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GEN IV International Forum
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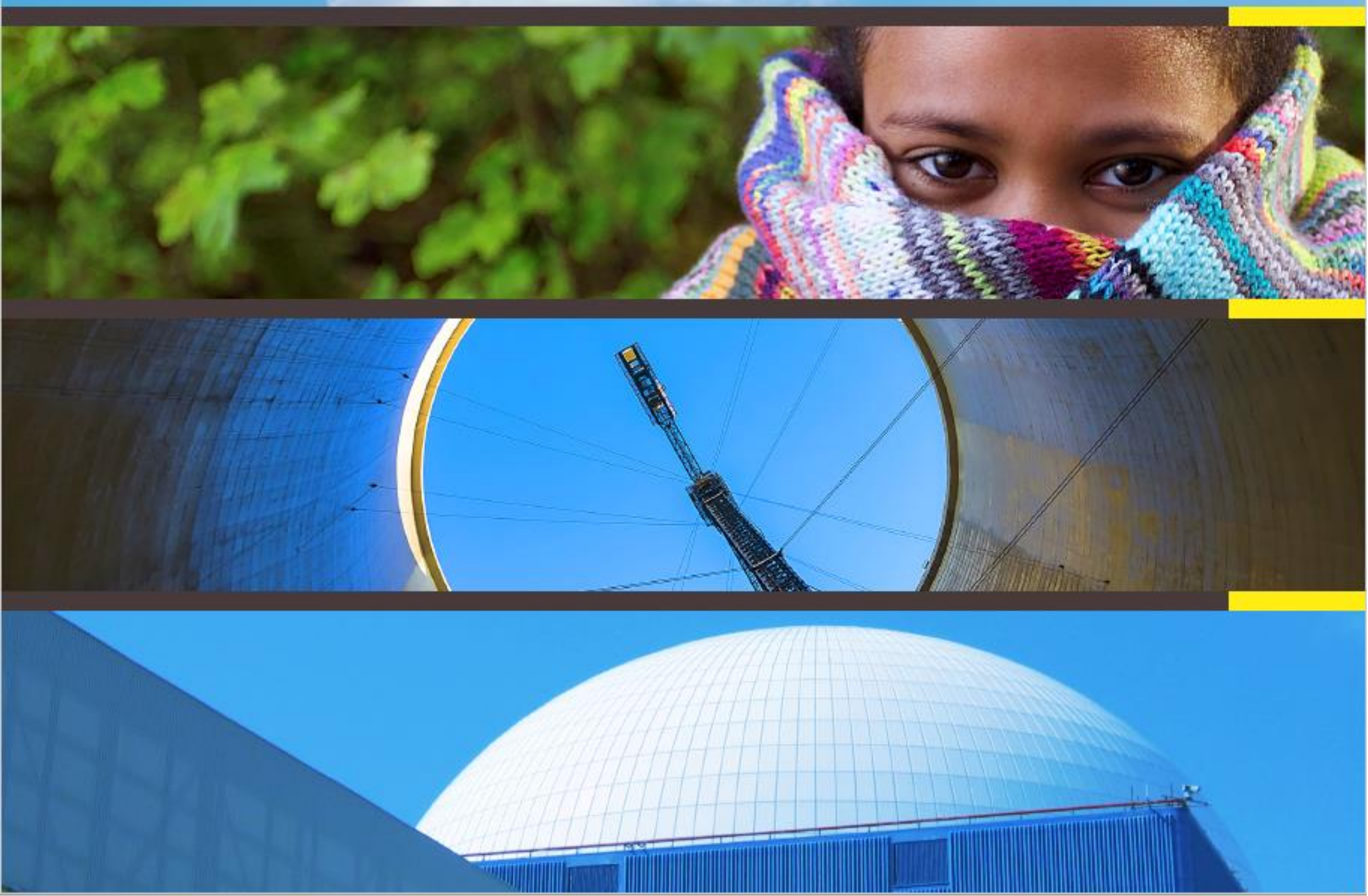
GIF SODIUM-COOLED FAST REACTOR

Proliferation Resistance and Physical Protection White Paper

October 2021



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

This report is part of 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 the status of Proliferation Resistance & Physical Protection (PR&PP) characteristics for each of the six systems selected by the Generation IV International Forum (GIF) for further research and development, namely: the Sodium-cooled fast Reactor (SFR), the Very high temperature reactor (VHTR), the gas-cooled fast reactor (GFR), the Molten salt reactor (MSR) and the Supercritical water–cooled reactor (SCWR).

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. Cross-cutting PR&PP aspects that transcend all six GIF systems are also being updated and will be published as a companion report to the six white papers.

Abstract

This white paper represents the status of Proliferation Resistance and Physical Protection (PR&PP) characteristics for the Sodium-cooled Fast Reactor (SFR) reference designs selected by the Generation IV International Forum (GIF) SFR System Steering Committee (SSC). The intent is to generate preliminary information about the PR&PP features of the SFR reactor technology and to provide insights for optimizing their PR&PP performance for the benefit of SFR system designers. It updates the SFR analysis published in the 2011 report "Proliferation Resistance and Physical Protection of the Six Generation IV Nuclear Energy Systems", prepared Jointly by the Proliferation Resistance and Physical Protection Working Group (PRPPWG) and the System Steering Committees and provisional System Steering Committees of the Generation IV International Forum, taking into account the evolution of both the systems, the GIF R&D activities, and an increased understanding of the PR&PP features.

The white paper, prepared jointly by the GIF PRPPWG and the GIF SFR SSC, follows the high-level paradigm of the GIF PR&PP Evaluation Methodology to investigate the PR&PP features of the GIF SFR reference designs. For PR, the document analyses and discusses the proliferation resistance aspects in terms of robustness against State-based threats associated with diversion of materials, misuse of facilities, breakout scenarios, and production in clandestine facilities. Similarly, for PP, the document discusses the robustness against theft of material and sabotage by non-State actors. The document follows a common template adopted by all the white papers in the updated series.

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List of Acronyms

ACS	Above Core Structure
AHX	Air Heat Exchanger
AFR	Advanced Fast Reactor
BOP	Balance of Plant
C/S	Containment & Surveillance
DBE	Design Basis Event
DHR	Decay Heat Removal
DHX	Decay Heat Exchanger
DRC	Direct Reactor Cooling
EFR	European Fast Reactor
ESFR	European Sodium Fast Reactor or Example Sodium Fast Reactor
GIF	Generation-IV International Forum
IAEA	International Atomic Energy Agency
IHX	Intermediate Heat Exchanger
ISI&R	In-Service Inspection & Repair
IVS	In Vessel Storage
JAEA	Japan Atomic Energy Agency
JSFR	JAEA Sodium Fast Reactor
KALIMER	Korea Advanced Liquid Metal Reactor
LWR	Light Water Reactor
MA	Minor Actinides
MC	Mixed Carbide
MOX	Mixed Oxide
MSP	Mechanical Secondary Pump
MUPN	Mixed Uranium Plutonium Nitride
PRISM	Power Reactor Innovative Small Module
PP	Physical Protection
PR	Proliferation Resistance
PR&PP	Proliferation Resistance & Physical Protection
SDV	Sodium Dump Vessel
SFR	Sodium Fast Reactor
SG	Steam Generator
SMFR	Small Modular Fast Reactor
SSC	System Steering Committee
TRU	Transuranics

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1 Overview of Technology

A basic description of the Sodium-Cooled Fast Reactor (SFR) system is given in the Annex of the GIF SFR Systems Arrangement [1], and the five current design "tracks" are described in the GIF SFR System Research Plan [2]. This section will provide an overview of key SFR technology features. The fuel cycle options will be identified in Section 2.

The SFR system was identified during the Generation IV Technology Roadmap [3] as a promising technology to perform the actinide management mission and, if enhanced economics for the system could be realized, also providing electricity and heat production. The main characteristics of the SFR that make it especially suitable for the actinide management mission are:

- Consumption of transuranics in a closed fuel cycle, thus reducing the radiotoxicity and heat load which facilitates waste disposal and geologic isolation;
- Enhanced utilization of uranium resources through efficient management of fissile materials and multi-recycle;
- High level of safety achieved through inherent and passive means that accommodate transients and bounding events with significant safety margins.

The SFR system uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume fraction. While the oxygen-free environment prevents corrosion, sodium reacts chemically with air and water and requires a sealed coolant system which makes in-service inspection and repair (ISI&R) more difficult. The primary system operates at near-atmospheric pressure with typical outlet temperatures of 500-550°C; at these conditions, austenitic and ferritic steel structural materials can be utilized, and a large margin to coolant boiling is maintained. The reactor unit can be arranged in a pool layout, a compact loop layout, or a hybrid of these two arrangements. Plant sizes ranging from small modular systems to large monolithic reactors are being considered. A wide variety of fuels and fuel cycles are being considered, as described in Section 2.

There are many predecessor sodium-cooled fast reactor conceptual designs that have been developed worldwide in national advanced reactor development programs. In particular, the operating BN-600 and BN-800 Reactors in Russia [4], the European Fast Reactor in the EU [5], [6], [7], the Advanced Liquid Metal Reactor (PRISM) and Integral Fast Reactor Programs in USA [8], [9], and the Demonstration Fast Breeder Reactor in Japan [7], [10], [11] have been the basis for many SFR design studies. For the Generation-IV International Forum collaboration, several new design concepts have been contributed by the participants to guide the R&D research activities. These designs cover a wide range of reactor size and configuration options [12]. Within the following subsections, the five GIF contributed reactor "tracks" are briefly illustrated and described [13].

