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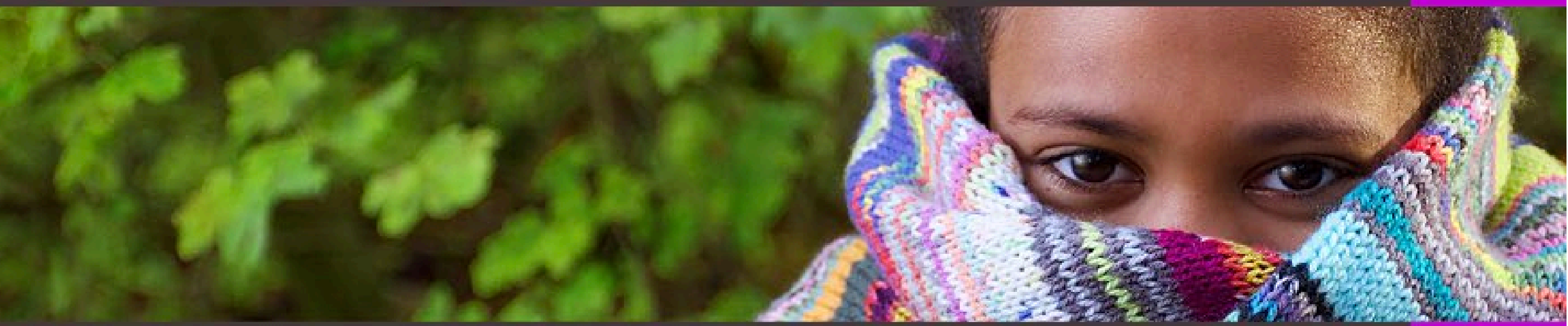
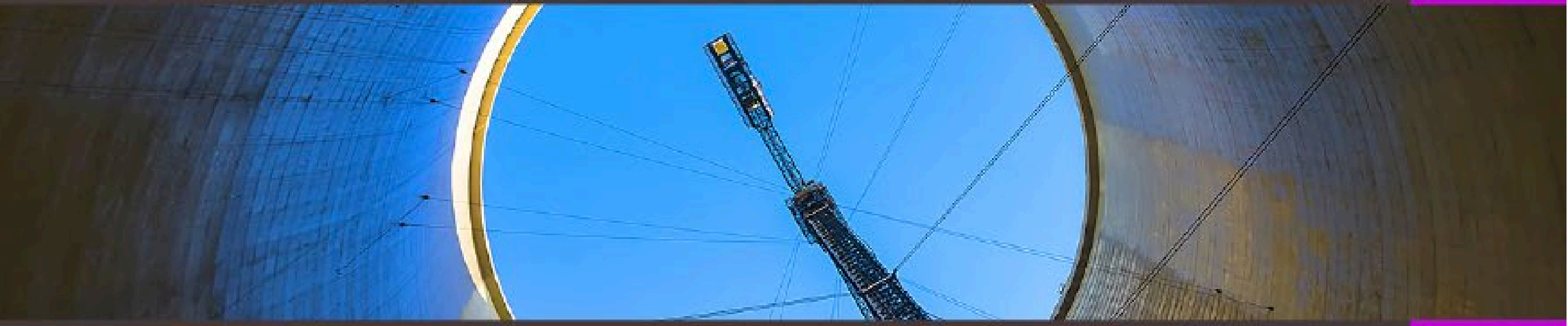
GIF GAS-COOLED FAST REACTOR

Proliferation Resistance and Physical Protection White Paper

April 2022





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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 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. 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 Gas-cooled Fast reactor (GFR) reference designs selected by the Generation IV International Forum (GIF) GFR System Steering Committee (SSC). The intent is to generate preliminary information about the PR&PP features of the GFR reactor technology and to provide insights for optimizing their PR&PP performance for the benefit of GFR system designers. It updates the GFR 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 GFR SSC, follows the high-level paradigm of the GIF PR&PP Evaluation Methodology to investigate the PR&PP features of the GIF GFR 2400 MWth reference design. The ALLEGRO reactor is also described. The EM2 and HEN MHR reactor are mentioned. An overview of fuel cycle for the GFR reference design and for the ALLEGRO reactor are provided. 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

ANL	Argonne National Laboratory
BOC	Beginning of Cycle
BNL	Brookhaven National Laboratory
CEA	Commissariat à l'Énergie Atomique et aux Énergies Alternatives
CRDM	Control Rod Drive Mechanism
CSD	Control and Shutdown Devices
DIV	Design Information Verification
DHR	Decay Heat Removal
DSD	Diverse Shutdown Devices
EFPD	Equivalent Full Power Days
EM2	Energy Multiplier Module
EOC	End of Cycle
FP	Fission Products
GA	General Atomics
GANEX	Global Actinide Extraction
GFR	Gas-cooled Fast Reactor
GIF	Generation-IV International Forum
GTCS	Gas Turbine Conversion System
HEN	High Energy Neutron
HSS	Helium Supply Service
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
JAEA	Japan Atomic Energy Agency
MA	Minor Actinides
MHR	Modular Helium Reactor
MIT	Massachusetts Institute of Technology
MOX	Mixed Oxide
N3S	Nuclear System Supply System
PP	Physical Protection
PR	Proliferation Resistance
PR&PP	Proliferation Resistance & Physical Protection
PWR	Pressurized Water Reactor
SSC	System Steering Committee
UOX	Uranium Oxide

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1. Overview of Technology

The Gas-cooled Fast reactor (GFR) system features a high temperature helium cooled fast spectrum reactor with a reference indirect combined cycle (incorporating a helium turbine plus a steam generator), for electricity production. GFR operates with a closed fuel cycle, thereby combining the advantages of fast spectrum systems (long term resources sustainability, in terms of use of uranium and waste minimization, through fuel multiple reprocessing and recycling of Plutonium and minor actinides) with those of high temperature operation (high thermal cycle efficiency and the possibility of hydrogen production and other industrial applications).

