

MATERIAL TYPE AND SAFEGUARDABILITY CONSIDERATIONS FOR INNOVATIVE SODIUM FAST REACTORS FUEL INCLUDING DIFFERENT MINOR ACTINIDES COMPOSITIONS

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ABSTRACT

According to the Generation IV International Forum Technology Roadmap, Sodium Fast Reactors (SFR) could be a promising technology for minor actinides management. In view of a much higher radiological barrier, the addition of minor actinides to fresh fuel assemblies would change the way in which fresh fuel can be stored and handled, impacting not only on routine operations but also on the activities carried out during international safeguards inspections.

While it is generally considered that the presence of minor actinides in fresh fuel assemblies would decrease the attractiveness of this potential target for a proliferator willing to divert nuclear material - thus increasing the proliferation resistance of the entire facility -, it might have perverse repercussions on the overall safeguardability of the target. In particular, the presence of minor actinides might complicate the measurement activities performed by safeguards inspectors during physical inventory verifications (PIV). The level of impact depends on the actual composition of the available fuel and might affect the current safeguards approach.

This paper will present some considerations on a) the fuel assemblies' material composition and its attractiveness for a potential weaponisation phase, b) the potential increase of the PR of a system employing MA-bearing fresh fuel, and c) the safeguardability of MA-bearing fuel assemblies.

INTRODUCTION

According to the Generation IV International Forum (GIF) Technology Roadmap [1], Sodium Fast Reactors (SFR) could be a promising technology for minor actinides (MAs) management. In view of an improved sustainability of the nuclear fuel cycle, the decrease of the average life of nuclear waste could be achieved via burning/transmuting long-lived radioactive elements produced in nuclear reactor fuel. Via the transmutation of MAs, i.e. Neptunium (Np), Americium (Am) and Curium (Cm), the average life of radioactive nuclear waste would decrease from tens/hundreds of thousands of years to hundreds of years [2], improving both waste management and the nuclear fuel cycle public acceptance.

One of the most promising ways to achieve MAs transmutation is burning them in fast spectrum nuclear reactors such as sodium-cooled fast reactors. One of the technical options on the table to achieve this goal is to add MAs to the reactor's fresh fuel. Since the addition of MA to the fresh fuel (FF, usually composed by a mixture of uranium and plutonium coming from reprocessed light water reactors' spent fuel) would increase the radiological barrier of one of the most attractive targets for a potential nuclear proliferator, this approach is commonly considered as beneficial in terms of increased proliferation resistance of the nuclear energy system.

This paper will look into this assumption considering the following three aspects:

- The attractiveness of the nuclear material contained in MA-bearing FF assemblies for using it in a nuclear weapon. Three different ways of tackling the problem available in literature [3-5] will be presented, discussed and applied to an example SFR MA-bearing FF compositions under analysis for deployment in future SFRs.
- The effect of adding MA to FF in SFRs on the measures defined by the GIF Proliferation Resistance and Physical Protection (PR&PP) Evaluation Methodology [6]. Under the assumption of a State willing to proliferate adopting a diversion strategy, a brief comparison between the attractiveness of a non-MA-bearing FF assembly and a MA-bearing FF assembly as the target for diversion will be done.
- The effect of adding MA to FF on the *safeguardability* of the FF and therefore on the safeguards activities that could be carried out within a safeguards approach.

Before plunging in the above-mentioned considerations, the definition of nuclear proliferation resistance as intended within the GIF, together with the identified way of evaluating it by the GIF PR&PP evaluation methodology will be briefly recalled.

PROLIFERATION RESISTANCE AS INTENDED BY GIF

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*”[6].

As can be seen, the definition explicitly restricts the concept of proliferation resistance to the proliferant action of a Host State, without taking into consideration possible attempts to acquire nuclear explosive devices by sub-national groups, foreign States or international groups. The threat posed by the latter actors is dealt with within the physical protection robustness part of the evaluation, where physical protection robustness is defined as “*that characteristic of an NES that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices (RDDs) and the sabotage of facilities and transportation by sub-national entities and other non-Host State adversaries*”[6].

To evaluate the proliferation resistance of a nuclear energy system, the GIF PR&PP methodology foresees an approach based on acquisition pathway analysis. Such approach is summarised in Figure 1. There are six PR measures to be evaluated on the identified segments and then to be possibly aggregated on the entire acquisition pathway.

