, improve the security against sabotage threats. The GIF Risk and Safety Working Group follows many similar principles to the PR&PP working group, and as such will present opportunities for more collaboration in the future.

- Economics: While in general PR&PP costs may be small compared to the total lifetime revenue of the plant, they do affect the overall plant economics. One goal of PR&PP by design is to consider PR&PP features early in the design process to avoid costly retrofits and provide more economical designs. Physical protection costs in particular can be large during the operation of the plant, so new methods to reduce burden while maintaining robust protections deserves consideration. The GIF Economic Modeling Working Group examines these issues.

Thank You!

All current reports can be obtained at:
https://www.gen-4.org/gif/jcms/c_9365/prpp