GEN IV International Forum

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PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION CROSSCUTTING TOPICS

December 2022

DISCLAIMER

Preface to the 2021-2022 edition of the SSCs, pSSCs & PRPPWG white papers on the PR&PP features of the six GIF technologies and crosscutting topics

This report is a companion document to a series of six white papers, prepared jointly by the Proliferation Resistance and Physical Protection Working Group (PRPPWG) and the six System Steering Committees (SSCs) and provisional System Steering Committees (pSSCs). This publication is an update to a similar series published in 2011 presenting crosscutting Proliferation Resistance & Physical Protection (PR&PP) characteristics for the six systems selected by the Generation IV International Forum (GIF) for further research and development, namely: the Gas-cooled Fast Reactor (GFR), the Lead-cooled Fast Reactor (LFR), the Molten Salt Reactor (MSR), the Sodium-cooled Fast Reactor (SFR), the Super Critical Water–cooled Reactor (SCWR) and the 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 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 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. As such, the application of the evaluation methodology offers opportunities to improve the PR and PP robustness of system concepts throughout their development cycle starting from the early design phases according to the PR&PP by design philosophy. The working group released the current version (Revision 6) of the methodology for general distribution in 2011. The methodology has been applied in a number of studies and the PRPPWG maintains a bibliography of official reports and publications, applications and related studies in the PR&PP domain.

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 by GIF in 2011 as individual chapters in a compendium report.

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. During two days of technical discussions, the advancements in the six GIF designs were presented, the PR&PP evaluation methodology was illustrated together with its case study and other applications in national programmes. The need to update the 2011 white papers emerged from the discussions and was agreed by all parties and officially launched at the PRPPWG meeting held at the EC Joint Research Centre in Ispra (IT) in November 2017.

The current update reflects changes in designs, new tracks added, and advancements in designing the six GIF systems with enhanced intrinsic PR&PP features and in a better understating of the PR&PP concepts. The update uses a revised common template. The template entails elements of the PR&PP evaluation methodology and allows a systematic discussion of the systems elements of the proposed design concepts, the potential proliferation and physical protection targets, and the response of the concepts to threats posed by a national actor (diversion & misuse, breakout and replication of the technology in clandestine facilities), or by a subnational/terrorist group (theft of material or sabotage).

The SSCs and pSSC representatives were invited to attend PRPPWG meetings, where progress on the white papers was discussed in dedicated sessions. A session with all the SSCs and pSSCs was organized in Paris in October 2018 on the sideline of the GIF 2018 Symposium. A drafting and reviewing meeting on all the papers was held at Brookhaven National Laboratory in Upton, NY (US) in November 2019, followed by a virtual meeting in December 2020 to discuss all six drafts.

Individual white papers, after endorsement by both the PRPPWG and the responsible SSC/pSSC, are transmitted to the Expert Group (EG) and Policy Group (PG) of GIF for approval and publication as a GIF document. Crosscutting PR&PP aspects that transcend all six GIF systems have been updated and are presented in this companion report.

Abstract

There are several topics related to PR&PP which crosscut the various system white papers. To avoid redundancy in each individual white paper, discussion on these topics is presented in this companion document from a technology-inclusive perspective but with a focus on their impact on PR&PP. Crosscutting topics may either be common to all the various system designs or crosscutting with similar themes across all system designs. This paper updates and widens the topics covered in the crosscut section of the 2011 report including the six systems white papers. New topics, including Small Modular and Microreactor Options, Life Cycle, Flexibility, and Cyber Threat have been added.

This document, prepared by the GIF PRPPWG, follows the high-level paradigm of the GIF PR&PP Evaluation Methodology to investigate the key points of PR&PP features crosscutting the various designs. The high-level conclusions from the twelve areas considered are presented at the end of the paper.

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Acknowledgements

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List of Acronyms

3S	Safeguards, Security, and Safety
AFR	Advanced Fast Reactor
B-VHTR	Block-Very High Temperature Reactor
BWR	Boiling Water Reactor
CoK	Continuity of Knowledge
COTS	Commercial Off The Shelf
C/S	Containment & Surveillance
CSA	Comprehensive Safeguards Agreement
DBT	Design Basis Threat
DIV	Design Information Verification
EMWG	Economic Modeling Working Group
EPRI	Electric Power Research Institute
GIF	Generation-IV International Forum
GFR	Gas-cooled Fast Reactor
GW	Gigawatt
HALEU	High Assay Low Enriched Uranium
HEU	High Enriched Uranium
HM	Heavy Metal
IAEA	International Atomic Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INSAG	International Nuclear Safety Group
ISAM	Integrated Safety Assessment Methodology
LCOE	Levelized Cost of Electricity
LEU	Low Enriched Uranium
LFR	Lead-cooled Fast Reactor
LWR	Light Water Reactor
MOX	Mixed Oxide
MSFR	Molten Salt Fast Reactor
MSR	Molten Salt Reactor
NDA	Non-Destructive Analysis
NEI	Nuclear Energy Institute
NPT	Treaty of Non-Proliferation of Nuclear Weapons
O&M	Operation and Maintenance
PP	Physical Protection
PR	Proliferation Resistance
P-VHTR	Pebble Very High Temperature Reactor

RSWG   Risk and Safety Working Group
SBD   Safeguards by Design
SCWR   Supercritical Water Reactor
SFR   Sodium Fast Reactor
SMR   Small Modular Reactor
SQ   Significant Quantity
SSTAR   Small, Sealed, Transportable, Autonomous Reactor
TRU   Transuranic
VHTR   Very High Temperature Reactor

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1. Introduction

The Generation IV International Forum (GIF) has recently updated six system white papers on the proliferation resistance and physical protection (PR&PP) aspects for each advanced reactor class being examined in the GIF [1]. The purpose of the white papers is to examine PR&PP aspects and considerations unique to each general reactor class and provide guidance on safeguards and security for future vendors, policy-makers, and other stakeholders. PR&PP by design is a key focus of this work and includes considering PR&PP threats early in the design process to increase the confidence in the security and safeguardability of future nuclear reactors. The Appendix provides additional information about the reference systems, white paper organization, and PR-relevant intrinsic design features.

There are several topics related to PR&PP which crosscut the various system white papers [2]. Crosscutting topics may either be common to all the various system designs or crosscutting with similar themes across all system designs. This paper is meant to be a companion document to the six system white papers and describes crosscutting topics from a technology-inclusive perspective but with a focus on their impact on PR&PP. It updates and widens the topics covered in the crosscut section of the 2011 report including the six systems white papers. New topics, including Small Modular and Microreactor Options, Life Cycle, Flexibility, and Cyber Threat have been added.

The topics covered in this paper include:

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

All the above topics have an impact on PR&PP aspects of advanced reactors. For some crosscutting topics (Coolant/Moderator for example), the differing designs can lead to different PR&PP threats that must be examined. Other topics (Cyber Threat for example) must be considered across all systems, and the differences between systems may be smaller.

The following definitions [3] [4] form the basis for this work:

Proliferation Resistance is that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear explosive devices.

Intrinsic proliferation resistance features relate to the inherent properties or physical design features of a nuclear energy system or component. An intrinsic feature is likely very difficult or impossible to alter, is therefore very robust and desirable, and the term may be applied both to PR and to PP.

Extrinsic proliferation resistance features relate to the actions undertaken to impede proliferation, sabotage or theft, by States or other Institutions. These actions may be institutional, legal or operational in nature.

Physical Protection includes characteristics of a nuclear energy system that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices and the sabotage of facilities and transportation by sub-national entities and/or non-Host States.

Safeguards includes activities conducted by an independent agency to verify that commitments made by States under safeguards agreements are fulfilled. Verification agencies include the IAEA, Euratom, and the Agencia Brasileño Argentina de Contabilidad y Control de Materiales Nucleares.

Safeguardability refers to 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.

Note that Safeguards are a part of Proliferation Resistance and generally refer to many of the extrinsic features.

This document is meant to provide additional guidance to reactor vendors and other stakeholders on PR&PP considerations that apply to all advanced reactors.

2. Reactor Design Aspects

The reactor fuel, coolant, moderator, refuelling modes, and small and microreactor options all may have crosscutting implications on PR&PP. Some of these design components may be common across different systems, but there are general themes and conclusions which can be drawn based on the high level design features. The following four sections examine PR&PP aspects in more detail.

2.1 Fuel Type

Fuel type refers to the physical form, chemical form, and isotopic characterization of the fissile or fertile components of a nuclear reactor. There is a close link between Fuel Type and Fuel Cycle Architecture, with physical, chemical and isotopic properties of the fuel potentially being different in the various locations where fuel occurs in the fuel cycle—a complete safeguards and PR&PP assessment needs to account for potentially multiple locations and fuel forms in the fuel cycle where fuel occurs, such as fuel manufacturing, fresh fuel transport and storage, in-reactor, spent fuel interim storage, spent fuel transport and long-term storage and/or reprocessing.

Physical Form

Conventional reactor core designs use solid fuels comprised of multiple fuel rods or multiple fuel plates incorporated into fuel assemblies. Fuel assemblies are the basic modules from which the core is made up, and aggregating the multiple fuel rods or plates in an assembly makes it more practical to load and unload the core than would be the case with individual rods or plates. In a prismatic VHTR core, the fuel assemblies are comprised of monolithic blocks of graphite moderator which holds cylindrical fuel compacts (sticks) containing TRISO fuel microspheres embedded in graphite. In the pebble bed VHTR core, the core is comprised of individual fuel pebbles, each containing TRISO fuel microspheres embedded in a graphite matrix. A variant on this approach uses pebble fuel cooled by molten salt. Molten salt reactors either use solid TRISO fuel with a molten salt coolant or liquid fuel with fissile materials dissolved in the molten salt. Liquid-fueled molten salt reactor operation more resembles that of a chemical plant such as a reprocessing facility and therefore share some of the same safeguards and PR&PP characteristics.

Conventional safeguards methods are applicable to fuel assemblies, with each assembly being an individual accounting item. For pebble bed reactor designs, the pebbles will be counted in and out, and burnup measurements of exiting pebbles will be utilized, but individual pebbles will not be identified. For liquid-fueled molten salt systems, bulk accounting as in a reprocessing facility will be needed.

An important consideration for proliferation resistance is the amount of nuclear material contained in a single fuel assembly, either when fresh or when irradiated. For proliferation resistance assessments, nuclear materials masses are expressed in terms of the Significant Quantity (SQ). An SQ is defined by IAEA as the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded [5]. For Pu (containing less than 80% ^{238}Pu) and for and ^{233}U a SQ corresponds to 8 kg, A SQ is 25 kg ^{235}U at enrichments of ≥20% ^{235}U in U, 75 kg for enrichments <20% (or 10 t for natural U or 20 t for depleted U). From the PR&PP perspective, the fissile inventory of a single assembly should preferably be much smaller than 1 SQ. Diversion or theft of either a fresh or irradiated fuel assembly can provide a source of fissile material, and if each assembly contains only a small fraction of an SQ, a theft/diversion scenario would require the acquisition of a large number of assemblies, increasing the logistical difficulties for an adversary. The configuration of the fuel, e.g. monolithic vs. dismantlable design; has direct implications for identifying potential proliferation pathways, e.g., pin diversion and clandestine production (reconstitution of fuel with fertile material).

For physical protection, a major consideration is the mass and bulk of a fuel assembly, since a combination of large mass and bulk would make it more difficult to divert or steal, necessitating heavy lifting equipment and heavy transport equipment. There are threat scenarios where an adversary might attempt to use conventional explosives to disperse nuclear materials, including unirradiated or irradiated fuel assemblies. In such a scenario, it is beneficial if the fuel form is not susceptible to being widely dispersed in air or water and if the gaseous fission products are retained in the fuel microstructure rather than released into fission gas plenum spaces.

Materials Properties and Chemistry

The physical and chemical properties of the materials used in nuclear fuels have important implications for PR&PP. For proliferation resistance, the physical and chemical compositions of the fuel pellets (or in the case of VHTR, the fuel compacts/pebbles) and the clad material, determine how readily the fuel could be reprocessed and the fissile material separated. Metal and oxide fuels can be reprocessed using existing reprocessing flow sheets, with lower technological barriers to counter the proliferation threat. Alternative fuel diluents, such as thorium oxide (ThO), are not as easily dissoluble in acid and require further process flowsheet development, thereby presenting an additional barrier. The reprocessing of TRISO fuel particle would require first the separation of the pyrolytic carbon from the ceramic fuel kernel, then cracking of the SiC capsule, which presents a technological barrier to proliferation, and this technology has not been developed to commercial maturity.

