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Fundamentals of reactor physics with a view to the (possible) futures of nuclear energy

Fondamentaux de physique des réacteurs et application à l'étude des futures possibles de l'énergie nucléaire

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ABSTRACT

This paper present basic nuclear reactor physics that may help to understand next challenges that nuclear industry have to face in the future. The ones considered in this work are waste production and natural resources consumption. This paper shows that waste and resources are linked by the plutonium status that could be considered as the principal waste or a valuable material that should be saved for a future transition to breeder reactors that could be for instance Sodium-cooled Fast Reactors (SFRs). This kind of reactors does not rely on natural resource supply, as it produces its own fissile material, plutonium-239, after a neutron capture on uranium-238. However, the operation of SFRs needs a huge amount of plutonium that should be produced in current Pressurized Water Reactors (PWRs).

Natural uranium available on earth is expected to allow the operation of the global current fleet until approximately 2100 without major issues. The transition from PWRs to SFRs is then needed if and only if the nuclear industry will face an increase at a global scale during this century. If not, plutonium, the most radiotoxic element produced in PWRs, should be considered as a waste. Consequently, the plutonium status depends on the future evolution of nuclear energy. This paper shows that a status-quo means that plutonium should be considered as the most problematic element that should be handled on a long-term basis. On the other hand, a strong increase in nuclear energy on a global scale would imply that plutonium is a valuable material that would make a transition to SFRs possible.

RÉSUMÉ

Cet article présente les bases de physique nucléaire et de neutronique permettant d'appréhender deux des principaux enjeux auxquels devra faire face l'énergie nucléaire dans le

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futur : la production des déchets nucléaires et la consommation des ressources naturelles. Nous montrons que ces deux problématiques sont liées par le statut du plutonium, qui peut être considéré, soit comme le déchet principal, soit comme une matière valorisable qui doit être conservée pour la transition vers des réacteurs régénérateurs comme ceux refroidis au sodium (SFR en anglais). Ce type de réacteur ne dépend pas des ressources naturelles, car il produit sa propre matière fissile, le plutonium 239, après une capture neutronique sur l'uranium 238. Cependant, l'exploitation des SFR nécessite un très grand inventaire de plutonium, qui doit être produit dans les réacteurs actuels comme les réacteurs à eau sous pression (PWR en anglais). L'uranium naturel considéré comme disponible sur terre aujourd'hui devrait permettre le fonctionnement des réacteurs actuels jusque vers 2100. La transition des PWR vers les SFR est nécessaire, si et seulement si le développement de l'industrie nucléaire connaît un développement très important pendant ce siècle. Sinon, le plutonium, l'élément le plus radiotoxique produit dans les REP, doit être considéré comme un déchet. Ainsi, le statut du plutonium dépend de l'évolution future de l'énergie nucléaire. Ce papier montre que la gestion du plutonium, comme élément le plus difficile à gérer sur le long terme, doit être optimisée, puisqu'il est une matière nécessaire à la transition vers les régénérateurs. Nous présentons ici la physique nucléaire essentielle à la compréhension des enjeux essentiels que rencontrera l'énergie nucléaire dans le futur. Ceux considérés sont la production des déchets nucléaire et la consommation des ressources naturelles. Cet article montre qu'ils sont liés par le statut du plutonium, qui peut être considéré, soit comme le déchet principal ou comme une matière utile qui rendrait la transition vers les SFR possible.

1. Introduction

Nuclear energy has always been subject to discussion and speculation for its evolution in the future. Different institutions that build scenarios for energy prospective are able to draw radically opposite trajectories for nuclear trends. The Negawatt Association [1] for instance, shows a complete shutdown of all reactors present in France by 2050 coupled with voluntarism energy economy, high growing of renewables and massive electricity storage. At a global scale, the "450-ppm scenario" of [2], which is built to limit the CO_2 concentration in the atmosphere below the limit of 450 ppm, shows an increase by a factor of 3 to 4 for nuclear energy by 2035, despite a strong decrease in energy consumption. Finally, Bouneau et al. [3] succeeded in building a global energy mix that would satisfy three constraints: a limit in CO_2 emission, an energy consumption of 20 Gtoe in 2050, and a reduction of the inequalities in energy consumption. In that mix, the nuclear, considered as a free parameter that would allow the mix to fulfill the criteria, would increase by a factor of 8 to 9.