1.1 Compact Loop Configuration SFR

To promote favorable economies of scale, many SFR designs have targeted large monolithic plant designs. For this approach, a prominent recent concept is the JAEA Sodium Fast Reactor (JSFR) [14], [15], [16], [17], [18] which is a sodium-cooled, MOX (or metal) fueled, advanced loop-type evolved from Japanese fast reactor technologies; the conceptual plant layout is shown in Figure 1.

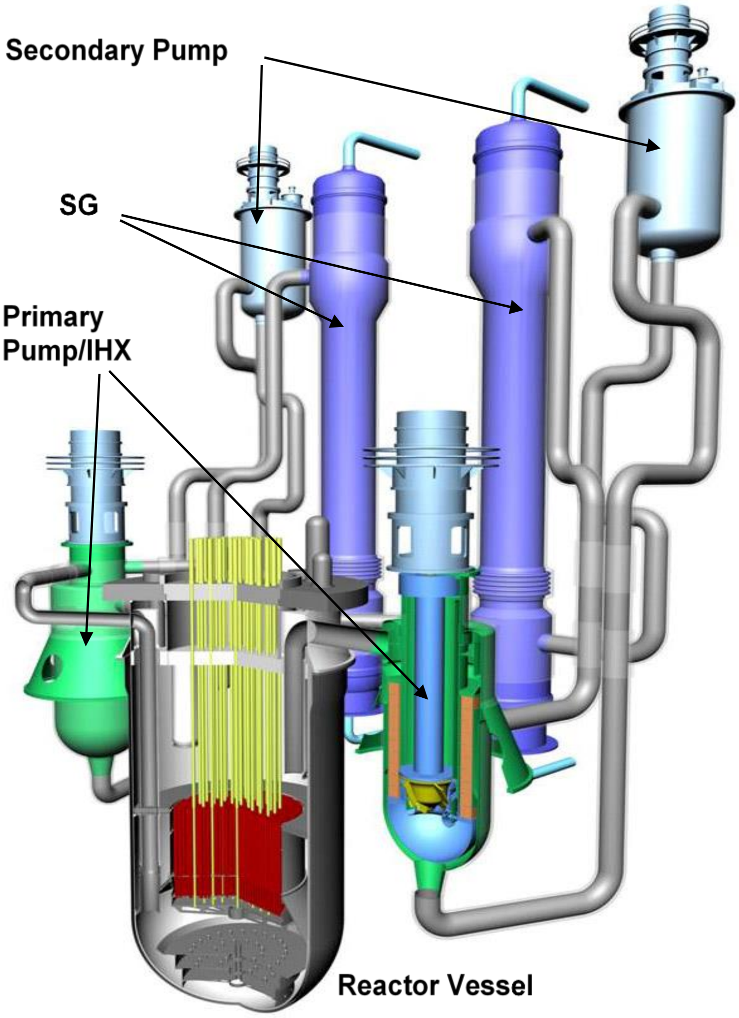


Figure 1: Conceptual Plant Layout of the JAEA Sodium Fast Reactor (JSFR) [12].

The JSFR design employs several advanced technologies to reduce the construction cost: compact design of reactor structure, shortened piping layout, reduction of the number of loops, integration of components, and simplification of decay heat removal system through enhancement of natural circulation capability. These measures include innovative technologies such as 12Cr-steel with high strength, an advanced structural design standard at elevated temperatures, three-dimensional seismic isolation, and re-criticality free core.

The JSFR design utilizes passive safety measures to increase its reliability. The improvement of ISI&R technology is concentrated to confirm the integrity of internal structures, including core support structure, and coolant boundaries. The means of access is taken into account in design.

The JSFR design studies consider plant sizes ranging from a modular system composed of medium size reactors to a large monolithic reactor. The large-scale sodium-cooled reactor utilizes the advantage of "economy of scale" by setting the electricity output to 1,500MWe. On the other hand, a medium-scale modular reactor would offer advantages of flexibility in power requirements from utility companies and the reduction of development risk compared with large-scale reactors.

1.2 Pool Configuration SFR

Three different pool configuration design tracks (KALIMER-600, ESFR[1], and BN-1200) have been

[1] The ESFR acronym is for the European Sodium Fast Reactor design track contributed by Euratom [22], [23]. This is different from the hypothetical Example Sodium Fast Reactor that was evaluated in PRPP studies from 2004-2008 [30], which utilized the same acronym.

contributed by the Generation-IV SFR Members. These concepts vary in size, key features (i.e., fuel type), and safety approach. Brief design descriptions are included for each concept in the following subsections.

1.2.1 KALIMER-600 Design Track

Moderate size pool configuration SFR designs have also been proposed; in this case, cost reduction relies on design simplification and factory fabrication techniques. A recent example is the KALIMER-600 [19], [20], [21], pool-type reactor design, shown in Figure 2, evolved from previous pool-type SFR designs such as PRISM [8], [9], SuperPhénix, and EFR [5], [6], [7]. A pool-type reactor provides many important design advantages in plant economy and safety. The entire Primary Heat Transport System (PHTS) piping and equipment is located inside the vessel completely eliminating the possibility of a PHTS piping break outside the reactor vessel. Also the large thermal inertia characteristics of a pool-type reactor enhance passive safety mechanisms. The safety of KALIMER is enhanced further by loading its core with metal fuel which has inherent safety characteristics resulting from large negative power reactivity coefficients.

For improvement of plant economy over previous designs, KALIMER reduces the commodities and/or entirely eliminates equipment through design simplification, compact configuration, and higher plant efficiency. Its net plant efficiency is designed to reach 39.3% with conventional steam plant. The introduction of the innovative passive decay heat removal circuit system could enable an increase in the size of the system to 1,000 MWe or more. KALIMER requires neither active component operation nor operator action in managing accidents, reducing reliance on safety grade emergency power sources. These safety design features provide very high reliability in safety management and can accommodate design basis events (DBE) and beyond design basis anticipated transients without scram (ATWS) events without any operator action or support of active shutdown system operation. The grace period during accidents can be measured in days without violating core protection limits.

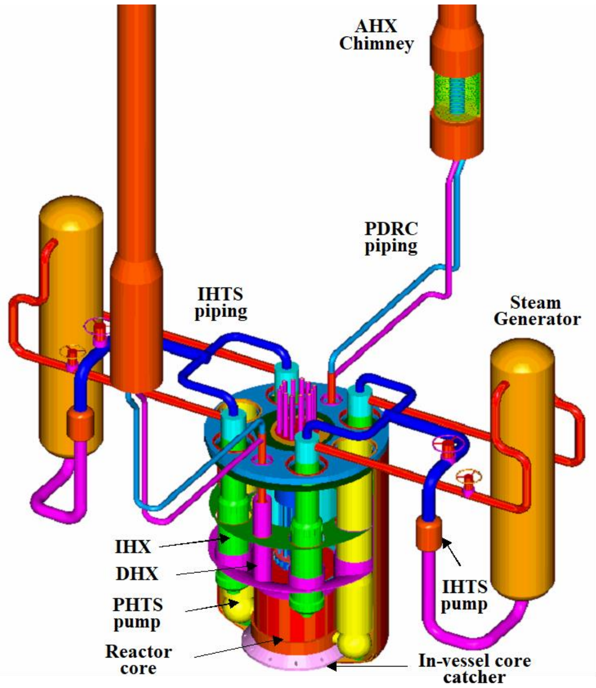


Figure 2: KALIMER-600 System Configuration [19].

1.2.2 European Sodium Fast Reactor (ESFR) Design Track

A large pool SFR is proposed for economy of scale and benefiting from generic characteristics of the pool concept including design simplification and compactness. ESFR is a large pool type industrial Sodium Fast Reactor of 1500 MWe which has been studied within the 7th Euratom Framework program of the European Commission [22]. The design objectives for ESFR include simplification of structures, improved In-Service Inspection and Repair capabilities, reduction of risks related to sodium fires and to the water/sodium reaction, improved fuel maintenance, with the capability for a whole core discharge and improved robustness against external hazards.

The ESFR core is composed of two enrichment zones of inner and outer fuel assemblies and 3 rows of reflectors. There are two independent control rod assembly systems. The core design proposes a fuel management scheme with a flexible breeding and minor actinide burning strategy.

The ESFR primary system is sketched in Figure 3. It is based on options already considered in previous and existing pool sodium fast reactors, with several potential improvements regarding safety, inspection and manufacturing. Particular attention is also given to compactness. The reactor vessel is cooled with sodium (submerged weir) and is surrounded by a hanged safety vessel. Some provisions have been made for internal and external core catchers. The reactor vault can be inspected for maintenance.

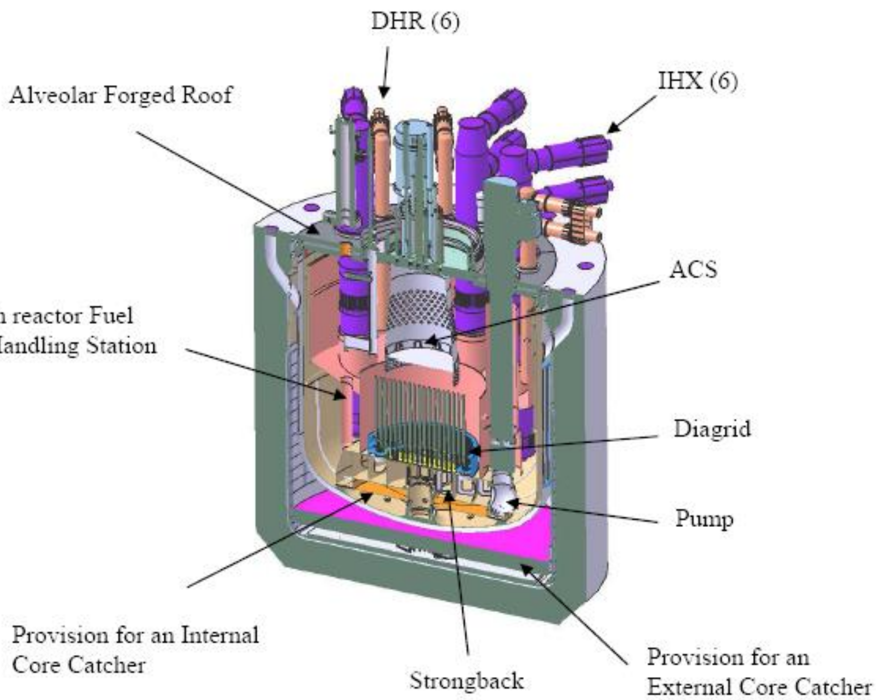


Figure 3: 3D View of ESFR Primary System [22].

