# NON-PROLIFERATION ASPECTS OF ADVANCED RECYCLING FOR FAST REACTORS FUEL CYCLE. OVERVIEW.

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## INTRODUCTION:

The technology of fast neutron reactors has a long history, nevertheless it remains on the list of innovative reactor technologies in IAEA and GIF. The relevant technologies of nuclear fuel for Fast reactors and its recycling technologies are largely determined by the fact that plutonium is the key fissile material in this process. However, this has been one of the factors hindering the development of FBR technology for many years. The brief overview summarizes the main approaches for the fast reactor's plutonium-contained fuel and examines aspects related to nuclear fuel recycling technologies from a nonproliferation point of view: the possibility of plutonium account and control, aspects of the application of safeguards to fuel recycling technologies based on uranium and plutonium, as a part of Nuclear Energy Systems based on Closed Nuclear Fuel Cycle with Fast reactors.

## 1. TECHNOLOGICAL APPROACHES FOR FAST REACTOR FUEL RECYCLING

Currently, the industrially developed technology of SNF reprocessing is PUREX-based processes. This technology is applicable for FR SNF reprocessing, including irradiated MOX fuel. This has been demonstrated at existing SNF reprocessing plants for power reactors. This technological approach is based on recovery of purified components – uranium and plutonium with high decontamination factors from fission products (around $10^8$). The pure products, as usual in form of oxides, can be used for further manufacturing of fresh fuel for fast reactors. As the main products are in form of oxides, the main technology for fuel manufacturing is MOX-pelletaizing technology and the PuO2 product after PUREX-process is main sources of fresh fuel manufacturing. At the same time, various options are possible, such as FR SNF reprocessing together with LWR fuel when mixing a fraction of FR MOX at the cutting-dissolution stage, or separate processing, which, however, requires a limit on criticality.

The results of MOX-fuel reprocessing by PUREX-based processes were published in France, Russia, Japan and other countries.

It should be noted that the Russian reprocessing complex - MAYAK Plant - operates on a regular basis with the BN-600 reactor's uranium spent fuel for followed using of resulted reprocessed HALEU in the Russian nuclear fuel cycle. Plutonium is accumulated for subsequent use in fast reactors mainly.

In parallel with the PUREX process, developments and pilot projects on other technologies are underway. Advanced aqueous-based and low-temperature methods and technologies that are under development, included the following:

- Advanced processes based on aqueous extraction or precipitation, including processes without separation of U and Pu.
- Advanced methods for minor-actinide (MA) recycling that also very important for fast reactors fuel recycling, especially for further transmutation.
- Other low temperature methods, as example, are based on room-temperature ionic liquids or on critical CO2 extraction.

All these methods, as a rule, have been tested only at the laboratory level. However, two existing projects with the introduction of improved technologies are close to industrial implementation.

This is the large-scale reprocessing plant in Japan at Rokkasho-mura, whose technology includes incomplete separation of uranium and plutonium, and the production of their mixture. Another Experimental and Demonstration Center was commissioned in Russia in 2025, which is designed to test new aqueous-based reprocessing technologies with reducing of radioactive waste generation. Both projects were constructed as LWR SNF reprocessing facilities and their technological lines are not focused on FR SNF reprocessing.

The second line of developments for FR SNF recycling is high-temperature processes. They also have a long story of R&D and pilot testing, but they had no industrial applications for different reasons, such as problems with process material in the early stages and an absence of industrial needs today.

High temperature recycling processes for FR SNF include:

- (First of all) Pyro-process (electrorefining, electrowinning, precipitation etc.) in molten salts (chlorides, mainly) tested with FR SNF on pilot levels.
- Fluoride volatility process is based on fluorination of SNF that also was demonstrated on limited amount of short-cooled FR irradiated fuel. Currently this method is considered as part of combined reprocessing systems for removal of main part of UF6 from spent fuel.
- Other methods with limited chemical operations are based on Oxidation-Reduction methods (ex. DUPIC).

