Electronuclear scenarios with PWRs and SFRs.
Status and management of Plutonium

CS IN2P3 of February 3rd 2022

I. Team and project structuring

a. Human resources

At IN2P3, research on electronuclear scenarios is carried out in active and close collaboration at the national level. The members of this national team are divided between two IN2P3 laboratories: Subatech in Nantes and IJCLab, formerly IPNO, in Orsay.

Subatech

The activities at Subatech are organized around Nicolas THIOLLIERE, lecturer at IMT Atlantique. He is one of the pillars of the theme since its launch in 2012. Over the years, he has been supported by several temporary positions, including Baptiste MOUGINOT and Baptiste LENIAU, whose work in software and methodological development has enabled the teams to build new, high-performance digital tools. The contract of Baptiste MOUGINOT between 2012 and 2015 was financed by the IMTA and the IN2P3. The contract of Baptiste LENIAU between 2013 and 2016 was financed thanks to a collaboration with IRSN and a service for EDF R&D. The strong scientific dynamics carried by these researchers allowed a rapid growth of expertise and the supervision by Nicolas THIOLLIERE of a first PhD entirely dedicated to the theme: that of Fanny COURTIN, launched in 2014 and defended in 2017 financed by the doctoral school "Matière, Molécules et Matériaux" linked to the University of Nantes. In parallel with these research staff, the research activities on scenarios at Subatech have been enriched by the work done by the students supervised by them during various internships and research projects of engineering students.

IPNO, now IJCLab

During the first years the barycenter of the activities of the theme was located in Nantes thanks to the leadership of Nicolas THIOLLIERE and the strength of the temporary staff, but the activity has been coordinated at the national level since the beginning with a strong involvement of researchers located in Orsay. Xavier DOLIGEZ, CNRS Research Fellow, devotes a large part of his research and supervision to the theme since the beginning. The involvement of Orsay was reinforced in 2016 by the recruitment of Marc ERNOULT on a position of CR CNRS. This involvement of permanent researchers on the theme was supported by several doctoral students. Thus Marc ERNOULT, whose thesis had begun before the launch of the theme in 2011 and was financed in the framework of a collaboration with AREVA, invested the last months of his thesis in the dynamic simulation of electronuclear scenarios applying the tools and methods developed at Subatech. Then Léa Tillard's PhD thesis, co-supervised by Xavier DOLIGEZ in the framework of a collaboration with IRSN between 2016 and 2019. Marc ERNOULT, once hired, has then supervised the PhD thesis of Jiali LIANG between 2018 and 2021 financed by the PHENIICS graduate school linked to Paris-Saclay University. In the framework of a collaboration with Polytechnique Montreal, Xavier DOLIGEZ also co-supervised two research master's degrees, each of which included 18 months of research work and the writing of a research master's thesis. Xavier DOLIGEZ has co-supervised with Guy MARLEAU, professor at École Polytechnique Montréal, the research master's degree of Martin GUILLET between 2017 and 2019 and the research master's degree of Maxime PARADIS between 2019 and 2021. In parallel to these supervisions, the permanent researchers have also been supported in their work by temporary staff working on the theme of scenarios, such as Abdul-Aziz ZAKARI-ISSOUFOU who worked, financed by IN2P3 between 2016 and 2019, on scenarios of americium recycling in PWRs, and more recently Maxime PARADIS, financed by NEEDS between 2021 and 2022, who is working on the impact of taking into account the core scale on the evolution of the plutonium inventories of the French nuclear power plants. Finally, the research activities on scenarios at Orsay have been enriched by the work done by the students supervised by them during various internships and research projects of engineering students.

Thus, the theme of electronuclear scenarios is carried out at IN2P3 by two research fellows and a senior lecturer supported by various CDD and PhD students.

b. Projects structuring the research

Research on electronuclear scenarios at IN2P3 is mainly structured by two types of projects: IN2P3 master-projects and NEEDS projects which allow IN2P3 to be part of the national environment by collaborating with other actors in the nuclear energy field in France.