Decay heat removal function is provided by the Direct Reactor Cooling (DRC) System which comprises six sodium loops positioned in and around the above core structure (ACS). All loops extract heat from the primary sodium of the hot pool by means of immersed sodium/sodium dip coolers (DHR) each removing 50% of total residual power, and reject the heat to the environment using sodium/air heat exchangers situated on the periphery of the reactor building roof within air stacks. In this concept, diversity (operational and structural) and redundancy of the 6 DRC loops is ensured by 3 natural convection and 3 forced convection loops (i.e. with pumps in sodium and air to increase efficiency of the exchangers and with different component designs).

The ESFR secondary system comprises six 600 MWth parallel and independent sodium loops, each connected to an Intermediate Heat Exchanger (IHX) located in the reactor vessel. Each loop includes one Mechanical Secondary Pump (MSP), six modular Steam Generators (SG) and one Sodium Dump Vessel (SDV). Each secondary loop hosts 6 modular Steam Generators of 100 MWth each made out of modified 9Cr1Mo (ASME grade 91). Compared to a 600 MWth single Steam Generator layout, modularity is aimed at reducing the impact on the IHX of a Sodium/Water reaction and at improving overall plant capacity factor.

One of the most structuring options for the design of the nuclear island layout is the twinning of two reactors with a shared fuel handling building and a shared component maintenance building. The aim is to reduce the weight related to these two heavy investment cost items by sharing it for two production units. Further, the arrangement of the buildings is also determined by the requirements such as independent reactor safety related buildings and reactor operation, redundant electrical systems, geographical separation of safety systems and buildings with regard to internal and external hazards and seismic resistance criteria. Material type and proliferation resistance features were analyzed for different types of cores and fuels in the context of a European Project CP ESFR [23].

1.2.3 BN-1200 Design Track

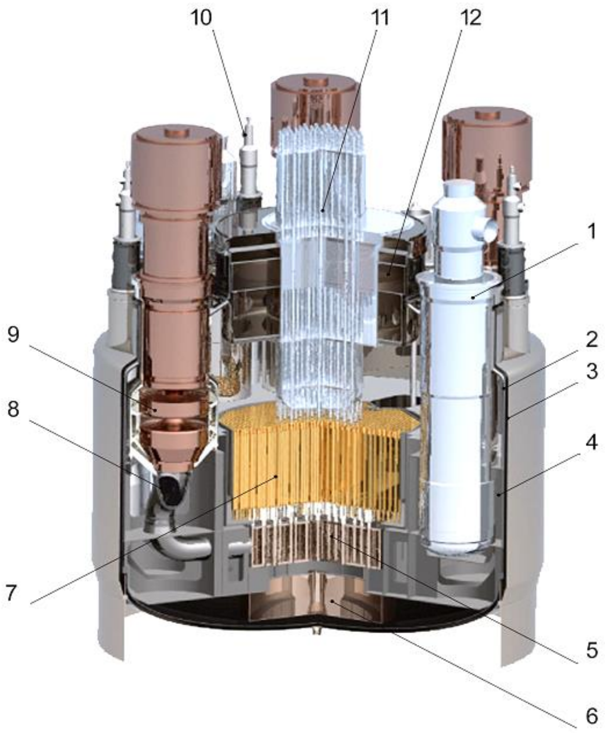
The large pool SFR design of the commercial BN-1200 power unit evolved from previous pool-type SFR designs such as BN-600 and BN-800. The BN-1200 is developed as a GEN-IV reactor to provide sustainability of future nuclear power. The BN-1200 design is aimed at enhancing safety by applying the inherent safety features and passive safety systems of SFRs, while improving the design against possible internal and external hazards. The BN-1200 design is aimed also at reducing capital investment cost and the cost of electricity through simplification and diminution of reactor components and structures [24]. The basic design characteristics of the BN-1200 are presented in Table 1.

The BN-1200 core is designed with two different mixed uranium-plutonium fuel options – advanced mixed uranium-plutonium nitride fuel (MUPN) and conventional MOX-fuel [25]. Decrease of a specific power density in the core allows improvement of its resistance against severe accidents and increase of power unit load factor (more than 0.9) due to extended fuel cycle length. A special sodium cavity (plenum) is provided above the flattened core to decrease significantly the positive sodium void reactivity effect in case of sodium boiling under severe accident conditions [26], strongly reducing the potential for an energetic scenario under severe accident conditions. There is an upper boron axial shield above the sodium plenum. A core catcher is designed in the bottom of the reactor vessel to hold a full volume of the core materials while avoiding criticality, and a special compartment over the reactor top is foreseen to confine a radioactivity release under severe accident conditions. In any severe accident, radioactivity release outside of the power plant site that would require an evacuation of the population is excluded.

All systems and components containing radioactive sodium of the primary circuit, including auxiliary sodium systems in particular purification systems and other chemical-engineering control systems are located inside the reactor vessel surrounded with the guard vessel. This arrangement practically eliminates leaks of radioactive sodium outside primary circuit boundaries. A layout of the BN-1200 primary system is shown in Figure 4.

In the BN-1200 design, significant attention is given to the application of passive safety systems. Two passive shutdown systems are used in addition to two standard active protection systems. One passive shutdown system uses hydraulically suspended absorber rods. The second system is based on high temperature actuation. The decay heat removal system consists of four sodium loops that provide heat transfer from the primary circuit by means of immersed sodium/sodium decay heat exchangers (DHX) and then dissipate it into ambient air through sodium/air heat exchangers (AHX) in fully passive operation mode with natural circulation of the primary and intermediate sodium and air [27].

The significant decrease of capital costs is implemented by the following design measures: simplification of the refueling system by increasing the capacity of the in-reactor vessel storage (IVS) and eliminating the storage drum of spent fuel subassemblies that provided direct unloading of spent fuel subassemblies; replacement of sectional modular steam generators (SG) by large modular ones (two large SG modules in each secondary loop); significant change of layout schemes that results in decreasing reactor building sizes.



1 – Intermediate Heat eXchanger; 2, 3 – main and guard vessels respectively; 4 – supporting structure; 5 – inlet plenum; 6 – core catcher; 7 – core; 8 – pressure pipeline; 9 – Main Coolant Pump-1; 10 – Decay Heat eXchanger; 11 – Control Rod Driveline Mechanism; 12 – rotating plugs

Figure 4: 3D Layout of the BN-1200 Primary System [24].

1.3 Small Modular SFR

The Advanced Fast Reactor-100 (AFR-100) is aimed at exploiting characteristics inherent to fast reactors for application to small grid applications. The reactor size of 100 MWe was selected for a specific niche market where industrial infrastructure is not sufficient for larger systems and the unit cost of electricity generation is very high with conventional technologies [28]. Examples of this situation are remote areas in Alaska, small grid systems in developing countries, and Pacific-basin islands. The basic goal is to make the operation, safety, and fuel management as simple as possible; for example, by the application of a long-lived reactor core that eliminates the need for on-site refueling. The SFR characteristics that enable this approach are:

- The non-corrosive character of sodium coolant does not degrade the reactor core material and primary system components even over very long residence times;
- The excellent neutron economy of fast spectrum and metal fuel can be exploited to design a small core with a conversion ratio near unity, obviating the need for refueling to account for reactivity losses over an extended cartridge lifetime.

A variety of innovative design features have been incorporated into AFR-100 to simplify the design and improve performance. Some of the key features include: a metallic fuel core with inherent safety characteristics, compact reactor configuration for modular construction and transportability, cool pool configuration, advanced shielding materials, limited free bow core restraint, self-cooled electromagnetic pumps, twisted tube heat exchangers, and supercritical CO_2 Brayton cycle power conversion system. The primary plant concept is depicted in Figure 5; the primary systems are embedded below the ground level for physical protection. The primary system is configured as a pool arrangement with the core, pumps, intermediate heat exchangers, and auxiliary cooling decay heat exchangers all contained within the reactor vessel. A core cover diverts the coolant flow directly to the primary heat exchangers resulting in an isothermal (cold) pool concept. The intermediate sodium exits the vessel and flows to the nearby sodium-to-CO_2 heat exchangers.

