Proliferation Resistance Considerations within the Collaborative Project for a European Sodium Fast Reactor

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Abstract:

The collaborative project for a European Sodium Fast Reactor (CP-ESFR) is an international project where 25 European partners developed R&D solutions and concepts for a European sodium fast reactor. The project was funded by the 7th EU Framework Programme and covered topics such that the fuel, the fuel element and the fuel cycle, the safety concepts, the reactor architectures and components and the balance of plant. Within sub-project 3, dedicated to safety, a task addressed proliferation resistance considerations. The Generation IV International Forum (GIF) Proliferation Resistance & Physical Protection (PR&PP) Evaluation Methodology has been selected as the general framework for this work, complemented by punctual aspects of IAEA-INPRO Proliferation Resistance (PR) assessment methodology and other literature studies in particular for material type characterization. In the paper the main core characteristics and the so called working horses, for a loop and a pool Sodium fast reactor concept are firstly presented, by highlighting those features more relevant for the proliferation resistance. Selected activities carried out in the project for its proliferation resistance considerations are then illustrated.

Keywords: proliferation resistance; sodium fast reactors; PR&PP.

1. Introduction

The collaborative project on the sodium fast reactor (CP-ESFR) [1] is an international project where 25 European partners develop R&D solutions for a European Sodium Fast Reactor concept [2, 3]. The Project explores aspects related to the main design aspects of the system, such as the fuel, the fuel element and the fuel cycle, the safety concepts, the reactor architectures and its components and the balance of plant. Within sub-project 3, dedicated to the system's safety concepts, a specific task led by JRC-ITU, with contributions of AREVA, EdF and ENEA addressed proliferation resistance issues [4].

The aim of this task was to propose an approach to evaluate the level of protection of a given NPP design with respect to nuclear proliferation. Before doing applied studies, an approach was to be defined to take into account the methods and the parameters used to evaluate the proliferation resistance aspects of interest. This had to integrate the contributions of the Generation IV International Forum (GIF) Proliferation Resistance & Physical Protection working group (PR&PP) activities [5, 6], as well as the activities on proliferation resistance (PR) carried out within the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) of IAEA [7]. In order to collect the system's PR relevant information, the structure of the GIF PR&PP White papers [8] has been chosen, and following it a reflection on the system's possible response to the GIF proliferation threats (concealed diversion, concealed misuse, breakout and replication of technology on clandestine sites) has been performed in a qualitative way.

Since a full PR analysis for the entire system was beyond the scope of this task, the high level reflections made following the GIF white paper helped in identifying the diversion scenario as the most interesting one to investigate further. The focus was therefore put on a more detailed analysis of the

impact of the core alternatives under consideration on a potential diversion scenario. The study identified the potential diversion targets, the potential diversion points for each target and performed an analysis of the attractiveness of the available targets for a potential proliferant State. This activity has been carried out taking the GIF Proliferation Resistance and Physical Protection Evaluation Methodology (GIF PR&PP EM) [5] and its Addendum [6] as the general guideline for identifying targets and potential diversion points. The targets proliferation attractiveness has been analyzed in terms of the suitability of the targets' nuclear material as the basis for a weaponization stage. Since the PR&PP Fissile Material Type measure was felt too coarse for a thorough investigation, other literature studies and their related metrics have been applied [7, 9, 10, 11] to the nuclear material items present in the considered core alternatives [4, 12].

A nuclear system's proliferation resistance emerges from the synergy of intrinsic features and institutional measures. To provide some guidance to ESFR designers in terms of features that would facilitate the application of international safeguards to their system, a high-level safeguardability analysis was performed, and two possible illustrative safeguards approaches for the ESFR system were proposed, one based on near real time monitoring of the nuclear inventory and one based on current practice in European water reactors.

This paper will summarize the main ESFR design aspects relevant for PR and illustrate the high level reflections made following the GIF white paper by presenting the structure of the GIF PR&PP White Paper template and its application to the ESFR reactor.

2. The GIF PR&PP White Paper Template on six Generation IV systems

In 2011 The Generation IV Proliferation Resistance and Physical Protection Evaluation Methodology Working Group and the six System Steering Committees of the Generation IV International Forum published a joint report [8] illustrating the main PR and PP features of the six Generation IV conceptual designs (gas-cooled fast reactor – GFR -, very-high-temperature reactor – VHTR -, supercritical-water-cooled reactor – SCWR -, sodium-cooled fast reactor – SFR -, lead-cooled fast reactor – LFR -, molten salt reactor – MSR -), together with a number of common cross-cutting issues.

