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Current and future impacts of SMR/AMR projects on Safeguards in France

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Abstract:

There is a worldwide interest in small modular reactors (SMRs) including microreactors and advanced modular reactor (AMR). Indeed, the last IAEA booklet on the status of SMR technology developments selected more than 80 SMR designs and concepts under various stages of development, in 18 countries [1]. This emulation of projects is also taking place in France, and particularly recently with a strong financial support of French government for SMR projects (France relance and France 2030 programmes).

Thus, in France, more or less mature projects are materializing. These projects are supported by the well-known French nuclear industrials (EDF CEA, Naval Groupe, Technicatome and Tractabel have launched the Nuward SMR project, a PWR-type SMR) but also by startups (Naarea with a MSR-type and Jimmy Energy with a HTGR-type SMR), which is new in France. Some of these projects involve international cooperation (with the establishment of an international advisory board, or/and involving transnational startups such as Newcleo (France, United-Kingdom, and Italy), Transmutex (France and Switzerland). These projects also need R&D support for these concepts and technologies, particularly for AMRs whose technologies are disruptive. Therefore, several French actors are involved in different R&D programmes related to SMRs, mainly funded by the Euratom research and training programme which have already an impact on safeguards such as Additional Protocol (AP).

This paper presents an overview of national and transnational SMR/AMR projects in France, with a particular focus on the most advanced projects and their impact on the safeguards in France (currently mainly AP). Furthermore, the impact of future evolution of fuel cycle facilities on safeguards will be discussed due to a front-end requirements like fuel supply adaptations (Tri-Structural Isotropic (TRISO) fuel fabrication, higher uranium enrichment with High-Assay Low-Enriched Uranium (HALEU) fuel…) to support the SMR projects (and meet national markets but also international ones).

[1] Advances in Small Modular Reactor Technology Developments (2022), IAEA.

Keywords: Nuclear safeguards, Nuclear nonproliferation, Small Modular Reactors, Advanced Modular Reactors, Additional protocol

1. Introduction

Small modular reactors (SMRs), as well as microreactors and advanced modular reactors (AMRs), are gaining interest across the world[1]. Indeed, the last International Atomic Energy Agency (IAEA) booklet on the status of SMR technology developments selected more than 80 SMR designs and concepts under various stages of development, in 18 countries [1].

These numerous designs cover a wide spectrum of reactor technologies, including Pressurized Water Reactor (PWR), High Temperature Gas-cooled Reactor (HTGR), Molten Salt Reactor (MSR), etc. They can also employ a wide range of fuel types: Uranium Oxide (UOX), U/Pu Mixed Oxide (MOX), TRI-Structural is Otropic (TRISO), etc., at various enrichments other than the conventional Light Enrichment Uranium (LEU). Indeed, higher enrichments such as High-Assay Low-Enriched Uranium (HALEU), enriched in U-235 between 5% and 20% (or LEU+ for an enrichment around 6 %) are being considered.

This increased interest in SMRs can be attributed to the multiple benefits they provide because of their compact size. They are easier to implement, faster and cheaper to build (with a lower investment required), and easier to operate. Their power can cover small city, home or industrial demands for electricity or heat. They also represent an important business opportunity as they could be made available for countries developing nuclear power for the first time (first-time buyers).

Existing SMR designs are in various developmental stages and some of them are expected to be deployable in the short term. However, some SMRs based on fourth generation technology (GEN IV) are mostly in the design stage, requiring extensive R&D studies on both the reactor and the fuel.

Emulation for SMR is also taking place in France, supported by French government's founding for SMR projects included in “France relance” and “France 2030” investment plans. It is therefore essential to follow these projects with regards to France’s safeguard obligations as the French fuel cycle will certainly be transformed by SMR developments.

2. SMR projects in France

As mentioned, the French SMR market is expanding. For several years, France has had a credible and government backed SMR project, called Nuward. This SMR is led by historical actors of the nuclear industry, with a consortium including EDF, CEA, TechnicAtome, Naval Group and Tractebel. Recently, following the French government's announcement of financing SMR initiatives, new SMR startups have emerged, with new SMR development and commercialization projects. Startup are a novelty in the sector, which is usually built around well-known companies.

