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White Papers on Proliferation Resistance and Physical Protection Characteristics of the Six GEN IV Nuclear Energy Systems

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ABSTRACT

This paper provides an overview of an activity that evaluates the proliferation resistance and physical protection characteristics of the six advanced reactor systems selected for further research and development by the Generation IV International Forum (GIF). Since 2018 the GIF Proliferation Resistance and Physical Protection Working Group (PRPPWG), in collaboration with the system designers, has been updating the white papers on the proliferation resistance & physical protection (PR&PP) robustness of the six GIF design concepts. The current update reflects changes in the six GIF systems with enhanced intrinsic PR&PP features since the original publication of the PR&PP white papers in 2011. The PR&PP evaluation assesses each design against potential threats using the technical design information to gauge the response of the system. PR threats included, a) concealed diversion or production of material, b) use of the system in a breakout strategy, and c) replication of the technology in clandestine facilities. PP threats included, a) theft of material for nuclear explosives or dispersal devices, and b) radiological sabotage. The PR&PP white papers' development demonstrated the application of the PR&PP-by-Design concept to the six GIF designs.

INTRODUCTION

The Generation IV International Forum (GIF) is an international initiative set up to carry out R&D on six selected reactor technologies, namely Gas Fast Reactor (GFR), Lead Fast Reactor (LFR), Molten Salt Reactor (MSR), Super-Critical Water Reactor (SCWR), Sodium Fast Reactor (SFR) and Very High Temperature Reactor (VHTR). The Proliferation Resistance and Physical Protection

Working Group (PRPPWG) was established by GIF to develop, implement and foster the use of an evaluation methodology (PRPPEM) to assess Generation IV nuclear energy systems with respect to the GIF-PR&PP goal, whereby: "*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*". The PRPPEM methodology provides designers and policy makers a technology neutral framework and a formal comprehensive approach to evaluate, through measures and metrics, the Proliferation Resistance (PR) and Physical Protection (PP) characteristics of advanced nuclear systems. The working group released the current version (Revision 6) of the methodology for general distribution in 2011 [1]. The methodology has been applied in a number of studies [2] and the PRPPWG maintains a bibliography of official reports and publications, applications and related studies in the PR&PP domain. [3]

In parallel, the PRPPWG, through a series of workshops, began interaction with the Systems Steering Committees (SSCs) and Provisional Systems Steering Committees (pSSCs) of the six GIF concepts. White papers on the PR&PP features of each of the six GIF technologies were developed collaboratively between the PRPPWG and the SSCs/pSSCs according to a common template. The intent was to generate preliminary information about the PR&PP merits of each system and to recommend directions for optimizing its PR&PP performance. The initial release of the white papers was published, in 2011, by GIF as individual chapters in a compendium report. [4]

In April 2017, as a result of a consultation with all the GIF SSCs and pSSCs a joint workshop was organized and hosted at OECD-NEA in Paris. The need to update the 2011 white papers emerged from the discussions and was agreed by all parties and officially launched in November 2017.

The update uses a revised common template [5]. The template entails elements of the PR&PP evaluation methodology and allows a systematic discussion of the system elements of the proposed design concepts, the potential proliferation and physical protection targets, and the response of the designs to threats posed by a national actor (covert diversion of nuclear material & misuse of nuclear technology, breakout and replication of the technology in clandestine facilities), or by a subnational/terrorist group (theft of material or sabotage). Each paper includes an appendix on PR relevant intrinsic design features based on the IAEA STR-332 [6].

Currently two papers, (LFR and SFR) have been completed and the other four white papers are being finalized. The target is to have all the six white papers published in the course of 2021. This article presents the main findings from each of the updated PR&PP white papers, focussing on their intrinsic design features. A hint on the crosscutting topics that will be addressed in a companion report is also included.

PRPP WHITE PAPERS FOR THE GEN IV SYSTEMS

The current white paper update reflects changes in designs, new tracks added, and advancements in designing the six systems with enhanced intrinsic PR&PP features and in a better understating of the PR&PP concepts. Table 1 presents, for the six GIF technologies GFR, LFR, MSR (liquid fuel and solid fuel designs), SCWR (vessel and pressure-tube designs), SFR (loop and pool designs), VHTR (pebble and block designs), their corresponding reference designs and design tracks that are considered in the updated white papers.