And of course, a number of efforts were carried out for testing of the Combinations of pyro-process and aqueous methods (FLUOREX, Preliminary selected process of UPuN recycling for BREST reactor and so on).

However, so far only two laboratories have conducted pilot tests with FR SNF reprocessing and recycling. They concerned only the fuel of reactors with the status of research EBR-II and BOR-60.

The specifics of non-aqueous processes have been attractive since the late 1950s, given the ability to work with short-cooling fuels, while the media does not contain neutron reflectors or organic substances that can decompose during radiolysis.

In comparison with PUREX-based processes, non-aqueous approaches are more focused on restoring the physical properties of the FR fuel with low purification (low decontamination factor from fission products) and based on refabrication of new nuclear fuel by remote methods, such as vibropacking for MOX and casting for U-Pu-Zr metallic fuel.

R&D and pilot studies are continuing in different laboratories.

## 2. INFRASTRUCTUR APPROACHES FOR FAST REACTOR FUEL RECYCLING

In addition to the issue of technologies for the FR SNF recycling, it is advisable to consider the issue of infrastructure for such recycling. The infrastructural aspect of Fast Reactors' closed fuel cycle is an essential element.

Current processes can be adapted for reprocessing of FR SNF, and it requires a centralized reprocessing plant with integration of transport operations for SNF and separate Pu throughout the whole cycle and fuel re-fabrication from highly purified fuel.

The application of current industrial SNF reprocessing systems for FR SNF will be included in the following facilities chain:

- At reactor intermediate storage of FR SNF
- Transportation system for FR SNF

- Central reprocessing plant based on PUREX or some advanced aqueous (or combined) processes
- Storage facilities for Pu-contained materials
- Centralized FR fuel refabricating facilities
- Transportation system for fresh FR fuel.

Another infrastructure conception, more accepted for innovative recycling technologies and facilities can be implemented as part of one complex with the reactor at the same site (Fig.1). Its key elements are the following:

- Reprocessing/refabricating facilities on Fast reactor(-s) site
- Advanced and simplified reprocessing/recycling technologies
- No transportation outside site

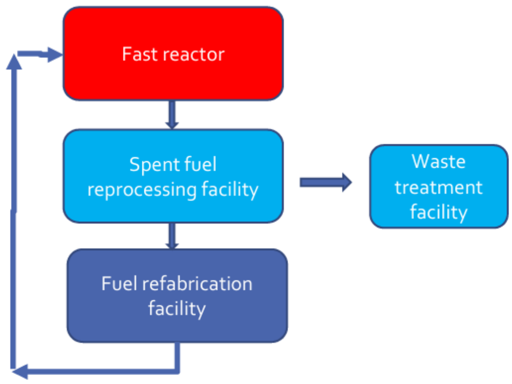


*FIG. 1. Composition of Fast reactor with on-site recycling.*

This concept has been promoted by ANL and INL for many years, and its version named Integral Fast Reactor (IFR) has been actively discussed since the 1980s. The EBR-II Closed Fuel cycle facility was one of early prototype for on-site siting FR and FC facility.

In parallel, in the USSR, from late 1960s the methods for short recycling of FR SNF were developed and tested together with the COMECON states (DDR and Czechoslovakia). This complex development included high-temperature recycling and vibropacked fuel refabrication considered as Atomic Technical-Economical Complex with BN reactors. The fluoride volatility technology and pyroelectrochemical technology were tested, followed by simultaneous production of vibropaked MOX fuels. The main experimental base was and remains the Research Institute of Atomic Reactors (RIAR) in Dimitrovgrad. The semi-industrial level was implemented only in Dimitrovgrad, where the pyro-process is used for the regular production of BOR-60 reactor fuel and for large pilot batches of MOX fuel for BN-600 and BN-800 reactors. It was suggested (in 1990s) to call the process developed and tested by RIAR as DDP (Dimitrovgrad Dry Process)

Thus, two aspects are important in the FR SNF recycling: technology and infrastructure.