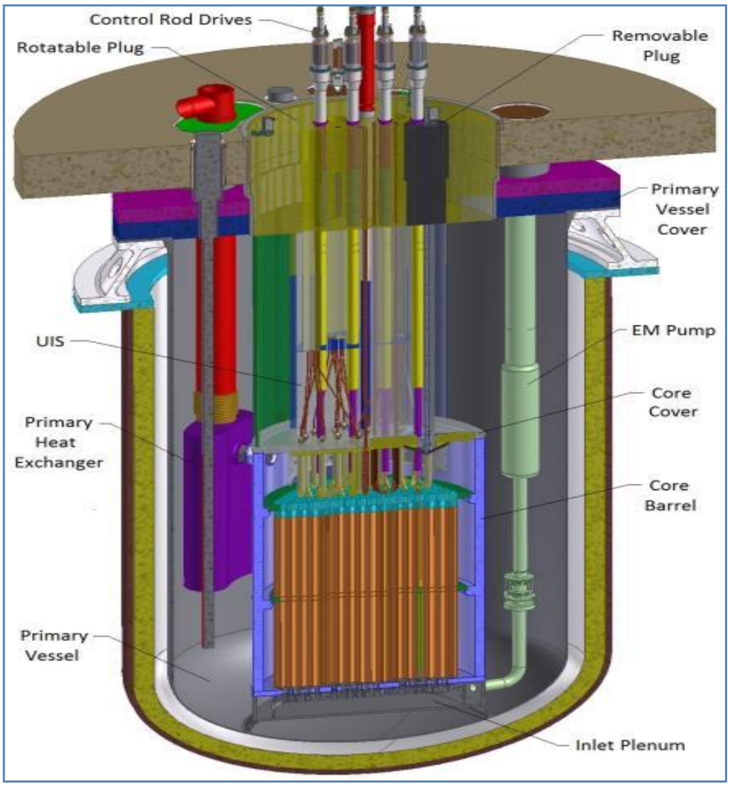


Figure 5: AFR-100 Primary Plant Concept [28].

A key design feature of the AFR-100 is the long-lived core than can operate 30 years with no refueling. This long lifetime improves proliferation resistance by eliminating all aspects of on-site fuel management: new fuel acceptance, spent fuel handling, and out-of-reactor storage. The AFR-100 incorporates all the inherent safety features developed for SFR applications to avoid plant damage including a passive decay heat removal system directly from the primary coolant pool.

The base fuel cycle for AFR-100 is once-through. A 13.5% enriched uranium metal fuel form is employed with burnup and fluence limits similar to the KALIMER design. The once-through mode results in fuel utilization as used in LWRs. However, a closed fuel cycle could be implemented (off-site) to improve fuel utilization. The significantly reduced power density to achieve the 30 year lifetime design goal results in high specific (per MWt) fuel inventory and specific system size compared to other SFR concepts. Conversely, the unit investment and construction time will be reduced for small reactors. Overall, the AFR-100 energy generation cost is acceptable for the intended niche market application where the small size and design simplicity are more important considerations.

1.4 Summary of Generation-IV SFR Tracks

Table 1 summarizes the key design parameters of the SFR design concepts identified in the previous three subsections. It is important to note that all of these SFR systems are designed with flexibility in size, specific fuel design, and fuel loading configuration. These particular designs are indicative of current international SFR design studies that cover a wide range of power applications (sized from 100-1500 MWe). The question of size involves a cost reduction approach of economies of scale for large systems as compared to modular factory fabrication for small systems. Other factors like capital investment limits or electrical grid limitations may dictate the optimal deployment system power rating.

Table 1. Key Design Parameters of Generation IV SFR Concepts.

Design Parameters	*JSFR*	*KALIMER*	*ESFR*	*BN-1200*	*AFR-100*
Power Rating, MWe	1,500	600	1512	1220	100
Thermal Power, MWt	3,570	1,500	3600	2800	250
Plant Efficiency, %	42	40	42	43.5	40
Core Outlet Coolant Temperature, ^{o}C	550	545	545	550	550
Core Inlet Coolant Temperature, ^{o}C	395	390	395	410	395
Main Steam Temperature, ^{o}C	503	503	490	510	517[a]
Main Steam Pressure, MPa	19.2	16.5	18.5	17.0	20[a]
Cycle Length, years	1.5–2.2	1.1	1.35	1.0	30
Fuel Reload Batch, batches	4	5	5	Up to 6	1
Core Diameter, m	5.1	4.2	4.72	4.18	3.0
Core Height, m	1.0	0.89	1.0	0.83/1.0	1.1
Fuel Type	MOX (TRU bearing)	Metal (U-TRU-10%Zr Alloy)	MOX	MUPN/ MOX	Metal (U-10%Zr Alloy)
Cladding Material	ODS	HT9M	ODS	AAS/FMS/ODS	HT9
Fuel Fissile Content (Pu/HM), %	13.8	25.2	15.7	Up to 20	13.5[b]
Burn-up, GWd/t	150	139	100	Up to 100/125 (average)	100
Breeding Ratio	1.0–1.2	0.74	1.0-1.2	1.35/1.2	0.8

[a] Energy conversion medium is supercritical CO_2, not steam
[b] (U-235/HM), %

With regard to the fuel and loading, any of the systems can be designed for different actinide management missions. The reactor performance noted in Table 1 is for converter mode designs (see actinide management discussion in Section 2); each concept could readily be modified to breeder or transmuter configurations by changing the fuel assembly design to modify the uranium loading. Furthermore, the SFR reactor performance can be achieved with different fuel forms, depending on the success of the advanced fuels research to develop and demonstrate recycled fuels. The current SFR system development status is presented in Appendix 2

2 Overview of Fuel Cycle(s)

From the initial conception of nuclear energy, it was recognized that full realization of the energy content of uranium would require the development of fast reactors. In the current once-through fuel cycle, enriched uranium is utilized as LWR fuel and over 99% of the energy content of the initially mined uranium remains in the residue from the enrichment process and used LWR fuel. Conversely, the favorable neutron balance in a fast spectrum sustains the fissile material. This behavior improves the performance of both once-through (breed/burn and long-lived core concepts) and recycle strategies, by enabling extended fuel burnups from a fixed fissile inventory.

For closed fuel cycle applications, a thermal spectrum leads to the generation of higher actinides that complicate subsequent recycling. Conversely, fission is favored in a fast spectrum limiting higher actinide generation. This behavior allows full recycle enabling complete consumption of uranium and transuranic elements, while eliminating the need for uranium enrichment. Significant waste management benefits can also be realized by excluding the long-term heat production elements (actinides) from the waste stream.

The previous comments are true of any fast reactor system. The fast spectrum flexibility allows a wide variety of actinide management strategies to be deployed in Generation-IV SFR reactors. The uranium loading can be varied to operate in different modes:

- A conversion ratio[2] less than 1 (“transmuter” mode) which means that there is a net consumption of transuranics. Here, “transmute” means to convert transuranics into shorter-lived isotopes;
- A conversion ratio near 1 (“converter” mode) which provides a balance in transuranic production and consumption. This mode results in low reactivity loss rates with associated control benefits;
- A conversion ratio greater than 1 (“breeder” mode) which means there is a net creation of transuranics. This approach creates additional fissile materials, but requires the inclusion of extra uranium in the SFR and fuel cycle.

An appropriately designed SFR has flexibility to shift between these operating modes; and the desired actinide management strategy will depend on a balance of waste management and resource extension considerations.

Most Generation-IV SFR concepts are intended for utilization in a closed fuel cycle. The primary options (i.e., as employed in the contributed design tracks identified in Section 1) are oxide fuel with aqueous processing and metal fuel with electrometallurgical processing. However, a wide variety of advanced fuel cycle options are being considered for future SFR closed fuel cycle concepts, including:

- Alternate nitride and carbide fuel forms (included in scope of the SFR Advanced Fuels technical project);
- Alternate fuel fabrication processes (e.g., vibration compacting, extrusion);
- 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;
- Once-through fuel cycles at very high fuel burnups.

It is important to note that research and development of these advanced fuel cycle technologies is not included in the Generation-IV SFR scope. The fuel performance and fabrication are part

[2] The conversion ratio is defined as the ratio of the transuranic production rate to the transuranic destruction rate, whereas, the breeding ratio is a similar ratio for the fissile material.

of the GIF research projects, but all work on the separations technology has been excluded. Thus, a detailed description of closed fuel cycle options cannot be defined for the Generation-IV SFR concepts, nor is this information forthcoming as a product of the GIF R&D collaborations.

Besides the above observations, it is clear that the results obtained on minor actinide (MA) bearing fuels (form, performance, burn-up and integrity) will influence the fuel cycle strategy. In particular, the choice between homogeneously (2-5%) or heterogeneously (up to 10-20% in blanket elements) fueled cores with MA has PR&PP implications, because MA bearing fresh (and irradiated) fuel elements present a different attractiveness than U-Pu ones, and a higher degree of difficulty in handling.

With the focus of Generation-IV SFR collaboration on the reactor concept, the main PR&PP fuel cycle issue at the reactor site is the fuel handling. A variety of fuel handling schemes are proposed in different SFR concepts. Most designs rely on a conventional multi-batch refueling scheme with 1/3 to 1/5 of the core replaced at regular intervals that range from one to several years. One key aspect of the Advanced Fuels Project is to extend the discharge burnup of SFR fuels; the fuel lifetime in conventional SFRs is limited by irradiation damage not reactivity degradation. This development would reduce the fuel handling frequency (e.g., either extend cycle length or reduce batch size) at the same power density. Conversely, some recent concepts (e.g., the AFR-100 in Section 1.3) propose a cartridge refueling strategy where the entire core is replaced at long time intervals of 15 to 30 years. Because the same fuel burnup limits apply, this requires a reduced power density, resulting in a larger system with associated economic penalties.