Physical Protection assessment can potentially be influenced by the materials and chemical properties of fuel assembly materials. Physical properties of fuel materials, such as melting point, mechanical strength, brittleness, combined with chemical properties such as susceptibility to dissolution and retention of fission products in the fuel microstructure would figure in assessments of the threat of an adversary wanting to disperse radiological nuclides from stolen fuel assemblies. Inherent robustness to high temperatures, chemical attack and mechanical shocks (such as from explosives) would be beneficial in such scenarios.

Isotopic Composition

The isotopic composition of fuel determines how attractive fissile material would be in a state-sponsored weapons acquisition program or in scenarios involving theft by an external adversary. The GIF PR&PP Evaluation Methodology [4] proposed an illustrative categorization of nuclear materials inside a given target "based on the degree to which its characteristics affect its utility for use in nuclear explosives". It defines WG-Pu as "weapons-grade plutonium, nominally 94% fissile Pu isotopes", RG-Pu as "reactor-grade plutonium, nominally 70% fissile Pu isotopes", DP-Pu as "deep burn plutonium, nominally 43% fissile Pu isotopes".

The IAEA defines the strategic value of nuclear material as a relative measure of the usefulness of a nuclear material to a potential diverter for producing nuclear explosives and identifies three categories [5] of nuclear material:

Direct-use material that can be used for the manufacture of nuclear explosives components without transmutation or further enrichment, such as plutonium containing less than 80% Pu-238, uranium enriched to 20% and higher in ^{235}U (HEU) and ^{233}U. Chemical compounds, mixtures of direct-use materials, such as MOX and thorium and ^{233}U mixtures, transuranic fuels, and plutonium contained in spent nuclear fuel also fall into this category.

Unirradiated direct-use material does not contain substantial amounts of fission products; it would require less time and effort to be converted to components of nuclear explosive devices.

> **Indirect-use material** encompasses all nuclear material except direct use material. It includes: depleted, natural and low enriched uranium, and thorium, all of which must be further processed in order to produce direct use material.

Irradiated nuclear fuel typically contains plutonium or ^{233}U (from thorium fuel matrices) that could be used for state sponsored weapons acquisition or scenarios involving an external adversary. The presence of fertile blanket regions is important because for breeder regions containing ^{238}U the isotopic quality of plutonium produced is high. Some of the Gen-IV systems completely avoid separate fertile regions, while some (such as MSFR) have a separate blanket region. Furthermore, for any fertile region in the core (^{238}U or ^{232}Th), the local burnup tends to be low, which would simplify the reprocessing of fertile breeder fuels. Co-reprocessing of breeder blanket and core driver fuels is strongly preferred as it leads to a mixing of isotopics and provides a uniform background irradiation field from fission product and transuranics.

In thermal reactors, higher burnups generally lead to higher concentrations of even plutonium isotopes in uranium fuels, which is beneficial for proliferation resistance. However, the sensitivity is relatively low because even very poor isotopic quality plutonium is regarded as potentially weapons useable, and plutonium does not move into a lower risk category unless it consists predominantly of ^{238}Pu which generates significant heat by alpha decay making 80% or greater ^{238}Pu isotopic composition rather unsuitable for weapons—this is not achievable through irradiation. In thorium systems, the presence of ^{232}U at high ppm levels in ^{233}U is widely considered to offer protection, but there are strategies a state-sponsored diversion program or an external adversary could use in partial mitigation [6].

Radiotoxicity, heat load, and spontaneous fission are some of the other fuel properties related to the isotopic composition. These properties are often associated with the material type attributes of PR&PP target materials. The use of minor actinide target fuels (Np, Am and Cm), for which fast spectrum systems are most suited, has implications for proliferation resistance and physical protection. For proliferation resistance, the presence of minor actinides in high concentrations would complicate the diversion of fresh fuel and the diversion of irradiated fuel, due to the higher radiological activities involved, but may impact negatively on safeguardability [7]. Moreover, the presence of minor actinides potentially poses increased threats from theft/dispersal scenarios at every stage of the fuel cycle.

Gen IV Systems Fuel Forms

TRISO Fuel: The fuel for VHTR designs is based on TRISO coated particles. TRISO-coated particle fuel has a small-diameter (nominally 200-500 μm) spherical ceramic fuel kernel of either uranium oxide or uranium oxy-carbide, or mixed oxides of other actinides. The kernel is coated with four layers of low-density porous pyrocarbon (buffer), an inner high density pyrocarbon (IPyC), silicon carbide (SiC) and an outer high density pyrocarbon (OPyC). The coatings on the fuel particles serve as the primary containment preventing the release of fission products assuming a maximum transient temperature. The operating conditions are specified to limit fuel temperatures during both normal operations and accident conditions so as to preclude the release of fission products.

In prismatic VHTR cores, the coated particles are loaded into fuel compacts (sticks) held together by graphitized carbon. The fuel compacts are loaded into holes in hexagonal prismatic block fuel elements. Fuel elements are stacked in the reactor core with fissile and neutron burnable poison loadings tailored so that the power distribution is peaked toward the top of the core where the inlet cooling gas has the lowest temperature. Spent fuel is retained in cooled storage containers that are embedded underground and located adjacent to the reactor cavity. Prismatic spent fuel, which is unloaded from the core during periodic refueling shutdowns, can be tracked remotely by cameras viewing the serial numbers on the fuel elements during handling and storage operations.

In Pebble Bed cores, the TRISO coated particles are incorporated into fuel pebbles (diameter ~60 mm), dispersed in a graphite matrix. Pebble fuel is not tracked individually by serial number as in the prismatic core, but the individual elements are counted, characterized, and checked following each of multiple re-circulations until they achieve the target burnup based on radioactivity measurements. Following several passes of each pebble through the core during on-line pebble recirculation, when measured pebble activity indicates sufficient burnup, the pebble is transferred to a storage container with a record kept of the number of pebbles transferred.

Fuel Assemblies: The SFR, LFR, GFR, and SCWR reactor types all use solid fuel assemblies and reliance on item accounting. The fuel assemblies for the five SFR designs in Gen-IV all use conventional fuel rods clad in high temperature steel alloys. The various fuel forms include: Mixed Oxide (MOX - UO_2/PuO_2), Mixed Uranium Plutonium Nitride (MUPU – UN/PuN), transuranic bearing MOX fuel, or U-10%Zr and U-TRU-10%Zr (transuranic bearing) metal alloy fuels.

The fuel assemblies for the three Gen-IV LFR designs all use conventional fuel assemblies comprising fuel rods in hexagonal fuel assemblies. Two of the systems implement full actinide recycle, one with oxide fuel and one with nitride fuel. The third system uses a sealed long-life core with no refueling and uses mixed nitride fuel with minor actinides.

In the Gen-IV GFR Reference Design the core consists of hexagonal fuel elements, each consisting of ceramic-clad, mixed-carbide-fueled pins contained within a ceramic hex-tube. The favored material for the pin clad and hexagonal tubes is silicon carbide fiber reinforced by amorphous silicon carbide (SiCf/SiC). The ALLEGRO demonstrator reactor will initially be fueled with oxide fuel pellets of High Assay Low Enriched Uranium (HALEU) in a stainless-steel cladding. These oxide fuel assemblies will later be used as the driver for test irradiations of the all-ceramic carbide fuels needed for the Reference Design.

There are eight Gen-IV SCWR systems, with a range of thermal, mixed and fast neutron spectra. The reference fuel for the SCWR is UO_2 or ThO_2/PuO_2 for the thermal-spectrum concepts and MOX for the mixed and fast-spectrum concepts.

Liquid-Fueled: There are a large range of systems included under Gen-IV MSR. The majority of the systems use circulating molten salts which act as the solvent for the fissile and fertile fuel materials, thereby avoiding the need for fuel assemblies. Some of the systems use fluoride salts and others use chloride salts. Another system uses separate chloride salt for the fuel and fluoride salt for the coolant, with the molten fuel salt contained in cladding tubes. Depending on the fuel cycle of the MSR the fuel salt may contain U, TRU+U or Th+^{233}U.

2.2 Coolant/Moderator

A moderator is only present in thermal reactors. Among the reactors described in the white papers, the VHTR, one of the design options of the SCWR, and some MSR designs are thermal reactors. In the case of the VHTR, the slowing down of neutrons occur in the carbon matrix of the fuel compact (TRISO particles embedded in pebble or prismatic block) and in reflector regions. For the SCWR either light water (the pressure vessel option) or heavy water (the pressure tube option) is the moderator.

The coolant environment affects safeguards systems. With the exception of the SCWR all other reactors described in the white papers rely on non-aqueous coolants:

- Helium gas for the GFR and the VHTR.
- Liquid metal for the SFR and the LFR.
- Liquid salt for the MSR.

The opacity of the coolant determines whether visual inspection of fuel assemblies in the core is possible. Liquid metal makes verification of core fuel by direct visual inspection difficult because the

coolant is opaque, and this affects safeguards operation. Alternative technologies for verification do exist however, and it is possible to design cores such that the upper part of the fuel assembly extends above the surface for continuous visual monitoring by cameras. This is the approach used in LFR (ELFR design), for example.

Liquid salt is an opaque coolant and the carrier of the MSR fuel, and the safeguards inspection of the MSR fuel is performed by sampling only. It is impossible to tag the MSR fuel by serial number. The corrosive nature of the coolant could also be an issue for safeguards monitoring instruments.

However, a transparent coolant is not a sufficient condition for ease of inspecting fuel elements. The accessibility of the fuel is another important aspect. For example, while the fuel in reactor cores of B-VHTR and P-VHTR is visible like LWR, it is not easily accessible. Reduced accessibility of the fuel could be an advantage from a PR point of view. For instance, if the coolant has to be isolated from the ambient air, the fuel handing is difficult, and the fuel has to be decontaminated from the coolant. A common concern shared by the LFR and the MSR is the solidification of the coolant when the reactor is shut down, which is undesirable during normal operation. For the SFR, heating is provided to prevent sodium solidification upon shutdown.

The chemical reactivity of the coolant is an important consideration for PP analyses. Coolants such as water, helium, lead, and molten salt are not reactive with air in the event of an accident or sabotage attack. Sodium is reactive with air and requires additional protections. The potential of the coolant to contain nuclear material as well as how dispersible that material may be also must be considered. Phase change is important for pressurized systems like Light Water Reactors (LWRs) that need a containment since a phase change presents the potential for energetic release. Differences in activation of the coolant also should be considered. Finally, solidification of molten salts, sodium, and lead at room temperature affects safety, and can have an effect on the fuel. A proper PP analysis [4] needs to take into account various types of sabotage scenarios for proper plant protection.

The accessibility and identification issues described above along with consideration of the coolant need to be considered in conjunction with the refueling mode.

2.3 Refueling Modes

Refueling is either performed offline with the reactor shut down (in periodic batches or full-core cassette replacement) or on-line continuously while the reactor is operating. The frequency and mode of refueling have relevance to PR&PP with respect to accessibility of the fuel before, during, and after the refueling process, and the potential misuse of the refueling process to produce and divert weapons-usable material.

A reactor operating with batch refueling has no provision for access to the core while the reactor is operating. LWRs operate in this mode. Access to the core is possible only with the reactor shutdown, cold and depressurized, at which point the reactor vessel head can be removed, the above-core space flooded, and the fuel accessed for removal or shuffling. All fuel in an LWR core is removed to the refueling pond and then some is returned back to the reactor while some is discharged. Thus, all fuel is accessible during the refueling outage. As discussed below, some of the GIF systems fall into this category and the systems share some of the same restrictions to accessing the core.

In many reactor systems, while the quantity of plutonium generated increases with burnup, the isotopic quality of the plutonium decreases monotonically with burnup. Some cores are designed to be adiabatic, and the isotopic content and actinide quantity will not change as much with time. The strategic value of the plutonium in a state diversion scenario depends on the balance between these opposing trends in quantity and quality.