The report was the outcome of a joint effort of the above-mentioned groups, implying a close collaboration via workshops and the compilation of a PR&PP White Paper template for each of the six designs. The structure of the White Paper template aims to capture the relevant pieces of information needed for a PR&PP analysis – PR&PP relevant design description and PR&PP considerations - in a structured way, and foresees the following chapters [8]:

1. Overview of Technology
2. Overview of Fuel Cycle(s)
3. PR&PP Relevant System Elements and Potential Adversary Targets
4. Proliferation Resistance Considerations Incorporated into Design
5. Physical Protection Considerations Incorporated into Design

For the compilation of chapters 3 (PR&PP Relevant System Elements and Potential Adversary Targets), 4 (Proliferation Resistance Considerations Incorporated into Design) and 5 (Physical Protection Considerations Incorporated into Design), the activity foresees the application of the PR&PP Evaluation Methodology framework, illustrated in Figure 1.

The Generation IV International Forum defines proliferation resistance as "*that characteristic of an NES that impedes the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other nuclear explosive devices*" [5]. According to the PR&PP methodology the proliferation threats to be considered for a host state actor are 1) *Concealed diversion,* 2) *Concealed production of nuclear material,* 3) *Breakout* and 4) *Production in clandestine facilities*. Threats of non-state actors are addressed in the context of physical protection and will not be further considered here.

A full PR evaluation of the systems design was beyond the scope of the project. The GIF PR&PP methodology framework has been used to decompose the system into system elements and to

identify and characterize potential diversion targets. The analysis then focused on high-level considerations on the four above-mentioned proliferation threats.

Given the outcome of the compilation of the ESFR White Paper draft, the activity deepened the analysis on the aspects that were considered to be more relevant for the project, i.e. targets characterizations in terms of nuclear material attractiveness for a proliferator and safeguardability considerations[1]. Limited diversion analysis were also carried out to identify for the different diversion targets, possible diversion points, related strategies, and an high level description of the pathways and of the proliferation actions.[1].

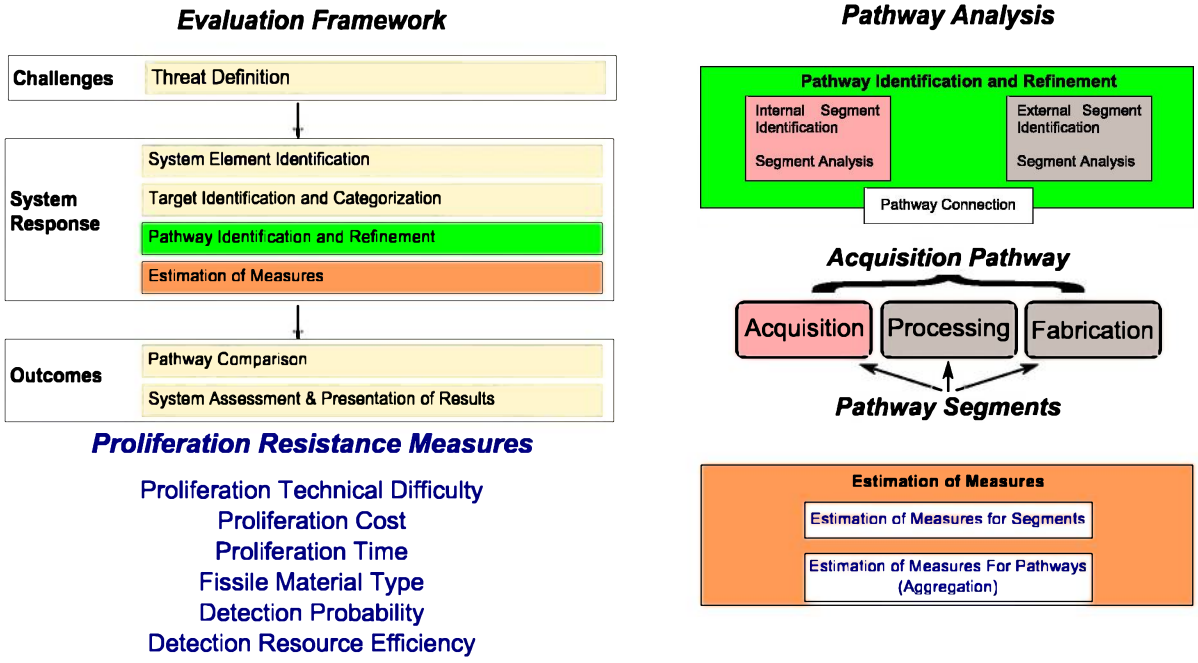


Figure 1: The GIF PR&PP methodology framework [5].

The following sections will illustrate the analysis carried out and therefore follows the above-described structure.