The use of liquid metal coolant dictates a sealed primary system to prevent coolant interactions with the environment and secondary fluids. Thus, any refueling outage will require removal and insertion of fuel through an inert environment configuration. Furthermore, specialized fuel handling machines have been developed for identifying and moving the fuel assemblies which remain under sodium. For multi-batch concepts the fuel is typically removed as individual assemblies, while the long-lived concepts require full core removal. For pool concepts (e.g., the concepts in Section 1.2), 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 compact loop configuration (e.g., the JSFR in Section 1.1), fuel storage space is not available inside the vessel and the discharged fuel must be removed directly and stored at a nearby location.

A common step will be the need to clean sodium from the fuel assembly before transport. After discharge and cooling, the spent fuel is transported to the separations or disposal facility. The transportation requirements will depend heavily on the fuel cycle architecture (co-located or centralized) and are beyond the Generation-IV scope, as noted above.

The typical characteristics of fresh and spent SFR fuel are noted in Section 3.0 where the proliferation resistance design issues are described.

3 PR&PP Relevant System Elements and Potential Adversary Targets

The term 'system elements' is defined as a collection of facilities[3] inside the identified nuclear energy system where nuclear material diversion/acquisition and/or processing, as well as theft or radiological sabotage could take place [29]. The following figure contains a high level diagram depicting the basic system elements of a typical SFR with on-site refueling. The SMFR with a long-lived core eliminates all aspects of on-site fuel management: new fuel acceptance, spent fuel handling, and out-of-reactor storage.

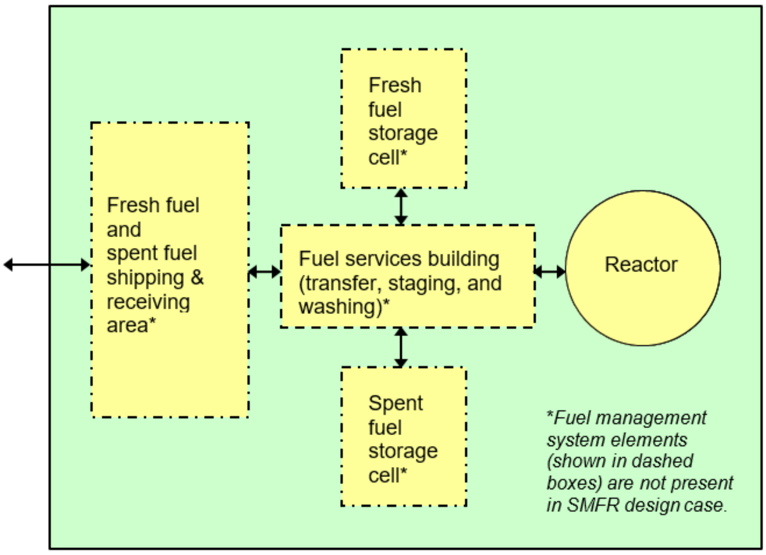


Figure 6: SFR System Elements containing nuclear material.

The material present in the fuel management system elements (shown in dashed boxes in the figure) will be in the form of intact fast reactor fuel assemblies. The TRU inventory in the SFR reactor core is 5-10 MT/GWe depending on the fissile fraction of the feed material and reactor configuration. The pool type SFR core could also contain in-vessel storage for one or more batches worth of fuel. The minimum fresh fuel storage inventory is one refueling batch, or 1/5 to 1/3 core size. The on-site spent fuel storage capacity depends on the cooling time requirements and frequency of spent fuel shipments to a fuel cycle facility.

The fuel assembly characteristics for the five design tracks are described in Table 2. All designs utilize solid fuels contained in steel cladding; the fuel pins are tightly packed with wire wrap spacers. The fuel assemblies are configured as ducted fuel pin bundles which are typically handled individually by in-vessel and ex-vessel transport machines.

[3] According to International Atomic Energy Agency (IAEA) Additional Protocol, facility means "(i) A reactor, a critical facility, a conversion plant, a fabrication plant, a reprocessing plant, an isotope separation plant or a separate storage installation; or (ii) Any location where nuclear material in amounts greater than one effective kilogram is customarily used". [International Atomic Energy Agency (IAEA). 1998. Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards. INFCIRC/540 (Corrected), IAEA, Vienna.]

Table 2. Fuel Assembly Characteristics of Generation IV SFR Concepts

Design Parameters	*JSFR*	*KALIMER*	*ESFR*	*BN-1200*	*AFR-100*
# of Fuel Assemblies	562	324	453	432	150
Assembly Pitch, cm	20.6	15.4	21.1	>18.1	16.5
Assembly Length, cm	457	458	474	470	421
Assembly Weight,[a] kgHM	219	53.4	180	>130	159
Cycle Length, years	1.5–2.2	1.1	1.35	1.0	30
Fuel Residence Time, y	8	5.5	6.75	6	30
Fuel Fissile Content (Pu/HM), %	13.8	25.2	15.7	Up to 20	13.5[b]
Burn-up, GWd/t	150	139	100	Up to 100/125 (average)	100

[a] The assembly total weight is roughly 3 times the heavy metal (HM) loading
[b] (U-235/HM), %

Although five design tracks were discussed in section 1, the potential adversary targets for all designs is similar, as shown in Table 2, so the remainder of this paper will not break out the different design tracks unless there is a unique feature.

The operations within the fuel management system elements will comprise fuel assembly handling, transfer, storage, and fuel assembly washing to remove adhered sodium from assemblies prior to spent fuel storage. Operations within the core include fuel loading and unloading, irradiation, and for pool type SFRs, in-vessel fuel storage. Material movement involves the transfer of intact fuel assemblies within and between system elements, in specialized transfer containers and possibly under sodium.

The safeguards system will focus on item accounting and containment and surveillance (C/S) and will likely include portal monitoring. Safeguards approaches for under sodium verification may also be utilized.

Potential PR targets include the system's declared fuel assemblies for diversion or theft, as well as undeclared fissile material produced by irradiating fertile material introduced into the reactor. Therefore, in addition to detecting the diversion of declared material, the safeguards system should be designed to detect illicit activities of facility misuse for the undeclared production of fissile material.

PP targets for theft are the fuel assemblies. Potential PP targets for sabotage include the heat removal systems outside of containment that connect to the ultimate heat sink, and sodium loops. The sodium loops for all reference designs are located within containment, so robust protections are in place. Most designs have considered sabotage already since coolant activation is closely monitored and exposure to air can lead to sodium fires.

The PR&PP Example Sodium Fast Reactor Full System Case Study [30] provides a more comprehensive overview of the safeguards and physical protection approach for the ESFR. The safeguards system is shown in Figure 7. Generally, a SFR would contain separate material balance areas for the reactor, fuel service building, fresh uranium fuel storage, and spent fuel storage. However, it is possible that some of these can be consolidated depending on the design. The reference goes into more detail on the C/S system for these areas. The C/S system is straight-forward using concepts from IAEA safeguards technology deployed at existing commercial power reactors. The primary strategy minimizes the risk of acquisition or concealed production of material by applying effective IAEA safeguards attended and unattended monitoring concepts. This uses a combination of design information verification, nuclear material accounting, and C/S.

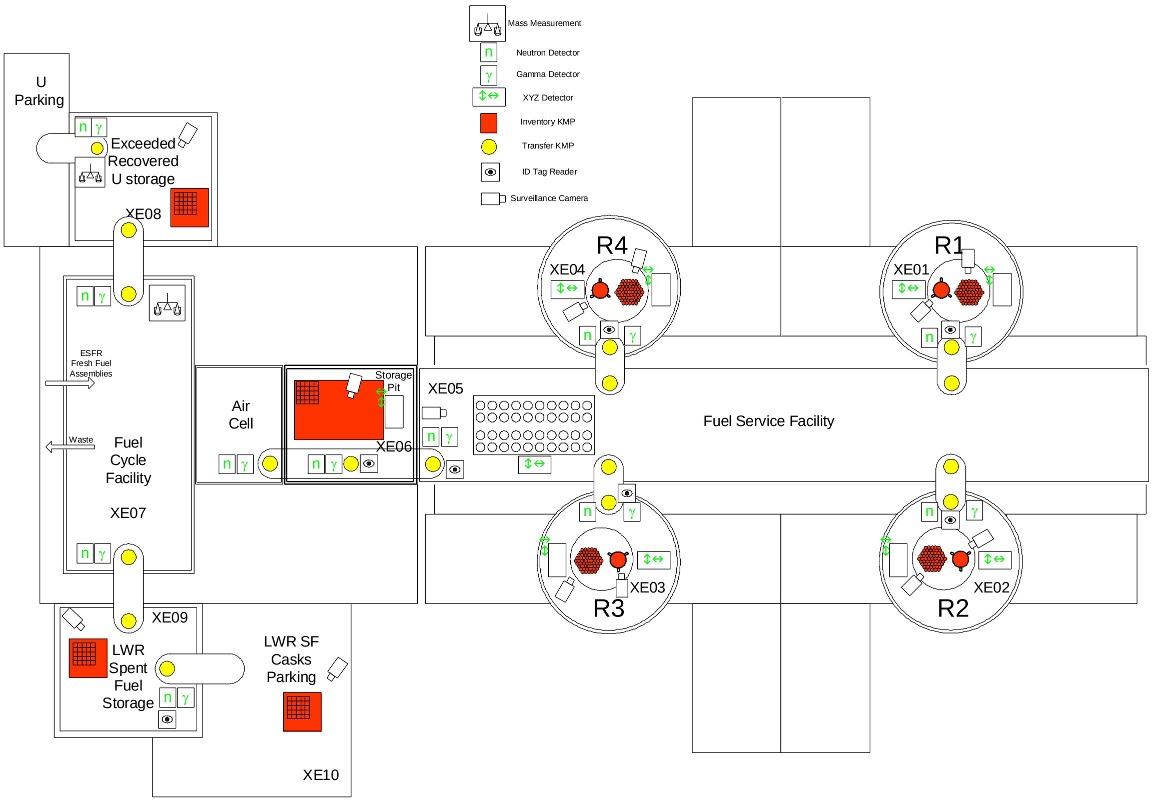


Figure 7: Safeguards system developed for the Example Sodium Fast Reactor (ESFR), object of the GIF PRPP Case Study [30]. The site co-locates 4 nuclear power units, a recycling facility and related fresh and spent fuel storage.