The last Master-Project of interest for the theme of nuclear scenarios was the Master-Project ASSURANCE (**A**nalyses de **S**ystèmes et de **S**cénarios **U**tilisant les **Ré**acteurs à eau et haute conversion par **A**nticipation d'un **N**ouveau **C**ontexte **E**nergétique) coordinated by Xavier DOLIGEZ. It extended since 2016 until the end of 2019. It was divided into three parts: SIRIUS (Simulation of Reactors of Interest for Uranium Economy and Safety), MEN (Multiphysics Experimental and Digital), MOISE (Modeling and Interdisciplinary Opening of Electronuclear Scenarios). The activities related to the electronuclear scenarios were included in this last component MOISE coordinated by Nicolas THIOLLIERE. This MP allowed, thanks to an associated endowment of the IN2P3 of between 5 and 10k€ per year, to make live the multisite team by allowing meetings.

A new MP will be launched in 2022 focused on the development and valorization of codes related to nuclear energy physics: OSCAR. By supporting the community of developers of CLASS, the dynamic simulation code of electronuclear scenarios developed by IN2P3 researchers involved in the theme, this MP should be able to take over the role of ASSURANCE for the coordination and visibility of our activities.

In parallel to these projects bringing funding and structure to the community, there is another central project that makes our research possible. It is the SIREN project at the IN2P3 Computing Center. This project is the support of our requests for storage space and processors time in this computing center. Thanks to SIREN, we have access to 1.5 million CPU hours per month and several Terabytes of disk space which allows us to do all the simulations necessary for our studies.

c. National collaborations

Moreover, the research activity has been structured by numerous collaborations. These collaborative projects started with the DOSE project (Développement d’Outils de Scénarios Electronucléaires) in 2013, funded by NEEDS (IRSN, IN2P3) and which allowed a coordination on the development of the CLASS code. Then, thanks to other projects funded by NEEDS, the IN2P3 teams have been involved in a more global way in the nuclear energy community. The projects were first of all targeted annual projects. Thus COMPRIS (Comparaison des Modèles et Propagation des Incertitudes dans le Scénarios) financed by NEEDS in 2014 and 2015 allowed to launch a collaboration between IN2P3, IMT Atlantique, IRSN and CEA by working on the comparison of physical models at the heart of the codes. Then PERMIS (Projet Exploratoire de Recherche de Méthodologies Innovantes pour les Scénarios) funded by NEEDS in 2016 and 2017 and involving, in addition to previous, AREVA and EDF, allowed a global reflection on the analysis of the sensitivity of the results of the scenario studies to the input parameters and the identification of the set of parameters allowing to obtain an acceptable or desirable trajectory.

In 2017, NEEDS decided to open the possibility for certain communities to file multi-year projects, called structuring projects. The electronuclear scenario community was contacted in the first year of the implementation of these new longer-term projects. On the advice of NEEDS, we therefore consulted with the leaders and participants of the other NEEDS scenario projects, which were then the interdisciplinary physics and economics project DIESE and the physics and sociology project PRIS. The structuring project thus created, PISE (Projet Interdisciplinaire sur les Scénarios Electronucléaires), brings together researchers from IRSN, Orano (replacing AREVA following the split), IMT Atlantique, CNRS (including IN2P3) and CEA and, because it results from the merger of three projects, two of which are strongly interdisciplinary, is interdisciplinary. Within this project, the place of physics is very strong and within the three main axes of the project, one is solely dedicated to the physics of electronuclear scenarios, focusing on innovative methodologies for the development and analysis of scenarios. In 2019, the structuring project is renewed by NEEDS, recast to create a coherent project that is no longer a simple juxtaposition of the axes: the CINEASTE project (Interdisciplinary Contributions on Nuclear and Energy: Scenario Analysis for Energy Transition) is established. This project is conceived from the beginning as a 3-year renewable project. It proposes an organization of collaborations along 3 axes and 2 transverse themes, analyzing the role of scenarios in political and industrial decisions and the consideration of temporality through the analysis and propagation of uncertainties in scenarios, the implementation of a techno-economic model of energy transition analysis and the analysis of energy mix. Like the PISE project before it, this is a deeply interdisciplinary project, but within which physics has an important place, in particular thanks to an axis (here the analysis of uncertainty) which is studied only by physicists.

These successive projects have involved researchers from different nuclear actors in France. And if the involvement of each actor has varied according to the project, the IN2P3 and CEA teams have always maintained a very strong involvement which has allowed the construction of a real scientific collaboration in depth between the CLASS (IN2P3) and COSI (CEA) teams.

In addition to the collaborations within the NEEDS projects, we have set up bilateral collaborations with different institutions to meet specific needs for close collaboration.