The issues that nuclear industry will have to face within the next 50 years would be strongly different if nuclear power is to greatly increase at a global scale, or, on the contrary, is to decrease. Regarding such oppositions in nuclear projections, nuclear technologies that are currently developed represent necessarily a large representative panel of different possible futures.

This paper explains those differences by focusing on two main issues: waste production and natural uranium consumption for a global fleet. Those two observables are strongly linked by the question of the plutonium that should be considered as a waste if nuclear power trends to decrease, whereas it should be consider as a valuable material if there is a strong demand for new reactors.

The first part of this paper describes basic nuclear physics that help up to understand nuclear reactor physics. It shows that a nuclear power plant design is a compromise between fuel enrichment costs and reactor costs, and explains why thermal reactors can operate with fuel enrichment to a few percents, whereas fast reactors must work with fuel with higher enrichment. The second part focuses on nuclear waste, their definitions, and characterizations. Finally, the last part is dedicated to natural resources consumption. It explains how plutonium can be used in new-generation reactors and presents the conditions for those reactors to be competitive. They are several possibilities for next-generation reactors; however, this paper focuses on the technology that is the most studied in Europe so far: sodium-cooled fast reactors (SFRs).

2. Chain reaction, criticality, and fuel evolution

Nuclear power plants are based on a chain reaction of neutron induced fissions of heavy nuclei such as uranium or plutonium. Uranium is the heaviest nuclei that can be found on earth; it has two main isotopes: ^{235}U and ^{238}U [4]. Only ^{235}U is fissionable, meaning that a neutron with any kinetic energy (even if it is equal to 0) can induce the fission of this isotope. Uranium-238 may fission with a neutron whose kinetic energy is higher than 0.8 MeV. Due to this fission threshold for ^{238}U, ^{235}U is the only isotope on earth that may produce a fission chain reaction. Fission produces two fission products (light nuclei), between two or three neutrons on average and releases a great amount of energy: 200 MeV. This value explains why nuclear energy is so concentrated: typically, in France, a 1-GW_e nuclear reactor provides electricity for 1.1 million inhabitants and fissions one metric ton of material per year.

2.1. Criticality definition

The fission chain reaction can occur only in particular conditions. If the probability of producing a neutron by fission is too low compared to the probability of the disappearance of a neutron, the chain reaction is not possible. The neutron multiplication coefficient is defined as the probability that a neutron is produced by fission over the probability that a neutron disappears, as expressed by Equation (1).

$$k = \frac{\text{neutron produced by fission}}{\text{neutron disappearance}} \tag{1}$$

If $k > 1$, the system is called overcritical, and the number of neutrons, and consequently the number of fission events (and the thermal power) increases. If $k < 1$, the system is called undercritical, and the chain reaction tends to stop because of a lack of neutron production. The only stable value is $k = 1$, where each neutron disappearance is exactly compensated by the production of a neutron by fission. The system is then called critical.

The two main types of disappearance are neutron leakage (neutrons escape the system) and neutron absorption by nuclear reactions. Each nuclear reaction is characterized by a cross section, and the reaction rate is expressed by the product of the considered nucleus concentration, N_i, by the considered cross section, σ_i^r, of the reaction r and by the neutron flux, ϕ. As an example, the fission reaction rate of ^{235}U is calculated by Equation (2).

$$\tau_{\text{fission}}^{^{235}\text{U}} = N_{^{235}\text{U}} \sigma_{^{235}\text{U}}^{\text{fission}} \phi \tag{2}$$

Knowing the average number of neutron emitted by fission, ν, the neutron multiplication factor of a reactor can be calculated by Equation (3).

$$k = \frac{\nu \cdot \sum_{i \in \text{isotopes}} N_i \sigma_i^{\text{fission}} \phi}{\sum_{\substack{i \in \text{isotopes} \\ r \in \text{reactions}}} N_i \sigma_i^r \phi + \text{neutronleakage}} \tag{3}$$

An infinite multiplication factor can be defined and characterizes the matter, neglecting neutron leakages that are due to reactor geometry design. This new multiplication factor is defined in Equation (4), where the neutron flux is simplified as it appears at the numerator and at the denominator of the ratio.

$$k_\infty = \nu \frac{\sum_{i \in \text{isotopes}} N_i \sigma_i^{\text{fission}}}{\sum_{i \in \text{isotopes}} N_i \sigma_i^r} \tag{4}$$

From Equation (3), one clearly sees that criticality depends on the ratio of cross sections and atomic concentrations.

