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PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION WHITE PAPERS OF THE SIX GIF GENERATION IV NUCLEAR ENERGY SYSTEMS AND CROSSCUTTING TOPICS: 2021-2022 UPDATE

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Abstract

Proliferation Resistance and Physical Protection (PR&PP) are core goals of the Generation IV International Forum (GIF). The GIF is an international endeavor seeking to develop the research necessary to test the feasibility and performance of Generation IV nuclear systems. The PR&PP Working Group within GIF performed an update of the PR&PP White Papers on the six GIF design concepts: Gas Fast Reactor, Lead Fast Reactor, Molten Salt Reactor (liquid fuel and solid fuel designs), Super-Critical Water Reactor (vessel and pressure-tube designs), Sodium Fast Reactor (loop and pool designs), and Very High Temperature Reactor (pebble and block designs). For each design option the PR&PP white papers identified the relevant system elements with respect to potential adversary targets and applicable safeguards and physical protection approaches. The study then proceeded to assess the design against potential threats using the technical design information to gauge the response of the system. PR threats include concealed diversion or production of material, the use of the system in a breakout strategy, and replication of the technology in clandestine facilities. Physical protection threats include theft of material for a nuclear explosives or dispersal device and radiological sabotage. These studies, performed in collaboration with the six GIF System Steering Committees, help to elucidate technical features of each reactor system that make it a very unattractive and the least desirable route for diversion or theft of weapons-usable materials and provide increased physical protection against acts of terrorism. The work has culminated in publicly available updates to the original 2011 white papers on the six GIF reactor technologies which are being finalized through 2021 and 2022. A companion crosscutting document is being developed which addresses PR&PP aspects that crosscut all GIF systems. The paper provides an overview of the key recommendations for each of the six designs as well as key recommendations from the crosscut document.
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1. INTRODUCTION

The Generation IV International Forum (GIF) Proliferation Resistance & Physical Protection Working Group (PRPPWG) was formed in 2002 to investigate tools and measures to analyze the proliferation resistance and physical protection robustness of the six GIF reactor technologies and support the GIF designers in meeting the PR&PP goal set out in the 2002 GIF Roadmap [**Error! Reference source not found.**]. The group developed a Proliferation Resistance & Physical Protection Evaluation Methodology (PRPPEM) that was refined over the years through selected case studies [**Error! Reference source not found.**]. The PRPPEM is currently in its sixth revision [**Error! Reference source not found.**].

The PRPPWG undertakes a comprehensive approach to evaluate the PR&PP characteristics of nuclear systems. In evaluating the response of a nuclear system against PR&PP threats, the methodology considers not only intrinsic features (by nature of the design) but also extrinsic measures (per institutional and regulatory requirement) that account for existing nuclear safeguards and security measures and techniques. Many PRPPWG members have applied and incorporated the PRPPEM in other international initiatives and concepts like those of the IAEA on Safeguards by Design in the INPRO methodology, which facilitates synergies and cross-fertilization between the various initiatives. To keep track and cognizance of the use of the PRPPEM inside and outside GIF, the group maintains a bibliography collecting articles, papers and reports that is updated annually and available on the GIF PR&PP external website [4].

Since 2007 the PRPPWG and the six GIF System Steering Committees (SSCs/pSSCs) have interacted regularly to discuss the status of each system design with respect to PR&PP. These interactions resulted in the 2011 publication of a PRPPWG and GIF SSCs/pSSCs joint report including white papers delineating the main PR&PP attributes of the six GIF reactor technologies [5]. The report also addressed a number of crosscutting issues common to the GIF technologies.

In the past decade, there has been significant movement toward small modular and advanced reactors driven by national programs as well as private and venture capital investment. In 2017, the PRPPWG and the SSCs decided to begin updating the PR&PP white papers on the six GIF systems to reflect these new designs and a deeper understanding of PR&PP features [6-8]. Crosscutting topics have also been updated to reflect current thinking on advanced reactor deployment. The hope is that reactor designers will use the white papers and crosscut document to incorporate PR&PP considerations early in the design process to help improve economics and maintain secure operation of nuclear power for the foreseeable future. The white papers LFR, SFR, GFR and SCWR were published [9-12] and the white papers MSR and VHTR and crosscut document are being finalized for expected public release by the end of 2022. The paper describes key lessons learned and takeaways from the white papers and crosscutting document.

