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# MICROREACTORS AND SMR FUEL CYCLES - NON-PROLIFERATION BY DESIGN AND FUEL CYCLE OPTIONS TO BE STUDIED IN CONCEPTUAL DESIGN

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## Abstract

Through a few examples of microreactors and SMR fuel cycles concepts, the presentation will highlight the need for application of Non-Proliferation by Design and for early consideration of fuel cycle options since their conceptual design.

Non-proliferation by design implies

- the choice of less « attractive » fuel cycles options during conceptual design,
- Protection of Technologies by Design,
- the choice of fuel cycles options reducing the need for safeguards
- and Safeguards by Design.

Focusing on proliferation during reactor operation is not sufficient since, depending on the SMR concept, proliferation weakness is often on the front-end or back-end of the fuel cycle.

But non-proliferation is not the only parameter to be taken into account; safety and economics are also key parameters. The fissile material market is about to experience significant change in the next 10-20 years. SMR developers must develop a robust business model taking it into account. Economic sustainability, high standards of safety and ambitious non-proliferation objectives are often antagonistic, but not always! Non-proliferating fuel cycle must be compatible with realistic economic conditions and credible and secured supply chain.

## 1. INTRODUCTION

IAEA, AEN, WNA, nuclear industries, national laboratories and authorities have all considered for a long time the advantages of Small Modular Reactors (SMR). Most of the current fleet of Nuclear Power Plants is neither small, nor modular. But, recently SMR are gaining interest again. These SMR have several advantages. One of them is that they are particularly attractive for new comers or remote areas.

Among these SMR, the smallest ones are the microreactors (MR) with a maximum output of about 10MWe. Their size, their simplicity, their flexibility and potentially their mobility make them very attractive for a large spectrum of users who are not only usual electricity/energy providers. They could typically replace diesel generators.

## 2. COMMERCIAL DEPLOYMENT – CONDITIONS OF SUCCESS

### 2.1 Respect highest requirements regarding non-proliferation and safety without prohibitive costs

Success of the SMR commercial deployment will mainly depend on their robustness, operational simplicity, simplification of administrative procedures and seamless integration in the users environment.

Key of success would be to allow this easy and quick deployment without any degradation, derogation nor compromise regarding the need of highest standards of safety, security and non-proliferation. Through inventive concepts, intrinsic and passive safety options, co-licensing with support of international organisations, SMR developers are confident in reaching satisfactory levels of safety. But Nuclear Safeguards and more generally non-proliferation might be the main pitfall impeding the fulfilment of marketing promises.

It is not easy to reach at the same time highest standards and requirements regarding safety and non-proliferation. It is still more complicated to satisfy those requirements and maintain electricity/energy production low prices. Indeed, safety and non-proliferation are often antagonistic. For example, highly radioactive fission products are good for non-proliferation since the nuclear material is less attractive but from a safety and radioprotection point of view, it could be an inconvenience. From an economic point of view, additional, high quality and redundant safety or safeguards equipment have a negative impact. But safety, non-proliferation and prices are not always antagonistic, and the objective is to optimize all these criteria without degrading one of them (see figure 1).