This paper will not apply the GIF PR&PP Evaluation Methodology: the latter will be exclusively considered as a context in which PR-related considerations and analyses will be presented. No actual systematic pathway analysis is here attempted, but given the three aspects highlighted in the Introduction, the considered proliferation strategy is that of a diversion scenario, where aspect 1 will cope with the *Fissile Material Type* measure, aspect 2 will concentrate on *Proliferation Technical Difficulty*, *Proliferation Cost* and *Proliferation Time* measures and aspect 3 (*safeguardability*) will be somehow related to *Detection Probability* and *Detection Resource Efficiency* measures.

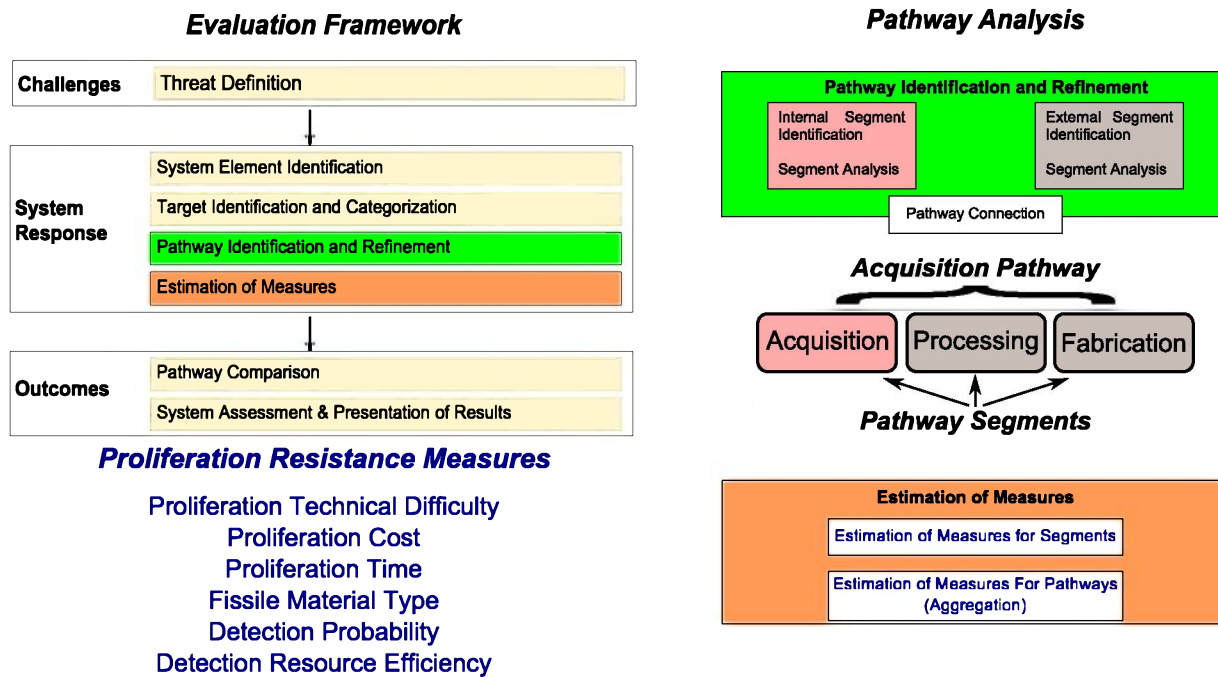


Figure 1. Summary of the GIF PR&PP Evaluation Methodology framework, pathway analysis and identified PR pathway measures. Adapted from [6].

ADDRESSING FISSILE MATERIAL TYPE

The definition for the *Fissile Material Type* measure foreseen by the GIF PR&PP Evaluation Methodology reads “A PR measure categorizing the material based on the degree to which its characteristics affect its utility for use in nuclear explosives. MT is estimated on metal material immediately prior to fabrication stage”[6]. The analysis is therefore focused on understanding the attractiveness of the nuclear material composition at disposal in terms of its suitability as a weapons nuclear material. For Pu, the PR&PP illustrative scale is based on the odd-numbered Pu isotopes concentration and follow a coarse categorization in Weapon Grade (WG) Pu, Reactor Grade (RG) Pu, Deep Burn (DB) Pu [6]. The categories are listed ranking them from the least to the most proliferation resistant. Given the illustrativeness and the coarseness of the metrics, a literature search for more refined metrics has been done. There are several literature studies trying to tackle this problem. The main nuclear material characteristics that need to be taken into account when considering a direct-use material for use in nuclear explosives are the bare sphere critical mass (the amount of material needed for achieving criticality – the lower the better), heat generation rate (the amount of heat generated by the candidate weapons material, potentially an issue for the stability of the explosive needed to achieve super-criticality in implosion weapons – the lower the better), spontaneous neutron emission rate (the amount of neutrons emitted by the nuclear material, potentially capable of inducing the pre-initiation phenomenon responsible for lower than expected yields – the lower the better) and the radiation dose rate emitted by the nuclear material (potentially an issue for the safe handling and storage of the device – the lower the better). Here three of the most recent efforts will be briefly presented, discussed and applied to an example MA-bearing SFR compositions under consideration for future fast reactors. The three studies are those from Pellaud [3], Kessler [4] and Bathke et al. [5].