2. INTERACTIONS WITH THE GIF SYSTEMS STEERING COMMITTEES

Since 2007 the GIF PRPPWG and the six SSCs/pSSCs have held several workshops to discuss the PR&PP characteristics of the considered systems designs and to identify research needs to ensure that each design incorporated key concepts embodying PR&PP goals. The collaborating groups systematically collected the design information needed to investigate the PR&PP concepts under consideration, and their analysis culminated in a series of internal reports, referred to as 2011 “white papers” inside GIF [5]. The 2017 workshop between the PRPPWG and the six SSCs/pSSCs launched an update of the white papers. The reactor design options evaluated in the white papers have evolved in the current revisions. Tables 1 and 2 highlight the six GIF reactor technologies and the main system design options presented in the updated white papers, together with a description of the analysis performed.

TABLE 1. 2021-2022 GIF PRPPWG WHITE PAPER GFR, LFR, AND MSR SYSTEM DESIGNS

GIF System	System Options Considered in Update	Design Tracks Considered in Update	Comment
GFR	Reference Concept	2400MWt GFR Mentions ALLEGRO as a GFR demonstrator	Other GIF designs include: EM2 (GA) ALLEGRO (V4G4) HEN MHR (High Energy Neutron Modular Helium Reactor) (CEA-ANL and GA-AREVA)
LFR	Large System	600 MWe (ELFR, EU)	These are the three reference design configurations discussed in the GIF LFR System Research Plan
	Intermediate System	300 MWe (BREST-OD-300, RF)	
	Small Transportable	20 MWe (SSTAR, US)	
MSR	Liquid-Fueled with Integrated Salt Processing	MSFR (EU), MOSART, (RF)	There is a wide variety of MSR technologies, encompassing thermal/fast spectrum reactors, solid/fluid fuel, burner/breeder modes, Th/Pu fuel cycles, and onsite/offsite fissile separation.
	Solid Fueled with Salt Coolant	Mk1 PB-FHR (US)	
	Liquid-Fueled without Integrated Salt Processing	IMSR (Canada)	

The GIF reference reactor systems cover a range of different designs and sizes—the variation in designs is larger for some reactor classes as opposed to others. One key difference in the current updates was more inclusion of small modular reactor reference systems. The different design choices expressed the full range of PR&PP considerations for the reactor classes.

TABLE 2. 2021-2022 GIF PRPPWG WHITE PAPER SCWR, SFR, AND VHTR SYSTEM DESIGNS

GIF System	System Options Considered in Update	Design Tracks Considered in Update	Comment
SCWR	Pressure Vessel	HPLWR (EU) (Thermal)	Most concepts are based on "familiar' technology, such as, light-water coolant, solid fuel assemblies, and batch refuelling. Implementation of Th and Pu fuel cycles creates additional special nuclear materials of concern.
		Super FR (Japan)	
		Super LWR (Japan) (Thermal)	
		CSR1000 (China) (Thermal)	
		Mixed spectrum (China)	
		Mixed spectrum (RF)	
		Fast resonant spectrum (RF)	
	Pressure Tube	Canadian SCWR (Canada) (Therm.)	
SFR	Loop Configuration	JSFR (Japan)	Expect key PRPP issues to be tied to fuel handling, TRU inventory and physical protection.
	Pool Configuration	ESFR (EU), BN-1200 (RF), KALIMER-600 (RoK)	
	Small Modular	AFR-100 (US)	
VHTR	Prismatic Fuel Block	Modular HTR, Framatome (ANTARES)	SC-HTGR is a follow on of the ANTARES and the GA GT-MHR development. Expect some PR&PP differences between the prismatic block and pebble bed design.
		SC-HTGR, Framatome (US)	
		GT-MHR General Atomics (US)	
		GT-MHR OKBM (RF)	
		GTHTR300C, JAEA (Japan)	
		NHDD,KAERI (RoK)	
	Pebble Bed	Xe-100, X-Energy (US)	
		HTR-PM (China)	

The updated white papers were also made more consistent with one another through the use of a common template. Table 3 reports the high-level structure of the updated template, together with some of the information requested for each section. The SSCs/pSSCs were responsible for updating sections 1 and 2 which provided the base information on the reference reactor systems. The PRPPWG and SSC/pSSC worked collaboratively to update sections 3-6. Each white paper includes an appendix on proliferation resistance relevant intrinsic design features based on the IAEA STR-332,[13], including:

- Features reducing the attractiveness of the technology for nuclear weapons programs;
- Features preventing or inhibiting diversion of nuclear material;
- Features preventing or inhibiting undeclared production of direct-use material;
- Features facilitating verification, including continuity of knowledge.