3. Aspects of the ESFR design relevant to proliferation resistance (Overview of Technology)

Two concepts of 1500 MWe reactors called "Working Horses" have been proposed in the context of CP ESFR: a pool and a loop design. For both designs, two core options have been considered: one with U and Pu oxide fuel and the other with U and Pu carbide fuel. For both carbide and oxide cores, the inner and outer fuel regions have different Pu mass content. The reactor architectures and the core of the working horses are shown in Figure 2, for the oxide fuel option.

A comparison of the working horses' characteristics with respect to the sodium fast reactor designs considered in the GIF sodium fast reactor white paper [8] is shown in Table 1.

[1] These aspects, covered by the task activities, will not be presented in this paper.

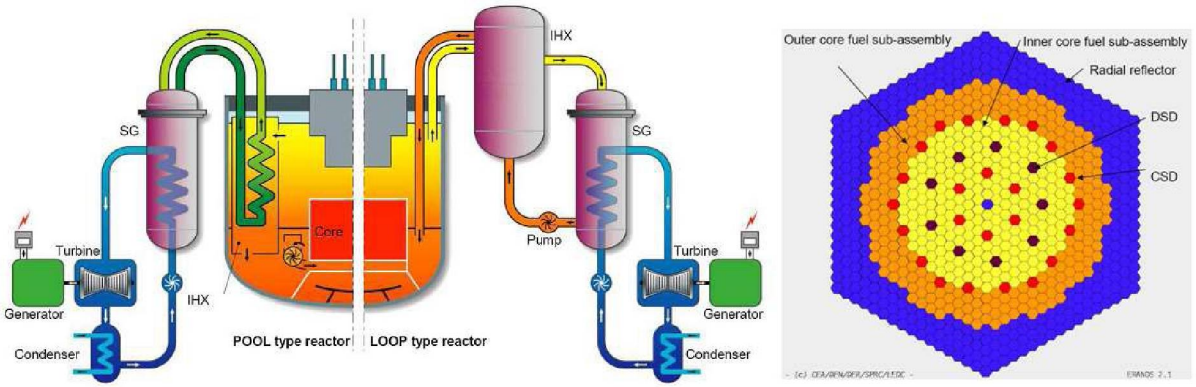


Figure 2: Schematic diagram of reactor architectures of the two ESFR working horses [13] and the SFR core with oxide fuel, no blanket case. CFD stands for Control and Shutdown device; DSD stands for Diverse Shutdown System. [14]

The systems could be used for minor actinide (MA) management, either in homogeneous or heterogeneous mode. Homogeneous MA management basically consists in replacing part of the uranium in the fresh fuel elements with minor actinides (4% MA), while heterogeneous MA management considers an additional radial blanket ring of fuel assemblies (FA) for the specified 'working horse' core [6].

Fresh radial blanket assemblies, when present, are always composed of depleted UO_2 (80%) and MAs (20%). The project partners investigated the possibility to perform MA management only within the oxide core.

Table 2 presents the main characteristics of the CP-ESFR fresh fuel elements, Table 3 reports the plutonium vector of the fresh fuel assemblies when homogeneous MA transmutation is considered, and Table 4 illustrates the related MA composition. The fresh fuel assemblies contain reactor-grade plutonium coming from spent LWR reprocessed fuel.

	SFR Design Concepts in [8]			ESFR	
Design Parameters	**JSFR[2]**	**KALIMER[3]**	**SMFR[4]**	**Oxide**	**Carbide**
Power Rating, MWe	1,500	600	50	1500	
Thermal Power, MWt	3,570	1,525	125	3600	
Plant Efficiency, %	42	42	~38	42	
Core outlet coolant temperature, °C	550	545	~510	545	
Core inlet coolant temperature, °C	395	370	~355	395	
Main steam temperature, °C	503	495	480	470	
Main steam Pressure, MPa	16.7	16.5	20	18.5	
Cycle length, years	1.5–2.2	1.5	30	2050 EFPD[5]	1600 EFPD
Fuel reload batch, batches	4	4	1	5	3
Core Diameter, m	5.1	3.5	1.75	4.72	4.10
Core Height, m	1.0	0.8	1.0	1.0	0.8
Fuel Type	MOX(TRU bearing)	Metal(U-TRU-10%Zr Alloy),	Metal(U-TRU-10%Zr Alloy),	$(U,Pu)O_2$	(U,Pu)C
Pu enrichment (Pu/HM), %	13.8	24.9	15.0	14.05-16.35	17.80-24.50
Burn-up, GWd/t	150	79	~87	100	144
Breeding ratio	1.0–1.2	1.0	1.0	-	-

Table 1: CP-ESFR reference cores characteristics compared with the SFR systems mentioned in [8].

[2] JAEA Sodium Fast Reactor. The system foresees a loop design [8].
[3] Korean pool-type SFR design [8].
[4] US pool-type Small Modular SFR design [8].
[5] Effective Full Power Days.