During an operating cycle, the fresh assemblies in their first irradiation cycle will accumulate significant burnup, sufficient to ensure the plutonium isotopic quality is at reactor grade classification. This first cycle burnup increment sets an upper limit on the plutonium isotope quality for a batch loaded reactor. All fuel assemblies accessible in the refueling pond during an outage, or in the spent fuel pond, will have been irradiated to at least the first cycle burnup increment for fresh fuel, with all assemblies containing plutonium with isotopic quality below the upper limit of the plutonium isotopic composition. Covert misuse scenarios are therefore limited with batch refueled reactors, with no opportunity to access low burnup fuel assemblies containing high quality plutonium. A batch refueling strategy can therefore be claimed to contribute to inherent proliferation resistance. While it is possible in principle that an operator might terminate a fuel cycle prematurely in a misuse scenario, in order to access assemblies with very low burnup, the premature shutdown would not be possible to conceal and would come under close safeguards scrutiny. However, this could be an issue in the case of a breakout scenario.

In a reactor operating with on-line refueling, individual fuel channels can be accessed at any time for replacing fuel assemblies. With on-line refueling there is a virtually continuous distribution of assembly burnups between zero and the discharge burnup, with a sub-population of fuel assemblies in the low burnup range that contain plutonium with higher isotopic quality than reactor grade. This is in contrast to a batch loaded reactor, where assembly burnups are clustered into discrete groups corresponding to the number of batches in the fuel management scheme. On-line refueling is therefore vulnerable to scenarios where the operator discharges selected fuel assemblies prematurely in order to create a stock of plutonium of high isotopic quality. It is therefore necessary to rely on safeguards measures, which are extrinsic controls. It should be also noted that the radioactivity is present even at low burnup, and corresponding technical difficulties would exist for the diversion.

A special case of on-line refueling is that of MSR. There are a wide range of MSR core concepts with a full spectrum of refueling and reprocessing options from no on-line reprocessing to full on-line processing. In the latter, the irradiated molten salt is extracted during operation and extensively processed, while fresh fissile material is added. Some MSR systems operate with a separate breeder loop containing ^{232}Th salt to breed ^{233}U. Such a breeder system could be the target of misuse if the ^{233}U was diverted. While the ^{233}U would contain problematic traces of ^{232}U, there are various mitigating strategies that could be put in place to minimize the impact of the high gamma activity associated with ^{233}U daughters. A specific PRPP assessment would be needed for each MSR design and its fuel cycle.

As for VHTR, there are two types: pebble-bed type (P-VHTR) and block type (B-VHTR). P-VHTR performs on-line refueling. The fuel spheres discharged from the core are measured for their burnup, and those that do not reach the specified burnup are returned to the core through the recharge piping. This loop of circulation through the core is performed at least several times for each fuel sphere. Those that have reached the predetermined burnup are transferred to the spent fuel storage and damaged fuel pebbles are segregated separately for storage. Since all these activities take place in closed piping system, it is an important task of IAEA safeguards to detect if there is any diversion by manipulating the piping.

As for B-VHTR, the IAEA inspectors cannot visually recognize the fuel (sub-)assemblies reloaded since there is no water shielding as is the case for LWRs. Verification must be done by unmanned manner using appropriate C/S and NDA equipment.

Some micro reactor designs that are in the design phase use cassette cores. Such micro reactors operate with a lifetime core and typically have a very long cycle length (15 to 30 years) that avoids the need for refueling. The long cycle length is possible because of the very low power densities at which the micro reactors operate. The strategy is to assemble the entire reactor vessel, including the fuel in a factory setting and transport the sealed vessel to the installation site. At the end of the reactor lifetime, the sealed vessel is transported back to the factory setting to be prepared for eventual disposal. This means that during the operational phase there is no provision to access the fuel assemblies and this constitutes an inherent proliferation resistance barrier.

The burnup evolution of cassette cores is distinct from that of batch refueling and on-line refueling. At the beginning of cycle condition, all the fuel in the core is at zero burnup, with potentially a high strategic value in a scenario in which the unirradiated fissile material was diverted. The burnup of the core will evolve linearly with cycle burnup and at any particular point in the cycle, there will be a relatively narrow distribution of individual fuel element burnups around the mean. If the core contains uranic material, there will be a gradual build-up of plutonium which will initially have very high isotopic quality that subsequently evolves to poor isotopic quality as the higher plutonium isotopes build up. The linear burnup evolution implies there will be a point at which the mass of plutonium and its isotopic quality will maximize its strategic value. However, the realities of removing the entire reactor/cassette should be considered. An assessment of the inherent proliferation resistance of a cassette core would need to take account of the evolution of the burnup distribution.

An assessment of the inherent proliferation resistance of a cassette core would need to consider the possibility that for technical or other reasons the reactor operates for less than its design cycle burnup. In a diversion scenario where the target material was the initial fissile load (may contain HALEU with enrichment higher than 5% and less than 20%), early termination of operation would leave a core with almost all the initial fissile content intact and at potentially very low burnup. These factors would give a high strategic value with a potentially low barrier to separation. In a diversion scenario where the plutonium produced by fertile conversion is the target material, a low burnup at the point of cycle termination, combined with a long cooling time could again lead to a combination of high strategic value material combined with low barriers to access. In this case, there would be a specific burnup that poses the maximum threat in the diversion scenario. Both cases could potentially lead to inherent proliferation resistance assessments that are similar to the situation of the first cycle fuel discussed earlier.

Looking now at the refueling strategies for the six GIF systems, five of the systems have design variations that are refueled offline in batches:

- the prismatic-block core VHTR;
- medium and large, pool or loop type SFRs;
- all SCWR designs;
- medium and large pool-type LFRs; and
- GFR.

All of these systems share aspects of on-site solid fuel management: new fuel acceptance, spent fuel handling, and out-of-reactor storage.

Two GIF systems have a design variation that is refueled by a full-core replacement:

- the small, sealed, transportable, autonomous reactor (SSTAR) variation of the LFR; and
- the small modular pool-type (AFR-100).

In SSTAR the compact active core is removed as a single cassette during refueling and replaced by a fresh core. Fresh or spent fuel storage is not envisioned as part of the normal operations, and full cassette core replacement would take place only at end of core life (15-30 years) and would be carried out by the reactor supplier. Similarly, a key design feature of the AFR-100 is the long-lived core (30 years with no refueling). Both of these systems eliminate all aspects of on-site fuel management: new fuel acceptance, spent fuel handling, and out-of-reactor storage—the elimination of these aspects are beneficial from the PR&PP viewpoint.

Two GIF systems have variations that are refueled continuously online:

- the pebble-bed version of the VHTR; and
- some liquid-fueled MSR designs.

The pebble-bed VHTR share aspects of on-site solid fuel management while also using an online automated refueling process. In the liquid-fueled MSR, however, refueling and liquid fuel processing are integrated in some designs. A small side stream of the molten salt is processed for fission product

removal and then returned to the reactor. For MSR without online reprocessing periodic addition of fresh fuel salt is needed to compensate for fuel burnup. If a thorium fuel cycle is used, thorium is the main component which has to be added during reactor operation in the form of thorium fluoride. The constraints on the storage of thorium are that of fertile materials. If the choice of a fertile blanket is made in the design, excess uranium management and storage will be necessary to store the uranium produced in excess of the fissile needs of the reactor. MSRs do not have spent nuclear fuel, except the fuel salt when the reactor salt is periodically replaced or upon decommissioning of the plant.

2.4 Small Modular and Microreactor Options

All six of the system white papers call out at least one small modular reactor as one of the possible designs [8]. These include the Advanced Fast Reactor-100 (SFR), the Small Secure Transportable Autonomous Reactor (LFR), Mark-1 Pebble Bed Fluoride High Temperature Reactor (MSR), Supersafe Reactor (SCWR), The X-Energy-100 (VHTR), and the Energy Multiplier Module (GFR). Microreactor designs are currently not called out in the white papers. There are several reactor designs moving into the small and microreactor space due to the advantages that come with small size, factory fabrication, transportability, and long fueling life. However, these aspects also present different PR&PP issues that crosscut all the small and microreactor designs.

Small Modular Considerations

Small modular reactors typically would have electrical outputs up to 300 MWe, and the specific ratings of the fuel and refueling strategies would be nearer to those of large plants. Distinctions between the PRPP characteristics of small modular reactors and large plants of the same type are likely to be smaller. The concept of significant quantity (SQ) is important, and all reactor designs contain at least one significant quantity of fissile loading. However, there are some differences that at least should be noted here.

The term "modularity" can be used in different contexts. Modular deployment refers to construction of multiple modules on one site. Modular construction refers to factory fabrication of many units, which is a goal of many of the reactor vendors. There are PR&PP differences with factory-loaded cores versus factory-fabricated modules that may be refueled on the reactor site. Cores which are loaded with fuel in the factory will place additional PR&PP considerations on the manufacturing plant.

One deployment strategy for small modular reactors is for a single unit to be deployed on a site near to a center of population. In this scenario, the PRPP characteristics can be considered the same as those of a large reactor, the only difference being of scale, and PRPP attributes generally are insensitive to scale. A second deployment strategy for small modular reactors is having multiple modules on a single site with a combined output comparable to large reactors. This allows for savings of scale, particularly from the various units sharing personnel and operating costs.

A small modular reactor deployed singly might reasonably be assessed as equivalent to a large plant in terms of safeguards requirements. However, multiple small modular reactor units deployed together present an increased challenge for safeguards. (Though this is also true for large sites with multiple units, the inspection cost on a per GWe basis would be larger for many small reactors as opposed to the large reactor designs.) One reason is that while a single large reactor might be expected to have a refueling outage once every 1 or 2 years, with multiple units it is likely that there be always one unit undergoing refueling. For a batch loaded reactor, refueling involves making the core more accessible, and operational and maintenance activities are increased. Therefore, during a refueling outage it is normal to see safeguards activity increasing. In a large reactor, this increased monitoring state only

applies for a small proportion of the time, whereas with multiple small units it would be needed most or all of the time. It could therefore be argued that the safeguards regime for a multi-unit small modular reactor plant would more resemble that of plants with on-line refueling operations.

Small modular reactor vendors are interested in reducing the number of on-site security staffing (as compared to large reactors) in order to achieve better overall plant economics. The state's regulatory body may allow for this due to advanced reactors' improved safety systems and the smaller size (which can significantly reduce the dose at the site boundary for potential sabotage scenarios). A physical protection analysis will need to balance the improved safety features with lower numbers of on-site personnel. The analysis will also need to take into account reliance on local law enforcement resources if needed. This type of analysis may require more integration between safety and security than what has been done in the past.

The deployment of SMRs in remote locations may present new challenges for safeguards inspections as well as physical security. Long response force times may lead to different strategies as compared to SMRs near larger cities. Transportable facilities, such as a floating reactor, present unique technical and institutional issues relative to stationary facilities. There could be many institutional challenges with transportable reactors going through different jurisdictions. Prefabrication of a sealed core at a factory and its transport to a plant site will pose additional safety, safeguards and security considerations.

Microreactor Considerations

Micro reactors are intended for deployment in remote locations, with autonomous operation. They may have sealed cores with no provision for access to the active core on location, or they may do refueling on site, but likely infrequently. Typically, the entire reactor is delivered from factory to the site as a single unit and eventually removed as a single unit. Not providing for on-site access to the core would be considered a positive aspect for PR&PP and one which distinguishes micro reactors from other designs. The core lifetime for micro- reactors is usually very long (15 or 20 years) and is achieved by having low power density or low specific ratings in Watts per kg or Watts per m^3. Designs that utilize periodic refueling will likely do so at an infrequent rate which can be a benefit to proliferation resistance.

A single-batch core has, of necessity, a higher initial fissile loading compared with a batch fueled system with the same lifetime energy output. Very roughly, the initial fissile loading is a factor 2 higher than a multi-batch system. Moreover, when a single-batch core reaches the end of its life, its residual fissile loading is much higher than the corresponding multi-batch core, comparable to the initial fissile loading of a multi-batch core. A higher fissile loading in isolation might be regarded as a negative PRPP characteristic and needs to be balanced against there being no on-site access to the fuel.