TABLE 3. HIGH LEVEL STRUCTURE OF THE UPDATED WHITE PAPER TEMPLATE

Section	Type of Information Requested
1. Overview of Technology	Description of the various design options in terms of their major reactor parameters, such as 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, or types, of fuel cycles that are unique to this GIF system and its major design options. Information such as recycle approach, recycle technology, recycle efficiency, 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	High-level, qualitative overview developed jointly by the SSC and the PR&PP working group, to identify and discuss the features of the system reference designs that create potential benefits or issues for each of the representative proliferation threats. Ideally the section should highlight the response of the system to the concealed diversion or production of material, the use of the system in a breakout strategy, and the replication of the technology in clandestine facilities
5. Physical Protection Features	High-level, qualitative overview developed jointly by the SSC and the PR&PP working group, to discuss those elements of the system design that create potential benefits or issues for potential subnational threats, with specific 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	Review 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. This section would ideally terminate with a bullet list of identified PR&PP R&D needs for the system concept.

3. PR&PP WHITE PAPER KEY LESSONS LEARNED

Existing and future advanced reactor designers can use the white papers for PR&PP considerations in the design of their systems. A key aspect of PR&PP by design, which is very similar to Safety, Security, and Safeguards by Design, is to consider proliferation resistance, international safeguards, and physical protection early in the design process to take advantage of intrinsic design features and to avoid costly retrofits in the future. The goals of the PR&PP working group are aligned with the economics goals of the GIF in that early consideration will help reactor designers develop cost-effective power generation systems. The following sections describe the key lessons learned and conclusions from each of the six white papers.

3.1. Gas-Cooled Fast Reactor (GFR)

The reference gas-cooled fast reactor concepts feature a high temperature, helium cooled fast spectrum reactor that utilizes ceramic-clad, mixed-carbide fuel pins. This concept assumes a closed fuel cycle where plutonium and minor actinides are co-extracted from uranium. The proliferation resistance characteristics are similar to other fast reactor systems that utilize depleted uranium and high plutonium content fuel. Uranium and plutonium are the main targets in terms of material attractiveness; inherent proliferation resistance mainly arises from the system design since there is no separation of individual actinides. Fuel pins are not separated from their assemblies on the reactor site. Production of plutonium in clandestine facilities would not be any greater risk for the GFR as compared to any Generation II or III light water reactor (LWR).

Physical protection for a GFR is robust given the pre-stressed concrete containment building and bunker-like spent fuel storage pool. The inert coolant gas and refractory fuel can sustain very high temperatures. The main safety buildings are designed as protective bunkers, and heat sinks are also contained within the containment building for protection from external hazards. Finally, high radiation levels for both fresh and spent fuel hinder theft.

3.2. Lead-Cooled Fast Reactor (LFR)

While various designs of the LFR were evaluated, all utilize a plutonium fuel with minor actinides in a closed fuel cycle and do not utilize pure plutonium fuel. The fuel cycle does not require enrichment, which eliminates a proliferation-sensitive fuel cycle technology. The European Lead Fast Reactor (ELFR) system works as an adiabatic core in that the inventory and isotopic composition is maintained constant throughout the life of the fuel assemblies. The ELFR fuel pin removal would not be possible at the reactor site, and the Small, Sealed Transportable Autonomous Reactor (SSTAR) small modular design maintains fuel in a lifetime-fueled core. The reactor designs are all highly automated with difficult-to-access areas, making diversion or clandestine production difficult. During operation, the reactor core is sealed and completely inaccessible.

From the physical protection viewpoint, the lead coolant is inert in air and so mitigates potential outcomes from acts of sabotage. There are no credible scenarios of significant containment pressurization, and the primary system is at low pressure. Finally, the designs exhibit a compact security footprint.