The first of these bilateral collaborations was set up with IRSN in 2013 and focused on the development of the CLASS tool. Thanks to the financing of several years of temporary researchers, this collaboration allowed us to quickly build an expertise and tools that allowed us to have a sufficiently operational and efficient tool in 2015 to take a full place in discussions, projects and collaborations. This collaboration continued with the co-supervision of the thesis of Léa TILLARD.

The second major national collaboration is the one that has been built for several years with the CEA. If for a long time our interactions were completely included in the successive NEEDS projects, the privileged scientific exchanges that have been built up over the course of the projects has recently led to the establishment of a specific and therefore more bilateral collaboration. It is within the framework of this new collaboration that a co-supervised thesis project is being built today, which will start in the fall of 2022.

In addition to these two long-term collaborations, other more ephemeral and targeted collaborations have existed in the past. For example, a short collaboration with Orano in 2020 led to the development of a module in CLASS allowing them to calculate the number of vitrified packages produced by the application of a given fuel cycle strategy.

d. International collaborations

Finally, despite the specificities of the situation of nuclear energy and its fuel cycle in France, which leads to scientific questions and problems that are also quite specific, we have succeeded in establishing strong collaborations with international partners.

The oldest of these collaborations is a bilateral collaboration with the **University of Madison Wisconsin**. It was born in 2015 (and will end in 2020) after Baptiste MOUGINOT, a former IN2P3 researcher, took a position at this university. It allowed to build a strong link with the developers of the American academic code Cyclus and to a PICS (projet international de coopération scientifique) carried by Nicolas THIOLLIERE.

Thanks to this PICS, it was possible to build an international project based on the comparison of methods and models used within the dynamic fuel cycle simulation codes. This **project named FIT (Functionality Isolation Test)** started in 2016 involving the two initial partners (University of Madison Wisconsin and CNRS) who designed a benchmark with a precise question to which several teams using several codes were invited to answer. In 2018, teams from three American National Laboratories, ANL, ORNL and INL, entered the FIT project. Then in 2019, European teams from CIEMAT in Madrid, Budapest University of Technology, SCK-CEN, and Tractebel Engie Belgium in turn joined the project, followed by a team from the Catholic University of Maule in Chile. In addition to coordinating the participants, IN2P3 researchers took charge of formatting the results and writing the paper that was submitted to a journal during 2020. This first test of functionality within the FIT project is now almost complete. But the FIT project is intended to include successive tests on several functionalities and is therefore not closed even if its activity has been reduced since the beginning of the pandemic.

In parallel to the FIT project, a bilateral collaboration with the **Ecole Polytechnique de Montreal** has been set up since 2017, in order to pool our expertise on nuclear power scenario simulation and the expertise on complete reactor core simulations of Professor Guy MARLEAU's team.

During the 2015 trip to Madison, Wisconsin USA for the bilateral collaboration, a technical discussion time around the simulation of nuclear power scenarios was organized. Given the richness of the exchanges and noting that this type of technical exchange between specialists did not exist for the growing community of physicists of the nuclear power cycle, we have undertaken the creation of an annual international workshop: **"Technical Workshop on Fuel Cycle Simulation".** The first edition of this workshop was organized in 2016 in Paris an annual international workshop on nuclear power scenarios. All the researchers of the theme at in2p3 participated in the organization of this workshop which was coordinated by Xavier DOLIGEZ. In 2017, the workshop was organized by the Americans of the University of South Carolina but Nicolas THIOLLIERE was still part of the scientific committee of the workshop. In 2018, the IN2P3 teams took over the organization of the workshop, again in Paris, this time coordinated by Marc ERNOULT. In 2019, the workshop was reorganized in the USA by the teams of the University of Illinois, Urbana-Champaign with Nicolas THIOLLIERE member of the scientific committee of the workshop. The 2020 edition was to be organized in Aix in collaboration with the CEA teams and coordinated by Fanny COURTIN of the CEA. It was postponed and then transformed into a online workshop in June 2021 following the COVID pandemic. Following the transformation in online, the IN2P3 researchers have been brought to take an important place in the organization. Thanks to the support of IMTA, we could all go to Nantes to manage together the technical organization and the animation of this very particular workshop.