2.2. A compromise between enrichment and slowing down

The atomic concentrations of ^{235}U and ^{238}U may be linked by the enrichment, ϵ, defined as the ratio of the ^{235}U concentration over the total uranium concentration as in Equation (5).

$$\epsilon = \frac{^{235}\text{U}}{\text{U}_{\text{tot}}} \tag{5}$$

Assuming that the nuclear reaction occurs only on uranium isotopes, one can transform Equation (4) in Equation (6). Absorption reactions are limited in that case to fission and neutron capture. For ^{238}U, fission can also be neglected.

$$k_\infty = \frac{\epsilon \sigma_{^{235}\text{U}}^{\text{fission}}}{\epsilon \sigma_{^{235}\text{U}}^{\text{absorption}} + (1-\epsilon)\, \sigma_{^{238}\text{U}}^{\text{absorption}}} \tag{6}$$

The cross sections of interest are presented in Fig. 1. As one can see, the ^{235}U cross section for the fission reaction is approximately 10 times higher than the capture cross section, whatever the neutron energy. Equation (6) then becomes Equation (7).

$$k_\infty = \frac{\epsilon}{1.1\epsilon + \frac{(1-\epsilon)\sigma_{^{238}\text{U}}}{\sigma_{^{235}\text{U}}^{\text{fission}}}} \tag{7}$$

To be critical, the infinite multiplication factor should be higher than 1, leading to a condition for the nuclear reaction cross section of uranium isotopes, depending on uranium enrichment.

The natural uranium enrichment is 0.7%. With this value, to obtain an infinite multiplication factor greater than 1, the fission cross section should be 100 times higher than the ^{238}U capture cross section, which is the case at low neutron kinetic energy, as shown in Fig. 1. Unfortunately, the neutrons produced by fission have a typical kinetic energy of 1 MeV. In that energy region, the cross-section ratio is not favorable.

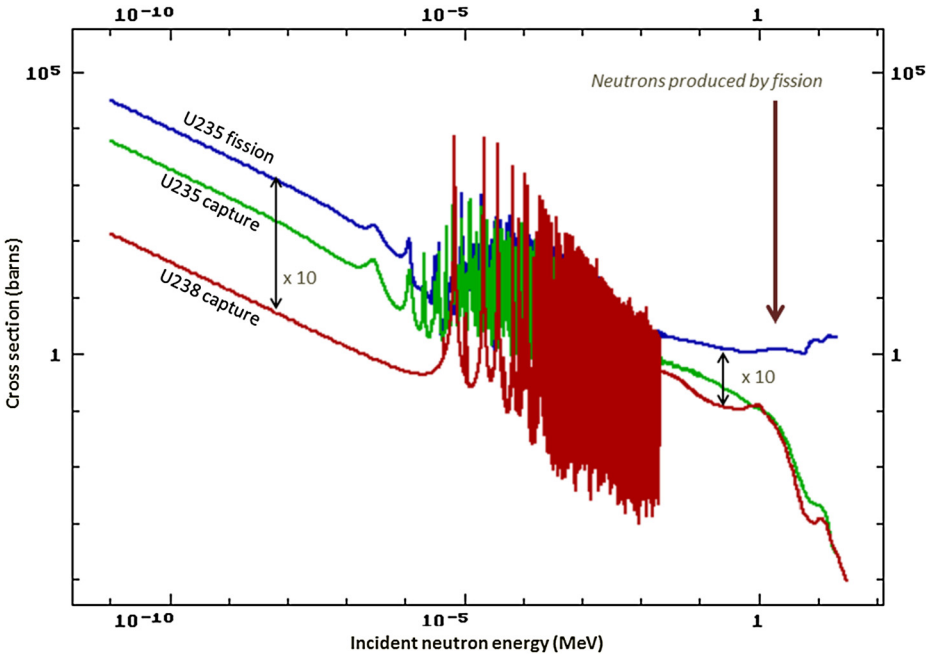

Fig. 1. Uranium–neutron reaction cross section.