Here is a brief and not exhaustive overview of the projects carried out in France with their main characteristics.

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[1] SMR are nuclear reactors with a power capacity of up to 300 MWe. They are deployable either as a single or multi-module plant and are designed to be largely made of pre-assembled factorybuilt modules, which can be transported to construction sites. Microreactors (or micro modular reactors MMRs) are a subcategory of SMRs targeting lower power levels from 1 to 20 MWe. AMRs are SMRs that are considered as innovative or from 4th generation (GEN4). They differ from PWR SMR mainly due to technological advances including the use of new forms of fuel and/or a greater temperature. Many SMRs/MMRs/AMRs have an “integral” design, wherein the reactor core and certain auxiliary systems (e.g., steam generators, pressurizers, and/or heat exchangers) are all placed within the reactor pressure vessel (into a single module).

The first SMR project is Nuward, a 340 MWe PWR-type plant, from two fully integrated reactors of 170 MWe each, derived from nuclear reactors based on French naval propulsion technologies. Thus, Nuward keeps the concept of current power reactors (LEU UOX fuel, neutron moderation and cooling by light water) and does not require a strong adaptation of the French nuclear industry. Only the reactor's compactness, with its integrated concept, brings some technological challenges. Nuward is in the design phase and initiated technical discussions with the regulator in order to prepare the review of the Safety Options' Report in 2023.

The Nuward project has been joined in recent years, by projects from new French startups:

- Naaera is studying a Molten Chloride Fast Reactor (MCFR) type of about 10 MWe, fuelled by fissile material made from spent fuel (reprocessed U, reprocessed Pu) or with depleted U, diluted in molten chlorides. The MCFR concept uses a fuel design completely different from the other concepts: the fuel and the coolant are here both in a liquid form and are thus inseparable (mixture of salts). In addition, a specific spent fuel salt treatment unit (and gas treatment), aimed at removing fission products, either in-line or in batch is required. It should be noted that since reprocessing of spent fuel is a high proliferation risk step, MCFR which require an on-site reprocessing station represent safeguards challenges.
- Jimmy Energy is developing a HTGR type thermal neutron SMR fuelled by HALEU TRISO fuel, moderated by graphite and cooled by pressurised helium. Jimmy's SMR will be deployed on industrial sites to support industrial processes requiring high temperatures. To achieve this goal, the SMR is designed to be transportable or relocatable (sealed transportable reactor). The TRISO fuel is designed as follows: TRISO particles which are spherical, core/shell type, and consist of a core of fissile material (typically UO2 or uranium oxycarbide (UCO)) coated with a porous carbon buffer, a layer of pyrocarbon (PyC), a layer of silicon carbide (SiC) and a final layer of PyC. These particles are then mixed with graphite to form either compacts (prismatic assemblies (prismatic block reactor concept)), or directly into pebbles (pebble bed reactor concept). Jimmy Energy will use UCO TRISO compacts.

Transnational startups such as Newcleo (France, the United Kingdom, and Italy) and Transmutex (France and Switzerland) have recently established their offices in France:

- Newcleo is developing two LFR (Lead-cooled Fast Reactor) type SMRs (20 and 200 MWe), fuelled by MOX fuel and cooled by molten lead.
- Transmutex is developing the TMX-START SMR. It is an ADS-type reactor (Accelerator Driven System). This SMR is a subcritical nuclear reactor driven by a high-power cyclotron proton accelerator to generate a high-intensity neutron source, leading either to the transmutation of thorium into U233 (which is fissionable), mixed with reprocessed Pu; or to the transmutation of reprocessed U mixed with Pu. The coolant used will be a mixed lead-bismuth liquid metals under atmospheric pressure.

Thus, the main SMR projects in France are listed in table 1.

Companies	*Reactor type technology*	*Fuel type*	*Refuelling cycle*	*Design phase status*
Nuward	PWR (integral)	LEU UOX	18 months	Conceptual Design
Naarea	MCFR	U(depleted)/Pu molten salt	*Not viable*	Pre-Conceptual Design
Jimmy	HTGR (prismatic)	HALEU UCO TRISO Compacts	No refuelling	Detailed design
Newcleo	LFR	MOX	16 months	Conceptual design
Transmutex	ADS Subcritical Reactor	Th/Pu or MOX	*Not viable*	Pre-Conceptual Design

Table 1: SMR projects in France with their main characteristics.