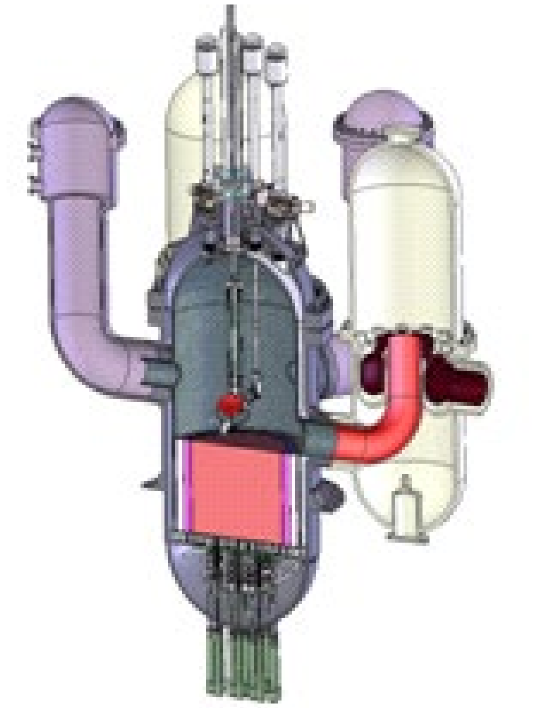
Its development approach is to rely as far as possible, on technologies already used for the High-Temperature Reactor (HTR), but with significant modifications (if not breakthroughs), needed to meet the objectives stated above. Thus, it calls for specific R&D beyond current and planned future work on thermal HTRs.

This document is an update of a previous White Paper [1]. Since the reference GFR system has not been significantly developed since 2011, the present document incorporates mainly minor amendments needed to bring it up to date.

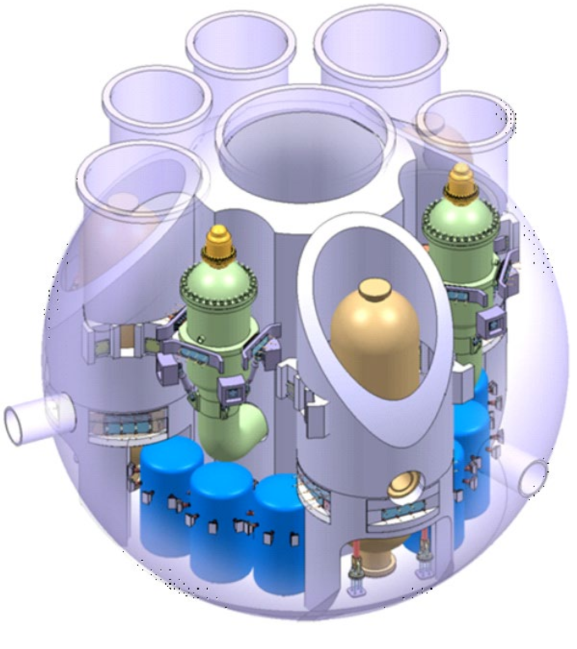
1.1. GFR reference design

A 2400 MWth unit power is chosen as the reference design (see Figure 1) for the pre-conceptual design phase, as the neutronic leakage for a large core is lower compared to a small size unit. It thus makes it easier to design self-sustainable cores with less challenging fuels [2],[3],[4],[5].

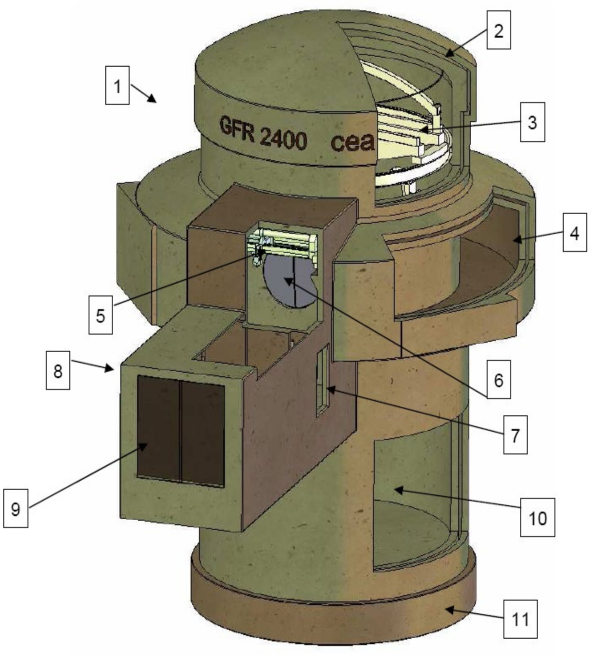
A 100 MW/m^3 power density is also selected as a result of core design optimization with respect to in-core Pu core inventory, safety and economics considerations. However, such a relatively high power density will require appropriate R&D to address decay heat removal challenges in some accident conditions.



Primary circuit & DHR loop



Spherical guard vessel



1. Reactor plant
2. Double wall reinforced concrete structure
3. General crane
4. DHR pools rooms
5. Auxiliary crane
6. Access doors to reactor building
7. Access to fresh fuel building
8. Access to spent fuel building
9. General access doors
10. Reactor pit
11. Reactor raft

The reactor in its containment building

Figure 1: Schematic views of the GFR reference design [3].

GFR cores should be designed to achieve a low pressure drop value in order to facilitate gas circulation during power operation, anticipated operational occurrences, normal shutdown cooling and accidents.

A medium containment pressure safety strategy is chosen for the emergency Decay Heat Removal: this means that the design has to include a guard vessel capable of maintaining a pressure of 0.6 to 1.0 MPa in case of primary circuit failure. The rationale for this is to establish compatibility with very low pumping power for the emergency gas circulation and to offer the possibility to transition to natural circulation at low pressure within a few hours of shutdown. The emergency shutdown cooling system is also designed to remove decay heat under fully depressurized containment conditions under a higher-power operating mode. Finally, a reinforced containment building protects the reactor from external hazards.

The main reactor and fuel parameters are listed in Table 1 below.

Reactor parameters	Design features & Target Values
• Nominal thermal power	• 2400 MWth
• Nominal electrical power	• 1150 MWe
• Lifetime	• ~ 60 years
• Primary coolant	• Helium
• Primary pressure	• 7 MPa
• Core in/out T°	• 400°C / 850°C
Fuel parameters	
• Fuel composition	• UPuC
• Clad	• SiC Composite Matrix Ceramic
• Fuel assembly	• Pins sub-assembly
• Fuel enrichment	• $U_{nat/dep}$ + 15-20% Pu (+ 1% M.A[1].)
• Burn-up	• 50-100 GWd/t

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[1] homogeneously dispersed in all fuel assemblies

• Refueling	• 3 - 5 years
Power unit	
• Cycle	• Closed gas cycle, indirect
• Secondary coolant	• Helium + Nitrogen
• Secondary pressure	• 6,5 MPa
• Secondary loops	• 3 + 3 steam generators
• Conversion	• 1 turbine
• Thermodynamic efficiency	• 45 - 48 %

Table 1: Main GFR parameters for the reference design,

For the power conversion system, the current choice is an indirect combined cycle, as shown in Figure 2 below, with a He-N_2 mixture for the intermediate gas cycle. The thermodynamic efficiency is 44.7%, based on assumed component efficiencies and pressure drops.

