IMPROVEMENT OF PROLIFERATION RESISTANCE BASED ON "BY-DESIGN" APPROACH

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Abstract

The implementation of safeguards at an early stage of the design of a given component of the fuel cycle will contribute significantly to the improvement of the proliferation resistance behaviour. The complete fuel cycle should be considered in the assessment of the proliferation resistance also during the design phase, although designs of nuclear reactors or fuel cycle elements are not complete and not all information and specifications on fuel cycle, installations/plants, location, etc are available. From the reactor designers point of view, the proliferation resistance, is not among the main technical parameters or constraints to be considered in the early conceptual design stage: in order to avoid intervening too late, after the optimisation interactions have frozen the neutron design, a clear and self-consistent set of proliferation resistance requirements should be given at a very early stage, as design constraints. This will allow to efficiently improve the proliferation resistance at reactor core design level. A possible approach to help the core designer to enhance the proliferation resistance characteristics will be discussed.

Keywords: *Proliferation Resistance, Fuel Cycle, Elicitation, Multi-Attribute Analysis, Core Design, Scenario Study*

Background

In recent years, following an increasing energy demand for economic growth and development while respecting environmental constraints, a renewed interest in the nuclear energy has been observed and, though less than anticipated, the number of ″embarking″ countries is still relevant. Moreover, new reactor systems (e.g. Gen-IV and Small Modular Reactors, SMR) are being developed and a number of countries consider the reprocessing of spent fuel as an option. These factors, including fuel enrichment and transportation, strongly influence the availability of fissile material potentially usable for nuclear weapons and the global nuclear proliferation risk. Therefore the strengthening of proliferation resistance features continues to be of paramount importance.

The commonly accepted definition of Proliferation Resistance (PR) is ″Characteristics of existing or proposed Nuclear Energy Systems (NES) in terms of *Intrinsic Features* and *Extrinsic Measures* that may impede the diversion or undeclared production of nuclear material or the misuse of technology″ [1, 2]. While the *Intrinsic Features* are those resulting from the technical design of NESs, e.g. nuclear fuel cycle materials and performances, the *Extrinsic Measures* result from decisions and undertakings related to NESs, such as safeguards, operations and national policies.

In order to manufacture nuclear weapons, the most important step for a proliferator is the acquisition of fissile material; therefore, diversion of weapon-usable material (including after misuse) from any point of a nuclear fuel cycle (NFC) is the primary concern. Access to the nuclear materials is possible at several points/phases of NFCs, from the front-end to the back-end: enrichment, fuel fabrication, transportation, irradiation, storage or temporary storage and, finally, disposal or reprocessing, depending on the fuel cycle option (open or closed). A combination of institutional and technical measures would be necessary to ensure barriers and robustness on facing proliferation risks.

Since the seventies, several initiative and efforts, also at international level, were made attempting to address technical and policy issues of the proliferation risk associated with the nuclear fuel cycle. Some of them have also developed methodologies to assess and improve the proliferation resistance.

Introduction

Proliferation resistance is a complex and multifaceted concept that requires taking into consideration the whole range of interactions among the elements of a nuclear fuel cycle. Considering both *Intrinsic Features* and *Extrinsic Measures*, a PR evaluation requires the analysis of the interdependencies between subjective and objective data, which would imply the use of a multiple approach.

Several methods for PR evaluation of a nuclear material, nuclear facility, system or whole fuel cycle have been proposed, [3-8].

Each of them is characterised by metrics and shows advantages and disadvantages; the common point is that there is not yet a method covering both the concepts-constraints of accuracy and reproducibility of the results. Methodologies based on ″expert elicitation″ can be accurate, but normally not repeatable. On the contrary, the methodologies providing reproducible results (numerical results) normally are not accurate due to their dependency on ″weight factors″ simulating the institutional context, which could be questionable.

In the first category of methodologies for PR's assessment, two separated methodologies have been developed:
- *INPRO methodology* (developed within the IAEA framework, [9]), mainly addressed to the NESs users, but providing also guidelines to the designers on how to improve proliferation resistance. This approach identifies a Basic Principle of Proliferation Resistance and five User Requirements for meeting this principle, along with seventeen indicators with specific criteria and acceptance limits. This methodology could require supplementary analysis to provide information needed to determine whether some of the User Requirements are met, [10].
- *GIF methodology* (developed within the GEN-IV framework, [3]), mainly addressed to the designers, identifies specific proliferation challenges, system feedbacks and outcomes; acquisition pathway analysis of various scenarios (e.g. diversion and/or misuse of nuclear materials and facilities) is a key element. Six proliferation resistance measures coming from the GIF goals have been identified to quantify and compare pathways and outcomes and they are addressed to designers, policy makers and stakeholders.