3.3. Molten Salt Reactor (MSR)

Of all the GIF reactors, MSRs present the most variation in design. Liquid-fueled reactors with integrated salt processing (removal of fission products on site) will have the most stringent accountancy requirements compared to LWRs as they use bulk materials as fuel for the reactor. However, obtaining a significant quantity[1] (SQ) of nuclear material requires a large amount of difficult-to-handle and highly radioactive fuel salt. The build-up of Pu-238 or U-232 (in the case of Th) impose additional technical difficulties in removal of weapons-usable material. Liquid-fueled reactors designed without fission product removal will need replacement of the fuel salt every 4-8 years, and if the fuel cycle includes salt processing, these fuel salt processing facilities will have accountancy challenges similar to any bulk processing facility; the challenges being accurate measuring of uranium and plutonium quantities amongst other radioactive nuclides. Hence, salt treatment operations will require suitable monitoring for safeguards. Solid-fueled MSRs only utilize molten salt as the coolant, which have proliferation resistance features similar to high temperature gas-cooled pebble bed reactors.

The high radiation generated by the liquid fuel salts are a barrier to theft for all MSR designs. Remote handling makes physical access very difficult, providing a physical protection advantage. The rather dilute actinide content of the fuel salt or pebbles renders these reactors as less desirable as targets for proliferation. The low-pressure, chemically inert coolant mitigates radiological risks in sabotage scenarios.

3.4. Super Critical Water Reactor (SCWR)

The PR&PP considerations for the SCWR are closer to the current fleet of LWRs than any other Gen-IV system. The fuel assemblies can be viewed via optical surveillance in any position. There is little distinction between the pressure-tube and pressure-vessel designs since on-line refueling is not under consideration for any of the reference SCWR designs. Higher concentrations of actinides in fuel for newer designs, (for example through the use of HALEU,) could slightly increase the attractiveness of fresh and spent fuel, but there are well-established approaches for safeguarding these fuel assemblies. Breeding Pu is a possibility in fast and mixed-spectrum reactors, but maintaining mixed minor actinides and fission products in fuel assemblies can enhance proliferation resistance.

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[1] "Significant Quantity" SQ, as defined by the IAEA. is "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded". For Pu (containing less than 80% ^{238}Pu) and for and ^{233}U a SQ corresponds to 8 kg, A SQ is 25 kg for U enriched in ^{235}U at 20%, or above, 75 kg for U enriched below 20% in ^{235}U (or 10 t for natural U or 20 t for depleted U). See the IAEA Safeguards Glossary for all details: International Atomic Energy Agency, "IAEA Safeguards Glossary, 2001 Edition", International Nuclear Verification Series No. 3, Vienna, Austria, 2002.

The risk of theft or sabotage for SCWRs is comparable to that of existing LWRs. The separation of the coolant and moderator in the pressure-tube design may provide a physical protection advantage. Overall, this reactor type will have safeguards approaches and physical protection designs that are similar to existing LWRs.

3.5. Sodium-Cooled Fast Reactor (SFR)

The SFR white paper considered a number of design variations, but little variation was found regarding PR&PP between the design variations. The PR&PP conclusions are common to other fast spectrum reactors. Fast reactors in general have a higher percentage of fissile material content in the fuel, and assemblies are smaller than fuel assemblies for LWRs, but item accounting of assemblies can be applied easily. The potential for higher radiation dose in the fuel and reactor operations (which are under sodium, requiring specialized equipment and fuel handling,) may provide a proliferation resistance advantage. Small modular reactor options may have sealed cores, in which the entire reactor could be treated as one item. The utilization of cores or assemblies for longer times will require less transport, reducing opportunities for acquisition and sabotage by terrorists, but there will be more fissile material when in transport. The use of blankets in designs can produce high quality plutonium in low concentrations. While these blankets might represent a potential proliferation challenge, the implementation of intrinsic features (like the insertion of minor actinides in the fertile assemblies,) and the level of maturity of extrinsic measures currently available to cover potential blanket misuse/diversion scenarios can effectively meet this challenge.

Remote handling of fuel assemblies restricts material access, which is a physical protection benefit, however the fresh fuel or spent fuel after cleaning and cooling would be targets. Sabotage scenarios consider attacks which specifically focus on sodium, but all reference designs effectively illustrate how the sodium coolant can be safely and securely contained.