Second, a low power density core has a correspondingly low radiation field both during operation and after operations have ceased. Therefore, the self-protective radiation field associated with the operational core and the post-operational core are lower than they would be for more usual high rated systems. An order of magnitude estimate of the unshielded 1 meter dose rate for micro reactor irradiated fuel indicates a dose of 1 Sv/h per kg initial heavy metal of fissile material. At such a dose rate, the inherent protective field may be insufficient to completely eliminate the threat of theft/diversion, since unshielded handling operations could arguably be completed in less than the time needed for incapacitation. This might also be regarded as a negative PR&PP characteristic. A less intense irradiation field would simplify spent fuel handling and reprocessing operations in a state proliferator scenario. For a scenario involving theft by a non-state actor, the lower protective field would need to be balanced against the relative inaccessibility of the fuel.

Autonomous operation implies no permanent security personnel on the site, but this concept would need to be proven through adequate PP analysis. There are challenges with remote operations tied into the power grid. However, a disruption in remote monitoring may require a special physical inventory

inspection to maintain continuity of knowledge (CoK). Remote operations have also been proposed but may be difficult to carry out in practice due to cybersecurity requirements. Either would require a major reassessment of overall physical security measures.

In addition, theft of the entire microreactor needs to be considered. The same aspects of microreactors that make them desirable (fit in a shipping container, easily transportable, desired for remote locations) also makes their potential theft a concern. No security personnel on site further complicates this issue. Emplacement of the reactor will need to be performed in such a way to make theft extremely difficult. Examples include underground installation or robust barriers that require specialized equipment to remove.

The absence of a permanent operational and maintenance team at the site would also simplify safeguards, with there being much reduced human activity to monitor. However, special arrangements would need to be made to allow safeguards inspectors to make physical inspections or to install remote monitoring equipment, with potential operational cost implications.

3. **Fuel Cycle and Grid Compatibility**

The overall fit of the reactor system into the fuel cycle and power grid has an impact on PR&PP. The following sections describe the fuel cycle architecture, the life cycle of the reactor including construction and decommissioning, and reactor flexibility for non-power applications or flexible power outputs.

3.1 Fuel Cycle Architecture

A PR&PP evaluation of various nuclear fuel cycles is outside the scope of the PR&PP working group efforts. However, the following provides some distinctions between different advanced reactors and the impact the fuel cycle has on the reactor.

Three of the six GIF reactor technologies are strictly fast neutron reactors (SFR, GFR, and LFR); two others can be built either as fast or thermal reactors (MSR and SCWR); and only one is foreseen to operate only with thermal neutrons (VHTR). Three of the six GIF systems (SFR, GFR, and LFR) employ only a closed fuel cycle, as do the fast spectrum design variations of the SCWR. The thermal spectrum SCWRs and the VHTR designs employ a once-through open fuel cycle and share the fuel cycle characteristics of today's nuclear reactor systems: mining and milling, conversion, fuel enrichment, fuel fabrication, fresh fuel transport and on-site storage, spent fuel storage, transport, and disposal. The MSR is more flexible in its fuel cycle architecture. Depending on their design and mode of operation, MSRs can operate in fast or thermal spectrum and employ either open or closed fuel cycle, including integral reprocessing as part of the plant system.

Most solid fueled GIF systems are likely to rely on off-site fuel fabrication plants for fresh fuel supply. A fuel cycle phase common to all solid fueled closed fuel cycle systems is the separation phase. Transportation requirements will depend heavily on the fuel cycle technology configuration (co-located or centralized). Most of the solid fueled closed fuel cycle GIF systems will likely transfer spent fuel to small regional or large centralized reprocessing facilities. However, some system design variations may allow for on-site spent fuel reprocessing and fresh fuel fabrication (e.g., liquid metal cooled reactors with co-located pyrometallurgical or pyro-hydro reprocessing).

Thermal reactor options relying on once-through fuel cycles typically foresee UO_2 fresh fuel with fuel enrichment of up to 6% and an exit burnup of up to 65 GWd/tHM. It will require LEU fuel enrichment and fuel fabrication facilities for fuel supply.

Some systems also foresee a thermal thorium fuel cycle. Since thorium is fertile, not fissile, a fissile material is needed to start the process. This fissile isotope is typically ^{235}U, ^{233}U (which is bred from an earlier thorium cycle), or ^{239}Pu. The thorium fuel cycles are being considered for some MSR designs and the pressure-tube SCWR design with a heavy-water moderator and light water coolant. The thorium direct-self-recycle option of the SCWR is a near-term means of exploiting thorium, without investing in expensive recycle technologies. PR specificities of the thorium fuel cycle are described in the MSR and SCWR white papers.

All design options of the SCWR foresee relying on an off-site fuel fabrication plant and an off-site (regional or centralized) facility with full actinide recycle based on conventional reprocessing. One mixed spectrum and two fast spectrum SCWR design options include a breeder blanket.

Many designs of the three solid-fueled fast neutron reactors (GFR, LFR, and SFR) do not foresee the presence of blanket assemblies for plutonium breeding. Instead, plutonium production takes place in the core driver assemblies, where burnup is high and the proportion of plutonium isotopes other than ^{239}Pu remains high. However, the possibility to make use of blanket assemblies is not excluded.

Some SFR, LFR, and GFR variants typically rely on depleted uranium as the fuel matrix. For multi-batch concepts the fuel is typically removed as individual assemblies, while the long-lived concepts require full core removal. All discharged spent fuel requires on-site cooling/storage for a length of time before it is safe to transport to a reprocessing facility. For SFR pool concepts, the fuel assemblies are typically cooled in storage racks within the reactor vessel for ~1 year so they can be handled without active cooling. For SFR compact loop configuration, fuel storage space is not available inside the vessel, and the discharged fuel must be removed directly and stored at a nearby location. GFR spent fuel assemblies are discharged from the reactor building into a pool storage unit. Similarly, LFR spent fuel assemblies are placed in on-site interim storage for cooling inside an appropriate area in the fuel building for at least one year before introduction into transport casks for shipping to the reprocessing site or the co-located fuel cycle facilities.

In addition to the reference configurations, a wide variety of advanced fuel cycle options are being considered for future closed fuel cycle concepts, including:

- Alternate nitride and carbide fuel forms

- Alternate fuel fabrication processes

- Advanced dry and aqueous separations technology with either grouped transuranic or elemental recovery

- Modular co-located or monolithic centralized separations facilities

- Heterogeneous recycle schemes for handling of minor actinide fuels

The MSR fuel cycle is more flexible but less well developed than any of the other GIF-system fuel cycles. Fuel cycle features of the MSR can vary depending on design and may include:

- Full, on-site separations to remove fission products, noble metals, gases, and provide refueling.
- Limited separations of noble metals and gases only with periodic replacement of the molten salt.
- Use of once-through TRISO fuel pebbles with molten salt coolant.

The potential co-location of a closed back-end might bring potential PR and PP advantages and disadvantages:

- Co-location can certainly provide substantial advantages from the point of view of physical protection and in terms of safety due to the elimination of any transport-related safety and security concerns. From a safeguards point of view, the transport of nuclear material is not a major concern, though it might prove a bigger burden in terms of efficiency. Safeguards is always carried out in ad-hoc transport casks that are sealed upon shipment and "unsealed" upon receipt by safeguards inspectors. Any diversion would be readily and easily detected.
- In terms of sabotage, co-location foresees the presence of several sensitive processes potentially able to result in radiological releases on the same site. If nuclear reactors are extremely robust in terms of radiological containment in accident scenarios, e.g. reprocessing facilities historically proved to be less so; an external release onsite would pose not only an environmental problem but also the (likely) forced shutdown of the co-located nuclear power units, resulting in an overall disruption that goes beyond the simple shutdown of the reprocessing facility. From a PP point of view, the higher sensitivity of the co-location option might be offset by the possibility of concentrating all the security efforts on one single site instead of having to distribute the effort over separate locations.
- From a PR point of view, the onsite processing and diversion technical possibilities are higher when more fuel cycle steps are co-located. While extrinsic measures (international safeguards) can offset them, it is also true that international safeguards experience usually suggests that complex facilities (especially when comprising bulk material) are equally difficult to verify and monitor than their separate equivalents.

3.2 Life Cycle

Looking at life cycle issues is important for PR&PP as it can be seen if certain phases of the plant life create more vulnerabilities for proliferation or physical protection. For example, there are significant differences in fresh fuel storage of direct-use materials prior to operation as compared to disposition and storage of spent fuel at end of facility life. From the IAEA perspective, the issues of safeguards and security must be examined over the entire life cycle of a nuclear power plant from the design phase to the decommissioning and decontamination phases [9]. Once a party to the Treaty of Non-Proliferation of Nuclear Weapons (NPT) has a Comprehensive Safeguards Agreement (CSA), it has the duty when deciding to construct a new nuclear power plant to notify the IAEA Safeguards Department [10]. The operator can also look to the safeguards authority for assistance with safeguards expertise, safeguards training, and arranging dialogue with other stakeholders [11].

Safeguards obligations [10] [11] under comprehensive safeguards agreements include, in addition to accounting reports (paragraphs 62–67), information on material before or at the starting point of safeguards (paragraph 34); nuclear material customarily used outside facilities (paragraph 49); exports and imports of nuclear material (paragraphs 92–95); requests for termination, exemption or de-exemption (paragraphs 35–38); and special reports, if needed (paragraphs 68 and 97), must also be reported. The State is also obliged to submit information regarding safeguards relevant features of facilities (paragraph 8) to the IAEA. It should be noted that the IAEA, as shown in Figure 1 below, sets six facility design stages that have set requirements for reporting and access by the IAEA.

Figure 1: Facility design stage [12].

The IAEA conducts comprehensive design information verifications (DIV) to affirm the declared status of a facility over its lifetime. When the IAEA verifies the conditions at a facility that is revising its status, it needs to have a technical basis for confirming that the facility has changed its declared status. There is little difficulty in verifying a change of status from "operating" to "closed-down" since that is mainly a matter of verifying that nuclear material has been removed from the facility. This is more of an inspection activity than a DIV. The IAEA has found that verifying a change in status from "closed-down" to "decommissioned" is more complicated. The distinction between a "closed-down" and "decommissioned" status is important because a decommissioned facility is subject to less stringent safeguards measures (actually no measures under traditional safeguards), so the Agency must be confident that the decommissioned facility cannot be restarted and misused (e.g., no inspections if decommissioned; complementary access possible in a state with the Additional Protocol in force). Hence, for PR&PP this can show whether there would be extrinsic measures for proliferation resistance in place during the end of life where fuels and technology may have a utility for misuse [13] [14].

It should be noted that INFCIRC/540 defines "Decommissioned" as meaning that residual structures and equipment essential for the facility's use have been removed or rendered inoperable. The IAEA has compiled lists of "essential equipment" for major facility types to aid inspectors in DIV inspections [15]. However, the definition in INFCIRC/540 does not state how much of the essential equipment must be removed or rendered inoperable in order to consider the facility as a whole to be decommissioned. A facility may be "mothballed" with many pieces of nuclear steam supply system equipment still in place. The IAEA desires to develop guidelines to identify the essential equipment that must be removed or rendered inoperable for major facility types in order to classify a facility as decommissioned for safeguards purposes. The IAEA wants to compile factors such as the time, cost, and practicability of re-

activating a facility as compared to building a new one elsewhere. Inspectors can use these guidelines when confirming that a facility is "rendered inoperable [16]."

Containment and surveillance are important aspects of PR&PP. The suite of advanced reactors in GIF will in some cases provide challenges in both the surveillance and containment measures and the verification tools. Furthermore, the types of spent fuel will pose challenges depending on how long the fuel is stored prior to shipment off-site. Conventional wet storage or dry storage in containers are safeguarded at present quite commonly with adequate containment, surveillance and verification measures (Cerenkov radiation viewers and/or NDA with gamma spectrum noting Cs-137 presence indicative of spent reactor fuel). However, spent fuel stored under heavy metals have challenges in that opaque liquids are impervious to viewing and spent molten salts and pebbles poise challenges due to their bulk versus item form. With respect to effective and efficient safeguards, the planning of spent fuel movements, storage, containers, and transport should be envisioned early in the design including recycling or direct disposal in a repository.