Both methodologies are based on hierarchical analytical structure including PR principles, high-level evaluation factors and multiple measures or criteria related to each high-level factor. Likewise, both methodologies consider and treat PR as a function of multiple extrinsic measures (like safeguardability) and intrinsic features (like: material attractiveness, fuel cycle facilities performances), while the concept of barriers to proliferation, although commonly accepted, is differently implemented.

The main difference among the two methodologies concerns the approach of the Proliferation Resistance.

The INPRO methodology, for instance, treats the whole system of a declared and safeguarded nuclear energy system, not considering explicitly clandestine facilities, setting the User Requirements and asking how the system satisfies the User Requirements.

The GIF methodology considers both declared and undeclared facilities and activities to produce a proliferation pathway from acquisition and processing of material to fabrication of a nuclear weapon, by dividing the whole system into components and performing for each of them the pathway analysis which should provide the basis of a PR evaluation.

The second category of methodologies for the PR's assessment concerns a Multi-Attribute Utility Analysis developed to allow comparative evaluation of PR's of different fuel cycles and facilities [5].

It is based on a series of attributes to determine a PR measure for each step in a process flow sheet, while weighting factors (for each attribute) are considered to determine its importance in the overall assessment. A set of attributes was considered in developing this methodology which generates a relative PR measure as a function of time for the history of a unit mass input into the NFC. A utility function based on expert knowledge and physical properties is associated with each of the attributes, which relates variations of the attribute value and its global effect on the PR measure. This methodology could be applied to advanced fuel cycle systems, allowing for relative comparisons among different systems and associated technologies. In such a context, the concept of "static" PR for the value of a generic process has been introduced, [5], defined by the relationship:

$$PR_i = \sum_{j=1}^{J} w_j u_j(x_{ij}) \quad (1)$$

where: w_j = weight for the j-attribute, u_j = utility function for the j-attribute, and x_{ij} = input value for the utility function for the j-attribute in the i-process.

Whatever the approach, the assessment of Proliferation Resistance becomes more complex with the increase in the demand for new NES and Pu recovery from recycling of spent fuel. A further difficulty for all methodologies is the ability to address the PR concept (and how to inject it) in reactor systems and associated fuel cycle still at conceptual level, when there is a lack of detailed information e.g. on facility design, operational concept, layout, etc. The recommended approach is the creation -at the early design phase- of a team of specialist on facility design and PR's assessment experts. Their interaction will facilitate a common understanding of the design concepts and constraints and of the PR needs, helping to avoid potential misunderstandings on addressing correctly the PR concepts within the facility design constraints. At the same time, it is essential to avoid that new concepts could potentially pose major challenges to the safeguard implementation at a later stage.

Boundary conditions

Methodologies for the PR assessment, i.e. the overall process of examining a nuclear energy system or a system element to determine its PR robustness, [11], should be based on the assumption that intrinsic features and extrinsic measures are implemented at all stages of the NFC, ensuring the least attractive materials for a nuclear weapons programme.

The NFC back-end is conditioned by the type, operative conditions and performances of the reactor. It means that, from a PR point of view, particular attention must be paid to the reactor's role in the context of the PR assessment. In this case the PR's experts recommendation to take into account safeguards implementation at an early stage of a NFC component design should be mandatory, conclusion particularly true considering the reactor system.

From the neutron designer point of view, the reactor core design is the result of an optimization process based on the knowledge of the materials behaviour and the application of physical laws within defined design constraints. If a clear and self-consistent set of PR's requirements (like design constraints) is given at a very early stage, i.e. before the conceptual design, PR's features could be introduced in the design. Timing is essential in order to introduce PR considerations in the design before optimizations (based on other constraints) freeze the neutron design. If specific PR ″requirements" are not available, it is essential for the designer, at the least, to be aware of the issue and have knowledge of guidelines to be used in this early phase.

However, it must be clear that PR considerations, despite their importance, are not the main technical parameters or constraints considered by designers in the early conceptual design stage. Approach also supported by the belief that the reactor itself poses less proliferation risks than other parts of the nuclear fuel cycle (e.g. fuel fabrication and reprocessing).

To meet the goal of the PR's improvement at design level, the PR assessment methodology should include the NPP specific conditions, weaknesses identification and how they were addressed, and finally core design constraints and performances: all of them together representing a sort of ″design extended constraints″. However, without forgetting that, actually, the degree of proliferation resistance results also from operational modalities, institutional arrangements and safeguards measures.