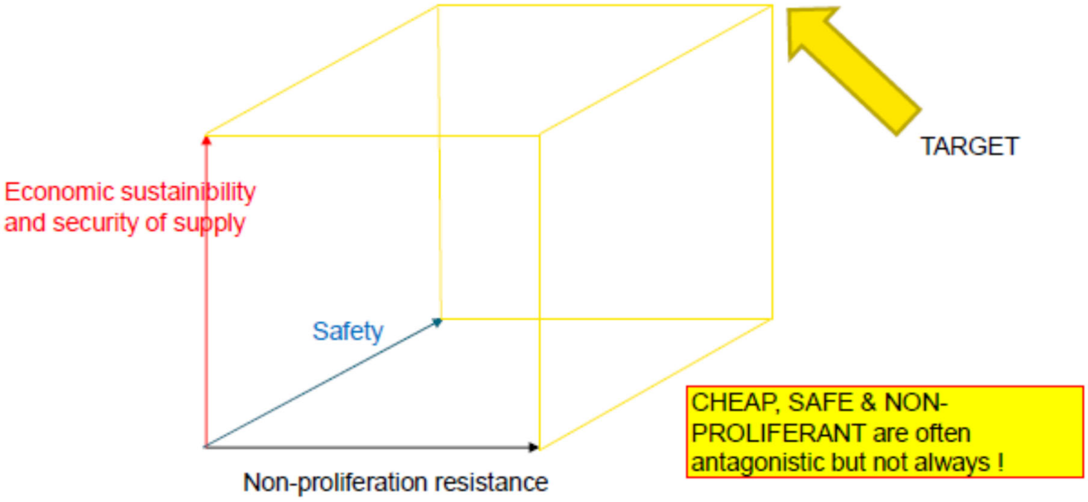


FIGURE 1: SMR target is to be cheap, safe and non-proliferating

## 2.2. Robustness of the supply chain

Choices of safe and non-proliferating fuel nuclear options shall not come with unacceptable industrial risks. New concepts are usually very different from current commercial nuclear plants with different type of fuels, using different supply chains. If the actors of this supply chain may remain the same in order to take benefit of their experience and know-how, the facility producing these new advanced nuclear fuels will be different. These new SMR designers shall guarantee that when these reactors will be at a stage of commercial deployment, all the supply chain will be available. It is an absolute necessity to secure a sustainable supply chain of the nuclear material. For instance, regarding metalized HALEU which could be an option, about 8-10 years are necessary to design, obtain regulatory authorization and build a production facility..

Robustness of the supply chain must come with some guarantee of acceptable nuclear fuel material prices.

Supply chain does not only concern front-end but also back-end operations. It is also necessary to anticipate the management of spent fuel from storage in site pools up to disposal of ultimate waste, including (or not) reprocessing options.

Regarding the supply chain, in parallel to front-end and back-end solutions, the question of logistics has to be taken into account since, depending on the U5 assay and physical form of the nuclear fuel, there may be no current licenced and cost-efficient solution for transportation of this nuclear material (for example transportation of UF6 with an U5 assay above 5%).

It is necessary to take into account during the conception phase all these aspects in order to reduce future costs.

# 3. NON-PROLIFERATION BY DESIGN

Best way to avoid unacceptable non-proliferation risks, unacceptable operational conditions, unacceptable costs and too cumbersome security measures and prohibitive physical protection is to anticipate.

Non-proliferation by design appears to be necessary.

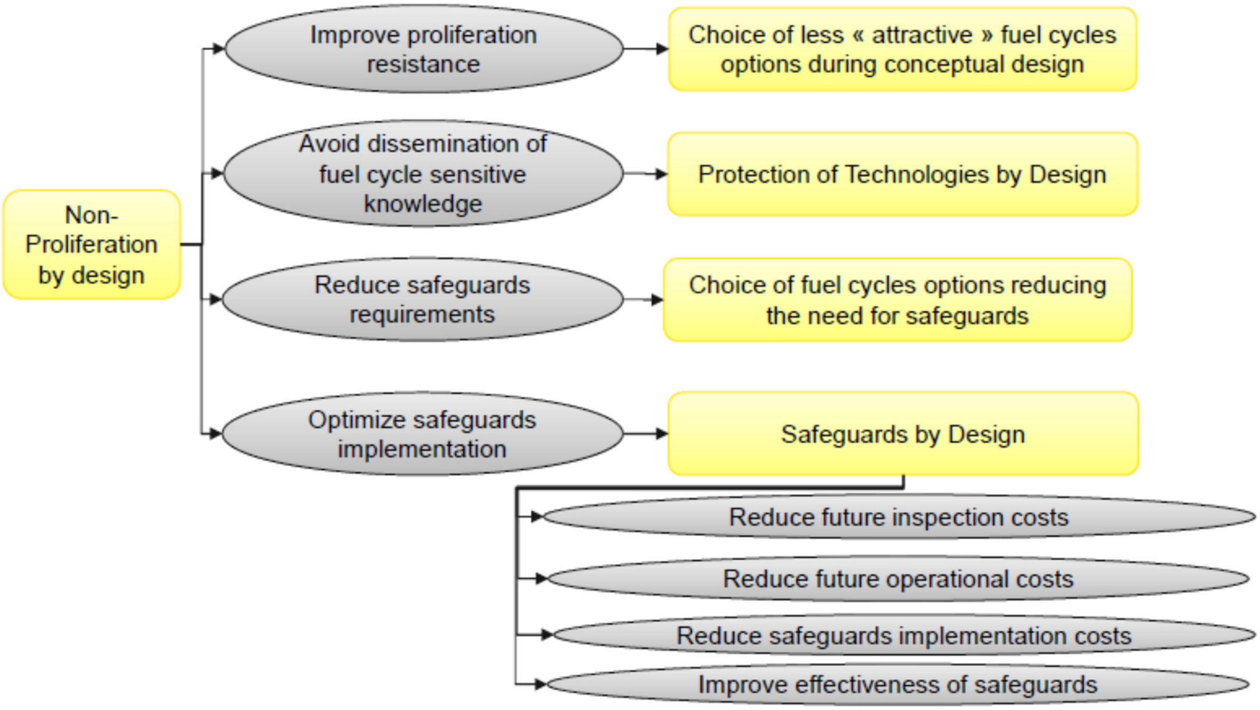
It is important not to focus only on the proliferation resistance of the microreactor concept but to consider proliferation resistance of all the fuel cycle since it is useless to obtain high level of proliferation resistance of a microreactor concept if at other stages of the nuclear fuel cycles the same high level is not reached.