There is two ways to increase the criticality level: to use a fuel with higher enrichment, or to slow down the neutrons with scattering on light nuclei. Hydrogen is an excellent nucleus for slowing down, but its absorption cross section is too high to conceive a nuclear reactor with natural uranium. Deuteron (in heavy water) has a much lower absorption cross section and is used in CANDU reactors with natural uranium. Carbon in graphite could be used too. Most of the reactors in the world (81%) are light-water reactors that work with uranium enriched between 3 to 4.5%, approximately.

2.3. Fuel evolution

The fuel, once charged in the reactor, will evolve while the reactor is operating. Indeed, ^{235}U will disappear because of fission, producing fission products, whereas ^{238}U will produce ^{239}Pu and several heavier isotopes. The evolution of each nucleus is described by Equation (8), where λ_i is the nuclear disintegration constant of isotope i, $\lambda_{j\to i}$, the one of isotope j, which leads to nucleus i.

$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = -\lambda_i N_i - \sigma_i^{\mathrm{tot}} N_i \phi + \sum_{j\in\text{isotopes}} (\lambda_{j\to i} + \sigma_{j\to i}\phi) N_j \tag{8}$$

This fuel evolution process is responsible for the formation of isotopes heavier than uranium: plutonium and minor actinides. As an example, a simplified evolution equation of plutonium-239 is given in Equation (9).

$$\frac{\mathrm{d}N_{^{239}\mathrm{Pu}}}{\mathrm{d}t} = -\lambda_{^{239}\mathrm{Pu}} N_{^{239}\mathrm{Pu}} - \sigma_{^{239}\mathrm{Pu}}^{\mathrm{tot}} N_{^{239}\mathrm{Pu}} \phi + \sigma_{^{238}\mathrm{U}}^{\mathrm{capt}} N_{^{238}\mathrm{U}} \phi \tag{9}$$

3. Nuclear waste

Nuclear fuel typically stays during three years inside the reactor core, and then must cool down for five years if transport is needed. After, it may be reprocessed to recover valuable matter or considered as a waste regarding the national fuel strategy. In any case, the reference long-term management of the different radioactive matter is very long-period underground storage.

To quantify the level of danger of those matters, one uses radiotoxicity, measured in sieverts. This radiotoxicity is a way to quantify the impact on the population if the matters would be released in the biosphere and would be transferred to food, or water consumed by the population. Obviously, the purpose of the storage is to prevent this from happening. However, radiotoxicity represents the source term for calculations.

3.1. Radioactivity characterization for waste management

The radiotoxicity of a typical UOx fuel is presented in Fig. 2. The evolution of the fuel is performed with the SMURE package [5]. The contribution of fission products is the red curve, that of plutonium the green one, and that minor actinides