4 Proliferation Resistance Considerations Incorporated into Design

As noted in Section 2, most Generation-IV SFR concepts are intended for utilization in a closed fuel cycle. The sustainability and waste management benefits of the technology derive from successful application of such advanced fuel cycles. It is important to note that R&D on fuel cycle technology is outside the GIF SFR scope.

A significant amount of past work has examined the proliferation resistance aspects of fast reactors and the fast reactor closed fuel cycle. References [30-39] provide more detail. This section is intended to be inclusive of this past work.

From the viewpoint of enhancing proliferation resistance of the SFR and its associated nuclear fuel cycle system, the following considerations have been proposed for incorporation into SFR designs:

- Recycling of spent nuclear fuel without the separation of plutonium (or possibly without the complete removal of fission products);
- Avoidance of the need for enrichment technology;
- Increased fuel burnup (reduces the fuel handling frequency and gives a higher radiation barrier for the spent fuel).

With the focus of the Generation-IV SFR collaboration on the reactor concept, the main fuel cycle issues at the reactor site are the core loading strategy including the source of the start-up core assemblies and the fuel handling. Thus, it is very important to facilitate ready application of safeguards on the fresh and spent fuel assemblies and to the overall reactor site. For perspective, some typical fuel characteristics are given below.

- The fuel material is Oxide (TRU-MOX), Metal (U-TRU-Zr), or Nitride (MNUP);
  - Mixed Carbide (MC) is also being researched;
- The fissile enrichment is ~15–30% fissile/Heavy-Metal;
- The fissile inventory in the SFR reactor core is 5-10 MT/GWe depending on the fissile fraction of the feed material and reactor configuration;
- Converter and breeder configurations utilize uranium blanket assemblies to enhance fissile material production; transmuters do not;
- The conventional fuel lifetime is 3-6 years, with long-lived cores (15-30 years) possible in de-rated power density concepts;
- Discharge burnup is ~80 – 150 GWd/t depending on the configuration;
  - Higher burnup (250 GWd/t or even higher for breed/burn concepts) is a key Advanced Fuels research target.

From a proliferation standpoint, there are some differences compared to conventional LWRs that should be considered. SFR fuel assemblies have a higher percentage of fissile inventory, but the assemblies are smaller. A smaller and lighter assembly (see Table 2) could be easier to remove, hide, or transport. Regardless, the SFR designs will not change the requirement for item accounting, containment, and surveillance of all assemblies at the reactor site, like any existing LWR.

All of the fuel used in sodium fast reactors typically have high activity and dose, making them difficult to handle. Operations under sodium further adds to the difficulties of diverting assemblies, but also complicates material tracking. Refueling is conducted in an inert environment under sodium, which makes assemblies less accessible until after sodium cleaning. There may be a proliferation resistance advantage due to this limited access.

Facility misuse scenarios are present in SFRs, just like in any reactor. Breeder configurations need to be evaluated, but surveillance and assembly tracking safeguards measures will be applied. Monitoring of the reactor for as-designed irradiation cycles will be an important part of a safeguards approach.

Long-lived cores will see much less frequent movement of fuel in and out. However, the total amount of fissionable fuel being handled (on a per unit of power basis) does not change. Therefore, with long-lived fuel management, larger amounts of fuel are handled per re-fueling, but there are fewer transfers; this feature will need to be accounted for in a safeguards approach. Sealed cores (like in some SMR designs) contain all the fuel in one location with the potential to eliminate all aspects of on-site fuel management (new fuel acceptance, spent fuel handling, and out-of-reactor storage).

4.1 Concealed diversion or production of material

Fresh SFR fuel assemblies would be a more attractive diversion target as compared to typical spent LWR fuel due to higher concentrations of fissionable material per assembly. Concealed diversion or production of material is deterred primarily by the application of effective international safeguards. At the reactor site, this applies to the material tracking of fresh fuel, blanket, and spent fuel assemblies. The fresh fuel has lower radioactivity while the spent fuel has significant heat loading and radioactivity. Handling methods for fresh fuel assemblies may depend significantly on minor actinide content (homogeneous recycle or heterogeneous recycle concentrated minor actinide targets). For fast reactors, the fissile content of fresh driver and spent fuel is similar. Thus, detailed accounting of fresh fuel is most important.

With regard to blankets, where present, the fresh assemblies are natural or even depleted uranium. The spent blankets have relatively low burnup and high quality plutonium material. Thus, detailed accounting and surveillance of the spent blanket assemblies is an important deterrent. Given the need for special fuel handling equipment and inert or sodium environment, it should be easy to determine when SFR systems are performing fuel handling operations. Proper identification and tracking of the spent fuel will be required anyhow for the subsequent reprocessing operations since the recovered materials must be blended to create recycle fuel. Thus, application of safeguards for the fuel handling procedures should secure tracking of this material.

The ESFR Full Case Study [30] found that there would be no credible pathways for the concealed diversion of SFR assemblies since diversion of whole assemblies would be detected by the safeguards system. The study also analyzed concealed production of material in great detail—a host state would need to accomplish several steps and encounter many difficulties in accomplishing such a task under an IAEA safeguards approach. The current design tracks considered in GIF do not include blankets.

4.2 Breakout

A breakout scenario assumes that a host state decides to pursue a nuclear weapons program, and institutional barriers like international safeguards are ineffective. Thus, the only barriers are intrinsic proliferation resistance features.

It is expected that SFRs will operate in fuel cycle states that will also provide other fuel cycle services including enrichment. In the longer term, the SFR closed fuel cycle can eliminate the need for enrichment, removing the enrichment pathway for breakout. As noted above, the fresh fuel has low radiation levels and isotopics and nuclear materials and TRU composition that is more attractive than the spent fuel with its high radiation fields and fission products. Hence, the fabrication step is the key fuel cycle phase for removing the attractive fresh fuel material.

In analysing the utility of blankets, for any neutron source the potential exists to create high quality plutonium in low concentrations within uranium assemblies. In the breeder closed fuel cycle, blankets are utilized to replenish the fissile material allowing the extension of uranium resources. However, even for non-blanket designs, fuel could be replaced with depleted uranium to breed plutonium. In either case, subsequent processing would be needed to recover the dilute fissile material.

4.3 Production in clandestine facilities

The SFR technology does not lend itself to clandestine application. The utilization of liquid metal coolant requires a specialized infrastructure. The relatively complicated fuel handling and unique fuel requirements (15-30% enrichment) are hard to conceal compared to alternative neutron sources for producing fissile material.

Furthermore, the sustainability of the SFR closed fuel cycle can reduce or even eliminate the demand for enrichment services in the global fuel cycle architecture. With proper international fuel cycle arrangements this may limit the widespread application of enrichment technology.

5 Physical Protection Considerations Incorporated into Design

For the reactor site, the key issues for physical protection are fuel handling (including transport) and material security. Thus, the key approach for the Gen-IV SFR regarding physical protection is to design modern security features directly into planning and building of new nuclear energy systems (and fuel cycle facilities).

For example, the following matters might be considered in the detail design stage of the SFR from the viewpoint of enhancement to physical protection:

- The design of the fuel handling equipment should account for application of security measures for physical protection and safeguards;
- It should be possible to restrict any unauthorized access or approach to both fresh fuel and spent fuel at the reactor site, for example by designing for exclusively remote handling.

5.1 Theft of material for nuclear explosives

The PR&PP Example Sodium Fast Reactor Full System Case Study [30] provides a more comprehensive overview of the physical protection approach for the ESFR. This study discusses theft targets as mainly being fresh fuel areas and spent fuel areas but notes the attractiveness difference of the two. These areas would all be contained within a Perimeter Intrusion Detection and Assessment System (PIDAS). Conclusions from the study are typical of many security analyses for nuclear facilities. Increasing delay time through distance or barriers gives responders more time to respond. Hardening the buildings helps to reduce adversary success. Insider access can be a significant factor, so controls like the two-person rule must be in place to prevent circumvention of physical protection system elements as much as possible. Overall, the ESFR Case Study showed that the physical protection system was robust to prevent adversary threats.

As noted in Section 4.1, the fresh fuel is the most attractive target because it has low radioactivity while the spent fuel has significant heat loading and radioactivity; for fast reactors, the fissile content of fresh and spent fuel is similar. The spent blankets have desirable isotopics at moderate radiation levels. The spent fuel must be cleaned (removal of residual sodium) after extraction from the reactor vessel. This makes transportation after cleaning, cooling, and packaging a more desirable pathway for theft. The transport techniques and security arrangements will clearly be quite different between co-located and centralized fuel cycle strategies. Reactors with co-located recycle facilities would still acquire initial start-up material from an off-site source.

5.2 Radiological sabotage

Generation-IV SFRs are designed with favorable inherent safety behavior (e.g., passive decay heat removal) to virtually exclude the probability of severe accidents with potential for core damage. Design measures to mitigate the consequences of severe accidents (e.g., seismic isolation, advanced containment, etc.) are also being researched.