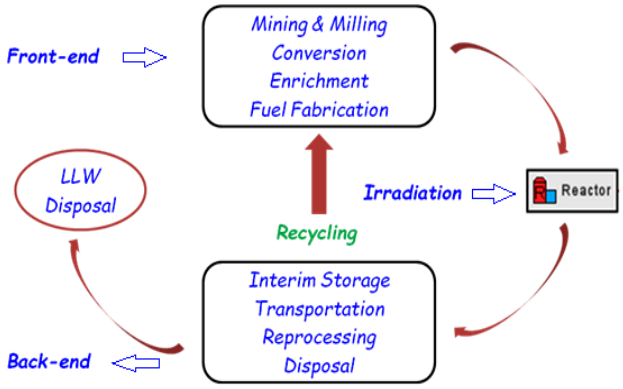


Fig. 1. Scheme of a generic Nuclear Fuel Cycle

Nuclear fuel cycle scheme shows the reactor's role, its relation with the front-end and its impact on the fuel cycle back-end. The relation with the front-end is mainly with the enrichment (in terms of fissile material) needed to achieve the criticality assuring the irradiation cycle length and refuelling strategy, while the impact on the back-end is directly depending on core design, fuel composition, operative conditions, actinides recycling options, fertile assemblies deployment strategy, burn up, irradiated fuel composition, spent fuel recycling options, etc.

In order to carry out a comprehensive PR assessment, the following technical details, inter alia, would be needed:
• fuel inventory through detailed fuel isotopic composition which provides information on the fuel attractiveness;
• decay heat at different operation times, allowing:
  - DHRs dimensioning and reliability;
  - shutdown at refuelling/other operating conditions;
  - final disposal acceptability;
• neutron source intensity at:
  - final disposal transfer (shielding dimensioning);
  - reprocessing/fabrication phase;
• radiotoxicity (in final disposal) at short, medium and long time;
• spontaneous fission rate;
• waste management evaluation;
• PR's behaviour assessment of the system (fuel+ reactor + cycle).

Many of the physical parameters of the front-end phase could be correctly evaluated using ″classical″ neutron design tools, while practically the totality of the physical parameters of the back-end phase requires the use of ″scenario studies″ tools, [12-16]. Scenario studies could also provide useful information for improving the PR at early design phase.

Approach's Development

Although it is clear that both intrinsic and extrinsic elements contributes to PR and it is not sufficient to rely only on design, it has also to be underlined that in designing a NES, though challenging, PR measures can be introduced or strengthened to reduce proliferation risks. However, trade-offs will be required and optimization of these trade-offs will not be always straightforward.

The purpose of this study is to outline a process (to be further developed if necessary) that could be useful to the reactor core designer from the earliest stages of the project, with regard to the elements to be considered in order to increase PR. To be noted that this study is not intended to attribute, or not, proliferating characteristics to a specific NES. Once more details have been defined and the design frozen, comprehensive PR assessments, based on GIF and/or INPRO methodology, should be carried out.

Details and results of the proposed approach, based on physical "observables" will be provided in this study; some of them are based on evaluations and results produced within international contexts dealing with nuclear fuel cycle optimization to assure the sustainability of energetic scenarios [17-19]. Comments based on ″Expert Elicitation″ and/or on Multi-Attribute Utility Analysis approaches, when possible, will be provided.

Fuel Enrichment

One of the proliferation factors to be taken into consideration is the fuel enrichment, in terms of fissile content in the fuel, for both fresh and irradiated fuel. It is a reactor physical observable directly connected to the fuel attractiveness through the Significant Quantity (SQ) of fissile material and linked to the proliferation risk.

Fresh fuel enrichment is defined by the criticality of the reactor and sustainability of the irradiation cycle, while irradiated fuel fissile – or Pu-content – is function of the reactor-type, the breading capabilities, the irradiation strategy, etc.

IAEA defines two classes of materials that require safeguards:
- Direct use nuclear material,
- Indirect use nuclear material.

According to IAEA [11, 20] Significant Quantity is approximately the amount of nuclear material for which manufacturing a nuclear explosive device cannot be excluded. It has to be noted that these amounts do not correspond to the critical mass, and could be understood as "the minimum quantity of fissionable material for which control is required to maintain sub criticality under all normal and credible abnormal conditions". The following values of significant quantity, for the two classes of nuclear materials, are considered:

▪ Direct use nuclear material:
- ^{233}U 1SQ ≅ 8 kg ,
- HEU ($^{235}U \geq 20\%$) 1SQ ≅ 25 kg of ^{235}U,
- Pu ($^{238}Pu < 80\%$): 1SQ ≅ 8 kg ;

▪ Indirect use nuclear material:
- LEU ($^{235}U < 20\%$) 1SQ ≅ 75 kg of ^{235}U,
  1SQ ≅ 10 tons of U_{nat},
  1SQ ≅ 20 tons of U_{depl},
- Th 1SQ ≅ 20 tons of Th.

It should be noted that the presence (or potential presence) of these materials as part of normal operation or as a result of a facility misuse, defines the level of the required safeguards in a given NES.