	Oxide Core	Carbide Core
Pu mass content (inner fuel region) (%)	14.05	17.8
Pu mass content (outer fuel region) (%)	16.35	24.5
Pu mass per item	> 1SQ[6]	> 1SQ

Table 2: Main characteristics of the CP-ESFR reference cores fresh fuel assemblies [4].

Pu Isotope	**^{238}Pu**	**^{239}Pu**	**^{240}Pu**	**^{241}Pu**	**^{242}Pu**
% w	3.60	47.76	29.89	8.29	10.46

Table 3: Pu vector for CP-ESFR reference cores fresh fuel assemblies in case of homogeneous MA transmutation [15].

Isotope	**^{237}Np**	**^{241}Am**	**^{242m}Am**	**^{243}Am**	**^{242}Cm**	**^{243}Cm**	**^{244}Cm**	**^{245}Cm**	**^{246}Cm**
% w	16.86	60.62	0.24	15.70	0.02	0.07	5.14	1.26	0.09

Table 4: MA composition of the CP-ESFR reference cores fresh fuel assemblies in case of homogeneous MA transmutation [15].

The original core options ("reference cores") have subsequently been subject to further analysis and new variants were put on the table for consideration ("optimized cores"). As long as PR is considered, the major design variation of the optimized cores is the availability of an axial blanket beneath the active part of the fuel element.

The main difference between the optimized and reference cores characteristics are reported in Table 5.

	Oxide Core		Carbide Core	
	Reference Core	**Optimised Core**	**Reference Core**	**Optimized Core**
Number of Inner core S/A	225	225	168	225
Number of Outer Core S/A	228	228	246	228
Active Core Height (m)	1.0	1.0	0.8	1.0
Number of fuel pins per sub-assembly	271	271	331	271
Outer clad diameter (mm)	10.73	10.73	8.0	8.5
Inner clad diameter (mm)	9.73	9.73	7.0	7.5
Fuel pellet diameter (mm)	9.43	9.43	6.87	7.37
Fuel pellet material	$(U, Pu)O_2$	$(U, Pu)O_2$	(U, Pu)C	(U, Pu)C
Inner Core Fuel Enrichment (atom%)	14.05	14.76	17.8	14.05
Outer Core Fuel Enrichment (atom%)	16.35	17.15	24.5	18.35

Table 5: Comparison of reference and optimized cores characteristics [17].

[6] The IAEA defines the significant quantity (SQ) as the approximate amount of NM for which the possibility of manufacturing a nuclear explosive device cannot be excluded. A SQ for Pu, containing less than 80% ^{238}Pu, is 8 kg [16].

4. ESFR PR relevant system elements and potential adversary targets

As defined in [5], "*PR relevant system elements"* are defined as a *"collection of facilities inside the identified nuclear energy system (NES) where nuclear material diversion/acquisition and/or processing, as well as theft or radiological sabotage could take place*", and proliferation targets are "*nuclear material that can be diverted or equipment/processes that can be misused to process undeclared nuclear materials or can be replicated in an undeclared facility*".

Figure 3 shows the basic system elements for both pool and loop type working horses[7]. Although the in vessel fuel handling systems of the reactors are different for pool and loop reactor types, both designs share the same conceptual system elements, shown in Figure 3.