A further issue that is relevant is if the facility is damaged in some fashion. The Chernobyl Nuclear Power Plant #4 and the four Fukushima Daichi BWRs all were damaged in accidents such that nominal safeguards were not possible [17]. With respect to PR&PP, data and extrapolation of past information and analysis of the accident is needed to recover fuel information. The IAEA has worked over the past decades to be able to develop a holistic approach to safeguards implementation measures; to monitor the recovery of safeguards; to facilitate discussion of relevant issues; and to consider possible approaches to tackle longer-term safeguards challenges.

Once the reactor does reach end of life the safeguards and PR&PP considerations do not end. The monitoring of the removal of and verification of the nuclear material transported and that remaining on-site is a challenge. Hence, spent fuel monitoring continues until all nuclear material leaves the site. The possibility of renewed surreptitious nuclear fuel cycle activities such as operation of the reactor and use of it to irradiate fertile materials is a concern until the facility is seen to have no capability for operation or use in irradiation of nuclear material.

Therefore, a reactor designer, operator, and regulator will need to consider PR&PP into all stages of lifecycle planning. This step should be implemented at an early stage to find any gaps in PR&PP in a reactor design and operation allowing for changes in design, regulation, and operation prior to reaching a critical point in the reactor lifecycle.

3.3 Flexibility

Though current generation nuclear plants are in principle able to operate flexibly, within certain limitations, the majority of them are not required to do so. This is largely because historically grid systems have operated with a large proportion of fossil fueled plants and lower proportions of renewables. Variations in load caused by fluctuations in renewables output could historically be met by bringing fossil on or off load from and to standby. Notable exceptions are countries where PWR plants have operated in scheduled daily load-follow maneuvers, such as France, with nuclear plants shedding load overnight to meet reduced demand. The French experience has shown that nuclear plants can demonstrate a high degree of flexibility if required to do so.

Recent trends in the generating mix of grid systems have seen a large increase in renewables generation, combined with a reduction in fossil capacity. Many countries have expressed a requirement to decarbonize generation, which will put further pressure on grid systems to be able to respond to the intermittency of renewables. This will apply to nuclear, and it is very probable that countries which currently do not require nuclear to provide flexible response, or only require a minimum of flexible response, will in the future demand much increased flexibility from nuclear plants. This could include frequency response, scheduled load follow response or even a requirement for nuclear plants to reduce

load or to rapidly increase load if operating at reduced power. The GIF Economics Working Group has published a paper which reviews the changing market environment in which Gen IV nuclear systems have to operate [18].

In the same context, the role of nuclear plants in providing diverse outputs is also under consideration. Alternative applications include district heat supply, heat supply to industrial processes, including hydrogen production and, in some countries, desalination. Nuclear plants supplying electricity to the grid combined with an alternative service such as hydrogen production would be able to offer flexibility by switching from electricity to the alternative and vice versa as demand requires. This model might work effectively for hydrogen production as a means of energy storage. The Electric Power Research Institute (EPRI) [19] has broadened the definition of flexibility for Generation IV reactors as any mode of plant operation in which electric power output is varied, either manually or remotely, in response to regional electrical grid demands.

International pressure to meet ever more demanding climate change and sustainability targets has increased considerably recently. For example, the UK has declared its intention to be carbon neutral by 2050 and has recently announced an accelerated target 78% decarbonization by 2035 [20]. Achieving such a target will demand major changes in energy for transport, domestic heating and industry and not just electricity supply. Generation IV systems will need to demonstrate themselves responsive to these changing demands.

New Grid Services

An additional role for nuclear plants in future grids would be the provision of inertia as a service. The gradual phase-out of fossil plants with synchronized generators will cause a reduction in inertia to cover loss of a plant for the few seconds that it takes for fast acting sources (such as pumped hydro) to activate. In a fully decarbonized grid, it is conceivable that only the nuclear component would provide any inertia and this could become a new key role for nuclear plants.

A difficulty in current electricity markets is the lack of any provision by means of which nuclear plants could be paid for providing flexibility and inertia, recognizing both these aspects as services. Since the avoidable costs of a nuclear plant are relatively small and the initial investment costs very high, nuclear plants need to maximize output in order to offset the fixed investment cost. There will need to be recognition in the market system of flexibility and inertia as products with corresponding funding mechanisms to support them.

Some innovative nuclear systems propose to store thermal energy using molten salts at times of low demand and use the stored heat to boost electricity output when there is high demand. This approach would allow nuclear plants to operate as energy storage systems as well as primary power sources.

PR&PP Implications

Against this background, flexible operation of nuclear power plants does generally not give rise to any major issues with respect to inherent PRPP. Flexible operation may have some minor implications for safeguards:

- A complex power history from flexible operations will complicate independent safeguards verification assessments. In particular, part load operation with control rod insertion will affect fuel inventories and may demand 3D inventory calculations.

- Independent safeguards verification could also be made more complicated by product flexibility.

However, one area where flexible operations may have an impact is that of siting close to cities. The vulnerability of nuclear systems to internal and external threats is assessed under the Physical Protection aspect of PRPP. Current nuclear power plants are normally situated remote from centers of high population density. This is a strong mitigating factor in scenarios involving loss of containment of radionuclides and dispersal into the environment. Where off-site evacuation plans are a requirement of a design, having a low population density in the area affected helps make such plans more manageable. Situating nuclear plants closer to high population areas can be beneficial if, for example, the intention is to supply district heating alongside electricity, avoiding unfeasibly long transmission distances for heat. But high population densities inside external evacuation zones would generate a strong incentive in favor of plant designs that do not demand off-site evacuation. It remains to be demonstrated whether public perception would allow siting nuclear plants close to cities.

Although the impact on PRPP from increased flexibility might be a minor issue for individual plants, there is potential for Generation IV systems to make a much increased contribution in net-zero carbon economies, perhaps with overall nuclear capacity many times larger than the current world fleet. A large expansion in capacity, combined with the deployment of smaller plants needed to meet for increased flexibility, would make much more demand on international safeguards. In turn, this would probably impact on PRPP assessments and introduce new challenges.

Fuel Flexibility

An additional aspect that should be included here is that of fuel flexibility. Gen IV nuclear plants can potentially burn uranium, plutonium or minor actinide fuels, with potential implications for inherent PRPP. A switch from uranium to plutonium or minor actinide fuels poses a different PRPP threat profile, particularly with new fuel manufacture, transport and on-site storage. The plutonium, ^{233}U, or TRU fuels can be seen as direct use materials easier to use in a weapons program. Hence, more scrutiny on the front end of the fuel cycle with such fuels is needed with respect to intrinsic versus extrinsic proliferation resistance qualities of such reactors with need for more stringent safeguards including developments in safeguards technology. There is less of a distinction in intrinsic and extrinsic qualities of proliferation resistance once fuel is irradiated and the self-protective effective of an irradiation field provides intrinsic barriers to ease of recycling and separation. IAEA Safeguards notably has recognized this in safeguarding fresh MOX more stringently than fresh LEU fuel but spent MOX and spent LEU fuel in the same manner as both contain irradiated plutonium.

During manufacture, storage and transport, fuels containing plutonium and/or minor actinides potentially pose increased threat, possibly requiring increased PRPP measures. Fresh fuel containing plutonium or minor actinides will have high radiotoxic content that could potentially cause a high degree of radiological contamination following deliberate dispersal in air or water. Whereas uranic fuels do not demand shielding, plutonium and especially minor actinides fuels require protection from elevated gamma emissions. Another PP consideration is the potential modification to the security plan for the protection of fresh HALEU fuel envisioned for many SMR designs.

A nuclear system which can burn multiple fuel types would add to the safeguards burden with increased verification load (see Section 4.1). Safeguards inspectors would be required to independently verify different fuel types that have been declared.

4. Common Interfaces

There are a number of interfaces to other aspects of reactor design that are common across all systems. These include international safeguards, operational transparency, cybersecurity, safety, and economics. All these areas present design constraints which have PR&PP implications.

4.1 Safeguards Topics

The proliferation resistance goal of GIF [21] will be met also through both enhanced safeguards and enhanced safeguardability – as appropriate to meet the needs of enhanced reactor and fuel-cycle technologies being developed. The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) evaluation methodology has a proliferation resistance volume that looks at the intrinsic and extrinsic qualities of a nuclear energy system with safeguardability being a key quality of a system [22]. The IAEA has also looked at the balance of safeguards, security and safety in their cross-cutting SBD Working Group. The group shares within the Agency the best practices regarding making a design more safeguardable within the fuel cycle.

While accountancy and control of nuclear material, with reliance upon containment and surveillance to provide continuity of knowledge, will remain an important tool, the transition to being fully information driven will add emphasis on other tools to international safeguards. Safeguards approaches and applied technologies will advance to reflect new processes and materials coming under safeguards.

Many advances in safeguards, such as unattended and remote monitoring, are policy-driven or economics-driven concepts with technology-dependent applications. Some advances in safeguards technology will be driven by technology alone, such as the requirement to verify fresh fuel with significantly different radiation signatures in closed fuel-cycle systems (SFR, GFR, LFR, MSR) than inspection regimes have been accustomed to distinguishing between in the past. Similarly, safeguarding of thorium fuel cycles (SCWR, MSR) will require an ability to verify non-fissile thorium fresh fuel, and spent fuel bearing quite different uranium isotopes (^{233}U and ^{232}U) and associated decay chains. Finally, although bulk and quasi-bulk fuel management (MSR, pebble-bed VHTR) will require significant changes in reactor safeguards instrumentation and approach, in order to provide an adequate level of material accountancy, safeguards should be simpler overall due to the low fissile content of fuels to be controlled.

It is expected that the more significant area by far of improvement in Generation IV systems will be that of safeguardability – the degree to which a technology facilitates safeguards, thus affecting both efficiency and ultimately effectiveness of the safeguards approach [23]. In this respect, most advances will be made in the areas of plant layout and fuel cycle. It is expected that any Generation IV system will incorporate, through the principle of Safeguards by Design, the lessons of past generations of reactor technology safeguards, which focus in large part on the path of fuel movement and storage of fuel within the plant. At the current stage of GIF system development, such details of plant layout are more of an academic issue for some systems, but for others the details are sensitive depending on level of maturity of the design.

Likewise, many fuel-related advances in safeguardability are beyond the scope of current GIF system development as they pertain to international fuel supply arrangements, with the inherent benefit to the control and accountancy of global nuclear material flow that these afford. Closed fuel-cycle systems, for example, can involve separation and movement of fissile material that is mitigated, from a proliferation resistance standpoint, by controlling the location and trade of the sensitive fuel-cycle components.

Some fuel-related advances in safeguardability do lie within the scope of current GIF system development. Any characteristic of fuel that minimizes its handling during operation will tend to reduce

the effort needed to verify its accountancy. This can be fuel that is more robust, less prone to disassembly, and less likely to leak or entire core cassettes that are inserted and removed by the reactor supplier (e.g., the SSTAR-LFR variant). In general, small modular reactor technology presents a number of advantages with respect to PR&PP and is a subject of current interest within the IAEA and the non-proliferation community with a key IAEA collaborative project on deployment of transportable nuclear reactors (SMRs and micro reactors) looking at crosscutting issues of safety, security and safeguards [24].

On the other hand, fuel that is, by its very nature, handled with high frequency on a bulk or quasi-bulk (MSR, pebble-bed VHTR) may facilitate robust verification through the provision of large amounts of operational data – in a similar manner to fuel processing and reprocessing facilities. This requires a new approach that relies upon the automated processing of potentially large amounts of operational data, but one that offers a significant level of knowledge of core operation. Recent advances in data analytics and machine learning may increasingly play a role in safeguards.

Other fuel-related features of GIF systems that impact the implementation of safeguards are the separation of Pu and minor actinides together, non-aqueous reprocessing, low fissile core content (MSR) due to on-line fueling, and in the case of VHTR – the relatively novel nature of the fuel itself that does not lend itself easily to reprocessing. Finally, recycling fissile materials will decrease enrichment requirements and thereby reduce the number and/or size of the enrichment plants to be placed under safeguards.