Non-proliferation by design of a nuclear fuel cycle must be considered though analysis of all the different stages of the fuel cycle, including front-end, operation in SMR and back-end operations. As specified in the figure below, non-proliferation by design is based on:

1. Choice of less proliferating options for the fuel cycle. These choices must be down very early in the conceptual design since a late modification will modify the business plan of the project. Indeed, economic sustainability of the project must be assured by a robust supply chain and be based on credible existing industrial chain. This supply chain of nuclear material, including transportation options is to be optimized to minimize proliferation risks. It is also the case for back-end options, long term storage

options or reprocessing. There are usually several options which can be contemplated, but designers must consider the ones reducing the risks.

2. Protection of Technologies by Design: At different stages of the nuclear fuel cycle, processing of the nuclear material may rely on very sensitive technologies: enrichment, metallization, reprocessing,… To assure the global non-proliferating aspect of a reactor concept, including its fuel cycle, it is important that technologies used are well protected from dissemination. Dissemination may come from many sources, including designers, reviewers, sub-suppliers, operators even national authorities, supranational or international control organization. Concepts of black boxes and limitation of information to what is strictly needed may be applied to all people who may have access to some sensitive information. For instance, some operators may not need to have an understanding/knowledge of the process. Or nuclear material accounting and control organization may not need to understand the details of the process to control correctly a facility; focussing on the inlet and outlet flows may be sufficient to control efficiently a facility, the sensitive process being protected as a black box. But this is only possible if such concept has been anticipated and if the original design of the facility allows such “technology protecting” controls.
3. Choice of fuel cycles options reducing the need for safeguards: Some options are less “proliferating” than other and require less safeguards. Less need for safeguards allows some relief regarding the burden for the operator and inspectorates. It also allows some cost saving. Some options are so “non-proliferating” that some designers claim for no need for safeguards. Such extreme position must be studied carefully and reduced safeguards may be a good solution. Thanks to State Level Concept which is becoming IAEA reference, approaches of control will take into account these efforts; safeguards will focus more on facilities and material presenting the highest proliferation risks.
4. Safeguards by Design: Regardless of the level of safeguards needed to satisfy non-proliferation requirements, the anticipation of the safeguards implementation at the earliest stage of the design is always the best option, improving effectiveness and reducing the costs of safeguards implementation.



## 4. EXAMPLES OF FUEL CYCLE OPTIONS TAKING INTO ACCOUNT NON-PROLIFERATION

SMR designers have well understood the importance of developing concepts satisfying high requirements of proliferation resistance. To illustrate this point, some examples of nuclear fuel cycles options presenting interesting proliferation resistance features are given below. There are, of course, many other fuel cycle concepts…

### 4.1. Metallic HALEU fuel

#### *4.1.1. Metallic HALEU Fuel*

HALEU stands for High Assay Low Enriched Uranium. U5 assay is above 5% but below 20% to respect non-proliferating objectives.

Metalized HALEU may be used in alloys with zirconium, silicon, molybdenum.

HALEU fuels are really adapted to SMR since it allows longer cycles than usual LEU (several years before refueling).

Higher assay allows operability and safety margins.

Generally speaking, HALEU significantly degrades the suitability of spent fuel plutonium for weapons purposes. For instance, percentage of Pu238 in usual UOX spent fuel usually reach about 2%; but it could reach about 10% for HALEU fuel. Therefore one can consider it as more proliferation resistant.