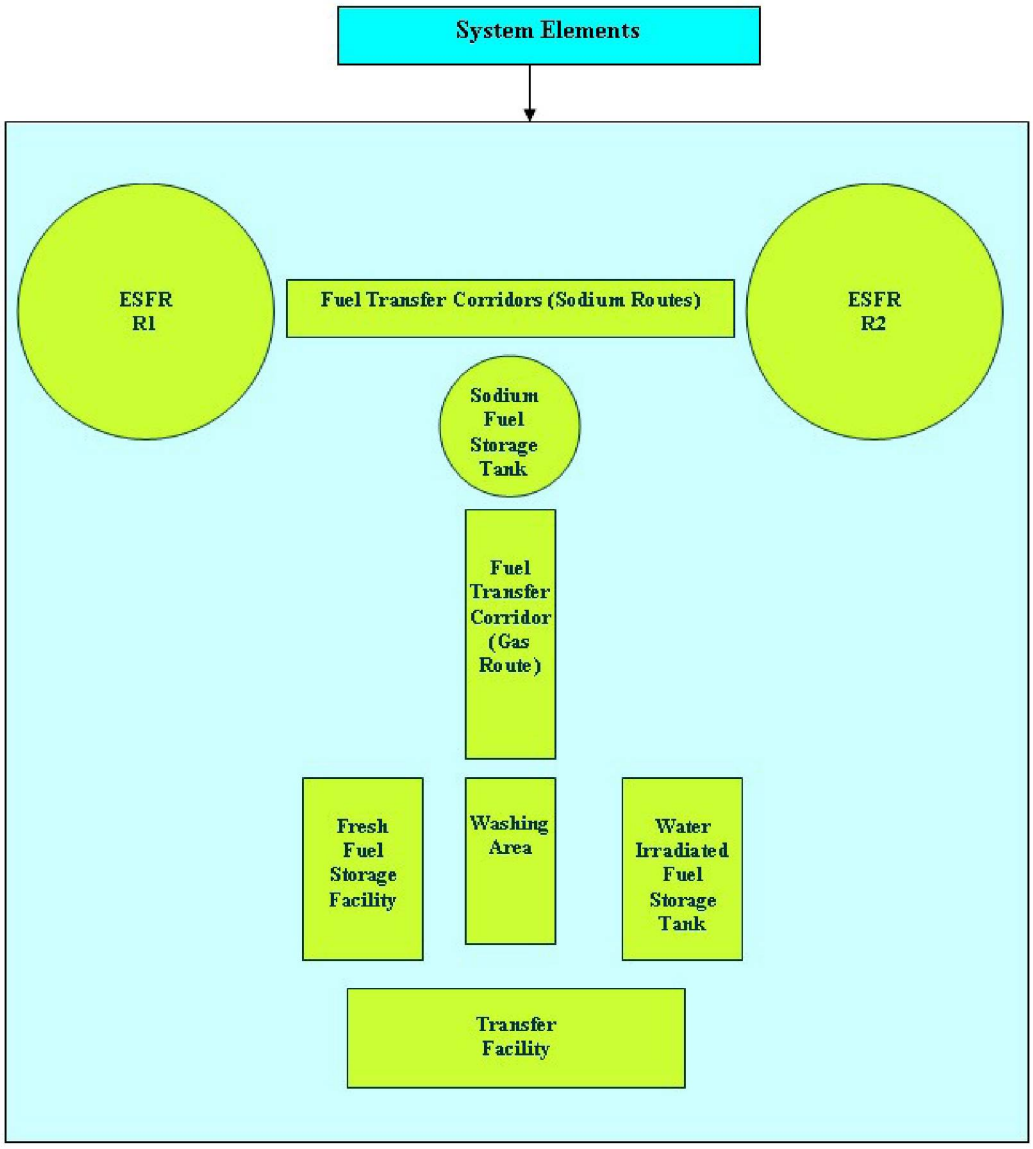


Figure 3: ESFR system elements.

[7] In case MA-bearing fuel is considered, there might be the need of adding a disassembly shop after the washing area or in the transfer facility allowing transport to the reprocessing plant. This would be required also for assembling the FAs with MA. This would add an additional system elements to the ones presented in the figures [4].

Targets for the reference cores

The possible ESFR diversion targets for the reference cores are the Fresh FAs, spent FAs and - if present – radial blanket assemblies. Figure 4 shows the possible diversion target types (in red) in the cases simulated within the collaborative project. The considered ESFR fuel assemblies have a much higher fissile material content compared to typical light water reactors. This makes the ESFR fuel assemblies, especially the fresh ones, an attractive target for a potential diversion strategy.

Under normal conditions, all fresh FAs, all spent FAs and the spent (irradiated) radial blanket assemblies contain Pu of RG type[8]. The Pu quality in the fresh fuel is that of the associated fuel cycle.

An additional adversary target is represented by the undeclared nuclear material production (by misusing the ESFR system) via the irradiation of fertile material in the reactor core [8].