These projects cover a wide range of possible combinations of nuclear fuels, moderators and heat carriers. Some startups have been working on them for a few years, while others have only recently debuted. As a result, projects are in various stages of completion. It should be noted that Jimmy recently submitted his Safety Options Report to the French safety authorities.

The following paragraphs present an overview of the consequences of the arrival of SMRs in the French nuclear industry with a focus on already noticeable impacts on French safeguards implementation and then on future modifications of the French fuel cycle and safeguards obligations.

3. Current impacts of SMR/AMR on safeguards in France

All these projects intended for the French market and/or for export, whether or not developed with foreign partners, already have an impact on safeguards implementation in France. The French National Safeguard Authority (NSA), represented by the Euratom Technical Committee (CTE, a department of the Prime Minister) is in charge of implementing the Euratom and IAEA safeguards in France. The Non-Proliferation and Nuclear Material Accountancy Department of the French Institute for Radiological Protection and Nuclear Safety (IRSN) is the Technical Support Organization (TSO) of the CTE in the area of safeguards. CTE, together with IRSN, help and guide the operators in order to comply with the French commitments related to safeguards (the French safeguards agreement (INFCIRC/290), the French Additional Protocol (AP), the EURATOM Treaty and its Regulation 302/2005, the secondary legislation of all these texts, and the bilateral agreements signed by France).

As of today, because of the involvement of foreign partners/entities in the R&D or cycle development plans of French SMR projects, the main declaration concerned by the emergence of SMRs, is related to the French additional protocol.

The additional protocol to the French safeguards agreement entered into force on 30 April 2004 (INFCIRC/290.add1) [2]. French AP aims to strengthen the IAEA's ability to detect clandestine nuclear activities in Non-Nuclear Weapon States (NNWS). It requires France to declare to the AIEA information on activities related to the nuclear fuel cycle, including or not the use of nuclear materials, in collaboration with NNWS (such as research and development, fuel cycle development plans or fuel cycle equipment manufacturing). The CTE is responsible to send the French declaration of the AP to the IAEA. IRSN prepares the declarations of the French AP and is requested to contact the entities covered by the French AP, informing them of their new obligations and collecting their declarations.

R&D contributions in support of SMR projects are essential both for classic SMRs PWR-type and for more technologically disruptive SMRs such as HTGR or MCFR (reactors, fuel, etc). The analysis of the source of public funding of SMRs projects allows to identify the different collaborations. The E.U. Research Innovation Programme is a funding programme for research and innovation in the European Union, characterised by openness to international cooperation. The Euratom Research and Training Programme complements it in the field of nuclear research, training and innovation. Horizon 2020 was the E.U.'s research and innovation funding programmes from 2014-2020. Horizon Europe has now succeeded to Horizon 2020. SMRs R&D was covered by Euratom funded Projects under EURATOM Programme in Horizon 2020 (such as ELSMOR or McSAFER). Subsequently, Horizon Europe covers SMRs R&D such as MIMOSA, TANDEM, SASPAM-SA, GEMINI 4.0 or INNUMAT programmes. When these R&D programmes include French participants among other NNWS participants, they are declared in the French AP annual declaration.

The conclusion of new international cooperation also leads to increase market opportunities. Thus, SMRs are also subject to international cooperation in their development. This is the case for companies setting up an advisory board, such as Nuward. Indeed, as announced in the press, Nuward is supported by an international network of industrial partners but also by an advisory board. This can also be the case for transnational companies and startups, where partnerships between subsidiaries can take place.

As shown in table 2, over the last 3 years, SMR R&D fuel cycle development plans for ten years represent a significantly increasing number of lines in the annual declaration (AD) of the French AP. The table 2 shows number of lines declared under article 2.a.i and 2.a.viii of the French AP. Both articles are respectively similar to articles 2.a.i and 2.a.x of Model AP (INFCIRC/540) for NNWS with comprehensive safeguards agreements.

Article	AD 2020	AD 2021	AD 2022
2.a.i (INFCIRC/290.add1)	4	5	10
2.a.viii (INFCIRC/290.add1)	0	0	3

Table 2: SMR programmes declared in the French AP over the last 3 years.