The primary helium transfers heat through an intermediate heat exchanger (IHX), to a secondary circuit, using the He-N_2 gas mixture as the working medium, and comprising a gas turbine, a steam generator, and a gas compressor. The steam yielded by the steam generator is used in a conventional steam cycle. Electrical energy is generated partly by the secondary circuit gas turbine, and partly by steam turbines mounted in the tertiary circuit. IHXs are located inside the guard vessel (represented by the orange circle in Figure 2), while the conversion systems are outside the guard vessel.

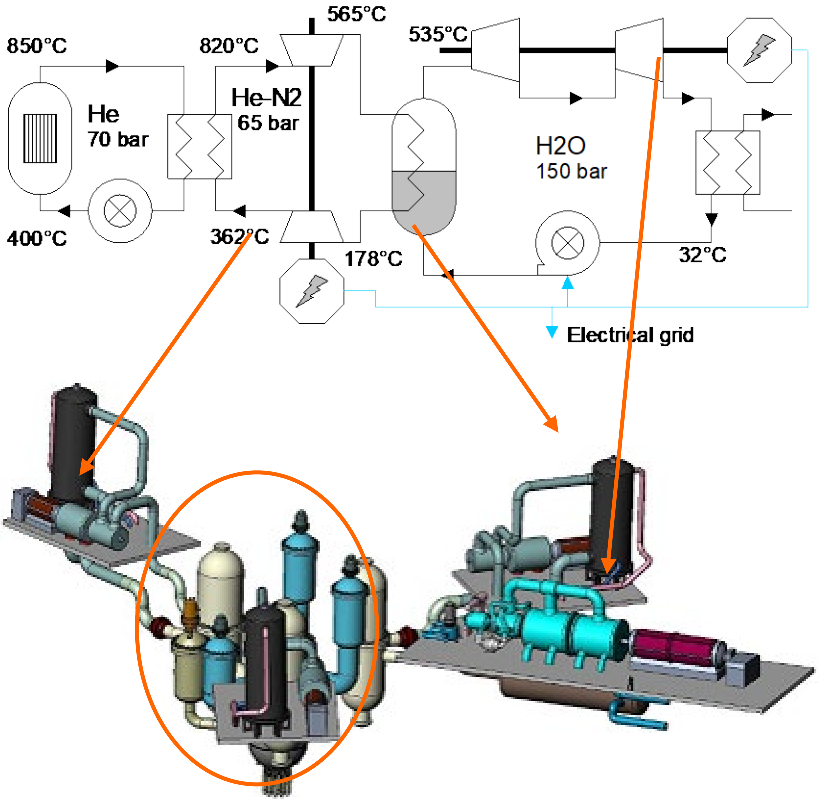

Figure 2: Indirect combined gas/steam power conversion system [3].

Finally, the secondary circuits of the normal and emergency shutdown decay heat removal systems are located outside the guard vessel as shown in Figure 3. The heat sinks of the emergency loops are located inside the containment building so that they are protected from external hazards.

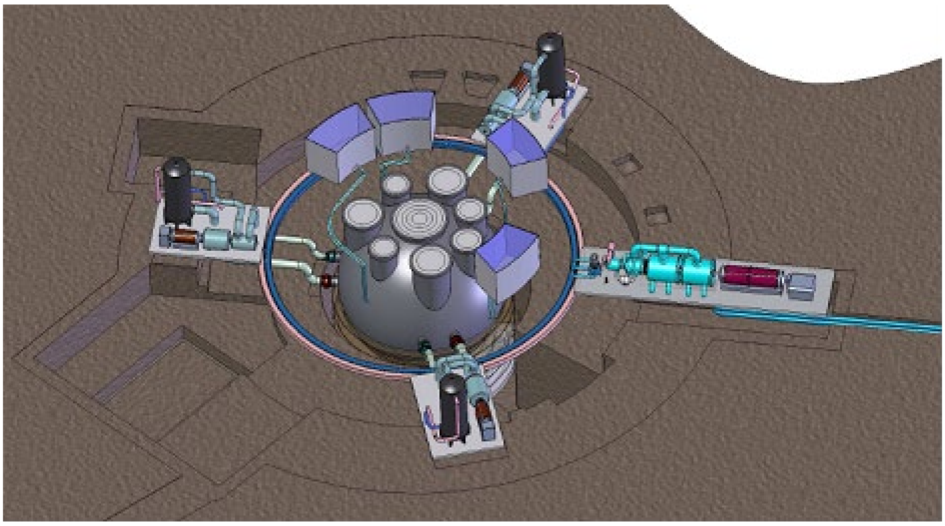

Figure 3: Overview of the secondary and emergency systems connected to the primary circuit through the spherical guard vessel [3].

1.2. ALLEGRO

ALLEGRO is an experimental fast reactor cooled with Helium being developed by the European Consortium “V4G4 Centre of Excellence” composed of the nuclear research organizations of the Czech Republic, Hungary, Poland and Slovakia associated with CEA, France, with the support of the European Sustainable Nuclear Energy Technology Platform. The objectives of ALLEGRO are to demonstrate the viability and to qualify specific GFR technology components such as fuel, the fuel elements, helium-related technologies and specific safety systems, in particular, the decay heat removal function, together with demonstration that these features can be integrated successfully into a representative system.

Starting from a reference design studied up to 2009 at CEA, the project is exploring a new target of nominal power (in the range of 30–75 MW thermal) and power density (in the range 50–100 MW/m^3) compatible with the safety limits and the design requirements [6].

The original design of the ALLEGRO consisted of two He primary circuits, three decay heat removal (DHR) loops integrated in a pressurized cylindrical guard vessel. The secondary gas circuits were connected to gas-air heat exchangers. However, the actual design that has been adopted utilizes two water secondary cooling circuits (Figure 4).

The ALLEGRO reactor would function not only as a demonstration reactor hosting GFR technological experiments, but also as a test pad of using the high temperature coolant of the reactor in a heat exchanger for generating process heat for industrial applications and a research facility which, thanks to the fast neutron spectrum, makes it attractive for fuel and material development and testing of some special devices or other research and development.