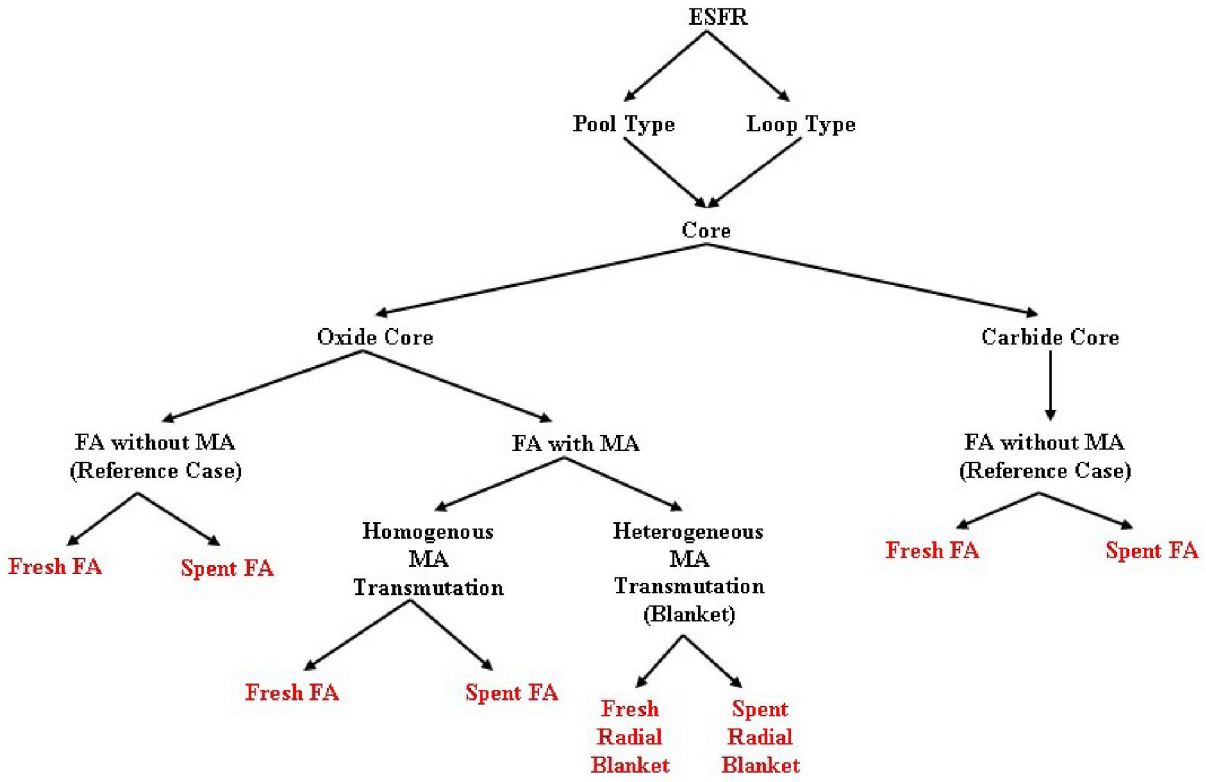


Figure 4: Reference cores diversion targets [4].

Targets for the optimized cores

The identified diversion targets for the optimized cores are the fresh FAs, spent FAs, and radial blanket assemblies. The optimized cores foresee the presence of a lower axial blanket in fresh FA made of depleted uranium. When the blanket is irradiated, an attractive Pu quality is produced and after irradiation the lower axial blanket in spent FA can be cut from the rest of the assembly in order to be processed separately. For this reason, Figure 5 shows also the lower axial blanket in spent FA as an additional potential adversary target to the already mentioned ones[9].

[8] Here the categorization of PR&PP WG [5] for Pu is adopted. PR&PP distinguishes Pu in weapon grade (WG) Pu, reactor grade (RG) Pu and deep burn (DB) Pu on the basis of the percentage of fissile Pu isotopes present (WG, nominally 94 % fissile Pu isotopes, RG nominally 70% fissile Pu isotopes, DB nominally 43 % fissile Pu isotopes. More detailed material type studies have been carried out in the project by using different metrics.

[9] In order to divert the axial blanket material, the diverter has to divert the full ESFR spent fuel assemblies.

With the exception of lower axial blankets in spent FAs, all fresh FAs, all spent FAs and the spent (irradiated) radial blanket assemblies contain Pu of RG type. The lower axial blanket in spent FA contain weapon grade Pu. Fresh radial blankets of both reference and optimized cores are Pu free.

As with the reference cores, another potential adversary target is represented by the undeclared nuclear material production via the irradiation of fertile material in the reactor core [8].