Table 1: System designs considered in the white paper updates

GIF System	System Options considered in update	Design Tracks considered in update	Comment
GFR	Reference Concept	2400MWt GFR ALLEGRO as a GFR demonstrator (EU)	Other GEN IV designs include: EM2 (GA) ALLEGRO (V4G4) HEN MHR (High Energy Neutron Modular Helium Reactor) (CEA-ANL and GA-AREVA)
LFR	Large System	ELFR, (EU))	These are the three reference design configurations discussed in the GIF LFR System Research Plan
	Intermediate System	BREST-OD-300, (RF)	
	Small Transportable	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)	
SCWR	Pressure Vessel	HPLWR (EU) (Thermal)	Most concepts are based on “familiar’ technology, such as light-water coolant, solid fuel assemblies, and batch refueling. Implementation of Th and Pu fuel cycles creates additional special nuclear materials of concern.
		Super FR (Japan)	
		Super LWR (Japan) (Thermal)	
		CSR 1000 (China) (Thermal)	
		Mixed spectrum (China)	
		Fast core (RF)	
	Pressure Tube	Canadian SCWR (Canada) (Thermal)	
SFR	Loop Configuration	JSFR (Japan)	Expect key PR&PP issues to be tied to fuel handling, TRU inventory and fuel cycle options.
	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)	

Using the technical information assembled by the system designers, each of the six GIF technologies was evaluated separately by members of the GIF PRPPWG with assistance from the SSCs/pSSCs. The evaluation assessed qualitatively the response of a reactor system to the four identified PR strategies (diversion, misuse, breakout, replication of technology in clandestine facilities) and the two PP strategies (theft, sabotage). The following sections summarizes some of the main findings of the whiter paper update, highlighting the intrinsic PR and PP design features of the six GIF technologies.

Gas-Cooled Fast Reactor (GFR)

The Gas-cooled Fast Reactor (GFR) system features a high temperature helium cooled fast spectrum reactor with a closed fuel cycle. The GFR reference design is a 2400 MWth reactor and a hexagonal fuel element core, each element consisting of ceramic-clad, mixed-carbide-fueled pins contained within a ceramic hex-tube. The reference cycle, GANEX cycle, is a closed cycle where Pu and Minor Actinides are co-recycled; Uranium is separated from the Transuranic isotopes which are reprocessed without separation of Pu. The updated White Paper also included a description of ALLEGRO but no PR&PP evaluation. ALLEGRO is an experimental fast reactor cooled with Helium being developed by the European V4G4 Consortium “V4G4 Centre of Excellence.”

GFR reference design exhibits a number of intrinsic proliferation resistance features:

- The PR characteristics of the GFR fuel design does not appear to distinguish it from other fast reactors using depleted U and high Pu content MOX fuel. The GFR’s fuel cycle is the same as other reactor systems utilizing the aqueous recycling process.
- Uranium and plutonium are the main targets in terms of material attractiveness. Each fresh or spent fuel assembly contains more than one significant quantity of reactor-grade Pu;
- Inherent Proliferation Resistance mainly arises in the aqueous processing of spent fuel with group extraction of actinides (no separation of certain trans-uranic elements from uranium);
- Fuel elements are not separated from their sub-assembly on the reactor site, and the presence of the wire wrapped around each pin suppresses the risk of clandestine pin extraction or pin replacement. This means that the potential targets are entire fuel assemblies rather than individual pins;
- As for the ease of production of Pu in clandestine facilities with a GFR, if available, it would be comparable to Gen II or Gen III light water reactors.

For physical protection the GFR design relies on many of the same protective measures used in PWRs (mainly with a reactor containment building) given the fact that inert gas (with no phase change) is used as a primary coolant. A guard vessel that envelopes the primary system should give an additional level of protection. The following protective measures are incorporated in the design:

- A pre-stressed concrete containment building and a bunker-like spent fuel storage pool are designed to prevent external hazards and theft of nuclear/radiological material;
- The refractory fuel can sustain very high temperatures and decay heat removal can be achieved by natural circulation of gas in most accident sequences;
- Main safety buildings (control room, diesel rooms, gas storage) are designed as protective bunkers;
- The heat sinks of the emergency loops are located inside the containment building so that they are protected from external hazards;
- High radiation levels for both fresh and spent fuel elements or sub-assemblies prevent them from being easily stolen on the reactor site.