Use of metallic HALEU may also reduce by 50% the quantities of Pu in the spent fuel as compared to UOx opened fuel cycle.

### *4.1.2.12 Specificities of metallic HALEU regarding the Front-end of the fuel cycle*

Front-end operations present proliferation risks given the higher enrichment than usual LALEU and given the sensitivity of metallization technology when it is used.

Hopefully, such proliferation risks may be mitigated thanks to non-proliferation by design options. Less attractive options shall prevail such as colocalization of over-enrichment & metallization. For instance the figure below shows an Orano project for production of metallized HALEU: two adjacent buildings allow colocalization of over-enrichment and metallization.

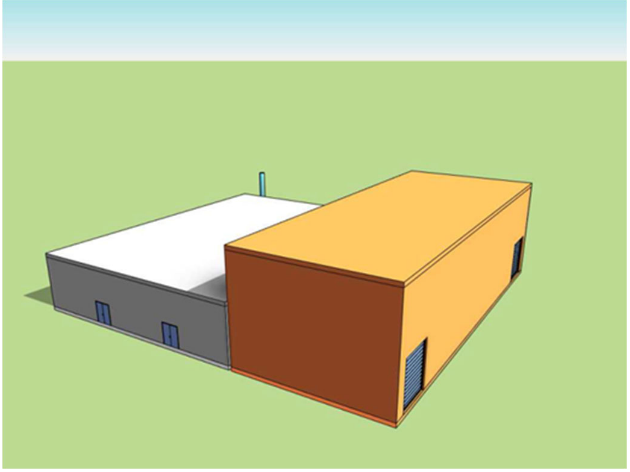


FIGURE 2: Metallic HALEU production line - project in Tricastin (France)

Currently worldwide production of HALEU is very limited and it will be necessary to secure the supply on the long term (about 8 to 10 years to design, obtain regulatory authorizations and build a new production facility). It is highly recommended to SMR designers to secure and anticipate future supply with potential providers.

### *4.1.3. Specificities of Metallic HALEU regarding the Back-end of the fuel cycle*

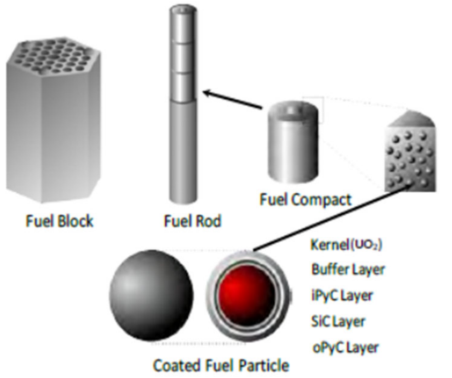
Reprocessing of HALEU spent fuel is possible, but sometimes not as cost efficient as compared to LALEU.

HALEU allows reduction of proliferation & security risks of the long-term management of SF thanks to highly degraded Pu quality (very high rates of Pu238 and Pu240).

## 4.2. Oxide TRISO fuel

### *4.2.1. TRISO Fuel*

TRISO stands for TRi-structural ISOtropic. Each TRISO spherule is made up of a fissile ceramic (usually uranium oxide or carbide) kernel and isotropic pyro-carbon layers. These spherules are placed in a graphite matrix.



A few decades ago, HEU (Highly Enriched Uranium) was commonly used but, for non-proliferation raisons, such proliferating nuclear material cannot be used anymore. For the new concepts, fissile material is usually HALEU. Fissile material can also be mixed. For instance with Thorium or Plutonium.

TRISO spherules will not melt in a reactor and can withstand very high temperatures well beyond the “worst case” scenario.

TRISO fuel is particularly well adapted to microreactors and for mobility.

One remarkable advantage of TRISO fuels is their proliferation resistance since it is very complicated to extract fissile materials from non-irradiated and irradiated TRISO fuels. Mixing different fissile material such as U-Thorium or Pu-U may also reduce the attractivity for proliferation of these fuels since it will increase the acquisition time.

If Plutonium is to be used in a mixture, it shall be civil grade and contain high concentrations of Pu240 to make it not-attractive for weapon use [2]. It is to be noted that there are more isotopes Pu238 and Pu240 in the spent TRISO MOXed fuel than in the spent TRISO UOX fuel. This significantly degrades the attractiveness of spent TRISO MOX plutonium for weapons purposes. The main advantage would be the possibility to reduce drastically the need for fuel reloads. It is possible to create and burn similar quantities of Pu during irradiation cycle in the microreactor: This solution would allow much longer irradiation cycles in the reactor or longer lifetime. Decade(s) would be reachable. It is particularly interesting when you consider factory sealed cores.