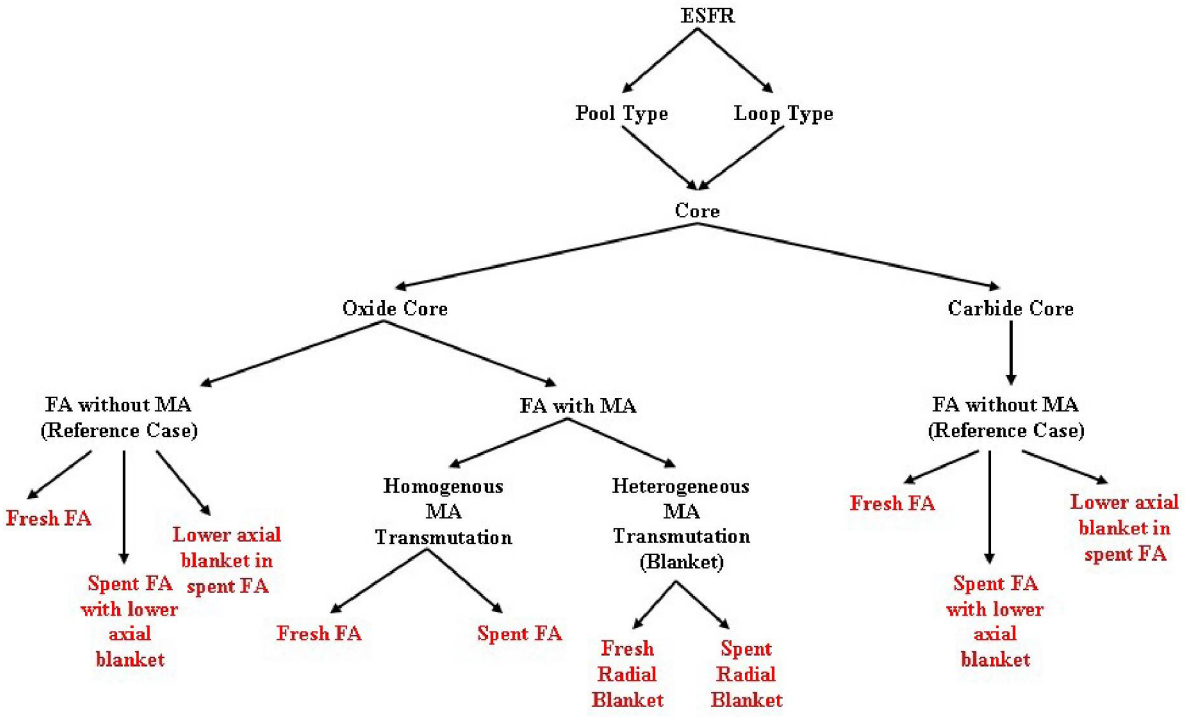


Figure 5: Optimized cores diversion targets [4]

5. ESFR proliferation resistance considerations

The PR strategies to be considered under a GIF PR analysis are the following [5]:

- Concealed diversion;
- Concealed production of nuclear material;
- Breakout;
- Production in clandestine facilities.

The following sections discuss the possible ESFR response to the considered proliferation strategies.

Concealed diversion

The oxide reference fresh core foresees a load of 11.6 tons of Pu and the carbide one foresees a load of 8.5 tons of Pu [18]. Each reference oxide core fresh fuel assembly contains an average of 25.6 kg of Pu and each carbide core's fresh fuel assembly contains an average of 20.5 kg of Pu[10], resulting respectively in 3.2 and 2.6 significant quantities (SQs) of Pu for each oxide and carbide core's assembly. Moreover the number of significant quantities in the fuel assembly does not change significantly with burn-up. This means that the diversion of one ESFR fuel assembly (either fresh or irradiated) is enough to obtain more than 1 SQ of plutonium. For a typical LWR spent fuel assembly, one fuel assembly contains less than 1 SQ of Pu. From this point of view, the ESFR fuel assemblies might represent a more attractive diversion target than those of a typical light water reactor, the quality of Pu being of reactor grade in both cases.

[10] These values are calculated using the data in [18]

Within ESFR, actinide management was explored for the case of the oxide fuel. As highlighted by [8], "*handling methods for fresh fuel assemblies may depend significantly on minor actinide content (homogeneous recycle or heterogeneous recycle concentrated minor actinide targets)*"[11]. MA bearing fresh fuel, as in the case of homogeneous minor actinide transmutation, has a higher radiation emission, making the handling of the fuel assemblies more complicate. This higher radiological barrier might increase proliferation resistance[12]. On the other hand, MA bearing fuel assemblies are more difficult to fabricate and might bring in new measurement challenges for the safeguards inspectors. Moreover, depending on MA-content, the ESFR system might need an on-site assembly shop which, despite radiation levels, may provide avenues for concealed introduction of fertile materials. This, combined with a more difficult irradiated FA composition analysis, would potentially enable concealed diversion and especially undeclared production of nuclear material, even though in fractional amounts of SQ per FA. Despite the presence of MA in fresh fuel, the resulting Pu in spent fuel will remain of reactor grade quality.

Spent blanket elements could have relatively low burn-up and could contain high quality plutonium material. In particular, radial blanket assemblies are normally sensitive items from a PR point of view. Using radial blanket in the design might cause a potential PR concern.

The addition of MA to the fertile radial blanket assemblies (heterogeneous minor actinides transmutation) might constitute a proliferation resistance feature and might provide additional technical difficulty to potential proliferators. Within ESFR, the doping of depleted uranium with 15-20 % of MA results – after irradiation - in Pu with a very high ^{238}Pu content, thanks to the presence of Np in the MA composition. This will constitute an important proliferation barrier in terms of nuclear material attractiveness. According to the PR&PP categorization the Pu of spent blanket will be RG Pu.

Both ESFR oxide and carbide optimized core foresee the presence of a lower axial blanket in fresh fuel made of depleted uranium which, when irradiated, will result in weapon grade Pu, this however will be diluted and several FA will need to be diverted to obtain an SQ of Pu (8 FA for spent oxide fuel and 10 for the case of spent carbide fuel).