These considerations embody the concept of Safeguards by Design (SBD) that has emerged as a guiding principle of effective and efficient safeguards within the IAEA and the nuclear non-proliferation community. Recent international dialogue on this concept [25] highlights the need for (SBD) procedures, specifications, and other guidance in the engineering community, as well as increased communication on SBD among all stakeholders (designers, regulators, IAEA, etc.). The IAEA started the publication of SBD guidance in 2009 with overarching high level guidance for facility design and operation to facilitate the implementation of IAEA Safeguards [26]. It moved to publish how to incorporate international safeguards in nuclear facility design and construction [9]**.** The IAEA has since published a series of facility specific SBD guidance documents for nuclear reactors [12], fuel fabrication [27], long term spent fuel management [28], uranium conversion [29], reprocessing [30] and enrichment [31]. The IAEA is working to build global partnerships [32] to foster an "SBD culture" that sees proliferation resistance as a natural and accepted component of nuclear design. To the extent that GIF system design incorporates the proliferation-resistance goal of GIF using the PRPP methodology as a primary tool, and that GIF itself encourages dialogue between the system technology designers and the non-proliferation community (represented by the PRPP Working Group), it is evident that the GIF development process is aligned with the concept of SBD.

4.2 Cyber Threat

Cybersecurity is an aspect that any new nuclear facility needs to consider as part of PR&PP. To some extent, cybersecurity has always been a part of digital systems and is considered for both security and international safeguards. Data authentication, for example, has long been an important aspect of international safeguards. Increased reliance on digital systems increases the need for considering cybersecurity early in new reactor design.

The IAEA has technical guides on cybersecurity which cover best practices for the design, management, and protection of digital assets. Malicious acts involving digital systems may include information gathering to inform a future attack, attacks disabling or compromising digital assets, or compromise of several systems combined with physical attacks [33]. Computer security of instrumentation and control systems in a nuclear facility is critical since these systems affect the safe operation of the plant [34]. These references provide information on key concepts, computer security measures, risk-informed

approaches, and considerations of computer security for the full system life cycle. For advanced reactors with minimal on-site staff the cybersecurity considerations to allow for the integration with physical security becomes more significant.

There are four aspects of cybersecurity that have significance with respect to continued advanced reactor development taking into account improvements in computer technology: cyber risk management, secure architectures, operational transparency, and supply chain assurance.

Cyber risk management focuses on prioritizing risks for treatment (i.e., modification, avoidance, transfer, sharing, or retaining/acceptance). While past large reactors may have had hundreds of safety critical digital assets, new advanced reactors may have thousands of critical digital assets. The necessary effort to meet all regulatory requirements may not be cost-effective where the only risk treatment option is modification (i.e. apply controls to lower the risk of compromise). Cyber risk management at an early stage helps to optimize risk treatment in a way to simplify compliance with regulatory requirements, thus being more cost effective (i.e., require implementation and maintenance of less controls) and may link to probabilistic risk assessment.

Secure architecture focuses on the development of instrumentation and control architecture that is robust, resilient, and reliable. Sensors, networks, and communications should be arranged within an architecture that is secure and attack resistive, especially against novel (previously unknown) attacks. The secure architecture should be validated through rigorous modeling and simulation and red-teaming exercises. Emulation is required to explore and test secure architectures. Hardware and software must be auditable and patchable.

Related to secure architectures is the concept of Operational Transparency, which is proposed as a potential proliferation resistance technique, particularly for the pebble bed and molten salt designs where real-time item accountancy is impossible. Operational Transparency allows for outside observers to have access to raw reactor data to form their own trends and will require secure methods of verifying and transporting this data to ensure recipients of its authenticity.

Finally, supply chain risk management includes tools and procedures to protect against malicious supply chain introduction, including tampered, counterfeit, fraudulent, or suspect items or technologies. Advanced reactor's reliance upon advanced materials, manufacturing techniques, modeling and simulation, as well as increased reliance on passive features, will result in the transfer of significant cybersecurity risks from operators to the vendors and their suppliers. Cybersecurity supply chain risk management affects standards for procurement of components and supplier validation. Commercial off the Shelf (COTS) digital devices and components will have vulnerabilities, which can be considered as COTS with undeclared content. A hazard analysis should identify failure modes of components, fault tree analysis, and hazards and operability analysis [35].

As briefly described above, cybersecurity has been a part of international safeguards as well. Data used for verification of declarations must be authenticated and validated. The use of tamper-indicating conduit and enclosures along with appropriate digital safeguards helps to ensure that data is not tampered with (altered, modified, fabricated, destroyed,) before it reaches the IAEA or inspector.

The cyber threat must be considered for all advanced reactor designs and needs to be worked into the protection of digital systems. Physical protection analysis, including attack scenarios, need to include cyber-physical attacks in which compromise (i.e, sabotage) of digital systems may make it more difficult for the plant to respond. The various reactor designs need to protect critical systems from a cyber-attack and be aware of sabotage scenarios that may be unique to a certain reactor class. The cyber threat must also be considered from a proliferation resistance perspective and examine how a cyber-attack could help hide diversion or misuse of a facility.

4.3 Operational Transparency

In general, nuclear facilities are becoming increasingly automated. In particular, a number of advanced reactor designs involve process flows (e.g., molten salt reactors, pebble bed reactors, online refueling, fuel reprocessing), and some SMRs are being designed to be at least partly, and even remotely automated, to minimize the number of staff on site. A process flow refers to the movement, activity, or any process associated with the nuclear material in the fuel handling cycle at a specific facility [36]. Process flows are usually monitored by sensors, whether intrinsic or extrinsic. An "intrinsic sensor" is a sensor that transmits signals inherent to the system and generates what is considered to be plant process data. An "extrinsic sensor" is an added sensor that is not needed for plant operations and monitors material properties such as mass, temperature, et cetera, which may be needed for the accounting of nuclear material.

Automation of new nuclear facilities (as discussed previously) requiring minimal manual operation provides an opportunity to utilize the abundance of process information for monitoring the occurrence of diversion of nuclear materials. A framework that monitors process information continuously can lead to greater transparency of nuclear fuel cycle activities and can demonstrate the ability to operate safely and securely, with appropriate safeguards of nuclear material. A nuclear fuel cycle is transparent when the parties involved (facility operators and relevant regulatory bodies) in assessment of relevant safety, security, or proliferation parameters can determine for themselves that there are no issues in need of immediate attention. In principle, a comparison between expected signals and observed signals is the foundation for identifying such issues; such a comparison can be conducted in real time by setting up alarm triggers when significant trend differences between expectations and observations transpire. Expected signals from a proliferation point of view represent the status of the facility when an activity is completed as declared; any discrepancy between expected and observed signals represents a possibility of diversion of nuclear materials and suggests that immediate attention is required [37].

It should be pointed out that a framework for operational transparency of a nuclear facility can provide a means for monitoring plant operations data that would help to inform and optimize safety, security and international safeguards aspects of the facility. A framework that monitors process information continuously can lead to greater transparency of nuclear fuel cycle activities and can demonstrate the ability to operate safely and securely. Such a framework of operational transparency "involves the cooperative sharing of relevant nuclear material, process and facility information among all authorized parties to ensure the safe and legitimate use of nuclear material and technology." [37] In this discussion, focus will be paid on how operational transparency can be used for implementation of nuclear material accounting, in support of satisfying security and international safeguards requirements for nuclear facilities.

There are five fundamental principles to follow in implementing an advanced operational transparency framework, in order to ensure that the framework provides quantitative results in real-time in a manner that utilizes measured plant process data and plant design information in comparison with declared plant process data: [38]

    a) All processes should be automated. There should be limited hands-on operation with limited access to the system. Where manual hands-on operation is required, extrinsic sensors should be in place to verify/monitor the operation.

    b) All signals should pass through a single central processing unit for all plant operations. This ensures that all generated facility data is available for analysis at a centralized location.

    c) System components and sensors should be highly reliable, fail-safe, and tamper resistant. Technology should be in place to provide secured plant process data.

d) The framework should provide secure, encrypted information systems to distribute the data without providing data to potential adversaries.

e) The framework should provide analysis tools to digest the data provided into a uniform standard. These tools will sort, optimize, and analyze large amounts of data in comparison with expected/declared baseline data, in a consistent form that can be reported in real-time to involved parties.

In the above principles, there is a common theme of ensuring the security of process information while the information is being processed and made available to involved parties. To the extent that information security can be ensured, trust between parties and openness in sharing information between the parties can be encouraged. To this end, the authentication and reliable transmission of data is of great importance: as such, robust cyber-security is required. Interaction of the hundreds of data flows from a nuclear facility is a complex relationship providing opportunity for trending software to look for particular anomalies, and trends of anomalies that will highlight the presence of data tampering, by using the properties of the processes to verify streams of data to one another. Another advanced technique of data authentication is to multiplex the raw signal data with a unique signature that corresponds specifically to the raw data source and can be manipulated in real time. The manipulation of the signature and corresponding timestamp ensure that the data originated from that specific source at that specific time and thus ensures that the data was not pre-recorded or spoofed by another source [38].

An attractive potential medium for the handling and analysis of plant process data is that of blockchain (or, distributed ledger) technology [39]. The attractiveness of blockchain technology to nuclear safeguard information management arises from its contributions to trust and decentralization. Transparency, data integrity, and immutability of blockchain data storage underpin the trust attribute. The integrity of data results from the requirement that transactions conform to a set of predefined rules and be authorized as according to a consensus protocol, as well as the practical immutability of blockchain. Blockchain decentralization refers to the way in which blockchain systems give multiple participants a role in maintaining the state of the ledger. Decentralization relies on varying levels of transparency, data integrity, and immutability, and provides a means by which users can become involved in the provision of the network, underpinning the consensus protocol which enables the creation of a trusted environment. With decentralization, blockchain technologies provide opportunities to utilize smart contracts, which automatically execute and perform transactions, on the blockchain, based on pre-specified logic. Such automated transactions gain security from the underlying blockchain and its consensus protocol [40]. The overall effect of implementing a blockchain or distributed ledger would create an environment with a high degree of trust for the handling and analysis of plant process data, which is an important prerequisite to an effective operational transparency framework.

With the above attractive features of blockchain technology discussed, it should be pointed out that the adoption of such technology to safeguards operations is currently in its infancy. In 2017, two projects in parallel began to explore the implications of the IAEA safeguards system [41], one being a small-scale prototype providing a framework for future testing of blockchain technologies, and the other focusing on transit matching of safeguards data at the IAEA. Both of these projects have already recognized possible non-technical hurdles to the adoption of such technology, such as legal and political barriers, as well as the extent of deployment costs. The adoption of blockchain technology in related government and energy sectors has already recognized a number of challenges that need to be addressed in the adoption of blockchain technology in such sectors, including issues of scalability, interoperability/scalability, reliability, resilience to security threats, support infrastructure, and high development cost.

The above discussion leads into an important consideration, that the operational transparency framework should be designed in manner to encourage the cooperation of plant operations and relevant state authorities. The use of technologies for secure handling of plant process and design information, such as with blockchain technology, is a step in the right direction, in that it has the potential to encourage

trust between involved parties. Further, however, the overall operational transparency framework should also be designed to ease operational burden, such as minimizing the use of extrinsic sensors, as well as the cost and effort involved in analysis, reporting, and management of process data.

4.4 Safety Interface

Many Gen-IV systems and small modular reactors (SMRs) are designed with inherent safety and security features as well as accommodations for effective and efficient safeguards. This highlights the importance of considering interfaces of safety with proliferation resistance and physical protection at all stages of the life cycle of a nuclear plant. A challenge to integrate safety, security, and safeguards (3S) is to identify 3S interfaces to enable the optimization of synergistic effects and the minimization of potential conflicts early in the design cycle.

Consideration of PP around a reactor system is an integral part of evaluating the ability of the reactor to withstand the threats of theft and sabotage. The coupling between PR&PP and safety objectives for Gen-IV systems is evident. For example, passive systems and structures that eliminate requirements for external power sources and frequent operator surveillance may satisfy performance requirements for both safety and security, if designed for both functions. Likewise, it is important to account for nuclear materials and protect them against hazards and threats from both PR&PP and safety standpoints. Human factors considerations can implement performance programs that are synergistic for both safety and security. In emergency response management there are clear areas of potential conflict between safety and PP related to providing multiple pathways for access and egress.

For PP, the details of the national regulatory requirements and their implementation changed and became less accessible after September 11, 2001. For PR reliance is made on the international treaties, agreements, and protocols to assure that behavior is within expected international norms.