3.6. Very High Temperature Reactor (VHTR)

The VHTR designs include both prismatic and pebble bed cores with TRISO fuels, which are robust to high temperatures and have excellent fission product retention. A key proliferation resistance advantage of VHTRs is the high dilution factor of the fuel which requires some metric tons and a large volume (tens of cubic meters) of TRISO fuels to obtain an SQ. In addition, the technologies for separating nuclides from TRISO fuels lack maturity for industrial deployment—therefore at this time this is less of a proliferation concern. The high burnup provides a proliferation resistance advantage due to the higher order plutonium isotopes and higher radiation dose rate. For prismatic designs, item accounting can be adopted similar to LWRs, although conventional Cherenkov signature observation is not applicable for spent fuel verification. For pebble bed reactors, safeguards approaches are similar to quasi-bulk fuel systems due to the continuous nature of pebble removal and re-loading. Burnup measurements on pebbles are required for process control, and containment/surveillance would most likely be required on the full pebble handling system. A quasi-bulk safeguards approach should be used to acknowledge the difficulty in tracking every pebble and that on the order of 50,000 to 100,000 pebbles need to be diverted to acquire a SQ of uranium or plutonium.

The large quantities of prismatic or pebble fuel provides a key physical protection advantage. However, spent pebbles will contain high quantities of radioisotopes are radiological targets, which will require physical protection to prevent theft. All advanced reactor designs consider sabotage to cooling and decay heat cooling systems, but VHTRs do have an advantage in that the fuel is designed to withstand very high temperatures.

4. PR&PP CROSSCUTTING DOCUMENT

The companion crosscutting document is meant to cover PR&PP considerations for additional aspects of the GIF reactors that crosscut many or all the reactor designs. The crosscutting topics from the original 2011 report were updated and expanded significantly. The document consists of additional topics to cover current thinking and challenges in the deployment of these new reactors. The following sections describe some key lessons learned from the draft crosscut document.

4.1. Fuel Type

PR&PP varies dependent on the fuel type and characteristics of the physical form, material properties and chemistry, and isotopic composition. The physical form refers to the differences between more traditional fuel assemblies, fuel compacts, pebbles, or liquid fueled designs. Larger items are more difficult to steal but will also contain more fissionable material per item. Smaller items may be easier to divert but will contain less fissionable material, thus requiring more items to obtain an SQ. Pebbles and molten salts may introduce bulk accountancy challenges. Material properties and chemistry refers to the chemical form of the fuel which affects ease of reprocessing. Oxide and metallic fuels have established reprocessing technologies, while reprocessing of TRISO fuels has not been demonstrated on a large scale. Finally, isotopic composition has key implications on attractiveness of the fuel. Fresh fuel and irradiated blanket assemblies with potentially fertile seeds are more attractive than spent fuel with higher burnups.

4.2. Coolant/Moderator

Advanced reactor designs utilize a variety of coolants including water, helium, lead, sodium, and molten salt. Moderator materials (for thermal reactors) include water and carbon. The opacity of the coolant affects the ability to visually verify fuel assemblies while in the reactor, although other techniques could be used. Reactor accessibility is also of interest since on the one hand a system that is highly accessible makes safeguards inspections easier while on the other hand less accessible systems may have a proliferation resistance advantage. From a physical protection standpoint, the chemical reactivity of the coolant/moderator, retention of fission products, and ease of dispersal needs consideration for proper protection of the plant against sabotage.

4.3. Refueling Modes

The refueling mode of a reactor has implications on PR&PP due to accessibility and potential misuse scenarios. With batch refueling, misuse is more limited because even one batch produces enough burnup to lower the material attractiveness. Early shutdown of the reactor would be difficult to hide but should be considered in breakout scenarios regarding proliferation. Continuous refueling could provide more opportunities to remove low-burnup fuel, so additional safeguards measures may need to be applied. Molten salt reactors are a unique case and have unique PR aspects particularly if on-line processing is utilized because of the potential for separating actinides. Microreactors or other small reactor designs that have long-lived, sealed cores will have limited movement of material as long as the reactors are not prematurely shutdown, but the inaccessibility of these long-lived cores may have safeguards implications (such as physical verification of fuel inventory in a timely manner).

4.4. Small Modular and Microreactor Options

Modular deployment of reactors, with potentially multiple reactors on one site, could increase safeguards burden if refueling is occurring regularly. Small reactor operators also have a desire to reduce security staffing on site to improve economics which will require new physical protection approaches. Some microreactors are considering single batch cores and sealed cores which could provide a proliferation resistance advantage. New PR&PP challenges are posed by deployment of either small or micro reactors in remote locations, and transportable or floating reactors. The potential for autonomous or remote reactor operations introduce additional PR&PP concerns.