The identification by open sources analysis of new entities, startups, R&D programmes, cycle development plans, greatly facilitates the completeness of the French declaration's closely monitored by IRSN [3]. Support for registrants is an important part of the IRSN analysts' work. Indeed, if stakeholders are familiar with technical fields, this is not necessarily the case with AP reporting requirements [4].

4. Future impacts of SMR/AMR on safeguards in France

The French nuclear fuel cycle will have to adapt to the construction and commercialization of SMRs. This adaptation can be simple with PWR-type SMRs such as Nuward, because the material and fuels are similar to actual NPPs in France (the fuel could be enriched, produced and reprocessed in the usual way by actual facilities). Nevertheless, for other SMRs developed in France and to meet the needs resulting from SMRs developed in other countries, some facilities in the French nuclear fuel cycle will have to be adapted or created. This will have many consequences on safeguards implementation in France, especially because every step of the fuel cycle is present on the French territory.

4.1. Fuel cycle adaptation

In this paper, it is anticipated that the French nuclear industry will meet the future needs created by the development of SMRs. This study assumes that current traditional manufacturers involved in areas such as enrichment, fuel fabrication, reprocessing, and waste management, will remain the only actors in charge of these cycle activities. It is therefore assumed that startups will not operate these support facilities themselves.

4.1.1.Enrichment

One of the challenges associated with enrichment for SMRs is that it will exceed the 5 % limit currently set in French nuclear facilities. Indeed, HALEU fuel is needed for SMRs with a longer period before refuelling and/or to reach high burn-up rates [5]. Criticality safety issues induce strong constraints for HALEU transportation. Therefore, among other challenges, the supply chain industry must design new types of authorized transport packaging (cylinder and protective overpack) for a broad range of uranium forms in order to transport significant amounts of HALEU fuel.

To respond to the foreseen demand in HALEU, the French enrichment facility Georges Besse II (Safeguarded by Euratom and by IAEA as derived from constraints resulting from the Cardiff treaty)[2] could be extended for HALEU production. Depending on enrichment needs, new centrifuge cascades may be added. In this respect, new safeguards requirements could arise and lead to the definition of new safeguards approaches. Regulation modifications will also be needed to authorize these levels of enrichment.

Nuclear material flow will be modified as well. At the front-end of fuel cycle, a significant increase in natural uranium feedstock to the cascades is required to produce HALEU, due to a higher separative work unit require to go from 5 % to 20 %. As a result of the enrichment of HALEU, there will be an increase in depleted uranium as a by-product.

Beyond the enrichment, the whole industrial chain must also be rethought and modified in order to obtain the appropriate types of material (oxide, salt or other).

4.1.2.Fuel fabrication

The final fuel specifications and manufacturing requirements for SMR fuel are determined by the SMR technologies under consideration [6]. Hence, specific HALEU fuels, such as metallic or TRISO HALEU fuel, but also any other kind of new type of fuel, will necessitate the modification of fuel manufacturing facilities. The different fuel forms for current SMR projects in France are:

- UOX and MOX: for these fuels no significant change to the existing facilities is expected; there would only be a higher production flow to meet the demand,
- TRISO: for this fuel, the production may be launched in existing facility (with adaptations),
- Molten Salt: the production of this fuel would require a facility able to make salt synthesis and chlorination to produce chloride salts.

For the world market, metal and nitride uranium are used to produce fuel for other SMR. A facility capable of fluorination (fluoride salts) would be needed for these MSRs.

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[2] The French Voluntary offer safeguards agreement (VOA) in force covers peaceful nuclear activities. France offers nuclear material and facilities (in its civil nuclear fuel cycle) for safeguards. Thus, and due to Cardiff TREATY, GBII facility has been All nuclear material and facilities defined as peaceful are safeguarded by Euratom.

In any case, in order to cover the needs for fuels in other forms than those currently used in the French reactors (UOX and MOX), it will be necessary to invest in adapting the industrial tools of the existing industries, either by adapting the facilities or by building new ones. New specifications will necessarily lead to different safeguards requirements for the fabrication step.