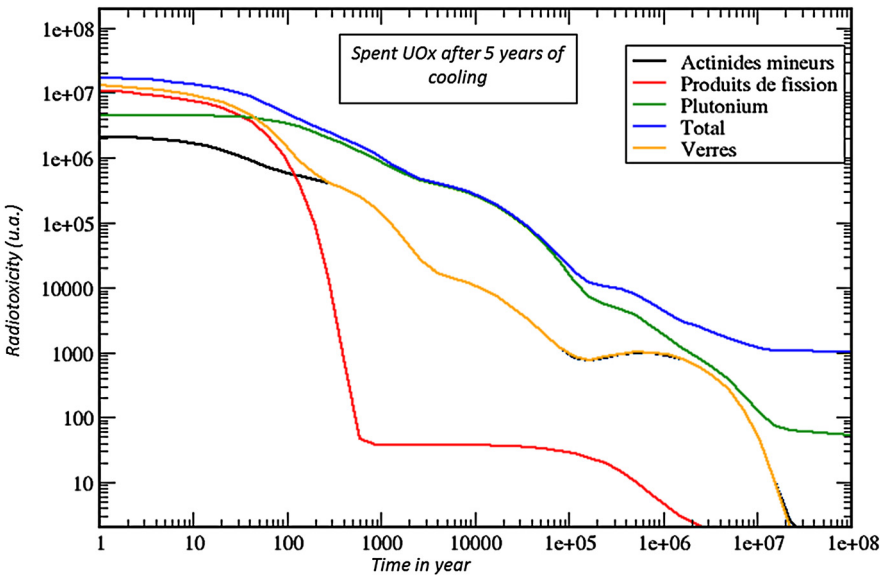

Fig. 2. Characterization of the UOx spent fuel: radiotoxicity during long-term storage.

Table 1
Waste definition regarding the fuel strategy.

	Waste	Valuable matters
One through (ex.: USA)	Uranium Plutonium Fission products Minor actinides	–
Plutonium mono-recycling (ex France)	Fission products Minor actinides	Uranium Plutonium MOx spent fuel

is the black one. Their sum is the blue curve. Minor actinides are heavy nuclei that are neither uranium nor plutonium, this includes mainly neptunium ($Z = 93$), americium ($Z = 95$), and curium ($Z = 96$). Fission products are the main contributors during a few centuries. After that point, plutonium isotopes represent the main part of radiotoxicity. The yellow curve in Fig. 2 represents the sum of minor actinides and fission products; this curve represents the waste in the current French strategy, as it is pointed out in the next paragraph.

3.2. Waste definition

From Fig. 2, it is clear that the waste management strategy will definitely depend on plutonium status. If this element is considered as a waste, the radiotoxicity to deal with for long-term storage is much higher (until one thousand times more) than if plutonium were considered as a valuable matter. Plutonium status depends on national legislations. With "one-through" strategies, like in the United States for instance, all the used UOx fuel, including plutonium, is considered as a waste. This kind of strategy is defined as an on-through strategy, as all the nuclear fuel is considered as a waste after irradiation. On the other hand, for reprocessing strategies, like in France, plutonium is a valuable material and is extracted from the used UOx fuel to produce a new fuel (MOx). The status of plutonium was, for example, defined in 2006 by the French government [6]. Table 1 summarizes status of different matters in the spent fuel regarding the strategy.

Therefore, nuclear wastes in the French strategy are composed only of fission products and minor actinides (orange curve in Fig. 2). Those elements are put together in glasses (*verres* in French) for long-term storage.

3.3. Plutonium burning

Plutonium recovered from the reprocessing of the spent UOx fuel is then mixed with depleted uranium to manufacture MOx fuel (Mixed Oxide) to replace some UOx assemblies in regular pressurized water reactors. The production of plutonium is quite inefficient in those reactors, and seven UOx assemblies are needed to produce the plutonium of a single MOx assembly.

To compare the radiotoxicity of different strategies, one has then to compare 8 UOx spent fuel assemblies against 7 UOx spent fuel plus 1 MOx spent fuel ones. Fig. 3 presents the results of those calculations: the blue curve represents the open