## 3. SPECIFIC CHARACTERISTICS OF CURRENT AND ADVANCED APPROACHES FOR FAST REACTOR FUEL RECYCLING

Current industrial SNF reprocessing technologies based on PUREX-processes, developed for separation of pure plutonium from irradiated uranium. Late this process was adopted to nuclear power SNF, and all industrial facilities applied this technology with modifications (Fig.2).

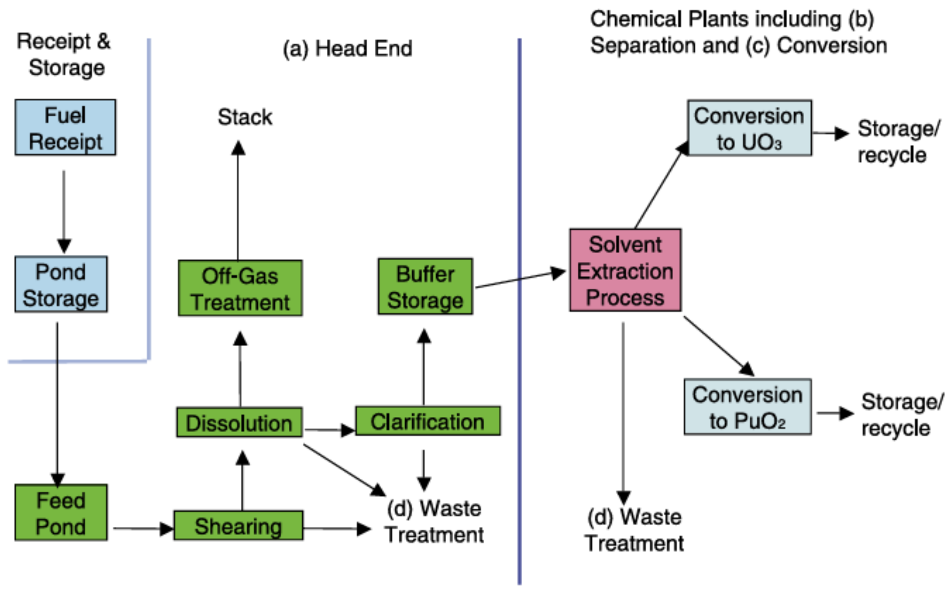


*FIG. 2. Flow-sheet of PUREX-based reprocessing technology.*

Two specifics of this technology are important for recycling of FR SNF. First of all, the separated plutonium in form of dioxide has high purification from fission products and minor actinides (DF > $10^4$), so it could be used for further manufacturing of any type of plutonium contained nuclear fuels in others manufacturing facilities. Second specific of this process is its continuing features: after head-end step (fuel pins cutting and fuel dissolution) all other steps designed in liquid forms (extraction, re-extraction) till final precipitation and calcination. All liquid technological flows are controlled by sampling and analysis. Complete mass balance control available on final stage.

Two approaches are applied for FR SNF reprocessing:

- Reprocessing together with LWR SNF as additions, taking into account criticality limitations for the equipment
- Reprocessing in separate technological line designed especially for high-enriched material where volume of equipment reduced followed criticality specifics.

Pyro-process options were initially developed only for restoring of physical propertied of FR fuel. As usual, simple technological procedures can be implemented for oxide and metallic fuels with a minimum number of chemical processing stages (Fig.3). In comparison with aqueous extraction technologies, these processes are the "batch" processes that include (as usual) two chemical transformations only.