In addition to these collaborations that we have created, we have also joined an expert group of the **NEA**: **Expert Group on Advanced Fuel Cycle Studies** within the **Working Party on Fuel Cycle** of the **Division of Nuclear Science and Education**. Since 2017 Marc ERNOULT is a member as a researcher of IN2P3. An active participation in the meetings and studies as well as in the formatting of the results of the study has allowed a great visibility of our tools and our research with new international partners.

Thanks to all these collaborations, our activities have gained a good international visibility and CNRS/IN2P3 researchers are now recognized internationally. An illustration of this recognition are the invitations for 4 presentations for which we have been invited to the international workshop organized by CIEMAT in Madrid on November 2 and 3, 2021.

II. Electronuclear scenarios and the status of plutonium

Research on nuclear power scenarios focuses on nuclear power plants and their evolution over time following the application of various strategies or the occurrence of various events. By studying the trajectory that a fleet follows over time under these conditions, scenario studies make it possible to understand the mechanisms that govern its evolution and potentially to evaluate its performance with respect to objectives.

a. Reference and starting point: the French nuclear fleet

Within our scenario studies, the French nuclear fleet plays a particularly important role for two reasons. First of all, it is a rather complex nuclear power plant involving different types of reactors and different fuel management, including recycling of materials from already irradiated fuels. The evolution of this fleet from its creation to the present day is therefore a good reference from which to evaluate the performance of our tools, even if the difficulty of accessing historical operational parameters and current isotopic inventories makes this evaluation very incomplete. Moreover, most of our scenario studies investigate possible evolutions of the French fleet in the future and simplified academic fleets inspired by the current French fleet are therefore the starting point. It is therefore essential to have a good knowledge of the French fleet.

The French nuclear power plant fleet is composed of 56 PWRs with an individual power output of between 900 and 1500 MWe. Together, they correspond to an installed capacity of about 61 GWe, with an effective electricity production of about 420 TWh in 2016 (330 in 2020). The most recent reactor is Civaux-2, an N4 PWR commissioned in 2002. The most recently shut down reactors are the two Fessenheim PWRs shut down in 2020. 20 reactors among the 900 MWe PWRs are 30% loaded with MOX fuel, made from depleted uranium and plutonium from recycled spent UOX fuel. The fraction of power produced by MOX assemblies in the entire French fleet is about 10%. The remaining 90% is produced by UOX assemblies.

The operation of these reactors requires various operations (ore extraction, fabrication, reprocessing, cooling, etc.), carried out on the fuel before and after its irradiation in the reactor. At each stage, the fuel passes through plants, also called units, in which these operations are performed. All of this constitutes the nuclear fuel cycle presented in figure 1.

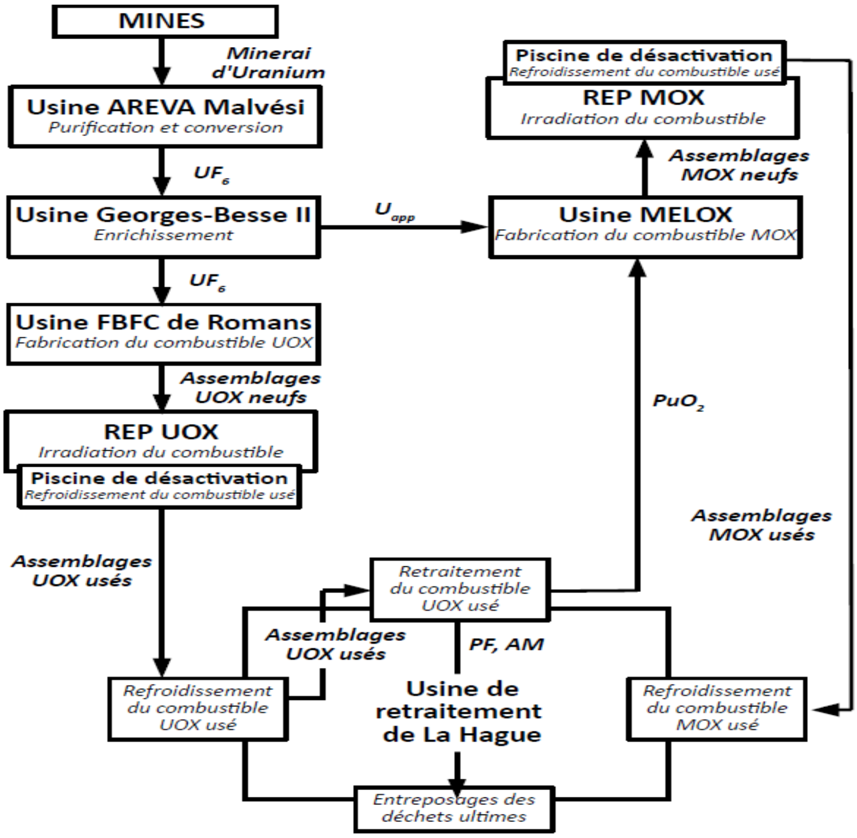

Figure 1: current french fuel cycle [PhD of F. Courtin]