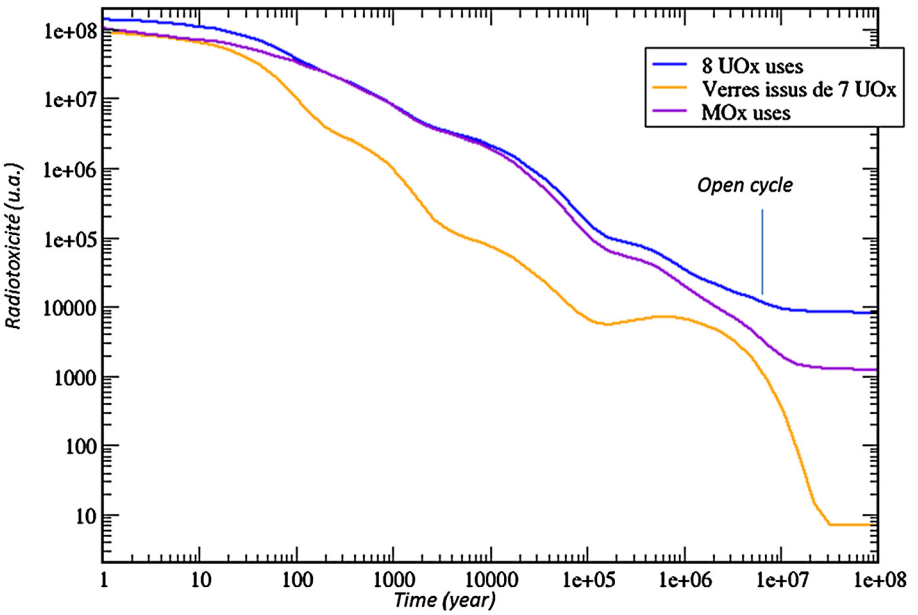

Fig. 3. Radiotoxicity comparison between open cycle and plutonium monorecycling strategy.

cycle strategy, the purple one represents the radiotoxicity of a single MOx spent fuel, and the orange one stands for the radiotoxicity of the waste produced by the reprocessing of the 7 UOx spent fuel needed for recovering the plutonium of the MOx fuel. The radioactive materials produced by the MOx strategy are then the sum of the purple and the orange curves.

As a result, we see that plutonium incineration in MOx fuel does not lead to a significant reduction in radiotoxicity. The heavier isotopes produced during the irradiation of MOx fuel compensate the incineration of plutonium (that fission and then disappear during irradiation), leading to a constant radiotoxicity after MOx irradiation.

The purpose of the MOx strategy is then not to improve waste management. The use of MOx fuel leads to a concentration of plutonium in few assemblies (spent MOx fuel) that would improve plutonium recovering in case of massive use of plutonium. Moreover, the MOx strategy allows small uranium savings (12,5%) regarding the open-cycle strategy.

4. Natural uranium savings

In regular pressurized water reactors, the natural uranium consumption is around 200 tons per electrical GW produced (for 1 ton of material that actually fissioned). With an improvement of the enrichment process and the use of MOx fuel, the natural uranium consumption could be reduced to 130 tons per electrical GW.

However, in new-generation reactors, plutonium production could be optimized to produce one ^{239}Pu (through ^{238}U capture) each time a ^{239}Pu disappears (through neutron fission or neutron capture). With this breeding process, the natural consumption would be reduced to 1 ton per electrical GW, as only ^{238}U is consumed. In France, there are around 300 000 tons of depleted uranium, which represent around 5000 years of French electricity production in breeder reactors.

4.1. Fissile nuclei breeding principle

Each fission releases a given number of neutrons, ν. Those neutrons should maintain the chain reaction: 1 neutron (and 1 only) is consumed to induce the next fission. But the fissile may also absorb a neutron without any fission (neutron capture, followed by gamma emissions). $\alpha = \frac{\sigma_{\text{capt}}}{\sigma_{\text{fiss}}}$ represents the number of captured neutrons for one fission. The fission chain reaction then consumes $1+\alpha$ neutrons and $1+\alpha$ fissile nucleus (in that case ^{239}Pu), which should be replaced by $1+\alpha$ neutron capture on ^{238}U. This simplified neutron balance shows that ν should be greater than $2(1+\alpha)$ in a critical system for an optimized fissile production.

Fig. 4 shows the number of available neutrons after breeding and criticality $\nu - 2(1+\alpha)$ as a function of neutron kinetic energy. The blue curve presents this number for the U/Pu cycle, whereas the red curve represents the Th/U cycle (where the fissile is ^{233}U; potentialities of this alternative cycle are not discussed here). The black curve presents a typical PWR neutron spectrum. One can clearly see that, in this spectrum, the number of available neutrons is negative, showing that plutonium breeding is not possible in this kind of reactors. The purple curve represents a typical Sodium cooled Fast Reactor (SFR) neutron spectrum. In that case, the number of available neutrons is positive and fissile breeding can be achieved.