In ″Expert Elicitation″ this observable is an objective of the ″Fissile Material Type″ PR's-measure, affecting also other PR's-measures in the acquisition analysis of a PR-pathway.

Core designer could try to mitigate or improve PR on the basis of the fuel enrichment in both loaded and discharged fuel. This information could be obtained with tools used for scenario studies as presented in Figures 2 and 3, showing the variation in time of enrichment, or Pu content's, of fast (model SFR) and LW reactors [17, 18].

Figure 2 shows that, for the model SFR and a given scenario, the Pu content in the discharged irradiated fuel is about 1% higher than in the loaded fuel, thanks to the breeder characteristic of the considered SFR.

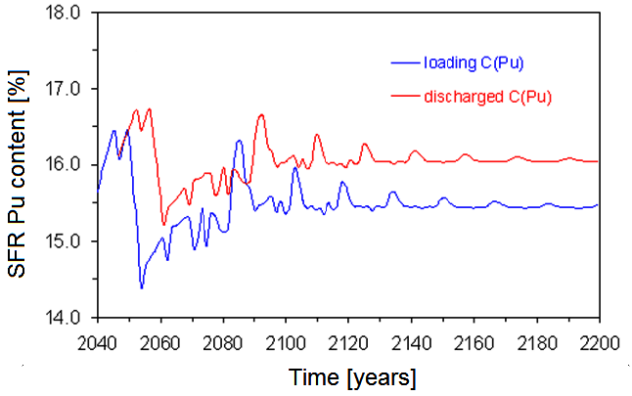


Fig. 2. SFR Pu content for a scenario of 2000TWhe, for 200 years

Likewise, with the scenario involving LWRs, Figure 3 shows that there are reactor design options allowing lower Pu inventory for the same scenario.

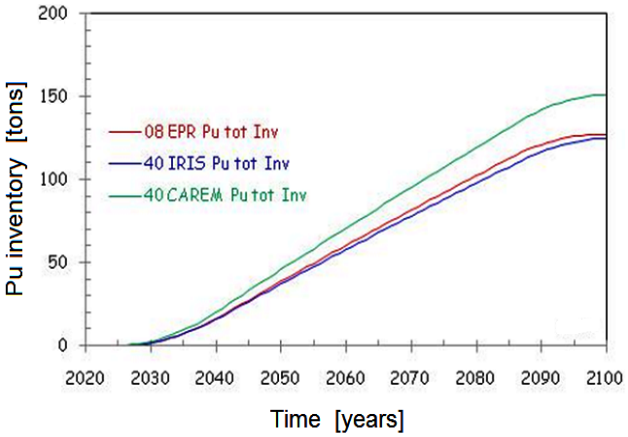


Fig. 3. Pu Inventory for a LWR Scenario of 105 TWhe, for 80 years

Information such as those given in above presented figures could help the reactor designer in finding core design solutions with an increased PR.

Fissile Material's Quality

From PR point of view, the fuel enrichment cannot characterize completely the ″material attractiveness″ which also depends on the fuel composition. Scenario study tools allow obtaining much information on this regard. Table 1, [17], presents the fresh fuel Pu isotopic composition for the model SFR in four different scenario configurations:
- Case 1: Break-even core at 5 years cooling time
- Case 2: Break-even core at 5 years cooling time with Minor Actinides (MA) recycling
- Case 3: Break-even core at 2 years cooling time
- Case 4: Breeder core at 5 years cooling time

Table 1 SFR loading Pu isotopic composition (%), [17]

	Case 1	**Case 2**	**Case 3**	**Case 4**
^{238}Pu	0.54	2.35	0.54	0.36
^{239}Pu	58.35	58.33	59.96	65.16
$^{239}Pu + ^{241}Pu$	61.73	60.67	61.75	66.61
^{240}Pu	34.32	33.25	34.30	30.52
$^{240}Pu + ^{242}Pu$	37.70	36.98	37.71	33.02

Likewise, Table 2, [17], shows the discharged fuel Pu isotopic composition for the same four different scenario configurations.

Table 2 SFR discharged Pu isotopic composition (%), [17]

	Case 1	**Case 2**	**Case 3**	**Case 4**
^{238}Pu	0.53	2.39	0.53	0.36
^{239}Pu	58.97	57.29	57.99	63.79
$^{239}Pu + ^{241}Pu$	62.43	61.49	62.45	67.41
^{240}Pu	33.87	32.64	33.86	30.07
$^{240}Pu + ^{242}Pu$	37.04	36.13	37.02	32.23

Based on the following classification, [4]:
- WG-Pu = weapons-grade Pu, nominally 94% fissile Pu isotopes;
- RG-Pu = Reactor-grade Pu, nominally 70% fissile Pu isotopes;
- DB-Pu = Deep Burn Pu, nominally 43% fissile Pu isotopes;
it follows that, for all the configurations, both fresh and discharged fuels have RG-Pu composition, which, according to the GIF-PR&PP methodology, has ″intermediate″ PR characteristics. It is worth noting that the RG-Pu has a very low content in ^{238}Pu, with a negative effect on PR.