4.1.3. Recycling and waste management

The nuclear waste generated by SMRs is rarely discussed [7]. This new waste type, whether it is spent fuel or technological waste (materials or the reactor itself) is also concerned by safeguards mainly until the immobilisation of nuclear wastes into conditioned wastes.

The amount of waste generated by SMRs will depend on the type of technology used (a MSR-type SMR, whose vessel and primary circuit are highly radioactive, will generate more waste than a PWR-type SMR).

The enrichment of uranium to produce HALEU rates will increase the amount of low-level radioactive waste (LLW). On the one hand, there is an increase in the production of depleted uranium, and on the other hand, the need for new cascades which will ultimately generate LLW waste when they will be out of service. It should be noted that France considers the depleted uranium stock from enrichment activities as a strategic resource and not as waste. However, due to the prolonged fuel lifetime due to higher burn-up rates, a decrease in high-level radioactive waste (HLW) is expected for HALEU spent fuel [5].

The fate of the reactor and the spent fuel, subject to safeguards, must be assessed for each type of SMR. SMRs deployed on industrial sites or in isolated geographical areas are likely to be transported with the core fuelled and sealed. A few years later, when the fuel will be totally consumed, they are to be returned to the manufacturers. The issue of waste management of sealed reactors is a significant challenge for safeguards [8].

For SMR HGTR-type, for TRISO fuel recycling, the separation of the graphite from the compact or the pebble from the particles is a challenge, as well as the de-coating of the TRISO core/shell particles. Indeed, the reprocessing feasibility of TRISO fuel in industrial scale has yet to be demonstrated. In case of non-recycling, it should be noted that this implies their disposal in a deep geological repository, which will have to be assessed if necessary. For the spent fuel salt from MSR-type SMR, their fate is unknown yet (reprocessing and/or immobilization to a conditioned waste).

Globally, the back-end for SMRs other than PWR-type is still uncertain and requires careful consideration and adapted safeguards measures. What is certain is that the SMR market will increase globally the flow of nuclear material in France and therefore generate more waste.

4.2. Nuclear material Import/Export notification

Nuclear materials for SMRs will be transferred between facilities and across countries at various stages of the fuel cycle. Any transfer of nuclear material from one country to another requires compliance with the provisions of several treaties or agreements. Indeed, the effectiveness of the non-proliferation regime is based on a system of declarations of operations involving nuclear materials and on on-site verifications by Euratom and/or IAEA inspectors. Therefore, the imports and exports of nuclear materials are particularly controlled.

International obligations include notifications of these transfers (information concerning the nuclear material and the shipment) to the European Commission and/or IAEA and/or third countries [9].

Imports/exports of nuclear materials must comply with:

- Euratom Regulation 302/2005;
- The French safeguards agreement INFCIRC/290;
- INFCIRC/207 that provides the agency with additional information on nuclear material exports and imports;
- Cooperation agreements concluded between the European Commission, mandated by the Member States, third countries, such as Euratom/USA, Euratom/Canada, Euratom/Australia, Euratom/Japan, etc.;
- Bilateral agreements signed by France and other countries.

To meet these commitments, import/export notification forms are filled in by the facilities and sent to IRSN analysts for processing and notification to international authorities [9], [10].
It is expected that the business related to SMR (national and international demand) will lead to more notifications, especially as the nuclear market is highly globalised.

4.3. Main impacts of SMR introduction in the French nuclear industry on safeguards declarations

In France, nuclear operators can rely on IRSN and CTE to help them to fulfil their safeguards obligations [9]. Safeguards obligations will also concern operators involved in SMR-related projects, these obligations include:

- Writing of BTC (Basic Technical Characteristics) /DIQ (Design Information Questionnaire):
    - For new facilities, a preliminary BTC with information such as the use of nuclear materials and the expected commissioning date, shall be communicated to the European Commission at least 200 days before construction begins (article 3 reg. 302/2005).
    - Final BTC including an inventory or annual throughput of nuclear material and all relevant information using the ad hoc questionnaire (Annex I reg. 302/2005) shall be communicated to the European Commission at least 200 days before the first consignment of nuclear material (article 4 reg. 302/2005).
    - Changes in the BTC shall be communicated to the Commission within 30 days after the modification is completed (article 4 reg. 302/2005).