The Generation-IV SFR designs exploit passive safety measures to improve reactor safety behavior and increase reliability. The system behavior will vary depending on system size, design features, and fuel type. R&D for passive safety will investigate phenomena such as axial fuel expansion and radial core expansion, and design features such as self-actuated shutdown systems and passive decay heat removal systems. The ability to measure and verify these passive features must be demonstrated. Associated R&D will be required to identify bounding events for specific designs and investigate the fundamental phenomena to mitigate severe accidents.

Gen-IV designs focus on prevention of severe accidents and avoidance of fuel damage; nevertheless, intentional violent acts against a facility need to be considered. Given that physical security costs can substantially increase the cost of the facility and operations (response force requirements), it is in a reactor designer's best interest to consider physical protection early in the design process to avoid costly retrofits. Prevention of attacks to core cooling and heat rejection to the ultimate heat sink is a primary consideration. The main concern is to continue to provide core cooling for decay heat removal. The Generation-IV design tracks employ multiple, diverse decay heat removal techniques. Most of these ultimate heat removal systems rely on passive features with redundant capacity.

For SFRs, attacks designed to create a sodium leak or fire in key systems must also be considered. All of the Generation-IV designs utilize a secondary sodium loop to isolate and maintain the primary coolant within the containment; for pool configurations the entire primary loop resides within the reactor vessel. Sodium incidents in the secondary loop do not threaten core cooling, and the activation in secondary sodium is limited.

Physical protection analyses for SFRs were considered in the design, licensing, and operation of prior demonstration reactors, but are not available in public documents. Modern physical protection strategies and technology should be integrated early in the design process, similar to safety considerations. As an example, double walls are suggested for sodium pipes from a safety standpoint, but a double wall will do little to prevent an intentional sabotage event. The five reference designs presented here all contain robust containment structures similar to light water reactors. Thick containments or missile shields are designed to protect the internal structures and vital systems from external threats, either natural or man-made. Protection of the reactor and all sodium pipes behind the containment the missile shield will help to protect the facility against sabotage events.

6 PR&PP Issues, Concerns and Benefits

A brief overview of the Generation-IV Sodium-cooled Fast Reactor (SFR) technology was provided in this white paper. The promise of improved sustainability and waste management performance in a closed fuel cycle is a primary motivation for the application of this reactor type. Thus, the safeguards and nonproliferation aspects of the closed fuel cycle are a key issue for the SFR.

A wide variety of actinide management strategies ranging from extended burnup once-through to closed fuel cycle technologies are being explored worldwide. *However, collaboration on separations technology is not part of the GIF SFR collaboration scope; and is typically the critical concern for closed fuel cycle strategies.* Therefore, only the general aspects of SFR closed fuel cycle were addressed in this white paper; and detailed information will not be available from the GIF R&D Projects.

Because PR issues have been examined for SFR system for several years, many current designs have made design choices to improve proliferation resistance. Avoiding enrichment in the fuel cycle, increased fuel burnup, and reduced transfers of material provides non-proliferation benefits. Blankets, where present, need safeguards applied at the same level as the fresh driver fuel. Production in clandestine facilities would likely be difficult due to the specialized infrastructure required for the liquid metal coolant.

A summary of the main PR relevant intrinsic design features of the three main design options is presented: in Appendix 1 according to the IAEA document Proliferation Resistance Fundamentals for Future Nuclear Energy Systems [40].

Generation-IV SFRs use high fissile content in small fuel assemblies compared to other reactor types, so the assemblies could be more attractive theft targets. At the reactor site, the key issue will be efficient application of safeguards for the fresh and spent fuel assemblies. A variety of fuel handling techniques were noted, and it will be important to consider safeguards and security in the final design of Generation-IV SFR concepts.

Sabotage targets that should be considered include the fuel, heat rejection system, and sodium coolant. SFRs can take advantage of passive safety systems when considering the physical protection designs.

References

[1] Generation IV International Forum, "Generation-IV International Forum System Arrangement for The International Research and Development of Sodium-cooled Fast Reactor Nuclear Energy System, Annex A," OECD NEA Document, Paris, February 2006.

[2] Generation-IV International Forum, "Generation-IV Nuclear Energy Systems System Research Plan for the Sodium-Cooled Fast Reactor, " NEA Document, GIF/SFR/SC/2006/007, Revision 1.4, October 2007.

[3] Generation-IV International Forum, "A Technology Roadmap for Generation IV Nuclear Energy Systems," GIF-002-00, USDOE, December 2002.

[4] A.I. Kiryushin et al., "BN-800: Next Generation of Russian Sodium Fast Reactors," International Conference on Nuclear Engineering, New York, United States, 2002.

[5] D. Beccaro et al., "The EFR safety approach," International Conference on design and Safety of Advanced Nuclear Plants, Tokyo, Japan, 1992.

[6] J.C. Lefevre et al., "European fast reactor design," Nuclear Engineering Design, vol. 162, Issue 2-3, pp. 133-143, 1996.

[7] B. Farrar et al., "Fast reactor decay heat removal: approach to the safety system design in Japan and Europe," Nuclear Engineering and Design, vol. 193, Issue 1-2, pp. 45-54, 1999.

[8] M.L. Thompson et al., "The Advanced Liquid Metal Reactor – Near, Medium and Long-Term Applications," ICONE-3, Kyoto, Japan, 1995.

[9] Y.I. Chang et al., "A next-generation concept: The Integral Fast Reactor (IFR)," USDOE Report, Argonne National Laboratory, 1992.

[10] T. Inagaki et al., "Current status of development of the demonstration FBR in Japan," Eleventh Pacific Basin Nuclear Conference, Banff, Canada, 1998.

[11] M. Miuracet al., "Design study of fast breeder reactors in Japan," International Fast Reactor Safety Meeting, Snowbird, USA, 1990.

[12] International Atomic Energy Agency, "Advances in Small Modular Reactor Technology Developments, 2020 Edition, " IAEA, 2020.

[13] Generation-IV International Forum, "GIF R&D Outlook for Generation IV Nuclear Energy Systems: 2018 Update," OECD Nuclear Energy Agency, 2019.

[14] Y. Sagayama, "Feasibility Study on Commercialized Fast Reactor Cycle Systems (1) Current Status of the Phase-II Study," Global2005, Oct.9-13, Tsukuba, Japan, 2005.

[15] S. Kotake et al., "Feasibility Study on Commercialized Fast Reactor Cycle Systems / Current Status of the FR System Design," Global2005, Oct.9-13, Tsukuba, Japan, 2005.

[16] M. Hishidaet al., "Progress on the Plant Design Concept of Sodium-Cooled Fast Reactor," Global2005, Oct.9-13, Tsukuba, Japan, 2005.

[17] T. Mizuno et al., "Advanced Oxide Fuel Core Design Study for SFR in the "Feasibility Study" in Japan," Global2005, Oct.9-13, Tsukuba, Japan, 2005.

[18] S. Kubo et al., "Status of Conceptual Safety Design of Japanese Sodium-cooled Fast Reactor," Global2005, Oct.9-13, Tsukuba, Japan, 2005.

[19] D. Hahn et al., "Design Concept of KALIMER-600," Global2005, Oct.9-13, Tsukuba, Japan, 2005.

[20] H. Song and Y. Kim, "The KALIMER-600 Core Neutronic Design with a Single Enrichment," Global2005, Oct.9-13, Tsukuba, Japan, 2005.

[21] J.H. Lee et al., "Mechanical Structure Design Features of the KALIMER-600 Sodium-Cooled Fast Reactor," Transactions SMiRT 19, Toronto, August 2007.

[22] G.L. Fiorini and A. Vasile, "European Commission – 7th Framework Program, The Collaborative Project on European Fast Reactor (CP ESFR)," Nuclear Engineering and Design, vol. 241, Issue 9, pp. 3461-3469, 2011.

[23] G. Renda, G.G.M. Cojazzi, and F. Alim, "Proliferation Resistance and Material Type Considerations within the Collaborative Project for a European Sodium Fast Reactor," Joint Research Center, European Commission, EUR 26996, November 25, 2014.

[24] B.A. Vasilev et al., "Development of the New Generation Power Unit with the BN-1200 Reactor," International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development FR17, IAEA CN 245 402, Yekaterinburg, Russia, June 2017.

[25] B.A. Vasiliev et al., "Specific Features of BN-1200 Core in Case of Use of Nitride or MOX fuel," International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development FR17, IAEA CN 245 408, Yekaterinburg, Russia, June 2017.

[26] A. Anfimov et al., "Safety Assurance for BN-1200 Power Unit During Accidents," International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development FR17, CN245-385, Yekaterinburg, Russia, June 2017.

[27] V. Pakholkov et al., "Integrated R&D to validate innovative emergency heat removal system for BN-1200 reactor," International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development FR17, CN245-416, Yekaterinburg, Russia, June 2017.

[28] C. Grandy et al., "Advanced Fast Reactor -100 – Design Overview," in Proceedings of. IAEA International Conference on Fast Reactors and Related Fuel Cycle FR13, Paris, France, 2013.

[29] The Proliferation Resistance and Physical Protection Working Group of the Generation IV International Forum, "Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems – Revision 6," GIF, 2011.

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

[31] H. Bengelsdorf, "Nonproliferation Risks and Benefits of the Integral Fast Reactor," IEALR/86-100, International Energy Associates Limited, Fairfax, VA, December 1986.

[32] R.G. Wymer et al., "An Assessment of the Proliferation Potential and International Implications of the Proliferation Potential and International Implications of the Integral Fast Reactor," Martin Marietta, May 1992.

[33] U.S. Congress, Office of Technology Assessment, Technologies Underlying Weapons of Mass Destruction, OTA-BP-ISC-115, Washington, DC: U.S. Government Printing Office, December 1993.