The model SFR breeder core (Case 4), with axial blankets, shows a ″worse″ PR, having an increased fissile content and a reduced content of Pu even isotopes. It is worth noting that from PR point of view, axial blankets solution is to be preferred with respect to the radial blankets one, since the axial ones could easily be reprocessed simultaneously with the whole fuel assembly, while radial blankets could be handled separately.

Minor Actinides homogeneous recycling does not affect significantly the Pu composition, excepting the ^{238}Pu content that ″increases″ the PR through the heating rate.

Regarding the Pu quality, the scenario studies can also provide to the core designer further information. For instance, Figure 4, [17], shows the behaviour of the fissile Pu quality defined by the ratio (^{239}Pu + ^{241}Pu) /Pu: at equilibrium this value is close to 62%.

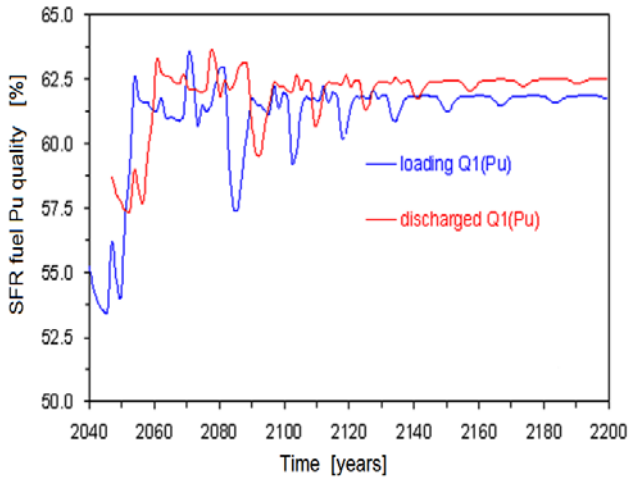


Fig. 4. SFR fuel Pu quality for a scenario of 2000TWhe, for 200 years

Looking at LWR scenarios studies, Table 3, [18, 19], shows LWRs spent fuel composition, clearly indicating that the composition of the Pu is close to RG-Pu, and that the fissile Pu quality is comparable to the one of the model SFR, though with different scenario. This demonstrate the importance to take into consideration fuel cycle length, refuelling batches number and strategy, burn up, etc.

To be noted is the lower value of ^{238}Pu content for the CAREM reactor, characterized by fresh fuel with low enrichment and low burnup discharged fuel.

Table 3 LWRs SF materials breakdown and Pu isotopic composition (%), [18, 19]

	EPR	**IRIS**	**CAREM**
Uranium	***98.538***	***98.551***	***98.913***
Plutonium	***1.314***	***1.293***	***1.013***
MA	***0.148***	***0.156***	***0.074***
^{235}U	0.775	0.823	0.993
^{236}Pu	< 1E-4	< 1E-4	< 1E-4
^{238}Pu	3.280	3.586	1.772
^{239}Pu	49.170	48.580	55.478
^{239}Pu + ^{241}Pu	64.170	63.801	69.908
^{240}Pu	24.086	23.877	22.780
^{240}Pu + ^{242}Pu	32.550	32.612	28.320

Assuming

$$C\ (^{A}Pu) = {}^{A}Pu\ /\ Pu,$$

the values in Tables 1- 3, according to some authors [20, 21], could be read in the following way respect to PR:
- C(^{238}Pu) < 9% implies a weak Pu composition with respect to PR, [20];
- C(^{239}Pu) > 50% implies also a weak RG-Pu composition with respect to PR;
- C(^{240}Pu + ^{242}Pu) > 32% means a ″good″ spontaneous neutron generator Pu composition;
- C(^{240}Pu) > 30% means a strong RG-Pu composition with respect PR [21].

Finally, core designer should take into consideration that while enrichment or Pu content of the loaded fuel is defined by the core criticality, fissile quality of the discharged fuel is defined by burn up level; meanwhile, both are conditioned by irradiation and refuelling strategy.

Physical Observables impact on PR

It has been already mentioned that some PR methodologies provide numerical results that could be used, even if their accuracy might be hampered by the use of weight factors (that could be questionable) simulating the institutional context. This is part of a Multi-Attribute Utility Analysis, [5], and some tools for scenario studies already include algorithms for numerical evaluations of some physical observables of the core design relevant for PR analysis.