Lead-Cooled Fast Reactor (LFR)

The GIF LFR PR&PP White Paper investigated the PR&PP aspects of the three GIF LFR reference systems designs. The three systems share the main technological features but represent three different fuel cycle architecture concepts: a large reactor (ELFR), direct replacement of a current large LWR reactor, a medium-size reactor (BREST-OD-300), compatible with the upper bound of what is accepted as Small Modular Reactor power range, and a sealed-core (SSTAR), long life micro reactor expressly designed having enhanced nuclear proliferation resistance in mind. All designs foresee Pu fuel with a closed fuel cycle with options to recycle MA. ELFR is associated with centralized reprocessing of spent fuel, the BREST-OD-300 demonstrator foresees co-located fuel fabrication and processing facilities, while SSTAR envisions the replacement of the whole long-lived cassette core. ELFR employs MOX fuel, while BREST and SSTAR employ nitride fuel.

For the main reference designs, intrinsic PR features that reduce the LFR technology attractiveness for nuclear weapons programs include the following points:

- The related fuel cycle does not require nor foresee any uranium enrichment technology, taking out the need or the rationale for a proliferation-sensitive fuel cycle step;
- The systems can work as an "adiabatic core", maintaining the inventory and isotopic composition of fissile plutonium roughly constant throughout the fuel assemblies' lifetime, and therefore avoiding spikes in potential attractiveness for a would-be proliferator throughout the entire fuel assemblies' life cycle;
- The foreseen closed back-end technologies and the specifications of the LFR fresh fuel allow for a reprocessing phase with homogeneous recycling of all actinides, avoiding the availability of separated uranium or plutonium at any stage.

For the main reference designs intrinsic proliferation resistance features that make them unattractive for nuclear material diversion and undeclared production are:

- Fuel assemblies do not foresee any fuel pin replacement, and are designed to make their disassembly in the reactor facility impossible or very difficult. In the case of SSTAR, the single fuel assembly constitutes the whole core, making it de facto impossible to be diverted;
- The facilities operation is highly automated, and all three reference designs foresee that the biggest share of the facilities' inventory will be in difficult-to-access areas, either sealed or exhibiting high radiation levels. The reactor cores do not foresee the presence of blankets, neither radial nor axial. The SSTAR sealed core precludes any access to the core by design. BREST-OD-300 operates with very small reactivity margins, making the replacement of standard fuel assemblies with target assemblies very difficult or even unfeasible;
- Since the fuel assemblies of the ELFR cannot be disassembled on site, pin replacement for breeding purposes is not an option. In case of co-location, the modifications of the BREST-OD-300 processing facilities is virtually impossible;
- In operation, the reactor core is sealed and completely inaccessible on all three systems.

The main reference designs exhibit several physical protection-relevant intrinsic features:

- System simplification makes the system safer and with fewer potential vulnerabilities;
- The use of a coolant chemically compatible with air and water and operating at ambient pressure mitigates potential outcomes from sabotage efforts;
- There is a reduced need for robust protection against the risk of catastrophic events, potentially initiated by acts of sabotage, due to reduced risk of fire propagation;
- There are no credible scenarios of significant containment pressurization due to the design features of the reference designs steam generators, limiting maximum flow rates;
- The low pressure of the primary system in operating and accidental conditions contributes to a safer system behaviour in case of sabotage, minimizing the opportunities to generate potential explosions leading to external radiological releases;
- The designs exhibit a compact security footprint.

Molten Salt Reactor (MSR)

The MSR white paper update expanded the PR&PP evaluation from one design (the MSFR) to three classes of MSR designs. An example system was selected for the evaluation of each class of MSR.

(1) Lquid-fueled with integrated salt processing - MSFR (European Union)
(2) Liquid-fueled without integrated salt processing – IMSR (Terrestrial Energy)

(3) Solid-fueled with salt coolant - Mk1 PB-FHR (UC-Berkeley, et al.)