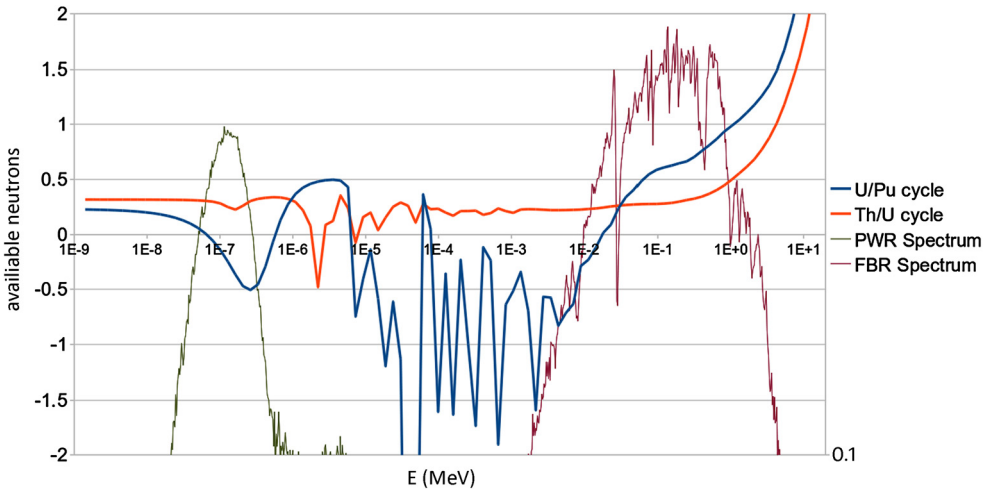

Fig. 4. Available neutrons after criticality and breeding for U/Pu cycle and for Th/U cycle as a function of the neutron energy [7].

Table 2
Uranium resources regarding its extraction cost.

	< 130 $/kg	< 260 $/kg
Proved resources	5.9 Mt	7.6 Mt
Identified resources	6.5 Mt	6.9 Mt
	Phosphate	Sea water
Unconventional	7.3 Mt	4500 Mt

4.2. Natural uranium resources

Once the first plutonium inventory loaded, this kind of reactor may be operated with no extra freshly mined uranium, as depleted uranium is largely available. From an economical point of view, those reactors are more expensive as they need extra safety procedure due to the use of liquid sodium; however, the cost of electricity does not depend on any uranium price market. On the other side, PWR electricity costs depend directly on uranium (consumption of around 200 tons per electrical GW·y).

Different estimations reckon that the uranium price where SFR becomes economically competitive vary from 230 $/kg to around 1000 $/kg [8]. Table 2 presents the uranium resources regarding its extraction cost. As one can see, there are around 15 million of tons available and the uranium extraction consumption was approximately 60 000 tons in 2015.

With the current uranium consumption, an economic uranium crisis before the end of the century is very unlikely. Even, if the nuclear electricity production increases by a factor of 2 by 2050, the natural uranium available on earth should protect us from a shortage of uranium. On the contrary, if nuclear electricity increases greatly (by more than a factor of 4 by 2050), it is quite obvious that the natural uranium production will not be sufficient to cover the consumption if the nuclear main technology remains PWR.

The plutonium status is then a tricky question, and could be summarized by a bet on the evolution of nuclear electricity demand and on uranium resources. If it increases by more than four times by 2050, the plutonium is then a precious element that may lead to a sustainable nuclear industry. On the other hand, if nuclear electricity production shall stay constant during the next 50 years, plutonium may be considered as the principal waste and the most dangerous one.

Plutonium is currently produced in PWRs at around 250 kg/GW·y. One single SFR needs approximately 20 tons of plutonium to be operated (including the spent fuel cooling and reprocessing). The present French fleet made of SFRs would require 1200 tons of plutonium, whereas the French strategy has accumulated 300 tons so far. This illustrates the status of valuable material of Pu for the future.