The PR&PP methodology evaluates plant performance by analyzing system responses to a postulated threat space imposed on the system. On the other hand, traditionally design basis threats (DBTs) developed by the regulator are used to assess the capability of the physical protection program, including physical barriers, system design feature, and response force to detect, assess, interdict, and neutralize threats of theft and radiological sabotage. The threats are directed against target sets, defined as a minimum combination of equipment or operator actions which, if all are prevented from performing their intended safety function or prevented from being accomplished, would likely result in significant plant damage or spent fuel sabotage barring extraordinary actions by plant operators. The Nuclear Energy Institute (NEI) proposed in a white paper [42] a consequence-based physical security framework and suggested its application to demonstrate that engineered safety features could provide a level of protection exceeding the capabilities of the design basis threat.

An approach to enhance the efficiency of PP requirements could be to demonstrate incorporation of security into designs to reduce reliance on human actions. For example, the NEI proposed in a white paper [43] three performance-based criteria for determining the applicability of alternative security requirements for a specific design or facility. The NEI evaluation approach is similar to the PR&PP methodology, relying on system elements and target identification.

Some of the same features that are being included in the design of advanced reactors as safety improvements may also improve their protection against physical protection/security threats. Design features may include several passive physical barriers and simplicity in systems required for safe shutdown. These may include such features as reactor pressure vessels and containment vessels located underwater or below grade, the reactor building located partially or completely below grade, and fewer safe shutdown systems and components requiring physical protection. The below-grade installation of some advanced reactors may provide additional security benefits, such as minimizing aircraft impact, limiting access to vital areas and the communication ability of adversaries. These

features may provide a means of enhancing security system effectiveness against radiological sabotage. Use of the traditional multilayered defensive approach of deterrence, detection, assessment, delay, and interdiction can potentially be used effectively for physical protection of Gen-IV systems.

Within GIF, the Risk and Safety Working Group (RSWG) addresses the safety of future nuclear energy systems. The GIF approach recognizes the need for integrated consideration of safety, reliability, proliferation resistance and physical protection approaches in order to optimize their effects and minimize potential conflicts between approaches. The assessments must consider the behavior of the nuclear energy systems under abnormal conditions, caused by a spectrum of challenges. Accordingly, the PR&PP and safety evaluation methodologies share a common framework/paradigm. The following paradigm underlies the PR&PP evaluation approach:

THREATS → SYSTEM RESPONSE → OUTCOMES

The safety and reliability assessment paradigm can be defined in a similar way:

ACCIDENT SYSTEM INITIATORS → RESPONSE → CONSEQUENCES

In each case, system response is determined by system design features and operational procedures, as well as protective measures. Moreover, the sabotage category of PP threats may involve the intentional triggering of accident initiators. Consequences of hypothesized accidents, although potentially severe, can be estimated through physical analysis. Outcomes of PR&PP hypothesized events can also be estimated through physical analysis. Finally, the two types of assessments require similar system information to be collected and analyzed at various stages of facility development, design, and operation. Parallel evaluations in these areas complement each other and can share information, and their results and implications for system design, operation, and protection are interrelated.

There are significant distinctions between safety and PR&PP evaluations which must be recognized and accommodated. The focus of a safety assessment is on the health and safety of the public and workers during the normal course of operation of these systems and as a result of accidents. In contrast PR&PP focuses on the prevention and mitigation of deliberate malevolent events instigated by nation states (PR-related threats) that would possess these systems or by non-host-state entities (PP-related threats).

The likelihoods of accidents for future nuclear energy systems, and their associated uncertainties, can be estimated. The likelihoods of malevolent acts involve strategic actions by a proliferant State or a sub-national adversary, and predicting their frequency requires an understanding of motivation, objective, strategy, and capability of the malevolent parties, along with analytical tools such as game theory. In general PR&PP studies do not assume a frequency of malevolent acts, but instead consider the response of the system contingent upon a malevolent act occurring. Nations establish "design basis threat (DBT)" definitions to set PP requirements based on their assessments of the likelihood of different potential types of attack. DBT information is sensitive, but at the conceptual design stage the general categories of potential attacks can be defined, and the system optimized to be resistant against these different categories of threats. For PR it is difficult to assess the probability that a State would choose to proliferate, so PR analysis is performed contingent on the assumption that an attempt would be made.

Topics for further discussion relative to PR&PP and RSWG collaboration have been identified since a decade and include: an integrating framework that would embrace both RSWG and PR&PP methods and concepts; elements of the evaluation methodologies and how they can be mutually supportive and consistent; and an integrated pilot demonstration of the PRPPWG and RSWG techniques in the early stages of a GIF design concept [44]. In the meantime, the work has progressed on both the RSWG and

PR&PP areas and the exchange of information has continued between the groups with crossed attendance to the respective meetings. A joint meeting between the PRPPWG and the RSWG was held at the 25th PRPPWG annual meeting hosted by UC-Berkeley in December 2015.

The RSWG has produced an "Integrated Safety Assessment Methodology" (ISAM) [45], for use throughout the Gen IV technology development cycle. The RSWG launched a joint effort with the SSCs on furthering the introduction of the ISAM to the GIF design concepts. Joint white papers have been prepared in the safety area for five of the six GIF technologies, and a reflection has been initiated on the safety of MSR technology.

In parallel an effort to develop safety design criteria and safety design guidelines has been initiated by a dedicated task force, later merged with the RSWG. Work started from SFR and is progressing also for other systems in collaboration with the system steering committees. While designing safety design criteria and guidelines, it is important that the impact on PR and PP is taken into account since the beginning and that the interfaces with safeguards and security are identified, with the possible synergies and conflicts.

The interface between Nuclear safety and Nuclear security is mentioned in several IAEA International Nuclear Safety Group (INSAG) publications, since more than a decade [46], [47]. INSAG and the Advisory Group on Nuclear Security are producing a new draft joint publication on the safety security interface. The interface between safety and safeguards seems less developed.

The growing interest worldwide on SMRs has triggered a number of initiatives by the IAEA. An important initiative on the Applicability of Safety Standards to Novel Advanced Reactors was initiated in 2020. Safety standards mainly developed for LWRs are systematically reviewed and modified for application to advanced reactors. Specific Safety Guides are being reviewed, i.e., for the following Nuclear Reactors areas: Reactor Core, Fuel Handling and Storage Systems, Reactor Coolant Systems, Containment, I&C and Electrical Systems, Support Systems. Safety guidelines for Nuclear fuel Cycle facilities are also reviewed. The review should provide the bases for identifying design elements impacting on safeguards and security and for identifying interfaces. Within the framework of that initiative IAEA is promoting a holistic approach on Safety-Security-Safeguards in design for novel advanced reactors. One of the objectives will be to produce a report on "Safety-Security-Safeguards considerations in design of novel advanced reactors", addressing gaps, challenges, potential interfaces and synergies.

Several GIF members are contributing to these IAEA initiatives. The matter has been discussed at the 2021 and 2022 GIF-IAEA Interface virtual meetings and was highlighted as a future collaboration area between GIF and IAEA [47].

4.5 Economics

There are strong grounds to argue that economic competitiveness will ultimately decide whether or not Generation IV nuclear systems will be deployed commercially. At the very least, Gen IV systems will need to be competitive compared with current Gen II/III systems. More importantly, Gen IV systems should also be economically competitive when comparing with the total system costs of renewable energy sources. The World needs to move towards net-zero carbon future and nuclear should be an important component towards low carbon generation. Nuclear, fossil generation with carbon capture and storage (CCS) and renewables would complement each other in low carbon generation, with renewables providing a large proportion of capacity and nuclear providing dispatchable output. Because nuclear and renewables provide different services to the electricity grid, it is not necessarily the case that Gen IV systems will need to match or undercut the costs of renewables and carbon capture systems, but Gen IV systems will need to fall within a range of costs that is not far above that threshold.

Levelized Cost of Electricity (LCOE)

The primary measure used by utilities to assess investment opportunities in electricity generation systems is the Levelized Cost of Electricity (LCOE). The LCOE is calculated by taking the ratio of the total discounted costs incurred in constructing, operating and decommissioning a plant and dividing by the discounted electricity output. The units of LCOE are $/MWh and the LCOE is the main metric that a utility would consider when deciding between different systems that it might invest in – it is an investment appraisal tool.

LCOE is very strongly affected by the discount rate that applies in a particular country. In countries with state investment in energy infrastructure, discount rates would typically be low and so the LCOE would reflect that. In countries with their energy infrastructure underwritten by private investment, discount rates can be higher, making the LCOE correspondingly higher. The LCOE of nuclear systems is very sensitive to the discount rate because of the long lead times for construction and indeed the interest accumulated during construction (IDC) can be the biggest single component of LCOE for nuclear plants.

Mainly because of the variations in discount rate, it is not possible to make a single breakdown of the LCOE for nuclear plants into its main components. All that can be meaningfully done is to make some broad generalizations without necessarily attaching fixed numbers to them. One such generalization is that the capital cost of nuclear plant (i.e. the cost of building and financing the plant) is always the dominant component of LCOE for a nuclear plant. In countries with private investment in energy infrastructure, the capital cost of a nuclear plant can contribute as much as 70% of the total LCOE. Another useful generalization is that the next highest contributors to LCOE are the Operating and Maintenance (O&M) cost and the fuel cost (including spent fuel management, waste management and disposal). These two contributors are usually comparable, though variations can be expected between countries and systems. Other costs, such as decommissioning costs usually make up less than 1% or the total LCOE.

While there are large variations from country to country, it is helpful to look at a specific example to understand the extent of the economic challenge facing Gen IV reactor systems: In the United States the overnight capital cost of conventional natural gas plants is currently (2021) around $1000 per kW, whereas advanced nuclear is estimated at around $5000 per kW. The levelized cost of electricity from new combined cycle natural gas plants is around $48/MWh of which only $1.5/MWh is from fixed operation and maintenance (O&M). The LCOE of advanced nuclear is projected at $90/MWh, and fixed O&M costs contribute $12.9/MWh to this total. Advanced nuclear reactors need to make progress on design improvements to reduce capital costs and O&M costs. Staffing requirements represent a major portion of the fixed O&M costs [48].

With regard to PRPP, the costs for a Gen IV nuclear power plant are difficult to quantify and are spread throughout the entire life cycle of the plant. The lifetime costs of physical protection and safeguards are substantial, representing tens or hundreds of millions of U.S. dollars. But that needs to be set against the lifetime investment and the lifetime revenue, which might both be measured in tens of billions of U.S. dollars, so that the contribution from PRPP costs to LCOE is very small. The economic impacts for a utility of the requirements of safeguards and physical protection are considered in the next two sub-sections:

Impact of Safeguards on LCOE

In respect of where in the life cycle of a Gen IV plant safeguards contribute to LCOE, here is a breakdown of the entire fuel cycle that identifies whether the costs of safeguards are incurred directly or indirectly by the utility:

1. The design and construction phase should consider PRPP and perhaps implement Safeguards by Design. There is the potential for design decisions made at this stage to generate additional

construction costs, but with the prospect of cost savings during the operational phase if safeguards and security requirements are simplified as a result. There is no direct contribution to LCOE for an operational plant, though it might be argued that cost incurred during the design are passed on to the customer as part of the capital cost, it is likely to be a minor component. It is very important for Gen IV plants employing novel technologies to incorporate PRPP at an early stage of the design, since retrospective modifications are costly, increasing so the later in the design they are implemented.

2. Complying with safeguards and security requirements is a through-life requirement for nuclear plants and is an operational activity. It is incurred by the utility through needing to comply with safeguards requirements. It falls under O&M and makes a direct contribution to LCOE.

3. The entire fuel supply chain is subject to safeguards and incurs costs for suppliers involved in it. The fuel supply route passes on any such costs through their commercial pricing practices to the utility. It is therefore an indirect cost to the utility. Again, given the value of fuel supply, the absolute impact on LCOE is small.

4. Spent fuel storage either on-site or offsite also requires safeguard measures. On-site storage might be in the spent fuel ponds or in the case of some Gen IV systems, in-reactor storage, or spent fuel might be transferred to dry storage casks. Either way, these aspects of safeguards contribute directly to operational costs at the reactor site. Offsite storage of spent fuel would incur an indirect cost to the utility included as part of the commercial service provided.

5. Spent fuel transport is subject to safeguards and the utility will see an indirect cost through the commercial pricing scheme with the specialist nuclear transport companies.