[34] Committee on Separations Technology and Transmutation Systems, National Research Council, Nuclear Wastes Technologies for Separations and Transmutation, National Academies Press, Washington, D.C., 1996.

[35] Nuclear Energy Study Group of the American Physical Society Panel on Public Affairs, "Nuclear Power and Proliferation Resistance: Securing Benefits, Limiting Risk," May 2005. Available at http://www.aps.org/public_affairs/proliferation-resistance/.

[36] U.S. Committee on the Internationalization of the Civilian Nuclear Fuel Cycle; Committee on International Security and Arms Control, Policy and Global Affairs; National Academy of Sciences and National Research Council, "Internationalization of the Nuclear Fuel Cycle: Goals, Strategies, and Challenges," National Academies Press, Washington, D.C, 2008.

[37] A.G. Croff et al., "U.S. Nuclear Regulatory Commission, NUREG-1909, Advisory Committee on Nuclear Waste and Materials White Paper, Background, Status, and Issues Related to the Regulation of Advanced Spent Nuclear Fuel Recycle Facilities," 2008. Available at http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1909/ sr1909.pdf/

[38] National Nuclear Security Administration Office of Nonproliferation and International Security, "Draft Nonproliferation Impact Assessment for the Global Nuclear Energy Partnership Programmatic Alternatives," 2008. Available at http://nnsa.energy.gov/nuclear_nonproliferation/documents/GNEP_NPIA.pdf/

[39] The Proliferation Resistance and Physical Protection Working Group and the System Steering Committees of the Generation IV International Forum, "Proliferation Resistance and Physical Protection of the Six Generation IV Nuclear Energy Systems," GIF, 2011.

[40] International Atomic Energy Agency, "Proliferation Resistance Fundamentals for Future Nuclear Energy Systems," STR-332, IAEA, 2002.

APPENDIX 1: Summary of PR relevant intrinsic design features. Reference IAEA-STR-332 [40]. Please refer to IAEA-STR-332, for full explanations and complete definitions of terms and concepts.

Summary of PR relevant Intrinsic design features	Compact Loop Configuration SFR	Pool Configuration SFR	Small Modular SFR
Features reducing the attractiveness of the technology for nuclear weapons programmes			
1. The Reactor Technology needs an enrichment Fuel Cycle phase	No enrichment is required.	No enrichment is required.	AFR-100 design track employs 13.5% enriched uranium
2. The Reactor Technology produces SF with low % of fissile plutonium	Fissile content starts higher with SFR assemblies, but high burnup fuel increases radioactivity in spent fuel.	Fissile content starts higher with SFR assemblies, but high burnup fuel increases radioactivity in spent fuel.	Fissile content starts higher with SFR assemblies, but high burnup fuel increases radioactivity in spent fuel.
3. Fissile material recycling performed without full separation from fission products	Recycling removes actinides from FP, but reactors can utilize actinides removed as a group.	Recycling removes actinides from FP, but reactors can utilize actinides removed as a group.	Recycling removes actinides from FP, but reactors can utilize actinides removed as a group.
Features preventing or inhibiting diversion of nuclear material			
4. Fuel assemblies are large & difficult to dismantle	Assembly dimensions are smaller than LWR. They are still large and difficult to move.	Assembly dimensions are smaller than LWR. They are still large and difficult to move.	Assembly dimensions are smaller than LWR. They are still large and difficult to move.
5. Fissile material in fuel is difficult to extract	Fissile material requires reprocessing.	Fissile material requires reprocessing.	Fissile material requires reprocessing.
6. Fuel cycle facilities have few points of access to nuclear material, especially in separated form	Radiation environment is very high, and limited penetrations into the facility.	Radiation environment is very high, and limited penetrations into the facility.	Radiation environment is very high, and limited penetrations into the facility.
7. Fuel cycle facilities can only be operated to process declared feed materials in declared quantities	It could be possible to remove material, but such a facility would be subject to extensive materials accountability systems. More R&D is needed on pyroprocessing safeguards.	It could be possible to remove material, but such a facility would be subject to extensive materials accountability systems. More R&D is needed on pyroprocessing safeguards.	It could be possible to remove material, but such a facility would be subject to extensive materials accountability systems. More R&D is needed on pyroprocessing safeguards.
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	Core configuration composed entirely of fuel and control assemblies. If blankets used, they would require safeguards similar to fuel.	Core configuration composed entirely of fuel and control assemblies. If blankets used, they would require safeguards similar to fuel	Core configuration composed entirely of fuel and control assemblies. If blankets used, they would require safeguards similar to fuel

Summary of PR relevant Intrinsic design features	Compact Loop Configuration SFR	Pool Configuration SFR	Small Modular SFR
9. The core prevents operation of the reactor with undeclared target materials (e.g. small reactivity margins)	Fast reactors tend to be more robust for utilizing different fuel types, but usually this is an advantage for actinide and minor actinide burning.	Fast reactors tend to be more robust for utilizing different fuel types, but usually this is an advantage for actinide and minor actinide burning.	Fast reactors tend to be more robust for utilizing different fuel types, but usually this is an advantage for actinide and minor actinide burning.
10. Facilities are difficult to modify for undeclared production of nuclear material	If blankets used, they would require safeguards similar to fuel.	If blankets used, they would require safeguards similar to fuel.	If blankets used, they would require safeguards similar to fuel.
11. The core is not accessible during reactor operation	Very high radiation environment.	Very high radiation environment.	Core designed to be sealed during entire life.
12. Uranium enrichment plants (if needed) cannot be used to produce HEU	Enrichment not needed.	Enrichment not needed.	AFR-100 design track employs 13.5% enriched uranium
Features facilitating verification, including continuity of knowledge			
13. The system allows for unambiguous Design Information Verification (DIV) throughout life cycle	DIV should be straight-forward.	DIV should be straight-forward.	DIV should be straight-forward, but sealed cores effect on DIV should be considered as well as multiple States involved in manufacture verification and transport
14. The inventory and flow of nuclear material can be specified and accounted for in the clearest possible manner	Item accountancy similar to LWRs, but the non-transparent coolant provides some challenges.	Item accountancy similar to LWRs, but the non-transparent coolant provides some challenges.	Item accountancy difficult for sealed cores, but also may not be needed if entire core is accounted for.
15. Nuclear materials remain accessible for verification the greatest practical extent	See above response.	See above response.	See above response.
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	Possible, it is unclear yet how much process monitoring measurements can or need to be used for verification.	Possible, it is unclear yet how much process monitoring measurements can or need to be used for verification.	Possible, it is unclear yet how much process monitoring measurements can or need to be used for verification.
17. The system provides for the installation of measurement instruments, surveillance equipment and supporting infrastructure likely to be needed for verification	No problem anticipated.	No problem anticipated.	No problem anticipated.

APPENDIX 2: Current SFR System Development Status

The SFR has vast worldwide experience compared to all of the Generation IV systems. Its development approach builds on technologies already developed and demonstrated for sodium-cooled reactors and associated fuel cycles in fast reactor programs worldwide; test SFRs have successfully been built and operated in Japan, France, Germany, the United Kingdom, Russia, and the United States. A major benefit of previous investments in SFR technology is that the majority of the R&D needs that remain for the SFR reactor technology are related to performance rather than viability of the system. Accordingly, the Generation IV collaborative R&D focuses on a variety of design innovations for actinide management, improved SFR economics, development of recycle fuels, in-service inspection and repair, and verification of favorable safety performance.

The GIF System Research Plan covers the needs of the viability R&D phase and the performance R&D phase for the SFR system envisioned in the GIF Technology Roadmap. Because technology options allow SFR designs to meet the Generation-IV performance goals, the viability phase is considered complete. However, a variety of new technology features aimed at improved system performance, such as supercritical CO_2 energy conversion, continue to be developed. The performance phase aims at the design inclusion and refinement of key SFR innovative design features by the end of 2022. Key R&D objectives and milestones for Generation-IV R&D collaborations on SFR technology are identified in the Generation-IV Technology Roadmap Update[4] of 2014. The research activities have been arranged by the SFR Signatories into four “Projects” to organize the joint GIF research activities:

1. System Integration and Assessment: This project will carry out the design and safety studies needed to define technical requirements for safety, fuels, and components of the SFR system. The results of the technical R&D projects will be integrated into generalized design concepts (contributed by the Members), and evaluated against Generation-IV goals and criteria.

2. Safety and Operation: This project includes the verification of safety tools, evaluation of the effectiveness of inherent mechanisms and design features, and identification of bounding events to consider in SFR licensing and containment design. This project also includes reactor operation and technology testing campaigns in existing SFR reactors.

3. Advanced Fuels: This project includes the development of high-burnup fuel systems (fuel form and cladding) to complete the SFR fuel database; research on remote fuel fabrication techniques for recycle fuels that contain minor actinides and possibly trace fission products; and the consideration of alternate fast reactor fuel forms for special applications (e.g., high temperature).

4. Component design and BOP: This project includes the development of advanced energy conversion systems to improve thermal efficiency and reduce secondary system capital costs. It also includes the development of advanced in-service inspection and repair (in sodium) technologies.

In addition to the Generation-IV SFR research & development Projects identified above, several of the GIF members countries have plans to build prototype or demonstration SFR systems in the 2015-2030 time frame; for example, BN-800 started power operations in 2016. These prototype designs typically reduce risk and system cost by employing more conventional technology options with reduced power output (for monolithic approach) or single module application (for modular approach). Thus, these modern systems provide unique opportunities to test the SFR technology innovations, and enable demonstration of the Gen-IV SFR performance potential.

[4] https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf

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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