Beyond the physical observables, like significant quantity inventory, Pu heating rate, weight fraction of even Pu isotopes, fissile material concentration and radiation dose rate, there are other utility functions related to size/weight of the processing single unit (e.g. a fuel assembly), measures, their frequencies, their uncertainties, separability of material, physical barriers, etc.

While the physical observables are a solid basis for PR considerations, the choice and reliability of the weight factors in combining the results of the single physical observables, according the formulation of Eq.(1), remains an open question. At an early core design phase, this aspect is beyond the designer task; nonetheless the collection of information on the impact of some physical observables on the PR behaviour remains useful.

On the Significant Quantity

Significant Quantity (SQ) is strictly connected to the fissile material quality and, therefore to the material attractiveness. Figures 5 and 6 show the SQ behaviour in time, per metric tonne of fuel, obtained using scenario studies tools, referring to the examined scenarios, [17].

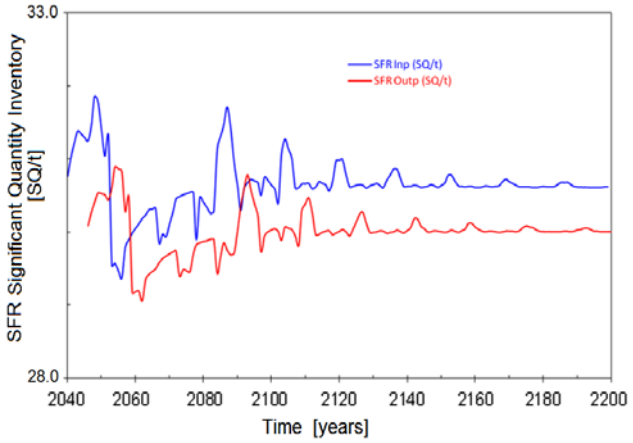


Fig. 5. SFRs Significant Quantity Inventory

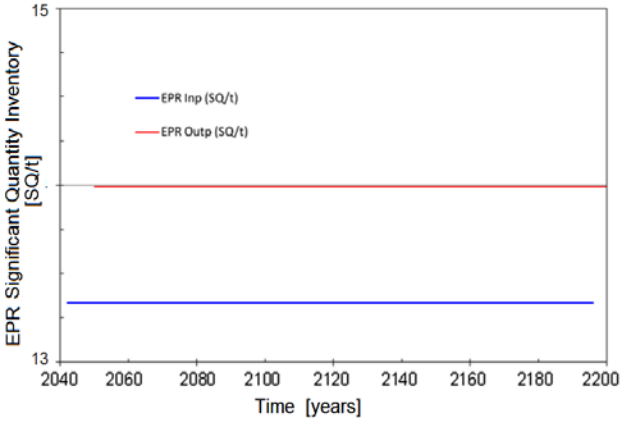


Fig. 6. EPRs Significant Quantity Inventory

While the Significant Quantity of the discharged fuel in model SFRs is lower than for the loaded fuel (as expected given the irradiation strategy), an opposite behaviour is observed for the EPRs thermal reactors (an increase of about 5%).

Concerning the model SFR, it is worth noting that about 75 tons of MOX fuel are requested for each reactor and that the criticality requirement is 15.5% ≤ C(Pu) ≤ 16.1% (from Fig. 2, where C(Pu) = Pu/(U+Pu) = Pu content); this implies a Pu demand between 11.6 and 12.1 tons per reactor. Considering that each reactor contains 451 Fuel Assemblies (FA), it means an amount of Pu per FA between 25.7 to 26.8 kg. Since the ^{238}Pu content is much lower than 80% (Tables 1 and 2), it means that 1SQ ≅ 8 kg of Pu, and it follows that the diversion of one FA would be enough to obtain more than 3SQ of Pu. Designers should be well aware of this type of considerations since the early stage of the core design.

Results displayed in Figures 5 and 6 have been obtained by the utility function, [5]:

$$u(x)=\begin{cases}1, & if\ x<1;\\ \dfrac{(30-x)^{1/3}}{7.18}+0.574 & if\ 1\le x\le x_{\max}=100;\\ 0, & if\ x>x_{\max};\end{cases} \quad (2)$$

where: x is the total inventory in SQ in the facility, and x_{max} is the maximum possible inventory.

Since each fuel cycle facility will contain some quantity of fissile material, its amount would define the attractiveness of the facility. The importance of the last utility function relies on the fact that it can provide responses on the attractiveness among the different fuel cycle facilities, especially for inventories with less than one SQ.