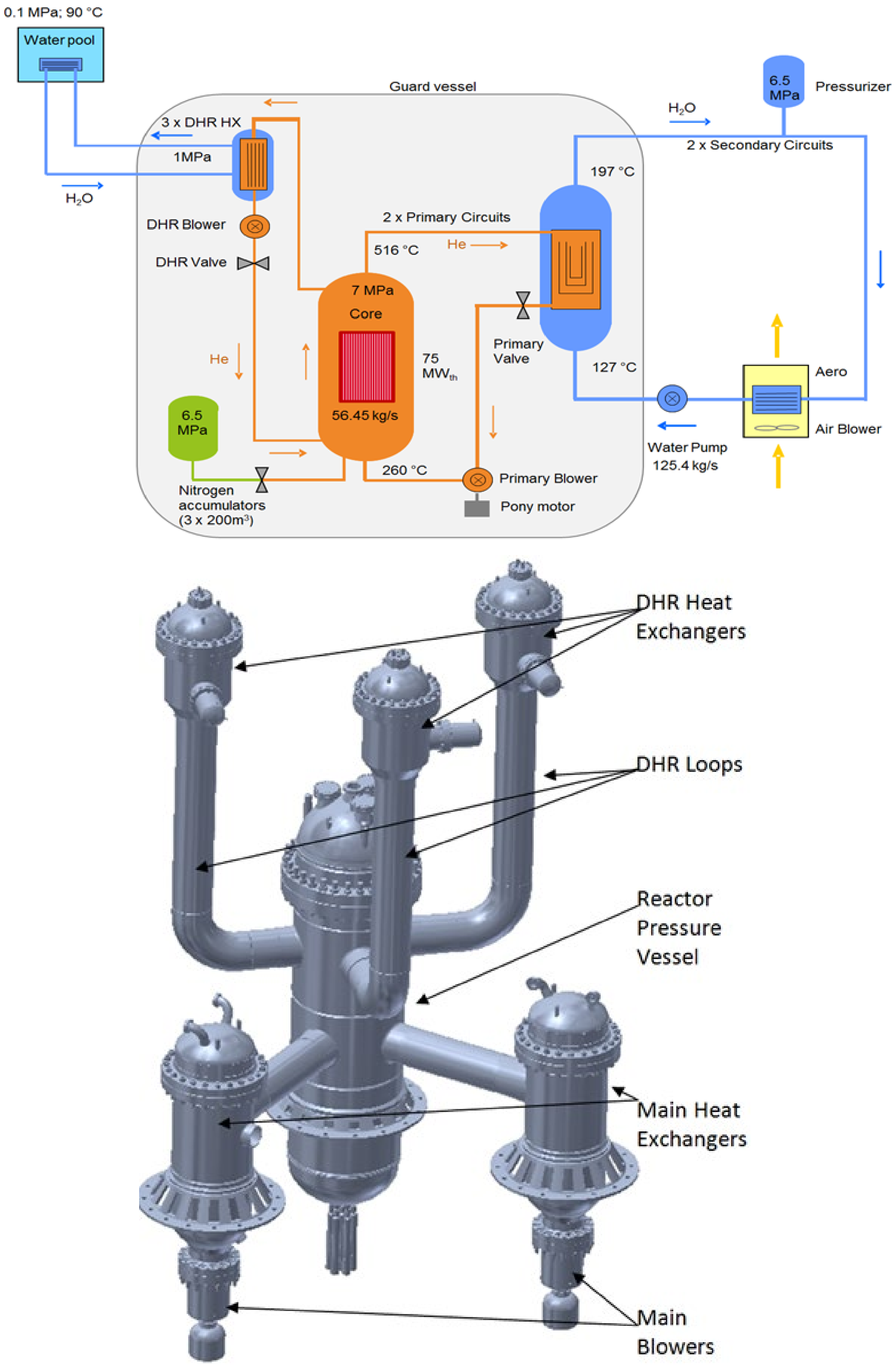

Figure 4: Design of the ALLEGRO demonstrator [7],[8].

The main reactor and fuel parameters for ALLEGRO are listed in Table 2 below.

Reactor parameters	Design features & Target Values
• Nominal thermal power	• 75 MWth
• Nominal electrical power	• 0 MWe
• Primary coolant	• Helium
• Primary pressure	• 7 MPa
• Driver core in/out T°	• 260°C / 530°C
• Experimental fuel in/out T°	• 400°C / 850°C
Driver core fuel parameters	
• Fuel composition	• UOX
• Clad	• 15-15ti Steel
• Fuel assembly	• Pins sub-assembly
• Fuel enrichment	• 18,5 - 19,5%
Heat removal	
• Secondary coolant	• Water
• Secondary pressure	• 6,5 MPa
• Secondary loops	• 2

Table 2: Main ALLEGRO parameters

1.3. EM2

General Atomics (GA) is developing a nuclear concept called the Energy Multiplier Module [9]. EM^2 is a helium-cooled fast reactor with a core outlet temperature of 850°C. It is designed as a modular, grid-capable power source with a net unit output of 265 MWe. The reactor employs a "convert and burn" core design which converts fertile isotopes to fissile material and burns it in situ over a 30-year core life. It can also use a variety of fuels, including spent fuel from light water reactors with no reprocessing, only refabrication.

1.4. HEN MHR

HEN MHR [10] (High Energy Neutron spectrum for a Modular Helium Reactor) was a concept studied between 2004 and 2008 in the context of an international collaboration between USA (ANL as leader, INL for fuel/materials, MIT and BNL for decay heat removal and GA for containment/sizing) and France (CEA and AREVA).

1.5. Other designs

Other designs of Gas-cooled Fast Reactors can be found in the literature. These projects are not investigated within GIF.

2. Overview of Fuel Cycle(s)

2.1. GFR reference design

For the 2400 MWth reference concept operating with a core outlet temperature of 850°C, the core consists of an assembly of hexagonal fuel elements, each consisting of ceramic-clad, mixed-carbide-fuelled pins contained within a ceramic hex-tube. The favoured material at the moment for the pin clad and hextubes is silicon carbide fibre reinforced by amorphous silicon carbide (SiCf/SiC).

The reference cycle for the GFR is a closed cycle where Pu and Minor Actinides are co-recycled, Uranium is separated from the Transuranic isotopes which are reprocessed without separation of Pu. This cycle uses the Global Actinide Extraction (GANEX) process and is called the GANEX cycle.