Pellaud [3] focusses on the spontaneous neutron emission rate of the plutonium mixture to be used in a nuclear weapon device. Historically the plutonium composition has been categorised in

terms of ^{240}Pu abundance as reported in Table 1. The table also reports Pellaud's assessment of the usability of each category for building a nuclear weapon device. It is worth noticing that although the reported categorisation is based on ^{240}Pu concentration, Pellaud performs his analysis on the global neutron emission of the plutonium sample given a certain burn-up, without limiting himself to assess the concentration of one isotope.

Category	^{240}Pu abundance range (%)	Usability for a nuclear weapon
Super-grade (SG)	< 3	Best quality
Weapon-grade (WG)	3-7	Standard material
Fuel-grade (FG)	7-18	Practically usable
Reactor-grade (RG)	18-30	Conceivably usable
MOX-grade	>30	Practically unusable

Table 1: Pellaud's assessment of the usability of various Pu categories. Adapted from [3].

By analysing only plutonium isotopics, Pellaud assumes a high-level acquisition pathway in which the proliferant State processes the acquired nuclear material to obtain separated plutonium. In case the State shouldn't have a declared reprocessing phase already producing separated plutonium (e.g. a purex facility), his analysis implicitly assumes that plutonium is separated by either *misusing* a declared reprocessing facility operating via a co-extraction process to separate pure Pu or processing it in a clandestine facility.

Kessler [4] tackles the problem from a different angle: given that an implosion-type nuclear explosive device requires the use of high-potential organic explosive and that this explosive surrounds the plutonium core, the heat generated by plutonium needs to be compatible with what can be tolerated by the explosive. Starting from this assumption, Kessler analyses various plutonium compositions varying the concentration of the contained ^{238}Pu isotope. Through various calculations he ends up setting the threshold for ^{238}Pu concentration to around 6%: over this value Kessler suggests that the heat generated by the plutonium core would be too high to be handled even for a technologically advanced State, and therefore the plutonium could be considered to be denatured. It is worth noting that in current nuclear fuel cycles this 6% threshold is far from being reached. As Pellaud, Kessler implicitly assumes an acquisition pathway in which the proliferant State processes the acquired nuclear material to separate plutonium and doesn't limit his analysis to the contribution of only one isotope, but computes the total heat generation rate of the plutonium sample. This is done on different plutonium isotopics with different ^{238}Pu concentrations.

Bathke et al. [5] tries to analyse the nuclear proliferation attractiveness of the separated nuclear materials foreseen by advanced reprocessing options currently investigated for future deployment. The objective is to understand whether these options represent a real advance in nuclear proliferation resistance and if nuclear safeguards could be relaxed on some of the mixtures there produced. Although explicitly reporting the GIF PR&PP definition of proliferation resistance, he considers also possible proliferant sub-national groups. The study presents the four Figures of Merit (FOM) reported below [5]:

$$FOM_1^1 = 1 - \log_{10} \left(\frac{M}{800} + \frac{Mh}{4500} + \frac{M}{50} \left[\frac{D}{500} \right]^{\frac{1}{\log_{10} 2}} \right) \quad (1)$$

$$FOM_2^1 = 1 - \log_{10} \left(\frac{M}{800} + \frac{Mh}{4500} + \frac{MS}{6.8(10)^6} + \frac{M}{50} \left[\frac{D}{500} \right]^{\frac{1}{\log_{10} 2}} \right) \quad (3)$$

$$FOM_1^2 = 1 - \log_{10} \left(\frac{M}{800} + \frac{Mh}{4500} + \frac{N}{10} \left[\frac{D}{500} \right]^{\frac{1}{\log_{10} 2}} \right) \quad (2)$$

$$FOM_2^2 = 1 - \log_{10} \left(\frac{M}{800} + \frac{Mh}{4500} + \frac{MS}{6.8(10)^6} + \frac{N}{10} \left[\frac{D}{500} \right]^{\frac{1}{\log_{10} 2}} \right) \quad (4)$$