The Molten Salt Fast Reactor (MSFR) is characterized by its low fissile inventory, disseminated in a small quantity (some %) in the fuel salt due to its high power density and the absence of excess fuel reactivity for operations. Obtaining a significant quantity (SQ, defined by the IAEA as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device –NED- cannot be excluded") of fissile material would require a sizable amount of fuel salt, and its absence from the reactor is readily detectable. The proliferation concern of Pu in TRU-started MSFR is somewhat mitigated by the net consumption of Pu during operation and the monotonic buildup of ^{238}Pu in the fuel salt with its fractional content (^{238}Pu/total Pu) increasing from a few % initially to over 50% at equilibrium condition. For the U-started MSFR, operated with Th, the unavoidable production of ^{232}U accompanying ^{233}U production, would generate additional constraints on the handling and transport of uranium, i.e. imposing additional technical difficulties. Diversion of Pa or uranium during the fuel salt processing step will upset the actinide balance of the fuel salt and should be readily detectable.

A notable feature of the Integral Molten Salt Reactor (IMSR) is the system for regular fuel top-ups that will not permit operators to subtract fuel from the core, precluding breeding and diversion in the main reactor vessel. There is a potential of UF_6 removal from fuel salt by fluorination as all liquid-fueled designs, including the IMSR, are equipped with gas (He, HF, H_2 and F_2) lines for salt treatment during reactor operation, and this requires suitable monitoring. For MSRs with no onsite fuel processing there is still an option of a centralized salt processing facility located elsewhere in the fuel cycle to handle the salt or core every 4-8 years—this facility would still have some of the accountancy challenges of a bulk reprocessing facility, as in the case of the MSFR.

The distinguishing feature of the solid-fueled MSR design using TRISO fuel, as in Mk1 PB-FHR, is its robust fuel, greatly diluted in carbonaceous material with high burnup capability. Solid-fueled MSRs are closer to item-counting facilities as opposed to bulk handling facilities for liquid-fueled designs. Diversion or misuse of the TRISO-particle-fueled MSR to acquire a significant quantity of U or Pu is hindered by the need to obtain a large number of hard-to-process fuel particles.

The high radiation presents an intrinsic barrier to theft of nuclear material for all MSR designs. The typical remote handling of fuel salt in a hot cell environment (operating at temperatures above the salt melting temperature) makes physical access for theft or sabotage difficult or impossible. The relatively small quantity of fissile material in fuel pebbles renders them less desirable as targets for theft. The layered construction of fuel pebbles and their ability to sustain high temperatures also make them more robust against radiological sabotage. Draining of fuel salt from the core shuts down the reactor, adding to the robustness against sabotage. Furthermore, MSRs differ from most other reactor types because they use a low-pressure, chemically inert coolant, and thus do not have any stored energy sources to pressurize their containment boundary, minimizing a driving force for radiological releases during a sabotage event.

Super Critical Water Reactor (SCWR)

The SCWR is a high temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point (374°C, 22.1 MPa). Two primary circuit concepts are being considered, pressure-vessel and pressure-tube. In addition, a variety of SCWR core designs are feasible, including thermal, fast, fast-resonant and mixed spectra. For the white paper update a combination of primary circuit designs and spectra provides several options for the SCWR:

1. The Canadian Thermal-Spectrum SCWR (pressure-tube; fuel: $(Pu,Th)O_2$)
2. The Chinese Thermal-Spectrum SCWR (pressure-vessel; fuel: UO_2)
3. The EU Thermal-Spectrum SCWR (pressure-vessel; fuel: UO_2)
4. The Japanese Thermal-Spectrum SCWR (pressure-vessel; fuel: UO_2)
5. The Chinese Mixed-Spectrum SCWR (pressure-vessel; fuel: UO_2/MOX)
6. The Russian Mixed-Spectrum SCWR (pressure-vessel; fuel: MOX)
7. The Japanese Fast-Spectrum SCWR (pressure-vessel; fuel: MOX)
8. The Russian Fast-Resonant SCWR (pressure-vessel; fuel: MOX)

The PR and PP characteristics of SCWRs are closer to the current fleet of light-water reactors (LWRs) than any of the other GEN IV systems. The fuel assemblies and even each fuel rod can be numbered, labeled, and are amendable to optical surveillance at any position, in the opened reactor, during fuel handling, or in the storage pool. With the Canadian Thermal-Spectrum SCWR abandoning online refueling as an option there is now little distinction between the pressure-tube and pressure-vessel design in term of PR&PP. Among the SCWR design variants the driver for differences in the intrinsic PR characteristics resides in their adopted fuel cycle.