4.5. Fuel Cycle Architecture

The reactor designs presented in the GIF PR&PP white papers envision both open and closed fuel cycles. 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 can provide both advantages and disadvantages from a PR&PP standpoint. Reduced transport of nuclear material is an advantage, but more nuclear material targets on site may be a disadvantage.

4.6. Life Cycle

The IAEA provides guidance on the application of safeguards through the full life cycle of a nuclear plant, from design through decommissioning. These guidelines describe monitoring of spent fuel at all times. The IAEA also must verify all nuclear material from the initial receipt of fresh fuel material, spent fuel storage through to reactor decommissioning and removal of nuclear material.

4.7. Flexibility

Future advanced reactors may see a wider variety in use as opposed to solely for baseload power. Flexibility of plant operations, whether for load following or non-electric sources of energy, will likely have little effect on PR&PP. Highly varying power output could make reactor inventory calculations less precise. The use of more reactors around the world for different purposes will place additional burden on the IAEA for safeguards which is probably a more significant impact on PR&PP. Siting reactors near population centers (which would be desirable for heat production) could raise additional physical protection challenges. Reactors with flexible fueling options could also increase safeguards burden, especially if the composition of fuel is changing with refueling.

4.8. Safeguards Topics

Safeguards approaches for advanced reactors with evolutionary designs (still based largely on fixed assemblies) are more straightforward than revolutionary designs (including the use of opaque heavy metal coolants, molten salt cores, pebble bed fuels and other radical departures from LWRs). The revolutionary reactor designs can benefit from Safeguards by Design (SBD) activities based on present LWR safeguards. The present safeguards equipment including non-destructive assay for fresh, core, and spent fuels; containment and surveillance; and the safeguards inspection planning and implementation historically used could work for evolutionary designs. However, 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). Additional concerns may arise with the type of fuels and techniques for verification of nuclear materials in the fuels, including accounting for fuel structures and elemental and isotopic compositions (especially spent fuel forms), storage, and disposal plans. Hence, PR&PP studies on selected designs of the six GIF technologies should provide input for safeguards efforts.

4.9. Cyber Threat

The next generation of nuclear facilities will be more highly dependent on digital assets as compared with many older LWRs. There are 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. Finally, 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, especially regarding sabotage of nuclear facilities.

4.10. Operational Transparency

The increasing extent of automation in nuclear facilities 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. Such a framework would compare expected behavior of relevant signals to measured signals, wherein measured deviations may signal diversion of nuclear material. The comparison would occur in a manner transparent to involved operators and regulatory bodies. 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. This should all be accomplished while minimizing operational burden as well as the cost and effort involved in analysis, reporting, and management of process data. Greater operational transparency could better support safeguards and increase proliferation resistance.

4.11. Safety Interface

Advanced reactors present new opportunities for the integration of safeguards, security, and safety (3S). IAEA has recognized this need through the establishment of a crosscutting 3S initiative. More integrated approaches will be required to generate efficient plant monitoring systems and efficient verification approaches. 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 PR&PP and safety evaluation methodologies share a common framework/paradigm. 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.

4.12. Economics

Nuclear energy must remain competitive with other clean sources of power. 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 safeguards by design is to consider safeguards and proliferation resistance features early in the design process to avoid costly retrofits and provide more economical designs. Likewise, security by design takes into account an optimization of upfront and operational costs through the life of the facility. Physical protection costs 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 and presents opportunities for continued collaboration with the PR&PP working group.

5. CONCLUSIONS

A key goal of the six PR&PP white papers and the companion crosscut document is to promote the concepts of PR&PP by design, or consideration of PR&PP very early in the design process. There is significant momentum currently for deployment of advanced reactors and new fuel cycle facilities in the near future. Host states, advanced reactor vendors, and utilities need to maintain high rigor in the safeguards and security of these new systems and take advantage of lessons learned from the past.

Consideration of PR&PP early provides an economic advantage in optimizing design and avoiding unplanned retrofits. The presented lessons learned and recommendations in this paper provide a first step for advanced reactor designers and policy makers in understanding PR&PP topics as they apply to increased and more sophisticated deployment of nuclear energy. The PR&PP working group of the GIF is a resource for future work into PR&PP aspects of future reactor designs.

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