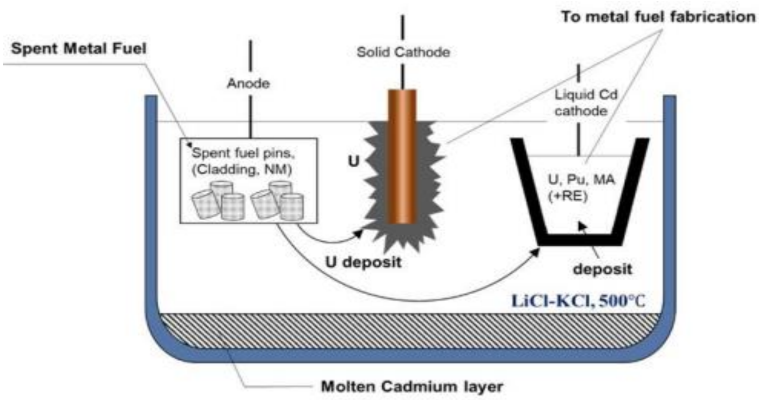


*FIG. 3. Principal diagram of pyro-refining for U-Pu-Zr spent fuel.*

Two key features of the molten salt pyro-processes are the following: the fuel is processed in certain batches and the final product ready for refabrication of nuclear fuel has low decontamination factor from fission products (DF 100-1000). Low purification of fuel significantly reduces the attractiveness of the material since the main products retain the standard of irradiated fuel and cannot be “attractive” without application of other purification technologies. So, the products after pyro-reprocessing keeps so-named standard of “spent fuel” and the reprocessed material contained Pu, could be considered as “self-protected materials”.

The Figs 4 and 5 published by ANL and RIAR are demonstrated this feature in comparison of materials after PUREX-reprocessing.