6. Spent fuel management and disposal is subject to safeguards and the utility will see an indirect cost through the commercial pricing scheme with the back-end providers.

For all these areas the costs of implementing safeguards are small when considered as a proportion of overall LCOE, but nevertheless significant in absolute terms, so that improvements in efficiency through inherent PRPP may still be very worthwhile. It is important to note that the international agencies responsible for safeguards (IAEA and Euratom) incur costs from implementing safeguards, from safeguards inspections, equipment installation, maintenance, surveillance and analysis, but that these costs do not figure in the LCOE. Rather these costs are funded from the budgets of the agencies. In a low carbon future with high nuclear deployment, there would be pressure for safeguards activities to be carried out as efficiently as they can be, to ensure that the international agencies can discharge their obligations within resource budgets.

Impact of Physical Protection on LCOE

Physical protection requirements are satisfied partly by incorporating physical security features and facilities in the design of the plant and partly through the deployment of security staff during the operational phase of the plant lifetime. The former contributes indirectly to LCOE as part of the capital investment component, while the latter represents a significant contribution to O&M.

Physical protection requirements can contribute significantly to the capital costs of a nuclear plant. For example, ensuring the plant is protected against missile or aircraft attack may require substantial structural design features to be incorporated into the buildings. Inherent features of the design of Gen IV systems, such as the ability to remove decay heat without active systems intervention, can reduce or eliminate the need for protective structures. Fuel forms that are robust to disruption and not easily dispersed would reduce the threat posed by an attacker seeking to cause radioactive contamination, with less need for protective structures.

During their operational and immediate post-closure phases, nuclear plants currently deploy security personnel to control access and respond to and deter security threats. This contributes to O&M costs,

but since modern large nuclear plants employ several hundred personnel in total, the relative cost is modest and manageable. The same would apply to Gen IV plants with high rated powers, or for small Gen IV plants deployed as multiple modules at a single site, but the situation will be different for small Gen IV plants deployed individually. Small plants will need to justify a proportional scaling down of security personnel requirements if they are not to suffer and LCOE penalty, with perhaps only 10 to 20 staff in total to run the plant. Autonomous micro reactors will operate with no personnel in attendance, and this will require an entirely new approach to ensuring the necessary standards of physical protection can be assured, with inputs from designers, international regulatory bodies, utilities and governments.

GIF Economic Modelling Working Group

The GIF Policy and Experts Groups promote interactions between the Economic Modeling Working Group (EMWG) and the PRPPWG as well as encouraging collaboration between the RSWG and the PRPPWG, and strongly encourage communication between the Methodology Working Groups (MWGs) and the SSCs. Some progress was made in this regard following the discussions carried out during the GIF Symposium held in September 2018 [49] and following meetings where representatives of MWGs and SSCs had opportunities to share information and experience. However, SSCs continue to place higher priority on R&D and tend to postpone horizontal work because they lack manpower and funding to support it.

Economic competitiveness is a prerequisite for Generation IV nuclear systems to be built and operated. GIF recognized upfront the importance of economic criteria and the EMWG was created in order to develop a methodology for assessing the economic performance of GIF designs. The methodology developed by the EMWG aims at providing a standardized cost estimating protocol offering decision makers a fair and credible basis to assess, comparing, and eventually selecting future nuclear energy systems, taking into account a robust evaluation of their economic viability.

The main outcomes of the EMWG are the Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, Rev. 4 [50], the G4ECONS Software Package with its User Manual [51], the Position Paper on Flexibility of Gen IV Systems [52], and the Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review [53]. The methodology and software have been tested on current nuclear generation systems and some advanced systems such as the Japanese Fast Sodium Reactor. However, owing to the preliminary status of GIF system designs, it has proven impossible so far to undertake an economic evaluation of any of the concepts under consideration by the various SSCs. Furthermore, applications of the EMWG methodology and running of the software package are data intensive and require a significant effort from SSC members for collecting and checking the consistency of input data and analyzing the results.

Collaboration between the EMWG and the PRPPWG could lead to a better understanding of costs and benefits of alternative design options which, in turn, could provide robust guidance to research teams aiming at optimizing their respective concepts. At the detailed level, the Code of Account of the EMWG methodology and software package includes cost items associated with proliferation resistance measures, safeguards control, and physical protection against theft and sabotage.

5. Conclusions

Twelve crosscutting topics related to advanced nuclear reactors that have an influence on PR&PP were examined. The following summarizes key insights in each of the crosscutting areas:

Fuel Type: The effect of the fuel type of PR&PP varies depending on 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. Pebbles and molten salts may introduce bulk accountancy requirements. 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 potentially fertile blankets are more attractive than spent fuel as higher burnups are achieved.

Coolant/Moderator: Advanced reactors 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. 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 PP standpoint, the chemical reactivity of the coolant/moderator, retention of fission products, and ease of dispersal needs to be considered for proper protection of the plant.

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 would be difficult to hide but should be considered in breakout scenarios. Continuous refueling could provide more opportunities to remove low-burnup fuel, so more safeguards measures may be applied. Molten salt reactors are a unique case and have unique PR aspects particularly if on-line processing is utilized. Microreactors or other small reactor designs that have long-lived, sealed cores will have a proliferation resistance advantage due to limited movement of material as long as the reactors are not prematurely shutdown.

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 at that site. 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 type of reactor in remote locations, transportable or floating reactors, and the potential for autonomous or remote operations.

Fuel Cycle Architecture: The reactor designs presented in the 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. Co-location of reactors and fuel cycle facilities can provide both advantages and disadvantages from a PR&PP standpoint. Reduced transportation is an advantage, but more 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. These guidelines describe monitoring of spent fuel at all times material is present for initial receipt of material through storage until the reactor is decommissioned.

Flexibility: Future advanced reactors may see a wider variety in how they're used 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 which is probably the more significant impact of PR&PP. Siting near population centers (which would be desirable for heat production) raises additional PP challenges. Flexible fueling options for reactors could also increase safeguards burden if the type of fuel is changing at different times.

Safeguards Topics: Safeguards for advanced reactor designs maybe evolutionary (still based largely on fixed assemblies) or revolutionary (including the use of opaque heavy metal coolants, molten salt cores, pebble bed fuels and other radical departures from LWRs). The evolutionary designs can benefit from SBD activities based on present LWR safeguards, the present safeguards equipment including nondestructive assay for fresh, core and spent fuels and containment and surveillance, and the safeguards inspection planning and implementation historically used. However, revolutionary designs will need to examine issues such as possible accessibility of inspectors and instruments to fuels (e.g., nuclear material) with respect to radiation barriers, visibility, and time spans for core accessibility (longer operating cores without refueling), the type of fuels and techniques for verification of nuclear materials in the fuels including accounting for fuel structures and elemental and isotopic compositions, and especially spent fuel forms and storage and disposal plans. Hence, PR&PP studies on selected designs of the six GIF technologies should provide input for SBD and safeguards efforts by the designers and IAEA safeguards.

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 that must be considered for managing the cyber threat. 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 in which data must be authenticated. Finally, the supply chain must be assured to prevent introduction of malicious hardware or software. The cyber-physical interface will be of increasing importance in the future threat space.

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 behaviour of relevant signals to measured signals, wherein measured deviations may signal diversion of nuclear material, for example, 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, in an environment that ensures trust between the involved parties, while at the same time minimizing operational burden, as well as the cost and effort involved in analysis, reporting, and management of process data.

Safety Interface: Advanced reactors present new opportunities for the integration of safeguards, security, and safety. IAEA has recognized this need through the establishment of a 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 Reactor Safety Working Group follows many similar principles to the PR&PP working group, and as such presents opportunities for more collaboration in the future.

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 of the goals of safeguards by design is to consider safeguards and PR features early in the design process to avoid costly retrofits. 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 need to be considered. The GIF Economic Modelling Working Group examines these issues and presents opportunities for continued collaboration with the PR&PP working group.

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Appendix: Reference systems, white papers template & proliferation resistance features

The Appendix provides additional information about the reference systems, the template utilized for the harmonised and organization of the white papers, and the listing of the proliferation resistance intrinsic design features derived from the IAEA-STR-332 report [3] and applied in the use of the white papers [54-56].

Table 1 highlight the six GIF reactor technologies and the main system design options discussed in the updated white papers, together with a mention of the analysis performed.

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

The updated white papers were also made more consistent with one another through a common template. Table 2 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 (Overview of Technology) and 2 (Overview of the fuel cycle) which provided the base information on the reference systems. The PRPPWG and SSC/pSSC worked collaboratively to update sections 3 (PR&PP Relevant System Elements and Potential Adversary Targets), 4 (Proliferation Resistance Features), 5 (Physical Protection Features) and 6 (PR&PP Issues, Concerns and Benefits).

Each white paper includes an appendix on PR relevant intrinsic design features based on the IAEA STR-332 [3] and are reported in the Table 3 and organized in the main blocks that:

- Features reducing the attractiveness of the technology for nuclear weapons programmes;

- 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 1: 2021-2022 GIF PRPPWG White Papers on GFR, LFR, MSR, SCWR, SFR, and VHTR 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) and 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

	Solid Fueled with Salt Coolant	Mk1 PB-FHR (US)	reactors, solid/fluid fuel, burner/breeder modes, Th/Pu fuel cycles, and onsite/offsite fissile separation.
	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 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)	

Table 2: High level structure of the updated PR&PP 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 (Fuel Form, Main Fertile Material, Fissile Material, Weight of Assembly, Dimensions of Fuel Assembly, Fuel Enrichment, Source of Fissile Material, Fuel Inventory, Presence and Type of Fertile Blanket, Presence and Type of Transmutation Targets, No. of Assemblies to make 1 Significant Quantity (SQ), Irradiation scheme, Composition and burnup of spent fuel elements, Composition of fresh fuel elements, Fuel storage and intra-site, transport methods, Safety approach and vital equipment, Physical arrangement - layout, segregation, etc. -)
2. Overview of Fuel Cycle(s)	High level description of the type, or types, of fuel cycles that are unique to this Gen IV 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 PP threats (theft of material for nuclear explosives 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 future 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

Table 3. Summary of PR relevant intrinsic design features presented in the PR&PP white papers. Please refer to IAEA-STR-332, for full explanations and complete definitions of terms and concepts [3].

Summary of PR relevant Intrinsic design features
Features reducing the attractiveness of the technology for nuclear weapons programmes
1. The Reactor Technology needs an enrichment Fuel Cycle phase
2. The Reactor Technology produces SF with low % of fissile plutonium
3. Fissile material recycling performed without full separation from fission products
Features preventing or inhibiting diversion of nuclear material
4. Fuel assemblies are large & difficult to dismantle
5. Fissile material in fuel is difficult to extract
6. Fuel cycle facilities have few points of access to nuclear material, especially in separated form
7. Fuel cycle facilities can only be operated to process declared feed materials in declared quantities
Features preventing or inhibiting undeclared production of direct-use material
8. No locations in or near the core of a reactor where undeclared target materials could be irradiated
9. The core prevents operation of the reactor with undeclared target materials (e.g. small reactivity margins)
10. Facilities are difficult to modify for undeclared production of nuclear material
11. The core is not accessible during reactor operation
12. Uranium enrichment plants (if needed) cannot be used to produce HEU
Features facilitating verification, including continuity of knowledge
13. The system allows for unambiguous Design Information Verification (DIV) throughout life cycle
14. The inventory and flow of nuclear material can be specified and accounted for in the clearest possible manner
15. Nuclear materials remain accessible for verification the greatest practical extent
16. The system makes the use of operation and safety/related sensors and measurement systems for verification possible, taking in to account the need for data authentication
17. The system provides for the installation of measurement instruments, surveillance equipment and supporting infrastructure likely to be needed for verification

THE GENERATION IV INTERNATIONAL FORUM

Established in 2001, the Generation IV International Forum (GIF) was created as a co-operative international endeavor seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems, and to make them available for industrial deployment by 2030. The GIF brings together 13 countries (Argentina, Australia, Brazil, Canada, China, France, Japan, Korea, Russia, South Africa, Switzerland, the United Kingdom and the United States), as well as Euratom – representing the 27 European Union members and the United Kingdom – to co-ordinate research and develop these systems. The GIF has selected six reactor technologies for further research and development: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very-high-temperature reactor (VHTR).

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