Where M is the mixture's bare critical mass in metal form in kg, N is the mass of a fuel assembly, h is the mixture's heat generation rate in W/kg, D is the dose rate of $0.2 M$ or $0.2 N$ evaluated at 1 m from the surface in rad/h and S is the intrinsic fission neutron production rate in n/s/kg [5]. These factors are mainly in line with the typical assumptions that to be suitable for a proliferation effort the nuclear material needs to contain more than 20% ^{235}U (for a Uranium proliferation strategy), have a radiation emission of less than 500 rad/h (considered to be a self-protecting barrier), have a heat generation rate inferior to that of a Pu isotopic composition containing 80% ^{238}Pu or more, have a neutron emission rate inferior to that of reactor-grade Pu (around 20% ^{240}Pu content – this factor is valid only for unadvanced proliferant states).

$FOM_1^{i=1,2}$ is to be used when the proliferant actor is a subnational group or a technically advanced host State, $FOM_2^{i=1,2}$ is to be used when the proliferant actor is a host State without the necessary technical expertise to overcome pre-initiation issues but still wants a reliable weapon. For both FOM_1 and FOM_2 there are two versions: FOM_1^1 eq. (1) and FOM_2^1 eq. (3) assume the availability of a heavily shielded hotcell, FOM_1^2 eq. (2) and FOM_2^2 eq. (4) consider a scenario in which the proliferator doesn't have access to heavily biologically shielded processing equipment, and therefore needs to wait a suitable amount of time for the radiation dose to decrease to safe limits before processing the material. FOM values above 2 are to be considered preferable for a potential proliferator, values between 1 and 2 are considered to be attractive, values between 0 and 1 are to be considered as unattractive but still theoretically usable, values below zero identify the mixture as definitely unattractive for a nuclear weapon device. Depending on which formula is used, there are multiple assumed underlying scenarios: Table 2 summarises the applicability of the formulas and the underlying assumed scenario.

Actor	FOM_1^1 eq. (1)	FOM_1^2 eq. (2)	FOM_2^1 eq. (3)	FOM_2^2 eq. (4)
Sub-national group	Diversion of best possible reprocessed product, no additional chemical separation	Diversion of best possible material and wait until sufficient decay occurred for separating plutonium	N/A	N/A
Technically advanced State	State processes acquired material to obtain separated plutonium	Not realistic	N/A	N/A
Developing State	N/A	N/A	State processes acquired material to obtain separated plutonium	State diverts best possible material and waits until sufficient decay occurred for separating plutonium

Table 2. FOMs, potential proliferators and resulting underlying scenarios.

According to [5], only a very limited amount of States willing to undergo a proliferation effort would not have the necessary technology to overcome pre-initiation issues due to spontaneous neutron emission, and therefore the formulas to be used are almost always (1) and in some specific cases (2). Contrary to [3], by not considering spontaneous neutron emissions in FOM_1 , the study discards the concentration of ^{240}Pu (and other neutron emitting isotopes) as an important material quality parameter. Moreover, (1) sets the ^{238}Pu concentration threshold to around 80%, in line with traditional assumptions and differently from [4].

Bathke et al. [5] is the only study of the three that analyses the attractiveness of mixtures other than separated plutonium, but in doing so it warns that it would make sense only for sub-national groups having the possibility to divert nuclear mixtures after the reprocessing phase. No State willing to start a military nuclear programme involving non-weapon-grade plutonium and able to overcome pre-initiation issues would lack the capability and the will to further separate a

nuclear mixture to obtain pure separated plutonium. Table 3 summarises the aspects that each study take into account and the related assumed high-level proliferation pathways.

Study	Bare sphere critical mass	Heat generation rate	Spontaneous neutron emission	Dose rate	Implicit acquisition pathway assumption
Pellaud	YES	NO	YES	NO	State processes acquired material to obtain separated Pu
Kessler	YES	YES	NO	NO	State processes acquired material to obtain separated Pu
Bathke (FOM ₁)	YES	YES	NO	YES	Developed State processes acquired material to obtain separated Pu Subnational groups don't perform chemical separation of the acquired material
Bathke (FOM ₂)	YES	YES	YES	YES	Undeveloped State processes acquired material to obtain separated Pu

Table 3. Characteristics considered by the three considered studies, together with the related assumed proliferation pathways.