To facilitate the initial deployment of the reactor technology, a GFR system could be deployed with a simplified fuel cycle where only uranium and plutonium are recycled and where minor actinides are separated and put into waste[9],[11]. This cycle would use the PUREX cycle, which is already in commercial use. This approach has the advantage that the carbide fuel fabrication facility would initially avoid the problem of the high volatility of americium carbide that tends to evaporate during the carbothermal reduction stage.

In both cases, long-lived fission products are separated from the fuel materials and treated as waste. The fabrication of MOX powder is the same as for the sodium-cooled system or PWR MOX fuel. The loss fraction of separated material is 0,1%.

Carbide fuel is obtained through carbothermal reduction under vacuum or nitrogen, with the following chemical reaction:

$$(U,Pu,MA)O_2 + 3C \rightarrow (U,Pu,MA)C + 2CO$$

for UO_2 and PuO_2 powders as starting material. The fabrication process is illustrated in Figure 5.

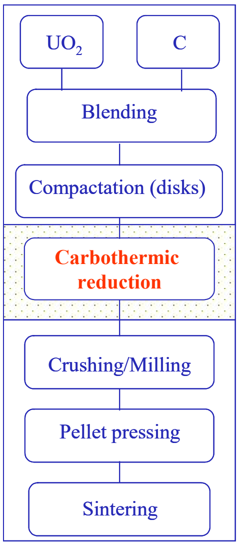

Figure 5: Simplified chart for carbide fuel fabrication

The first core Plutonium isotopic composition is assumed to be the average plutonium composition in France in 2016 and is called Pu2016. For the follow-on cores, the plutonium is obtained from GFR fuel recycling.

Table 3 gives the detailed core data of the reference refractory fuel[11],[12],[13].

Unit thermal power	MW	2400
Power density	MW/m^3	100
Specific power	W/g HM	35,5
Number of fuel assemblies inner core		264
Number of fuel assemblies outer core		252
Number of fuel pins per assembly		217
Core volume	m^3	23,6
Core height / diameter	m	1,65 / 4,268
S/A height	m	5,43
Fissile height	m	1,66
Core pressure drop	MPa	0,054
Fuel type		Carbide
Cladding		SiCf-SiC
Structures		SiC
Volume fractions		
(U,Pu)C	%	27,9
Helium		45,3
Structure matrix SiC		25,9
Liner (W-14%Re/Re)		0,9
Breeding gain		0
Core management	EFPD[2]	3 x 481
Average / Maximum Burn-up	GWd/tHM	50,7 / 74,5
Delayed neutron fraction BOC[3] / EOC[4]	pcm	370 / 361
Doppler BOC / EOC	pcm	-1020 / -876
He void reactivity BOC / EOC	$	0,85 / 0,91

Table 3: Core reference design data for the equilibrium cycle

The respective masses of fissile materials are given in Section 3.

2.2. ALLEGRO

Since the GFR reference fuel described above will require long term R&D effort to be developed and qualified, the first cores of ALLEGRO will use stainless steel cladded fast reactor oxide fuel.

The starting core with low enriched UOX fuel in stainless steel claddings will serve as a driving core for experimental fuel assemblies containing the advanced carbide (ceramic) fuel[7]. Six core positions, depicted as “STEEL” in Figure 6, will be reserved for the development of the refractory fuels through the irradiation of fragments, rods and sub-assemblies. Thermally insulated assemblies will be placed in these positions, where an elevated helium outlet temperature (800-850ºC) will be created by reducing the coolant flow rate.

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[2] Equivalent Full Power Days

[3] Beginning Of Cycle

[4] End Of Cycle

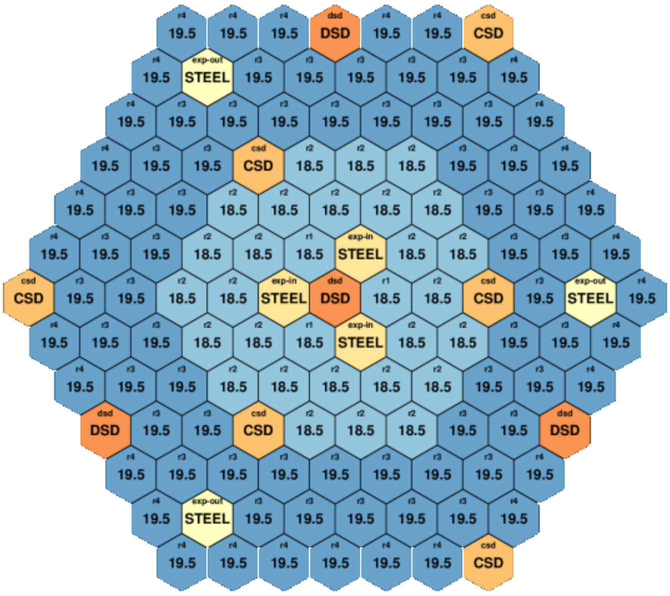


Figure 6: ALLEGRO starting core layout [8] with Control and Shutdown Devices (CSD) and Diverse Shutdown Devices (DSD) (light blue assemblies = 18,5 % enrichment, dark blue = 19.5 %).

When ready, a second generation of core will consist solely of the ceramic fuel and will enable to operate ALLEGRO at the high target temperature.

3. PR&PP Relevant System Elements and Potential Adversary Targets

This section and the following refer only to the GFR reference system, and not to ALLEGRO and other systems, which are not studied in the frame of GIF.

The PR & PP analysis has been conducted for the reference GFR system elements and targets and is consistent with the recommendations of the GIF PRPPWG methodology [14].

3.1. Relevant system elements

Presently, a GFR plant is seen as a single unit with its fresh and spent fuel management and storage unit. The fuel reprocessing and fabrication unit (which is not described here) is located outside and radioactive materials are transported by trucks.

The reactor site being considered as the nuclear system, its elements are the following:

- the fresh fuel reception area,
- the interim storage and operation unit,
- the reactor(s),
- the spent fuel storage building,
- the spent fuel shipping area.

For a single reactor plant, the nuclear system can be schematically represented as in Figure 7.