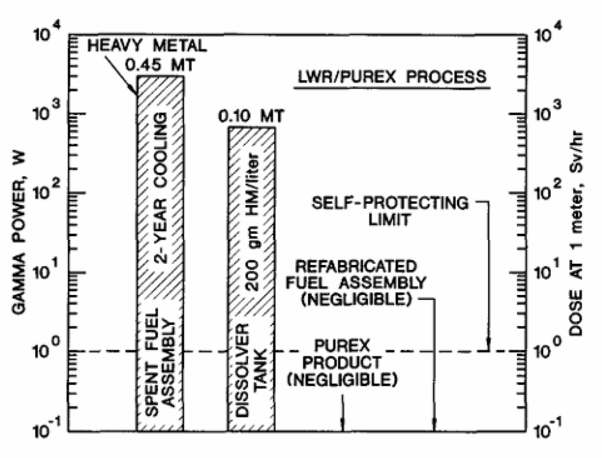


*FIG. 4. Gamma Radiation from Spent and reprocessed LWR Fuel*

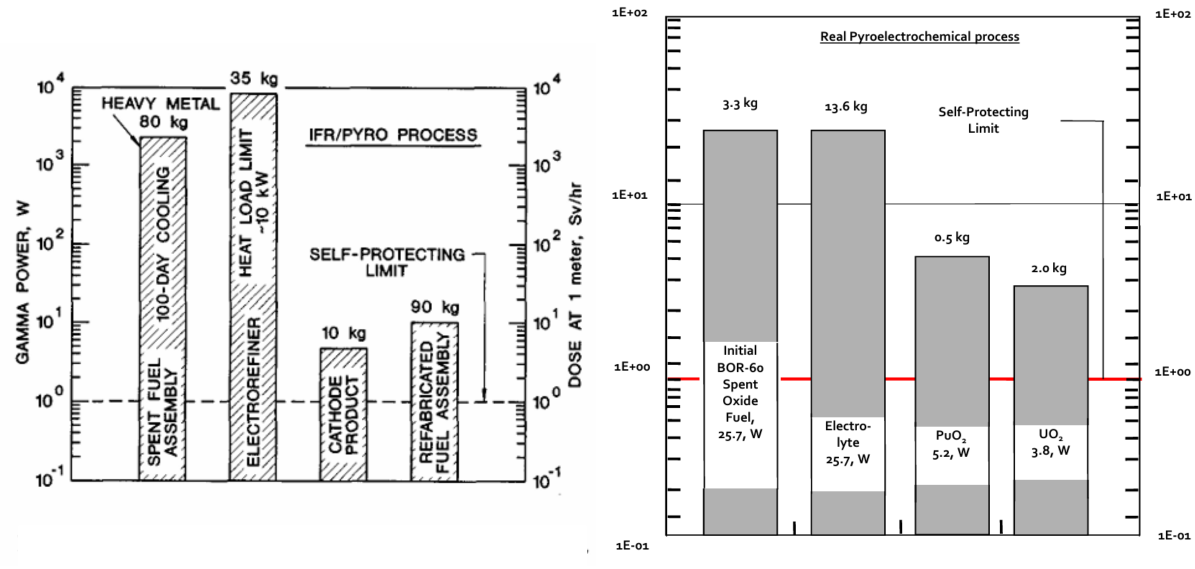


*Fig.5 Self-protection of IFR (1) and DDP (2) materials by gamma radiation*

The high radioactivity of the fuel and recovered products significantly improves the ability to control their relocation/movement in technological system. Batch processing also contributes to a more advanced option of fissile material accounting and control, as weighing and sampling are implemented at every stage (Fig.6).

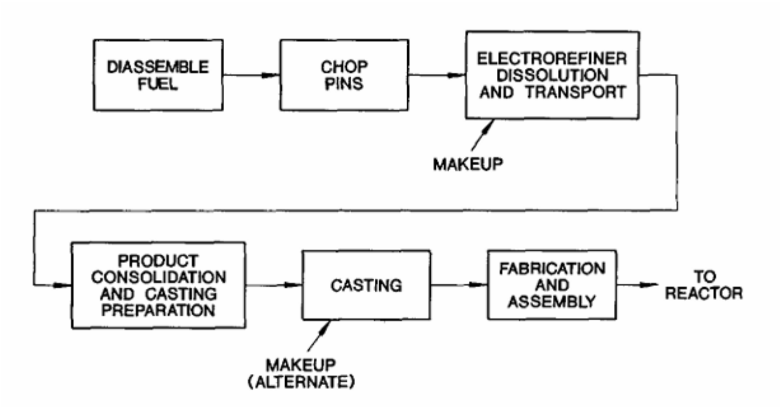


*Fig.6. Unit Operations in IFR Recycle Plant.*

So, combination of batch processes with technological mass control on each stage and low decontamination factors for products resulted two important effects from point of view of safeguardability: (1) low attractiveness of materials by to their high radioactivity (as SNF "standard") and (2) simplified technological control of all internal transportation due to batch process and high radioactivity.

In practice, several options for molten salt technologies have been demonstrated - for MOX fuel and for metallic U-Pu-Zr fuel. The results of R&D programs and the pilot tests demonstrated the mentioned specifics of these pyro-processes. The overview described some key results of mentioned R&D and pilot tests fulfilled at the Argonne National Laboratory (USA) and Research Institute of Atomic Reactors (USSR/Russia), which demonstrate mentioned features of FR spent fuel recycling through pyro-processes.

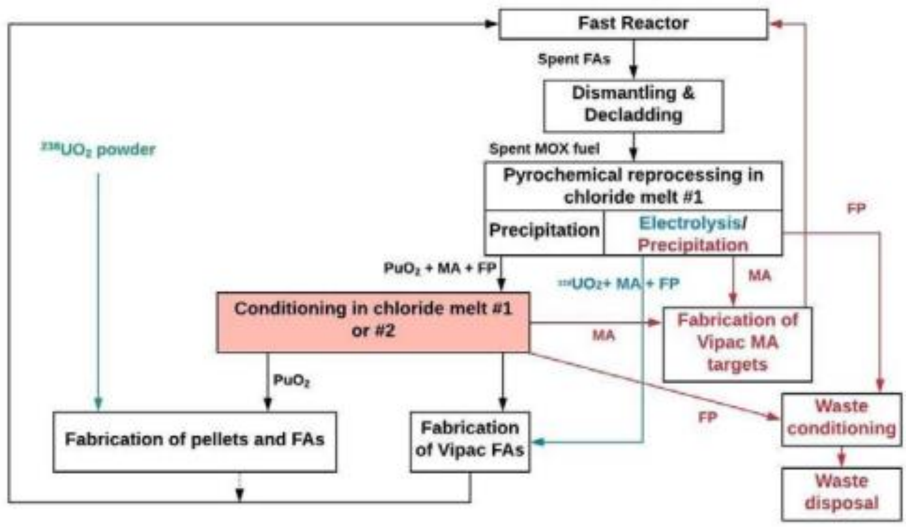


*Fig.7. Operations for production and recycling of FR MOX fuel by pyro-process and vibropacking included different options.*

In current time a number of laboratories are continue R&D in this area, mainly focused on metallic FR fuel. Combined process for U-Pu nitride fuel is under development in the frame of Russian project PRORYV for lead cooled FR BREST-OD-300.