From the above description it is already evident that in literature there are different takes with regard to the characterisation of the attractiveness of nuclear material in terms of usability for a nuclear weapon. On the other hand, all studies (and generally the majority of literature studies) agree on the fact that a proliferant State would always have the capability and the will to perform chemical separation on the nuclear material diverted for proliferation purposes. This aspect alone already highlights how the addition of MA to SFR FF could not be considered sufficient to degrade the attractiveness of the nuclear material potentially diverted. Nonetheless it is interesting to see whether the quality of the plutonium isotopics currently under consideration for future SFR cycles would still represent a theoretically weapons-usable material. To answer this question, the parameters discussed above have been calculated for the isotopic composition assumed for the GIF Example Sodium Fast Reactor Case Studyⁱⁱ [7], representative of a closed fast reactor cycle in burner and deep burner configurations and without blanket. The relevant fuel composition data are reported in table 4. It is important to stress that the study here presented doesn't want to analyse the GIF ESRF system's proliferation resistance: since the FF composition proved to be characteristic of typical SFR FF assemblies currently under design, the authors decided to take advantage of the open literature availability of the GIF ESRF system. For an application of the GIF PRPP EM to this system, including the analysis of a diversion scenario involving the theft of one significant quantity of TRU from the co-located reprocessing facility, see [7]. To investigate the possibility of using the mixture Pu+MA as it is (therefore considering the mixture itself as direct-use nuclear material), formula (1) of FOM₁ has been computed also for the mixture made of Pu and MA. The results are reported in Table 5. Heat generation rate, dose rate and spontaneous neutron generation rate are computed using Nucleonica [8]. Bare critical mass is computed using SCALE 6.1 [9].

	Pu in fuel (%)	MA in fuel (%)	Pu Vector %				
			²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu
DV0 – inner FF	16.71	1.57	3.02	52.27	32.64	4.62	7.45
DV0 – outer FF	22.73	2.32	2.93	52.56	31.57	5.43	7.51
DV1 – inner FF	39.16	7.44	5.84	30.89	40.43	7.47	15.37
DV1 – outer FF	57.53	10.02	4.77	38.28	35.84	8.16	12.95

Table 4. GIF ESRF FF composition. DVO: baseline (Conversion Ratio:0.73), DV1: deep burner (Conversion Ratio:0.22), data as from [7], corresponding to batch 0.

	If MA is separated from Pu				
	M (kg)	h (W/kg)	D (rad/h)	S (n/s/kg)	FOM ₁
DV0 – inner FF	5.65	20.59	2.41E-02	5.67E+05	2.48
DV0 – outer FF	5.63	20.05	2.42E-02	5.54E+05	2.49
DV1 – inner FF	6.09	36.82	4.46E-02	8.71E+05	2.24
DV1 – outer FF	5.91	30.62	3.77E-02	7.50E+05	2.32

	If MA is not separated from Pu (Pu+MA Mixture)				
	M (kg)	h (W/kg)	D (rad/h)	S (n/s/kg)	FOM ₁
DV0 – inner FF	5.72	76.94	4.63	1.53E+08	1.98
DV0 – outer FF	5.72	73.67	4.84	1.35E+08	2.00
DV1 – inner FF	6.16	168.38	8.42	3.59E+08	1.62
DV1 – outer FF	6.03	120.59	6.84	2.58E+08	1.77

Table 5. FOM results for DV0 (baseline) and DV1 (deep burner).

As it can be seen, the criteria defined by Pellaud would classify all Pu compositions of Table 4 as "practically unusable" for a nuclear weapon ($^{240}\text{Pu} > 30\%$). The other two criteria (FOM₁ > 2 and Kessler $^{238}\text{Pu} < 6\%$) consider the plutonium compositions usable for a nuclear weapon device.

Moreover for the Pu+MA mixture all the FOM₁ resulting values are in the attractive region. This result would support the statement that the plutonium + MA mixture would make a potentially usable weapons-material, and therefore there might be room to consider the mixture as direct-use nuclear material. From these results it would seem that the addition of MA to SFR FF elements would not influence the attractiveness of the contained nuclear material for a potential diversion effort.

ADDRESSING THE INCREASED PR DUE TO THE PRESENCE OF MA IN SFR FF

Having discussed the impact on the material attractiveness for the weaponisation phase of adding MA to fresh SFR FF, the discussion can now shift toward the investigation of the impact on Technical difficulty, Proliferation cost and Proliferation time of an acquisition path insisting on the diversion of MA-bearing SFR FF vs. the diversion of clean (non-MA bearing) SFR FF. To this respect, the following paragraphs will consider the impact of the presence of MA on the above-mentioned measures' estimates in the acquisition and processing stages of the acquisition pathway. Finally, the impact of the estimates variations on the overall pathway measures' estimates will be briefly discussed.