The intrinsic proliferation resistance of the SCWR fuel cycles have similarities to that of LWRs in the case of UO_2 or MOX fuels. However, some of the SCWR designs have more concentrated, high quality fissile material in their fuel cycle than LWRs do, in the form of either plutonium or uranium (in HALEU (High Assay Low Enriched Uranium)). A common, cross-cutting, concern for many fast reactors is the potential of significant amounts of Pu in both the fresh fuel and the spent fuel, which might require more effort for protection and surveillance. The existence of breeding assemblies in some of the fast and mixed-spectrum reactors might need some modification, such as blending them with minor actinides to make them less attractive for diversion. Unlike liquid-fueled reactors with a thorium cycle, the pure U-233 stream available by diverting Pa-233 is not considered a serious vulnerability in the SCWR solid-fuel cores as the fuel removal and reprocessing time would have to be on a very frequent timescale due to the short, 27 day, half-life of Pa-233.

The risks of theft or sabotage by non-state actors associated with SCWR design variants are expected to be similar to that of existing LWR designs. The separation of the coolant and moderator may have some PP benefit against sabotage in the pressure tube design.

Sodium-Cooled Fast Reactor (SFR)

The SFR white paper used five reference designs to examine PR&PP aspects: JSFR from the Japanese Atomic Energy Agency (compact loop), KALIMER-600 from Korea Atomic Energy Research Institute (pool), ESFR from European Commission funded projects (pool), BN-1200 from Rosatom in Russia (pool), and AFR-100 from the United States (small modular). Due to similarities in fuel and overall design of SFRs, little variation was found between different designs from a PR&PP standpoint. The following presents key conclusions from the white paper, and in many cases the conclusions are common to other fast spectrum reactors.

In terms of proliferation resistance, it is noted that fast reactors in general have higher percentages of fissile material inventory, and assemblies are smaller than for LWRs, but item accounting of assemblies can be applied easily. Detailed accounting of fresh fuel, of any potential blanket assemblies where present, and of spent fuel is required. The fuel is expected to achieve higher burnups as well. The high activity and dose of fuel along with operations under sodium may provide a proliferation resistance advantage. Fast reactors can burn group actinides which helps to burn down fissionable material and does not require separating plutonium.

There are some slight differences with the small modular designs. Enrichment is not required for many of the larger cores (which can reduce proliferation pathways), but the small reactor reference design uses 13.5% enriched uranium. Sealed cores may be treated as a unit for accountability, so if anything, accountability would be simpler for the small modular options.

Long-lived cores as well as sealed cores reduce the amount of fuel transfers, but larger amounts of fuel are handled per transfer. While reduction of transfers reduces opportunities for theft, it can be more of an economic benefit since fewer shipments need to be protected.

In the GIF Example Sodium Fast Reactor case study [2], no credible pathways were found for concealed diversion since diversion of whole assemblies would be detected by the safeguards system. Misuse scenarios were analyzed, but no additional misuse scenarios were found as compared to any other reactor. While blankets can produce high quality Pu in low concentrations, this misuse scenario can occur with any reactor even without blankets.

The utilization of liquid metal coolant requires a specialized infrastructure and complicated fuel handling. Both aspects make SFRs hard to conceal clandestine production compared to other easier ways of producing fissile material.

In term of physical protection, it is noted that the use of remote handling restricts access, which is a PP benefit. Theft targets are more likely to be fresh fuel or spent fuel after cleaning and cooling due to the difficulties of accessing material while in use.

Sabotage scenarios should consider attacks which specifically focus on core cooling and heat rejection systems. Unique to SFRs, attacks specifically on sodium loops must be considered due to the potential to create a sodium fire. All sodium loops are contained within robust containment or missile shields in the reference designs.

Very High-Temperature Reactor (VHTR)

The VHTR white paper examines PR&PP aspects for prismatic fuel core (abbreviated as B-VHTR) such as SC-HTGR (France) and GTHTR300 (Japan), and pebble-bed core (abbreviated as P-VHTR) such as Xe-100 (US) and HTR-PM (China). Both P-VHTR and B-VHTR use TRISO fuels which are quite robust to high temperatures and high burnup and have excellent fission product retention in the fuel, which provides advantageous nuclear non-proliferation and nuclear security features.