On the Heating Rate

One of the physical observables which could express the difficulty of designing a weapon device is the heating rate. Figure 7 shows the heating rate from Pu, [17], per unit mass of FA of the already considered model SFR, while the corresponding utility function, [5], is given by the following relationship:

$$u(x)=1-\exp\left[-3\left(\frac{x}{x_{\max}}\right)^{\frac{4}{5}}\right],\ \text{(W/kg)} \quad (3)$$

where: x is the heating rate (W/kg) from the Pu in the material, and x_{max} is the maximum possible heating rate, set to 570W/kg, which is the heating rate of pure ^{238}Pu.

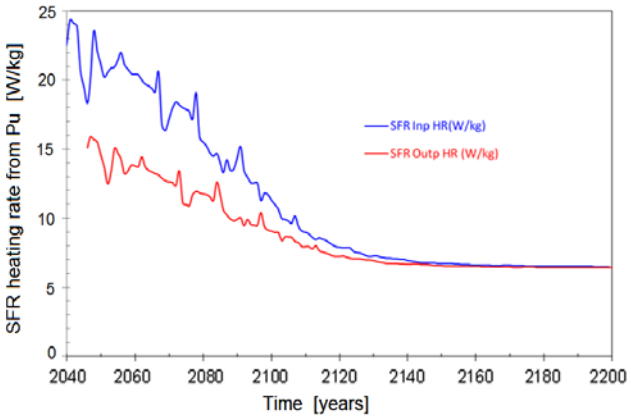


Fig. 7. SFR heating rate from Pu [W/kg]

In the equilibrium regime scenario, the heating rate of both loaded and discharged fuels is the same, while in the transition phase the fresh fuel is characterized by higher heating rates due to the higher Pu content in the fresh fuel.

On the Radiation Dose Rate

High–dose rate materials would be hazardous to handle and may require the use of special and expensive equipment. Extremely high–dose rate materials would provide acute biological effects incapacitating the potential proliferator, while it is assumed that above a threshold of about 600 rem/h/SQ, the death is certain. Therefore, the radiation dose rate could contribute to improve the PR characteristics. Small effects could occur in case of low-dose rates with a threshold at about 200 mrem/h/SQ, while significantly greater effects are expected for higher radiation dose rates.

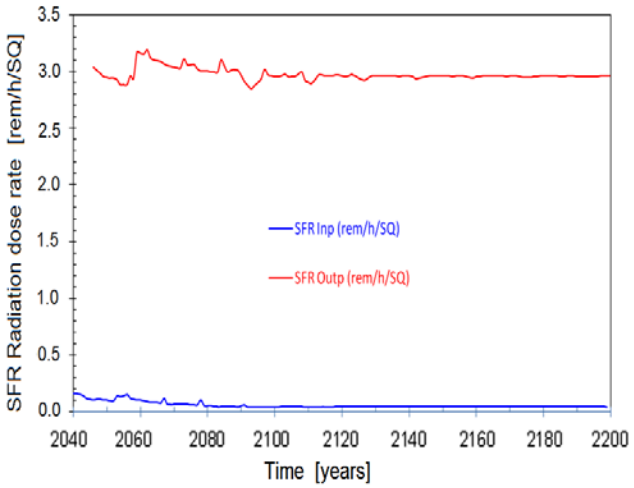


Fig. 8. SFR radiation dose rate [rem/h/SQ]

Figure 8, [17], shows the behaviour of radiation dose rate, in mrem/h/SQ, for the SFRs considered in the energetic scenario. Of course, the radiation dose rate is close to zero for the loaded fresh fuel, while appreciable values are observed for the discharged fuel.

Also in this case there is a semi-empirical utility function, [5], segmented on the range (0 - 600 mrem/h/SQ). It was developed based on acute biological effects of whole-body radiation dose of the potential proliferator.

It is worth noting that the evaluation of the radiation dose rate is rather a complex methodology which could require sophisticated tools and experienced evaluators.

On the Weight Fraction of Even Pu Isotopes

Due to the physical properties of the Pu even-even isotopes, their concentration could significantly complicate the manufacturing of a nuclear explosive device. Table 4 includes some of the nuclear properties and shows that the ^{240}, ^{242}, ^{244}Pu isotopes have a relatively high Spontaneous Fission (SF) rate, which could compromise the feasibility of an efficient explosive nuclear device, due to the pre-initiation and the consequent pre-detonation.

The utility function describing the SF impact on the proliferation resistance behaviour is given by the following relationship [5]:

$$u(x) = 1 - \exp\left(-\frac{7}{2}x^{9/5}\right), \quad x = \frac{\sum_{\text{even } J} N_J(^J Pu)}{\sum_{\text{all } J} N_J(^J Pu)} \quad (4)$$

In case the Pu is not present (or in very small quantities), the utility function value is equal to 1.

It is worth noting the ″dual aspects″ of the odd ^{241}Pu isotope which is an excellent fissile material, characterized by a half-life of 14.3y, [22]; however it decays by β^- in ^{241}Am, an absorber material, which behaves as poison of the "criticality" of the nuclear weapon device.