The major difference between handling and processing a MA-bearing assembly and handling and processing a clean FF assembly is certainly the higher dose rate receivable from the former. In the first row of Table 6 the gamma dose rate at 1 m for each of the considered fuel elements, their counterparts not containing MA and one 17x17 PWR spent fuel assembly with a burn-up of around 30000MWd/t and a cooling time of 5 years is reportedⁱⁱⁱ. These values give an idea of the handling difficulties to be overcome during the diversion stage of the proliferation strategy. The second row of Table 6 reports the gamma dose rate at 1m of one kg of the nuclear material contained in the above-considered assemblies. These values give an idea of the handling requirement during the processing stage of the proliferation effort.

The results show how the radiation barrier due to the presence of MA is higher than that of clean Pu bearing FF, but still far from that of a typical LWR SF assembly. Although for 1 kg of MA-bearing FF the expected dose rate is at least one order of magnitude less than that expected from 1 kg of LWR spent fuel, the safe handling and processing of the nuclear material would

nevertheless require appropriate biological shielding. In addition, it has to be noticed that the values reported are just gamma doses, and MA (curium in particular) are strong neutron emitters that require adequate protection.

	DV0	DV0 with MA	DV1	DV1 with MA	PWR SF
Gamma Dose rate at 1m (entire fuel element) (rem/h)	3.70E-01	80.4	3.85E-01	80.4	2.58E+04
Gamma Dose rate at 1m (1kg of material) (rem/h)	4.13E-03	8.93E-01	1.56E-02	3.37	51.6

Table 6: Gamma dose rate at 1m for the outer core SFR FF elements, with or without MA, compared to the Gamma dose rate at 1m for a PWR SF assembly with 5y cooling time.

To be on the safe side it is here considered that a shielded cask would be needed for transporting the MA-bearing assembly and that its processing would require a heavily shielded hot cell. Consequently, proliferation technical difficulty and proliferation cost would be higher than dealing with clean SFR FF assemblies. The impact on Proliferation time depends on the indigenous capability of the State to build a clandestine hot cell: in case the State has this capability or has a non-safeguarded suitable equipment, the impact on Proliferation time would be negligible; in case the State needs to rely on procurement campaigns and doesn't have a suitable non safeguarded equipment, a concealed proliferation strategy might imply an increase of this measure's estimate.

To understand the extent of the possible deterrence represented by a MA-doping of clean SFR FF, it is important to bear in mind that the underlying proliferation scenario is that of a State that decided to proliferate using reactor-grade plutonium, and therefore confident to be able to overcome big and expensive challenges during the weaponisation phase. It is therefore safe to assume that if a proliferant State is willing to proliferate by diverting clean SFR FF assemblies, the marginally higher difficulty and cost due to presence of MA in the target would not stop it from proceeding, since both technical difficulty and proliferation cost measures would here be largely dominated by the fabrication stage of the pathway. It is therefore reasonable to conclude that the presence of MA in FF would increase the PR of the system, but it would not be realistic to think that the presence of MA in fresh SFR FF would stop a proliferant State accepting the challenge of proliferating with RG-Pu from proliferating adopting this strategy.

ADDRESSING THE SAFEGUARDABILITY OF MA-BEARING SFR FF

The currently operating Fast Breeder Reactors (FBRs) do not usually use MA-bearing FF assemblies, but typical FBR reactors may rely on MOX coming from the recycling of LWR spent fuel. MOX in FF is considered to be un-irradiated direct-use nuclear material [10]. The standard approach to safeguard fresh MOX fuel is to keep it under Containment and Surveillance (C/S), and to perform C/S review, item counting and gross-defect verification^{iv} during Physical Inventory Verifications (PIVs). During inspections other than PIVs, the activities carried out are usually C/S review and item counting. In case the C/S should fail, the Safeguards inspectorate would usually require a re-verification of the MOX inventory that will involve also partial defect verifications^{iv}. In case the SFR FF assemblies would contain clean reactor-grade plutonium (either metallic or in oxide form), these item are likely to be dealt with as fresh MOX assemblies. In case MA are added to the mixture, two options would open up, depending on whether the special fissile material in the MA-bearing SFR FF would be considered to be unirradiated direct-use nuclear material or irradiated direct-use nuclear material. In the first case the safeguards approach would likely be equivalent to that for MOX-bearing FF, in the second case there might be the possibility that the safeguards measures could

be relaxed, eventually to the point of considering the same approach adopted for spent fuel. The main difference would be the requirement for partial defects verification, present for fresh plutonium bearing fuel and absent for spent fuel.