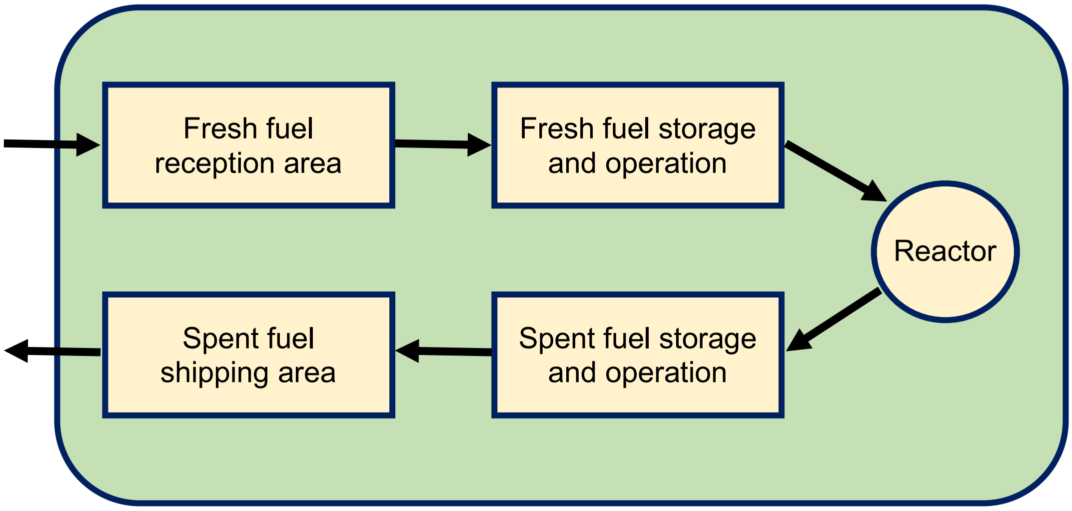
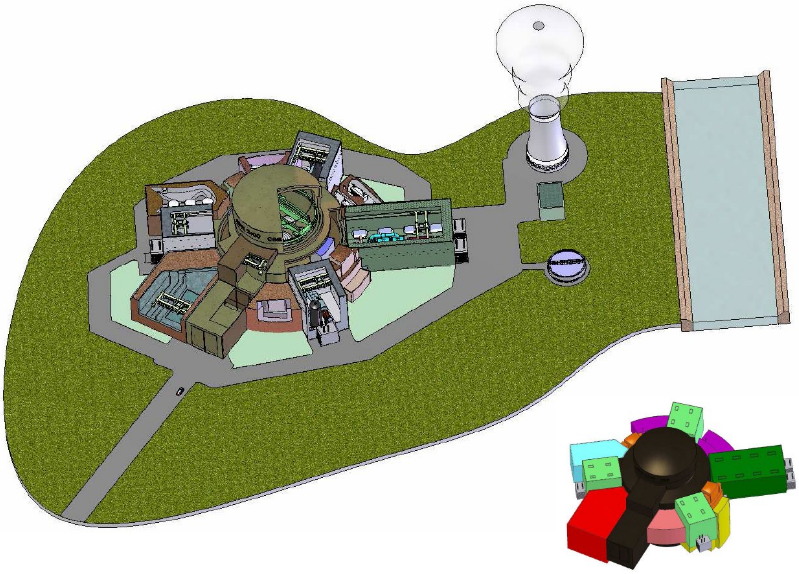


Figure 7: PR&PP relevant nuclear system elements for GFR.

Figure 8 illustrates a layout that might be adopted for a generic GFR plant.



Colour legend:

Red	Spent fuel storage building (bunker)
Pink	Fresh fuel storage and operation building
Light green	GTCS building (x3)
Dark green	N3S building
Purple	Diesel bunker type building (x2)
Orange	Control command operation building (bunker) (x2)
Yellow	Access to HSS and CRDM's handling building
Light blue	Helium and Nitrogen tanks storage (bunker)
Black	Reactor plant

Figure 8: General design of a GFR plant layout [3] (HSS = Helium Supply Service; GTCS = Gas Turbine Conversion System; N3S = Nuclear Steam Supply System; CRDM = Control Rod Drive Mechanism).

Fresh fuel assemblies, where fuel element bundles are enclosed in a canister, are delivered by truck to the interim storage unit. They are stored in air.

Spent fuel assemblies are discharged from the reactor building in the pool storage unit (in water). This unit is designed as a protective bunker to prevent external hazards and theft of nuclear/radiological material.

Materials movements between the different system elements involve the transfer of intact fuel assemblies, in air or under water. Surveillance and accounting safeguards will ensure that diversion of declared material will be detected. At this stage, the low maturity level of the GFR design gives the opportunity to envisage many other safeguard systems (monitoring cameras, neutron and gamma detectors, mass measurement equipment, tag identification systems…) and to specify their optimal locations inside the plant system elements.

With respect to the physical protection of the site, the GFR design appears to be fully compatible with the systems and procedures that are applied to existing reactors.

3.2. Potential adversary targets

Uranium and plutonium are the main targets in terms of materials attractiveness. For the GFR reference design, Table 4 reports the mass inventories at the beginning / end of cycle.

In core Pu inventory	t/GWe	10,1
Mean Pu content	%	16,1
Mass inventories BOC / EOC	kg	
U		56034 / 52247
Pu		10888 / 11166
Np		59 / 65
Am		436 / 382
Cm		112 / 131

Table 4: Overall material mass inventory at the beginning / end of cycle for the GFR reference design.

The following Table gives the U and Pu isotopic fractions for fresh and spent fuel.

	Uranium isotopic fractions (wt %)				Plutonium isotopic fractions (wt %)				
	^{234}U	^{235}U	^{236}U	^{238}U	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Fresh fuel	0.25	0.16	0.26	99.33	2.90	53.92	36.42	2.68	4.08
Spent fuel	0.27	0.16	0.30	99.27	2.88	52.73	35.79	4.58	4.01

Table 5: Relative U and Pu isotopic mass fractions at the beginning / end of cycle.

Given the overall number of assemblies in the core (see Table 3), each fresh or spent fuel assembly contains more than one significant quantity [5] of reactor-grade Pu [6].

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

[6] The GIF PR&PP Evaluation Methodology categorizes the nuclear material 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”. See the Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems - Revision 6,Technical report, Generation IV International Forum (GIF), 2011.

4. Proliferation Resistance Considerations Incorporated into Design

Inherent Proliferation Resistance mainly arises in connection with the fuel cycle. It is based on the idea of avoiding the separation of certain trans-uranic elements from uranium. Contributions to Inherent Proliferation Resistance can be claimed to come from the following features:

- Fissile materials are diluted in the fuel matrix;
- There is no use of enriched U; reprocessed U or depleted U;
- Low grade Pu coming from PWR irradiated fuel is used;
- Fresh fuel elements or sub-assemblies will incorporate Minor Actinides increasing radiation levels (see detailed discussion[15] conducted for other Generation IV systems).