Scenario Sustainability and PR Response

The scenario studies tools could provide useful information on sustainability strategies that could improve PR. In case of FRs deployment, the sustainability of a scenario would be subordinate to the Pu availability; therefore, this should be first consideration to address.

In case of an energy demand scenario where FRs progressively replace LWRs at constant energy demand, the scenario study response on the Pu availability for the FRs fueling is shown in Figure 9, [17], where the four given scenarios have been analyzed.

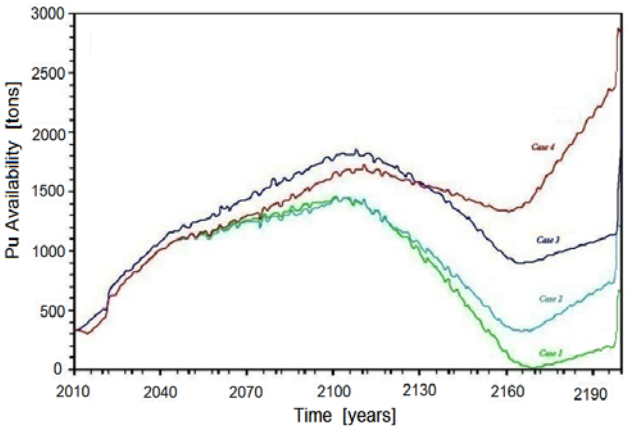


Fig. 9. Pu availability for an energy demand scenario with FRs deployment (Transition Scenario)

The first answer concerns the Case 1, i.e. the break-even core at 5 years cooling time which shows that the scenario is unsustainable, as the Pu margin is close to zero. For the remaining cases, there is enough Pu for the sustainability of the three scenarios, with Pu margin of about 325, 895 and 1340 tons respectively, but with a progressive worsening of the PR behaviour. It is evident that at scenario study level, the ″best″ solution for the scenario sustainability and PR behaviour is represented by Case 2, i.e. the break-even core at 5 years cooling time with MA recycling.

The breeding gain improvement by MA recycling allows the sustainability of the scenario without using fertile assemblies or reducing the cooling time; the last two options leading to a worsened PR. However, the MA recycling option could compromise its safeguardability, [23], leading to a worse PR.

Figure 9 and numerical results show that for the last two core configurations, i.e. Case 3 and Case 4, MA recycling could be avoided, thus avoiding also complications on safeguardability:

- a reduced cooling time, though higher than 2 years, could be enough for obtaining sufficient Pu margin (increase of 925 tons in of Pu inventory) for sustaining the scenario;
- an appropriate strategy on fertile assemblies (e.g. FA number with axial blanket and/or axial blanket length) could give a sufficient Pu margin.

Conclusions

Proliferation Resistance should become one of the primary topics to be addressed in the framework of nuclear energy systems development. There are no technologies that can eliminate the risk of proliferation, but technology and design could play a role in reducing the proliferation risk.

In this context, an approach to facilitate the identification of technological solutions in the early core design phase in order to improve PR behaviour has been suggested, based on the use of studies on energy demand scenarios as a supporting tool. These studies provide information on physical observables relevant to PR analysis, particularly useful at the early design stage. Even if they cannot provide all the information needed for detailed evaluations, they can still provide results and data that could be used by designers to improve PR features.

Some general conclusions, useful in early design phase to the facility designer are given below:

- Improved PR characteristics and behaviour of a given NES, has to be considered within a more complex framework, including the whole range of interactions among the elements of a nuclear fuel cycle;

- PR intrinsic features improvement can be achieved through, inter alia, breeding gain ″modulation″, burn up rate, isotopic detailed fuel composition, fissile materials SQ-inventory, nuclear material attractiveness, heating rate, radiation dose rate;

- PR extrinsic features improvement can be achieved for the whole fuel cycle, through choices on operative conditions of enrichment, fabrication and reprocessing plants, interim and other storages, and waste management plants;

- PR features improvement can also be achieved through an ″optimised″ strategy among different options concerning the design and the operating conditions of all the scenario components;

- PR performances comparison among different systems is feasible only at the same ″boundary″ conditions;

- During the conceptual design phase, after core design details, constraints and operations planning have been well defined (and frozen), a proliferation resistance assessment for the specific component (i.e., whole reactor) based on GIF and/or INPRO methodology should be carried out.

Generally, components of a fuel cycle which strongly impact the whole PR behaviour, i.e. enrichment plants, reprocessing plants, fabrication plants, stocks, temporary storage, transportations, etc., are not considered in the core design especially in the early stage; nonetheless, energy demand scenario studies would provide useful information on this regard.

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