While clean Pu-bearing SFR FF elements would not pose particular safeguardability issues, the addition of MA could compromise the possibility to perform gross-defects and partial-defects verification measurements. To investigate this aspect, Nucleonica has been used to simulate the gamma spectrum obtainable with a High Purity (HP) germanium detector given the composition of an outer ring DV0 FF element containing MA. The result is displayed in Figure 2.

As the Figure shows, most of the gamma lines related to the plutonium isotopes are masked by the presence of MA. The only two isotopes that could have a non-zero probability to be identified would be ^{238}Pu (via the lines emitted around the 800keV region) and ^{239}Pu (via the lines emitted around the 400keV region). These, if actually visible, might be considered to be sufficient for a positive conclusion in the context of a gross-defect verification measurement.

When a partial-defect verification measure is needed (failure of the C/S system), things get more complicate. The standard approach for a partial-defect measurement on plutonium consists of two measurements: a gamma measurement for determining the isotopic composition of the Pu sample under analysis and a passive neutron measurement on the assumption that the recorded neutron counts come from the spontaneous fission of the even numbered plutonium isotopes. By coupling the neutron measurement results with the information about the isotopic composition

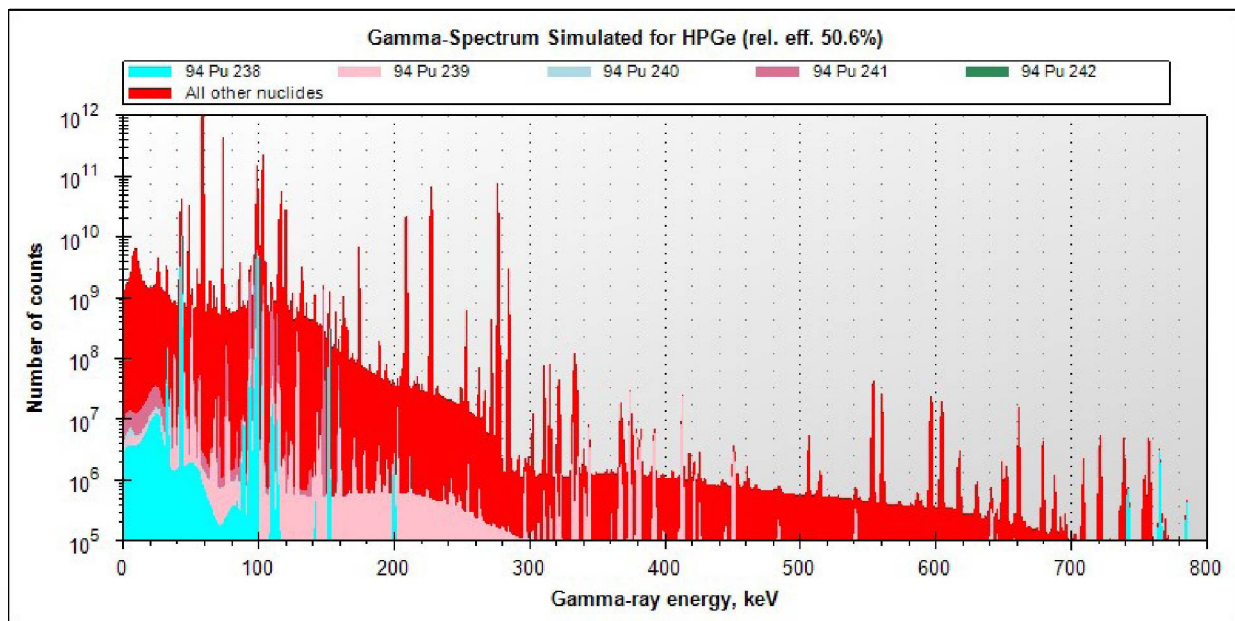


Figure 2: simulated gamma spectrum recorded by a HP Ge detector measuring a GIF ESFR DV0 FF assembly containing MA. The spectrum has been simulated with Nucleonica.

of the plutonium sample obtained via the gamma measurement, an estimate of the plutonium mass in the item could be derived. Given a spectrum as the one shown in Figure 2, an estimate of the plutonium isotopic composition would not be possible. In addition, the neutron emission of the item would be completely dominated by neutrons emitted by curium, very likely impeding any effort of estimating the plutonium mass inside the item. This would mean that the current verification techniques might not be suitable to safeguard MA-bearing SFR FF elements, and this would have a detrimental effect on the detection probability and eventually the detection

resource efficiency measures. In perspective these aspects might be mitigated via the development of more advanced verification techniques specifically for this issue; in the meantime it would be necessary to ensure that the need of partial defect verifications due to C/S failures would be as low as possible. Typically this could be achieved by implementing a dual-C/S system for MA-bearing SFR FF elements.