## 4. INTERNATIONAL STUDIES OF SEFEGUARD ASPECTS FOR ADVANCED APPROACHES FOR FAST REACTOR FUEL RECYCLING

First comprehensive consideration of safeguards aspects for advanced recycling by pyro-process was initiated by ANL, and a number of papers were published till the end of 1990s. These studies based on experimental validations with spent EBR-II fuel with Pu additions. This line for metallic based fuel has been continued by laboratories of Japan, Republik of Korea, EU, India. Russian activities for oxide fuel were demonstrated on limited amounts of real spent MOX fuel of BOR-60 and BN-350 with further recycling in BOR-60 reactor in form of separate fuel pins manufactured by vibropacking.

Both processes and equipment for metallic fuel and oxide MOX fuel were tested on markable amount of fuel in so-named: ”cold mode”: application of pyro-process for treatment of fuel of EBR-II in INL and pyroelectrochemical production of MOX and UOX fuel for reactor BOR-60, as well as a number of MOX fuel assemblies deliveries for BN-600 and BN-800 reactors (totally more than 4 tHM).

Practical demonstration and active R&D initiated a number of international studies of safeguardability of advances approaches for FR fuel recycling.

In the frame of IAEA INPRO project some collaborative studies were fulfilled. Based on INPRO methodology, that includes assessment of Nuclear Energy System with nuclear reactors and fuel cycles from sustainability point of view in Infrastructure, Economics, Safety, Environment, Waste Management and Proliferation Resistance, many collaborative studies were completed. Some of them directly considered safeguardability aspects including FR Closed Fuel Cycle:

- Assessment of Nuclear Energy Systems Based on a Closed Fuel Cycle with Fast Reactors. IAEA TECDOC 1639/Rev. 1, 2012
- INPRO Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (PRADA). IAEA TECDOC 1684, 2012
- Enhancing Benefits of Nuclear Energy Technology Innovation through Cooperation among Countries: Final Report of the INPRO Collaborative Project SYNERGIES. IAEA NE Series NF-T-4.9, 2018
- Waste from Innovative Types of Reactors and Fuel Cycles: A Preliminary Study. IAEA NE Series W-T-1.7, 2019
- INPRO Collaborative Project: Proliferation Resistance and Safeguardability Assessment Tools (PROSA). IAEA TECDOC 1966, 2021
- And series of IAEA publication on “International Safeguards in the Design” for Fuel Cycle Facilities prepared by experts of IAEA SG Department and INPRO.

The collaborative project PROSA was specially focused on non-proliferation aspects of for metallic fuel manufacture facility for Fast Reactors and reflected R&D carried over by Rep. of Korea. The Fig. is a good illustration of this study.

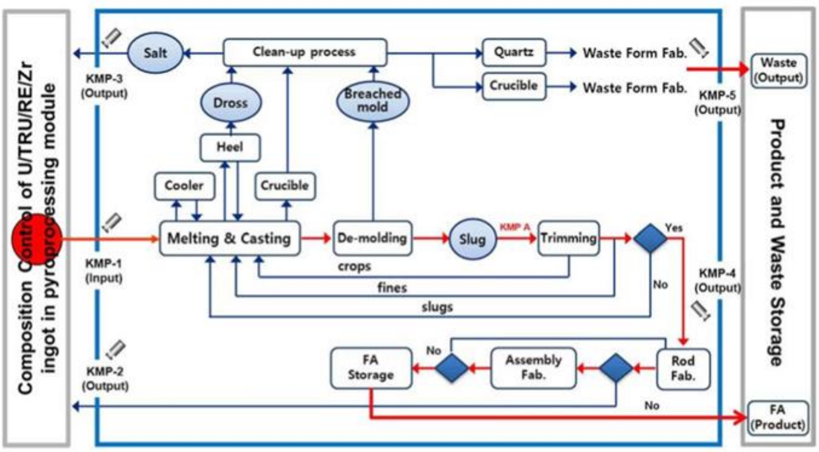


*FIG.8. Conceptual design of MBA and KMPs of the SFMF (from PROSA collaborative Study)*

The detail and complex study of proliferation resistance aspects and safeguardability of advanced recycling technologies were completed by GIF PRPP.