Finally, fuel elements are not separated from their sub-assembly on reactor site, and the presence of the wire wrapped around each pin and the substantial intra-assembly structures above and below the fuel pins increase the technical difficulty of a clandestine pin extraction. This means that the potential targets are entire fuel assemblies rather than individual pins, increasing the logistical difficulties involved in fuel handling and transport.

4.1. Concealed diversion or production of material

Concealed diversion or production of material is deterred primarily by the application of effective international safeguards. The GFR shares a similar fuel cycle with other fast reactors that use aqueous processing with group extraction of actinides, and thus would use similar safeguards methods. Because the GFR shares its closed fuel cycle technology with other Gen IV reactor types, the PR&PP for the reprocessing element is not discussed here and is instead treated as a crosscutting PR&PP evaluation topic related to the fuel cycle architecture.

Fuel fabrication processes have not been considered within the scope of the Gen IV GFR System Steering Committee, so information is not available. It is assumed, however, that these fabrication processes will share safeguards approaches and PR&PP characteristics with other Gen IV ceramic fuel fabrication technologies. The major variants will depend upon whether the fuels involve recycling of plutonium in glove boxes, with separate fabrication of minor actinide targets, or full transuranic recycling with fabrication in hot cells.

In terms of the onsite storage and handling system, the GFR reference design is not mature enough to study potential scenarios for the concealed diversion of entire fuel assemblies. However, unexpected handling actions would be easily detected by cameras and neutron detectors.

In terms of fuel transport, it is likely that safeguards protocols that will be at least as effective as for other reactors.

Undeclared production of valuable material would require one to irradiate a suitable number of target pins. Once again, due to the presence of the wire wrapped around each pin, such a scenario of clandestine pin replacement is highly unlikely on reactor site. However, a potential scenario for undeclared production would be to insert a few target pins while preparing the assemblies at the fuel fabrication facility and to divert them at the reprocessing facility. In this scenario, the proliferating action performed onsite would just be irradiation, and it reasonably could be possible and hard to detect. With a few fertile pins, the quantities of fissile material would be very small, so although the scenario would be difficult to detect, its impact would be limited. To be effective for ^{239}Pu breeding, it would be necessary to irradiate tonne quantities of ^{238}U and this implies a large number of pins, possibly an unfeasible amount. This helps ensure that undeclared production of a Significant Quantity of fissile material is unlikely to be practical. In addition, the insertion of a fresh fuel assembly entirely filled with target pins could be easily detected by assembly temperature monitoring due to the abnormal temperature level.

4.2. Breakout

It is expected that GFRs will operate in fuel cycle states that will also provide other fuel cycle services including enrichment. In the longer term, in the objective of a closed fuel cycle, GFRs may eliminate the need to perform enrichment. GFRs operate with plutonium isotopics ranging from reactor-grade to deep-burn grade. In a case where GFRs will use breeding blankets, as envisaged for other fast neutron systems, one possibility is to use fertile blankets loaded with Minor Actinides (MA). In such a case, MA and U are mixed in the fresh blanket and produce Pu and transmute MA under irradiation. The global isotopics of the blanket fuel never give access to pure Pu. Because breakout would focus on misuse of fuel cycle facilities, GFR breakout pathways are likely to be similar to pathways for other fast reactors using aqueous recycling technologies.

4.3. Production in clandestine facilities

Compared with actual Gen II or Gen III light water reactors, a GFR will not ease the production of Pu in clandestine facilities. However, the GFR technology reduces demand for enrichment services and thus also reduces incentive to expand enrichment capacity, potentially in states that do not currently have enrichment skills and equipment.

5. Physical Protection Considerations Incorporated into Design

Physical Protection is mainly connected today to the reactor system. It is based on the idea that a robust containment building should protect the core from external hazards. Some specific buildings, that need to provide a safety function, are also re-enforced to resist external hazards. The following protective measures are incorporated in the design:

- a pre-stressed concrete containment building;
- decay heat removal can be achieved by natural circulation of the gas in most accident sequences;
- main safety buildings (control room, diesel place, gas storage) are designed as protective bunkers (see figure 8).

In addition, the GFR can cite characteristics such as inertness of the Helium coolant and specifically the absence of chemical reactions and phase changes provided by this coolant.

Another helpful feature is the intrinsic ability of refractory fuel to sustain very high temperature:

- Clad ~1600 °C without FPs release
- Clad ~2000 °C without loss of geometry

For instance, a spent fuel sub-assembly behaves naturally safe (without any forced cooling) during handling.

5.1. Theft of material for nuclear explosives

As stated in the previous section, the high radiation level of either fresh or spent fuel elements or sub-assemblies prevent them from being easily stolen on reactor site, and standard safeguards should provide effective protection of the remote fuel handling systems from misuse.

The GFR has a similar fuel cycle with other fast reactor technologies that use centralized, aqueous reprocessing. The fresh fuel used in the GFR provides the most attractive target for theft, since it has the lowest level of contamination with fission products. In the case where the fuel is produced using group extraction of actinides, the radiation levels in fresh fuel requires significant biological shielding, which can also be designed to provide a passive barrier to theft. The GFR uses an advanced ceramic fuel design which requires a reprocessing technology not very different from the one used for conventional oxide fast reactor fuel (access to the fissile matter is made first through cutting the ceramic cladding and then nitric acid dissolves the fuel part).

5.2. Radiological sabotage

The GFR has both a containment building and a guard vessel that provide physical isolation and protection to the primary system. In case of a breach of the primary containment caused by a direct attack, the inert behavior of Helium minimizes the consequences of an environmental hazard (no fire nor explosion).

Even if they are bunkerised, the water storage pools where the spent fuel assemblies are cooled can also be the target of a direct attack. The ability of the SiCf/SiC cladding to withstand temperatures up to 2000°C provides time for hazard mitigation.

The normal shutdown cooling system relies on the power conversion system, for hot shutdown states and for short-term cooling (typically one week) following transition to cold shutdown states. It is located outside the containment building. For longer term hot shutdown and for cold shutdown states, the first level of emergency decay heat removal loops are used, as far as a sufficient pressure level is maintained in the primary circuit (typically more than 0.5 MPa). If this system fails, the second level of emergency cooling system carries on the safety function.

The second level can operate at low pressure. Those emergency systems are located inside the containment building but their ultimate heat sink is outside the reactor building (river or air cooling tower, see Figure 9). The first level system is operated through diverse AC power sources (external grid current, floating batteries, diesels) as it needs a limited electric power supply (typically 150 kWe per loop). This is not the case for the second level system that needs higher power supply (typically 500 kWe per loop). Each system is redundant with two or three loops.