In conclusion, it would seem that the presence of MA in SFR FF assemblies might create safeguardability issues that require careful investigations and might outbalance the limited (if any) positive impact they might have on the estimates of technical difficulty, proliferation time and proliferation cost within a diversion scenario. In addition it is worthwhile to note that the presence of MA in the FF elements would impose a much more complicate handling of these elements on the operator by e.g. making use of transport casks, and this might increase the time needed to transfer the assemblies within the facility and the risk of damaging the assemblies during their handling.

CONCLUSIONS:

Although the reason of adding MA to FF assemblies is to perform MA transmutation for waste management, their presence is commonly considered beneficial also from a proliferation resistance point of view. This paper investigated this aspect along three lines: an analysis of the attractiveness of the nuclear material contained in a MA-bearing SFR FF assembly for a potential proliferator, the impact of adding MA on the difficulty, time and cost to divert and process an SFR FF element, and the potential impact that the presence of MA inside of an SFR FF element might have on the safeguardability of SFR FF. The investigation led to the following initial considerations:

- The presence of MA does not have impacts on the attractiveness of the nuclear material in a Pu-bearing SFR FF element. Moreover, according to Bathke et al. proposed metric (FOM1), even the mixture composed by Pu and MA would be directly usable in a nuclear weapon device.
- While the higher radiation emission levels due to the presence of MA in the FF could numerically increase the estimates for PR measures as proliferation technical difficulty and proliferation cost (and might impact on proliferation time), it has to be recalled that the diversion of a SFR FF assembly assumes a proliferation scenario in which the proliferant State is willing to fabricate a nuclear weapon device using high burn-up reactor grade Pu. In this scenario, implying formidable challenges during the fabrication stage, these PR measures would be dominated by their estimates related to the fabrication stage, and the increased challenges (if any) due to the presence of MA in the target to be diverted would not deter the State from proliferating if willing to do so.
- The presence of MA might have a detrimental effect on the safeguardability of the SFR FF elements that need to be better investigated and that might outbalance the little (if any) positive impact that they could have in other areas of proliferation resistance.

These aspects are being further investigated and analysed in the framework of The Collaborative Project on the European Sodium Fast Reactor (CP-ESFR), where 26 European partners develop R&D solutions for a European Sodium Fast Reactor concept and JRC is leading a sub-task addressing proliferation resistance aspects of the proposed design options.

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ⁱFOM₁ doesn't take into account the spontaneous neutron emission rate: for sub-national groups it is assumed that even a fizzle would be satisfactory for reaching their goals, and for technically advanced States the study states that pre-initiation could be overcome without particular problems.

ⁱⁱ THE ESRF DESIGN VARIATION 0. it is a burner configuration (TRU conversion ratio of 0.73), and uses a TRU feed made of PWR spent fuel elements. The TRU consumption rate is 81.6 kg/year for each reactor. The core configuration 180 fuel assemblies, their composition foresees 22.1% of average TRU enrichment arranged in two core zones. The fuel assemblies overall residence time is 1300 days. The cycle length is 12 months.

THE ESRF DESIGN VARIATION 1. This variation is a deep burner configuration, with a TRU conversion ratio of 0.22. This implies a substantial variation in the overall fuel cycle strategy, deeply committed to burning transuranic elements, leading to a shorter cycle length (6.6 months instead of 12 months) and to a different fuel composition (in particular, the average enrichment in TRU is 58.5% , arranged in two zones, instead of around 22% for design variation 0). The TRU consumption rate is 241.3 kg/year per reactor. The number of assemblies within the core is the same as that for design variation 0 (but the number of pins per assembly increases to 324 from 271), and the overall residence time is longer (1445 days). The configuration uses 8 batches instead of 4 (design variation 0). This leads to more fuel handling operations within the core before final discharge.

ⁱⁱⁱ The PWR fuel assembly was irradiated and cooled down using SCALE 6.1 [9], and a subset composition was feed to Nucleonica for dose rates calculations, this providing lower bound conservative results. Dose rates are all computed with Nucleonica [8].

^{iv}Gross-defect verification is a non-destructive measurement aimed at identifying the diversion of an entire item with its replacement with a dummy. Partial-defect verification is a measurement aimed at identifying the diversion of part of the nuclear material contained in one item (typically more than 50% of the item's nuclear material) [10].