The publication of Case study for Example Sodium Fast Reactor with closed fuel cycle facility on site with reactor(s) could be considered as one of important stage for validation of innovative systems with fast reactors and fuels cycle toward enhanced safeguardability for fast reactor fuel cycle (Fig.9).

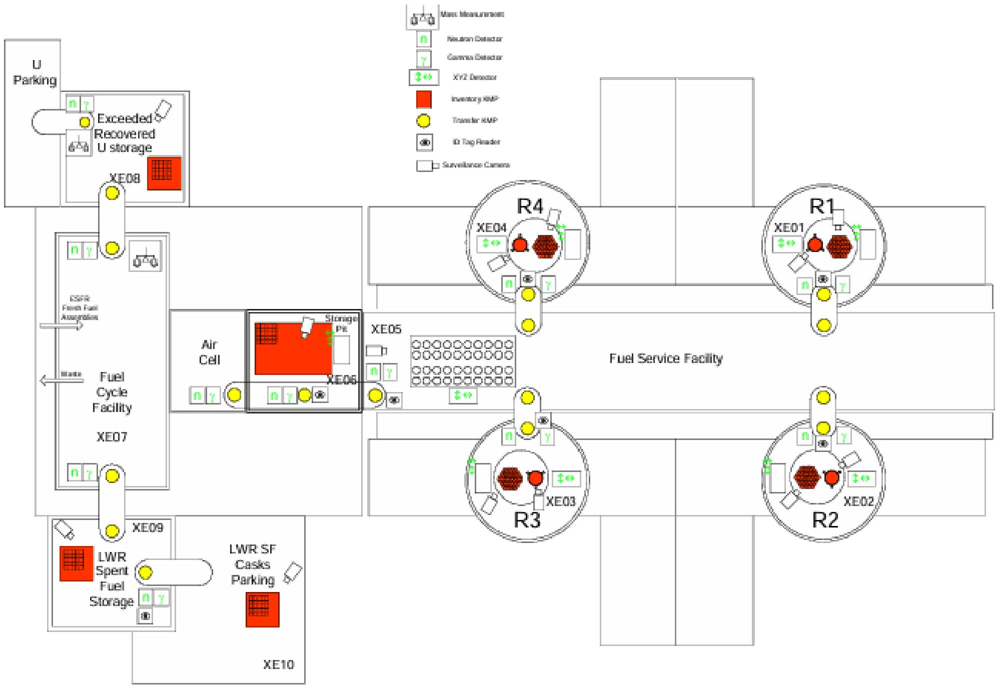


*Fig.9. Safeguards system developed for the Example Sodium Fast Reactor (ESFR), object of the GIF PRPP case Study.*

## 5. CONCLUSIONS

The potential of advanced recycling technologies is high, however, in order to implement safeguards verification measures, it will be necessary to develop special procedures simultaneously combined with Non-proliferation aspects of Fast Reactor's Spent Fuel Management.
The Safeguardability of current technologies for SNF reprocessing to apply for FR fuel could be adopted as for Pu0contaned fuel. Safeguardability and Self-protection aspects of advanced technology and infrastructural approaches for FR fuel recycling could be taken into consideration for new contractions of fast reactors and fuel cycle facilities. All necessary aspects should be assessed and analyzed before decisions on new construction of fast reactor and development of new infrastructure or using of existing one. FR CFC is a one of important elements of Nuclear Energy Systems Sustainability and non-proliferation aspects will be a key for this system, as it was fixed by INPRO and GIF studies.

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