  IRSN provides help and guidance in the writing of several documents required by regulations and agreements including BTC. For facilities containing nuclear materials safeguarded by IAEA under the French safeguards agreement (INFCIRC/290), DIQ are communicated by the European Commission to the IAEA. Besides, the FREnch Support Programme for Agency Safeguards (FRESPAS) proposed a task to provide to the IAEA a DIQ based on Nuward SMR, for safeguard by design goals [11].

  Derived from BTC/DIQ, particular safeguards provisions for Euratom and facility attachments for IAEA (and indirectly safeguards approach) will also need to be adapted with the arrival of SMR projects. Both documents include among other things, the material balance areas definition, the selection of key measurement points, the frequency of physical inventory taking and inspections, the containment and surveillance measures, etc.

- Communicating OPA (outline programme of activities): Annually, each facility shall send an OPA for the upcoming year to the European Commission (article 5 reg.302/2005). OPA should indicate the main activity schedules, dates and duration of physical inventory taking, and regarding nuclear materials, among others: types of operations; proposed campaigns with indication of type and quantity of fuel elements to be fabricated or reprocessed; anticipated schedule of arrival of nuclear materials; dates of dispatch. The multiplication of sites hosting SMRs will therefore multiply the OPAs. The production of new SMR fuels will also be reflected in the nuclear material flows described in the OPAs of all the facilities involved in the different steps of the nuclear cycle.

- AP declarations: For R&D activities and nuclear fuel cycle development plans, there is no doubt that the annual declaration will include an increased number of lines in the future. Besides, equipment and non-nuclear material are also targeted by French AP: the fabrication activities in cooperation with a NNWS (article 2.a.iii) and their exports to a NNWS (article 2.a.vii.a) (these articles correspond respectively to articles 2.a.iv and 2.a.ix of INFCIRC/540). Fabrication activities can concern for example graphite (neutron reflector, moderator or TRISO compacts), zirconium tubes or centrifuge equipment. French SMR projects are particularly oriented towards the export market, it is therefore expected that, in the future, France will export whole nuclear reactors and that those exportations will be declared in the appropriate section of the AP declaration.

- Other impacts linked to safeguards obligations:
  - With the arrival of SMRs, nuclear material quantity will increase in the French nuclear cycle and new flows corresponding to the manufacturing of new fuels will appear. Nuclear material accountancy and physical monitoring will therefore require more effort from operators, especially from startup operators that are not used to these practices.
  - To assess the correctness and completeness of the declarations, it is also expected an increase in on-site verification conducted by Euratom and/or IAEA inspectors. Indeed, new flows of nuclear materials, new facilities, new operators or suppliers and new reactors will lead to an increase of person-day inspection effort.
  - Industrial operators and mainly the new startups will need to be trained for the correct implementation of safeguards and the respect of the French commitments in the field of safeguards. This training should include awareness to Safeguards-by-Design. Integration of safeguards considerations in the SMR design process in conjunction with the development of new safeguard approaches could contribute to limit the need for on-site inspections (for both SMR sites and cycle facilities). New safeguards approaches will certainly be developed by safeguards authorities for each SMRs, for modification of enrichment facility, for new factories, etc.

Among its missions, IRSN is in charge of advising operators and authorities on safeguards implementation. With the introduction of SMRs in the French nuclear industry, IRSN will be witnessing all the changes described in this article that will have effects on many aspects of safeguards obligations. Advance analysis of changes and training efforts will be key to face the future challenges.

5. Conclusion

SMR projects in France, led by historical companies of nuclear industry and new actors such as startups companies, impact already the French safeguards system. As of today, only the French AP is concerned, as these projects are mainly at R&D development stages and because new fuel cycle development plans for ten years appear. Depending on the maturity of the projects, support within the framework of the SBD has started to be provided (for example for the Nuward project). In the future, the construction of SMRs, their export or the delivery of front-end or back-end services (supply of HALEU enrichment, new fuel fabrication or reprocessing of spent fuel, etc.) will increase the field of application of safeguards in France. This will concern all safeguards obligations (AP declaration, I/E notifications, BTC, OPA…). Raising awareness and providing extensive support on safeguards obligations will be particularly important to be able to fulfil the French commitments in the non-proliferation domain.

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