The sodium environment in many system elements represents a challenge to nuclear safeguards activities. Due to the sodium being visually opaque, new methods might be needed to identify and monitor fuel assemblies.

Concealed production of nuclear material (misuse)

There are multiple possibilities for misusing a system, and therefore there are many different possible pathway combinations. The weaker pathways with respect to PR should be identified and analyzed in detail and related safeguards requirements should be identified. It has to be noticed that generally a misuse strategy has the objective to produce a better-than-available fissile material quality (in this case weapon-grade plutonium).

Undeclared fissile material production by irradiating fertile material in inner, outer and blanket regions of the ESFR reference core might be a potentially attractive misuse strategy: replacing a FA in the inner or outer core region with a fertile target assembly could be a possible route for the concealed production of fissile nuclear material. The fertile material could be put in the fuel part of the FA or in the parts of the assembly just above or beneath the active part.

For the ESFR optimized cores, the plutonium available in the irradiated axial blanket is already weapon-grade, making the concealed production of better grade nuclear material not necessary and making concealed production a less interesting proliferation strategy then concealed diversion.

The other possible goal of a misuse strategy could be to produce a bigger quantity of high-quality nuclear material. The ESFR axial blanket is distributed over all the fresh fuel assemblies, resulting in having only a small part of the assembly containing weapon-grade plutonium. This would require the

[11] [8], Section 4.1.

[12] Although PR might be increased by the higher radiological barrier, its effectiveness in deterring a potential proliferator from diverting the target is debatable. For a discussion on this topic see [19]

diversion of several assemblies to acquire one significant quantity of weapon-grade plutonium. Trying to misuse the optimized reactor core to end up with a single element containing one or more significant quantities might represent a potentially attractive scenario. From this point of view, the ESFR system doesn't present peculiarities making it substantially different from other existing sodium fast reactors, and therefore its behavior in a misuse scenario would be similar to any other SFR.

In case of a concealed misuse scenario, the proliferator's biggest challenge is to avoid detection by the safeguards system. One of the proposed safeguards approaches within the CP-ESFR project activities relies on a near real-time monitoring of the reactor system, making this strategy particularly difficult to be implemented.

Breakout

Carbide and oxide reference fresh fuel assemblies contain on average 3.2 and 2.6 SQ of plutonium respectively. Thus, a breakout scenario would see the availability of a huge amount of significant quantities. According to IAEA, the conversion time for MOX fuel is of the order of 1-3 weeks [16]. However this material would be reactor grade Pu and not weapon-grade Pu, i.e. less than ideal for a weapon programme. The major concern posed by a breakout scenario would be the huge production capability of Pu of any desired quality, and the key parameter to assess would be proliferation time.

Production in clandestine facilities

As highlighted by other literature studies, the sodium fast reactor technology does not seem the most suitable one to be replicated in a clandestine facility. The intrinsic difficulties connected with the presence of sodium, together with the overkilling dimensions of a fully-fledged commercial power reactor makes the ESFR a very unlikely candidate for clandestine replication.

6. Conclusions

Following the GIF White Paper Structure, information has been collected for the two CP-ESFR working horses and related core concepts with emphasis on features relevant for PR. Both loop and pool working horses share the same core concepts. Although SFRs are item facilities and this facilitates accounting and control for safeguards purposes, liquid sodium is a hostile environment and an opaque coolant that makes the verification when the fuel element is under sodium very difficult. Both working horses foresee batch operation enabling the possibility to seal the core between reloading and reshuffling operations. In terms of safeguards it is of paramount importance to identify and track, possibly in real time, the location and – if feasible - the composition of the fuel elements.

From a PR point of view the two working horses options (pool or loop) are equivalent, provided that they are considered with the same core configuration, i.e. oxide (with or without MA) or carbide. The main common features are the following:

- Use of reactor grade Pu as feed;
- High fuel burn-up;
- Possibility of including MA in the fuel for MA management.

The addition of MA to the fuel and/or blankets might constitute a proliferation resistance feature and might provide additional technical difficulty to potential proliferators. This is remarkably true in the case of radial blanket fuel elements, if present, where the produced Pu will be of reactor grade type.

Lower axial blankets in optimized spent fuel assemblies contain weapon-grade plutonium. Given the size of the foreseen axial blanket region at least 8 spent oxide FAs (or 10 spent carbide FAs) need to be diverted to obtain 1 SQ of weapon-grade plutonium. Nevertheless the possibility to misuse the reactor to irradiate fertile targets for the concealed production of undeclared Pu remains, and needs to be addressed with appropriate safeguards measures and controls.

In the case of breakout, a Sodium Fast Reactor will exhibit a large inventory of fissile material, even though not optimal for a weapons program. Nevertheless the core physics will allow a huge Pu production capability of any desired quality.

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