### *4.2.2. Specificities of oxide TRISO regarding the Front-end of the fuel cycle*

Production of oxide TRISO spherules is complex and expensive.

Production of TRISO spherules with satisfying quality requires experience and excellent know-how in order to avoid scraps and reach all the specifications. In the last decades several projects of reactors based on TRISO fuels have been stopped due to excessive price of fuel production. Economic viability of the project is at stake.

Those oxide TRISO fuels usually contain HALEU and as mentioned previously, it is important to secure the supply of the fissile material. It is to be noted that compared to historical TRISO fuel, proliferation risks are reduced since no HEU is used anymore.

If these oxide TRISO spherules are based on Pu-U mixture, they shall be produced through a process integrating higher non-proliferation options/standards. Plutonium and Uranium shall be mixed all along the process. For instance, sol-gel process could be applied to a mixture of Uranium and Plutonium nitrates

#### *4.2.3. Specificities of oxide TRISO regarding the Back-end of the fuel cycle*

Because of the specificity of their design, it is very complicated to reprocess this type of fuel.

So they have an excellent proliferation resistance. Indeed it is very complicated to recover the fissile materials, including plutonium. And quality of plutonium is very degraded and not well fitted for weapon use. As compared to usual commercial fuels, they are far less attractive for diversion of the fissile materials.

### 4.3. Molten Salts fuel

#### *4.3.1. Molten Salts Fuel*

In a Molten Salts Reactor, fissile material is in a fluid form in a mixture of molten salts.

They are typically two types of molten salts:

- Fluorides for thermal reactors (with unclad graphite as moderator)
- Chlorides for fast reactors

The molten salts fuel gets critical only in the core. There is an external cooling outside of the core. They have many advantages, including safety advantages such as negative t°coefficient of reactivity and operation at very low pressure

MSR are very flexible with many possible fuel processing cycles options. They shall be consistent with non-proliferating objectives. As explained in paragraph 2.1, improving safety may degrade non-proliferation. For instance, frequent separation of HR fission products improves safety but degrades protection against proliferation.

Below, two examples of molten salts fuels cycles are presented : plutonium chloride for a fast reactor and thorium-uranium fluoride for a thermal reactor.

#### *4.3.2. Plutonium Chloride Fuel*

.Fast MSR allows the burning of Plutonium (and minor actinides) and therefore the reduction of the Plutonium stockpile. All grades of Plutonium can be used; It can be a final solution for eliminating Plutonium coming from spent UOX, MOX, HALEU,…

Burning of Pu Molten Salts provides high thermal energy which makes this cycle economically viable (typically 100MWth for burning of 35-40kg Pu/y.

Such Pu MSR are particularly adapted to a MOXed nuclear park since they can burn degraded Plutonium from spent MOX fuel.

Rigorous Non-proliferation By Design and Safeguards By Design implementation are needed for proliferation resistance since there are high security/proliferation risks before burning of the plutonium (see 4.3.2.1). But one can consider that it is easier to maintain satisfactory safeguards monitoring and control over short period on highly radioactive fluids than for longtime spent fuel storage/repository while Plutonium access becomes easier and easier (eventually turning into a Plutonium mine).

Thus, this is a Sustainable solution for managing Plutonium of a large park.

#### *4.3.2.1. Specificities of Plutonium Chloride Fuel regarding the Front-end of the fuel cycle*

Plutonium to be used is of course civil grade and contains high concentrations of Pu240 which make it not-attractive for weapon use [2].

To avoid transportation of separated Plutonium (Chloride) which presents risks in terms of security and non-proliferation, several options can be contemplated:

- The MSR can be installed on a fuel reprocessing site to avoid transportation of separated Plutonium
- The Plutonium Salt can me mixed with other salts (NaCL, MgCl2,…), with other fissile material (uranium or thorium chlorides) or even with minor actinides. Such mix would reduce drastically the attractivity for diversion of such Plutonium Salts.

#### *4.3.2.2. Specificities of Plutonium Chloride Fuel regarding the Back-end of the fuel cycle*

Only a limited flushing to remove fission products is necessary during operation. Main advantage of chlorides salts is that recycling is possible thanks to aqueous or pyrochemical processing solutions.