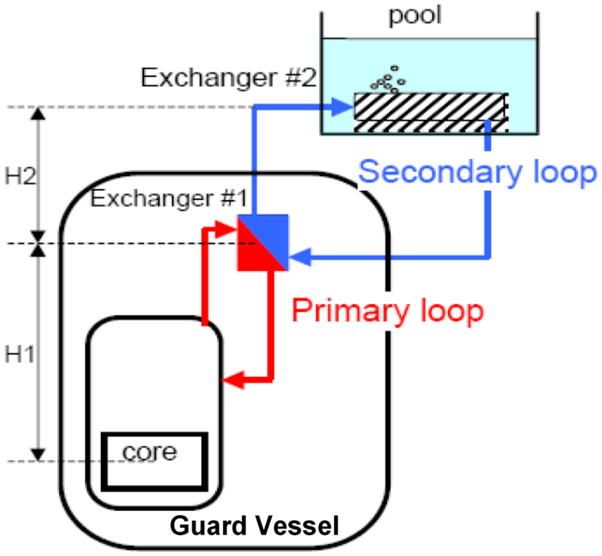

Figure 9: Schematic of the emergency cooling systems, from the core to the ultimate heat sink.

Major R&D effort is still needed to further improve provision for core cooling in accident conditions and to practically remove the risk of severe accidents in GFR.

The heat sinks of the emergency loops are inside the containment building so that they are protected from external hazards and sabotage threats.

6. PR&PP Issues, Concerns and Benefits

GFRs share similar safeguards and non-proliferation characteristics with other fast neutron reactor systems (either sodium or lead-cooled).

For proliferation resistance, the GFR's fuel cycle is the same as the one for SFR with aqueous recycling, using depleted U and high Pu content MOX fuel. Only slight distinguishing features can be cited due to the cladding and the fissile materials (respectively ceramic matrix composite and mixed carbide) or due to a specific design of the fuel element (honeycomb plate fuel element). At first, those differences do not affect the level of resistance to proliferation as we can evaluate it today.

It is difficult to discuss proliferation resistance issues in a context of an agreement where only the reactor and its fuel are studied. This is the case of the GFR steering committee. A large part of safeguards will come from international rules and controls, and by monitoring fuel composition all along the fuel cycle. These are common issues for all Gen IV reactors using aqueous recycling technologies.

For physical protection, the present design of GFRs relies on many of the same protective measures used in PWRs (mainly with a reactor containment building) given the fact that inert gas is used as a primary coolant. A guard vessel that envelopes the primary system should give an additional level of protection. Specific attention should be paid to the protection of the emergency cooling systems on which the global safety of GFRs relies.

Beyond these factors, there are the uncertainties associated with a system that is not precisely defined today. Much of the development of proliferation resistance and physical protection characteristics for reactors is a result of careful examination of systems and interactions by designers, the nonproliferation community, the weapons community, and the physical protection community. Only such interactions over a period of time can provide high confidence about the actual characteristics of an advanced reactor.

In summary, the areas requiring R&D to study and optimize the PR&PP characteristics of GFRs are:

- Ensure that a comprehensive evaluation of the PR&PP characteristics of the GFR includes the fuel cycle processes that are common to other GEN IV reactor systems.
- Identify the sensitivities of emergency shutdown cooling systems to external hazards.

A summary of the main PR relevant intrinsic design features of the GFR reference design is presented in Appendix 1 according to the IAEA document Proliferation Resistance Fundamentals for Future Nuclear Energy Systems [16].

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APPENDIX 1: Summary of PR relevant intrinsic design features. Reference IAEA-STR-332. Please refer to IAEA-STR-332, for full explanations and complete definitions of terms and concepts [16].

Summary of PR relevant Intrinsic design features	**GFR reference design**
Features reducing the attractiveness of the technology for nuclear weapons programmes	
1. The Reactor Technology needs an enrichment Fuel Cycle phase	No.
2. The Reactor Technology produces SF with low % of fissile plutonium	The mass fraction of Pu evolves between 16 % and 17 % during an irradiation cycle. The quality of Pu remains reactor grade during the irradiation cycle.
3. Fissile material recycling performed without full separation from fission products	The reference cycle is a closed one, where Pu and Minor Actinides are jointly recycled.
Features preventing or inhibiting diversion of nuclear material	
4. Fuel assemblies are large & difficult to dismantle	Each assembly contains 217 pins, without the possibility of being disassembled on reactor site. Individual pin extraction is impossible due to the presence of the wrapped wire.
5. Fissile material in fuel is difficult to extract	With the GFR carbide fuel, the GANEX process is more difficult to operate than PUREX process for standard UOx/MOX fuel.
6. Fuel cycle facilities have few points of access to nuclear material, especially in separated form	In the objective of a closed fuel cycle, the radiation level is very high and the nuclear materials are not separated.
7. Fuel cycle facilities can only be operated to process declared feed materials in declared quantities	Safeguards should detect undeclared material processing.
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	No blanket is foreseen in the reference GFR 2400 design.
9. The core prevents operation of the reactor with undeclared target materials (e.g. small reactivity margins)	The 2400 MWth core would not become subcritical if one assembly were to be replaced by an U target assembly, but safeguards would detect it.
10. Facilities are difficult to modify for undeclared production of nuclear material	The insertion of a few target pins in a fuel assembly would not be possible onsite.
11. The core is not accessible during reactor operation	The primary circuit operates at 7 MPa and, with Helium as primary coolant, the radiation level is high.
12. Uranium enrichment plants (if needed) cannot be used to produce HEU	No enrichment is required.
Features facilitating verification, including continuity of knowledge	
13. The system allows for unambiguous Design Information Verification (DIV) throughout life cycle	DIV should be straightforward.

Summary of PR relevant Intrinsic design features	**GFR reference design**
14. The inventory and flow of nuclear material can be specified and accounted for in the clearest possible manner	Yes, at least in a similar way to Gen II & III reactors.
15. Nuclear materials remain accessible for verification the greatest practical extent	The coolant transparency eases the monitoring and identification of fuel assemblies.
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	The coolant transparency eases the monitoring and identification of fuel assemblies.
17. The system provides for the installation of measurement instruments, surveillance equipment and supporting infrastructure likely to be needed for verification	Yes, at least in a similar way to Gen II & III reactors.

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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