In term of proliferation resistance of VHTRs, as a general remark, it is noted that one has to process some metric tons and tens of cubic meter quantities of TRISO fuels in order to obtain a significant quantity of nuclear material, using either grind-leach or burn-leach of electrolysis in nitric acid whose technology is still not matured at industrial level. In addition, high burnup of the spent fuel of both VHTR designs is also one of key proliferation resistance features due to higher order plutonium isotopes that produce decay heat and high dose rate.

International safeguards for B-VHTR can adopt item counting like LWRs. All movements of fuels are observed by surveillance cameras. Fresh fuel storage and spent fuel storage are sealed after fuel movement. Fuel inventory in the reactor core is verified by fuel flow monitoring with radiation detectors. One of the main differences compared to LWRs is the absence of water in reactor cores. Therefore, conventional Cherenkov camera observation by IAEA inspectors is not applicable.

For P-VHTR, on the other hand, its safeguards are considered to be quasi-bulk type: No identifiers are present on pebbles. The pebbles that have achieved a predetermined burnup are discharged through discharge tubes and are led to containers in the discharge compartment as spent fuel pebbles. Diversion of Pu might be possible by using this continuous fuel loading system and discharging fuel pebbles early from the reactor core before significant buildup of even-mass-numbered Pu isotopes. However, that kind of activity would be detected by adequate Containment and Surveillance (C/S) measures by IAEA safeguards.

In case that a proliferator decides to produce Pu in clandestine facilities, or even in breakout scenarios, B-VHTR could be used as Magnox-type reactors that have abilities to produce weapon grade plutonium on natural uranium targets. However, reactors should be operated in low reactor coolant outlet temperatures to keep the integrity of Magnox-fuels.

In term of physical protection, as was mentioned in proliferation resistance, terrorists need to steal metric tons of spent fuel blocks/pebbles. The subsequent reprocessing of these spent fuel would require substantial effort in order to get a significant quantity of Pu. In addition, Pu with a high concentration of even-mass-numbered Pu isotopes, such as ^{240}Pu, ^{242}Pu and even ^{238}Pu, would not be suitable for NED fabrication; however this would provide radiological targets for theft.

In case of radiological sabotage targeting power excursion, VHTRs are designed to achieve passive-safety by the nature of its fuel that maintains the fuel temperature below fuel-damaging threshold in normal operations and even in severe accidents, including beyond-design-basis events. The consequence of using VHTR fuel by terrorists in Radiological Dispersal Devices (RDDs) is mitigated by the fact that the diffusion of fuel particles would be limited by their weight compared to that of finer bulk materials such as powder and liquid.

CROSSCUT

There are several topics related to PR&PP which crosscut the various system white papers. Crosscutting topics may either be common to all the various system designs or crosscutting with similar themes across all system designs. A companion document is currently being developed that covers these topics and describes the impact on PR&PP. The following is a listing of the crosscutting topics with a brief description of each one.

- Fuel Type – Impact of different fuel types and configurations.
- Coolant/Moderator/Reflector – Impact of different materials in the reactor design.
- Refueling Modes – Impact of refueling differences.

- Small Modular and Microreactor Options – Impact of moving toward smaller designs.
- Fuel Cycle Architecture – Discusses the types of fuel cycles that may be considered.
- Life Cycle – Discusses cradle to grave impacts.
- Flexibility – Discusses differing energy production, load following, and flexible operations.
- Safeguards Topics – Focuses on IAEA safeguards.
- Operational Transparency – Discusses verification of reactors.
- Cyber Threat – Discusses increasing focus on cybersecurity.
- Safety – Interface with safety systems.
- Economics – Impact of PR&PP on plant economics.

CONCLUSIONS

The GIF PRPPWG, in collaboration with the system designers (GIF SSC/pSSC), updated the 2011 white papers that evaluated the PR and PP characteristics of the six GIF systems against threats of proliferation, theft and sabotage. The current effort helps to elucidate technical features of each reactor system that make the system very unattractive for diversion and misuse or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

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