### *4.3.3. Thorium-Uranium Fluoride Fuel*

Reactors operating with thorium-uranium molten salts fuel can be operated with standard LEU (Low Enriched Uranium) but HALEU (High Assay LEU) is more advantageous.

Thanks to fertile Thorium, the enrichment needs are reduced. Only U-235 enrichment is necessary. U-233 is produced through the irradiation of Th-232.

It also produces U-232 as an impurity (reactions on U-233, Pa-233, Th-232). The decay chain of U-232 quickly produces strong gamma radiation emitters (in particular Tl-208 at 2,6MeV) ; It implies that significant shielding and remote operations are compulsory.

Regarding diversion of fissile material and clandestine operation, it is to be noted that:

- U-232 with highly radioactive daughter products brings High protection to diversion (see 2.1, non-proliferation vs safety).
- Easy detectability of Thalium prevents diversion of fissile material.
- Fissile fuel freezes when cooled and its diversion is complicated.

- There is no need of excess fuel inventory; that reduces diversion possibilities from the reactor.

Difficulties & safety risks of fluorides transportation is to be taken into account. In that regard, transportation of UF4 is to be preferred to transportation of UF6.

### *4.3.3.1. Specificities of Thorium-Uranium Fluoride Fuel regarding the Front-end of the fuel cycle*

As for other fuel cycles, production and transportation of a mix of several salts including several types of fissile material is a preferred option. In that regard, the mix of thorium and uranium at the earliest stage makes this nuclear material still less attractive for diversion.

Deconversion from UF6 to UF4 is a first step of the mainly well-known metallization processes and protection of this technology/know-how shall be considered through the non-proliferation by design.

From a non-proliferation and safety point of view, transportation of separated UF6 at high assay is not the preferred option and choices regarding the global fuel cycle supply chain shall take that into account.

### *4.3.3.2. Specificities of Thorium-Uranium Fluoride Fuel regarding the Back-end of the fuel cycle*

Low fuel fabrication and high fuel utilization (almost all fissile material) reduces diversion possibilities outside the reactor

Only a limited flushing to remove fission products is necessary: once a year would be sufficient. For fluorides salts, industrial solutions for recycling are not available as for chlorides salts.

However, the choice of HALEU instead of LALEU allows reduction of proliferation & security risks of the long-term management of the spent fuel thanks to highly degraded Pu quality (very high rates of Pu238 and Pu240).

## 5. CONCLUSION

SMR developers shall keep in mind the strategic importance to secure their supports for the fuel management at the highest standards satisfying non-proliferation. Main issue which could hamper their commercial development is that there is currently no reliable proven industrial infrastructure to manufacture and manage advanced fuels all along their life cycle.

Nevertheless, this is often during these stages of the fuel cycle life outside the reactors that one can find the weak link regarding proliferation risks.

Most of SMR developers have chosen to design their reactors with fuels presenting robust assets against proliferation risks. Among these options, HALEU is largely chosen. Given the uncertainties regarding the importance of SMR commercial deployment and given that fuel price will be a substantial part of the total price of SMR and particularly of microreactors, we may conclude that:

- Governments and international organizations supports are essential in order to get financial supports, adequate legal framework and regulations, harmonization, authorizations granted within a reasonable time,…
- Efforts of SMR developers to choose less proliferating options is important for political and public acceptance but shall also come with adapted safeguards. Thanks to State Level Concept which is becoming IAEA reference, approaches of control will take into account these efforts; safeguards will focus more on facilities and material presenting the highest proliferation risks. Similar approach for security would motivate SMR developers to choose the more secured options.
- Given the costs, risks, technology complexity and administrative work to be done, it would be wise for SMR developers to cooperate and also to embark on their projects the major fuel cycle players.
- It is the role of the fuel cycles companies to support SMR developers in choosing the most appropriate fuel front end options, and also fuel back end options, regarding non-proliferation, technologic and financial and operational risks, and in securing supplies of advanced nuclear material. But they need to be convinced before embarking on the train and be in position to support efficiently and sustainably the SMR developers.
- Given the very long timeframes for any nuclear development and deployment, that is to be done at the very beginning of the conceptual design.

## REFERENCES

[1] ESA “Securing the European Supply” 2019 reports
[2] Plutonium : The first 50 years, DOE/DP-0137, US D.O.E, February 1996