4.3. Inventory vs. wastes

As we introduced in §3.1, plutonium is the element producing the most radiotoxicity inside a PWR during irradiation. Sodium-cooled Fast Reactors use this element for the chain reaction to produce energy without any need for ^{235}U, which is the isotope that has to be economized if nuclear industry trends to increase. This breeding process implies that electricity production does not rely on natural uranium anymore, but that plutonium has to be recovered after each irradiation campaign by reprocessing. Wastes are then, by definition, only minor actinides (if they are not transmuted) and fission

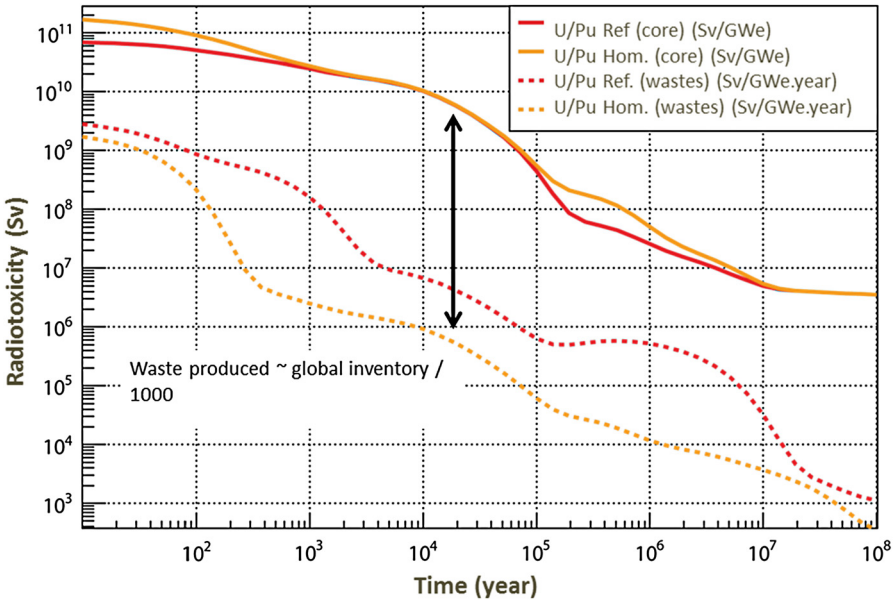

Fig. 5. Radiotoxicity of a SFR core inventory (solid lines) compared to the radiotoxicity of waste produced in a year of full operation. The red curves consider only plutonium multi-recycling, whereas orange curves consider also minor actinides transmutation [9].

products [9]. However, the huge amount of plutonium required in the cycle must be handled during fuel reprocessing and fabrication. Moreover, this Pu inventory represents a potential waste the day one decides to stop fission nuclear power.

Fig. 5 represents the radiotoxicity of the in-cycle inventory needed for one GW_e (solid lines), compared to the waste produced each year. The red curves represent SFRs without any transmutation (only plutonium is recycled), whereas the orange curves represent the homogeneous recycling of minor actinides (homogeneous transmutation strategies in SFRs).

As Fig. 5 shows, wastes produced in one year are less radiotoxic by a factor 1000, meaning that 1000 years of operation would produce wastes that are as radiotoxic as the in-cycle inventory. If the SFRs and the breeding strategy may reduce the radiotoxicity of the produced wastes, it appears that the radiotoxicity of reprocessed Pu is far higher than the annual waste production. This should lead scientists to elaborate end-of-game strategies whose purpose is to reduce the global radiotoxicity due to the plutonium needed to operate a SFR fleet.

5. Conclusions

This paper aims to present basic nuclear physics that helps us to understand what challenges nuclear energy will have to face in the near future regarding its evolution during time. Indeed, different energy scenario shows nuclear evolution that can be drastically different. Some of them show global nuclear shutdown, whereas others value its (CO_2-free) potential and tend to a huge increase worldwide.

Obviously, solutions and technologies will not be the same regarding the evolution of nuclear power. If there were to be an increase in the global nuclear energy, the available natural uranium would not be sufficient to satisfy the global demand with the current technology. A consequent increase in nuclear power plants would require a transition from PWRs to SFRs, which use plutonium as a resource. With this kind of reactor that performs a conversion of ^{238}U into ^{239}Pu, there is no natural uranium issue, but a potential plutonium shortage. Under this hypothesis, plutonium is then a valuable matter that should be considered as such.

On the other hand, plutonium is the most radiotoxic element that is produced inside current reactors (PWRs), and the natural uranium available allows us to operate the global nuclear fleet until 2100 approximately. If nuclear industry is to remain at the current level, a natural uranium economic crisis is unlikely. Under this hypothesis, plutonium shall be considered as the principal waste produced currently.

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