In the current French fuel cycle, there are plants in the front-end of the reactors dedicated to fuel fabrication. A conversion plant purifies and chemically transforms uranium from mines to prepare it for enrichment. A plant raises the isotopic percentage of U235 in the uranium from the 0.7% present in natural uranium to the percentage necessary to wait for the desired burnup in the reactors of the park, between 3 and 5%. Two manufacturing plants transform the materials resulting from enrichment or separation after recycling into the chemical and geometric form that allows them to be irradiated in a reactor.

Secondly, the units of the back end of the nuclear fuel cycle are in charge of the management of irradiated fuel. The first is the cooling pool located on the power plant site where the fuel is stored after irradiation to wait for its residual heat to decrease and make its transport possible. Then it goes to the spent fuel processing plant at La Hague where it is stored pending reprocessing. The UOX fuel is chemically reprocessed to extract the recoverable materials. The final waste is also conditioned and stored there while awaiting transfer to a final disposal site.

Recycling of plutonium from spent UOX

The choice to recycle the plutonium contained in spent UOX fuel is a very specific choice for the French nuclear industry. First of all, plutonium is responsible for the vast majority of the radiotoxicity of spent fuel from 150 years to 1 million years after the end of its irradiation. It is also a major contributor to the residual heat of this spent fuel over this period. In a fleet that does not recycle, called open cycle, plutonium is therefore the dimensional contributor to long-term waste management. Moreover, it is composed mostly of fissile isotopes, which allows it to be used as a replacement for U235 in new fuel assemblies. In addition to these physical data, there is an industrial advantage: it is necessary to extract plutonium from between 7 and 8 UOX assemblies to build a MOX assembly. There is thus a significant division of the storage space required for spent fuel assemblies.

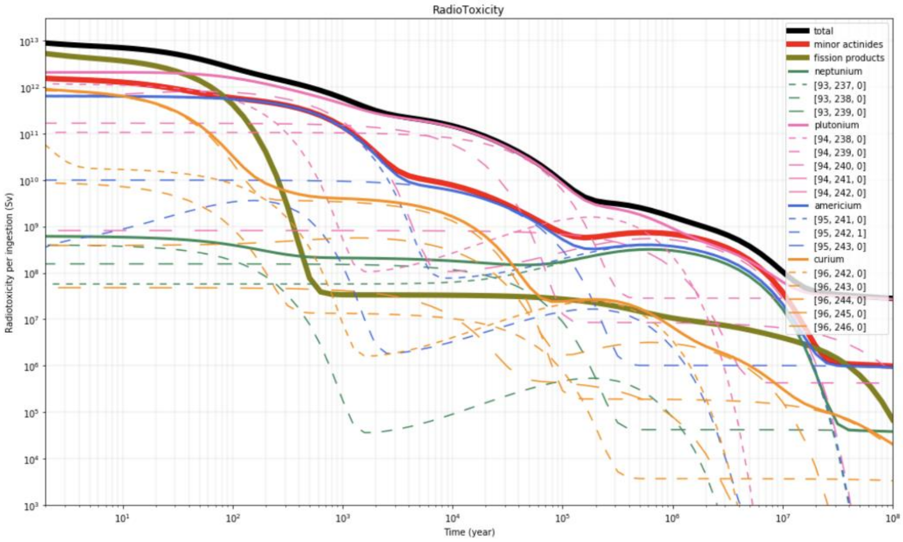

Figure 2: Radiotoxicity of French nuclear materials in 2015, after 25 years of implementation of Pu recycling strategy for spent UOX

However, the manufacture and management of MOX assemblies poses many difficulties that make the management of the fuel cycle much more complex. This complexity appears at the level of reactor physics, but also at the level of the fuel cycle, because each spent UOX assembly has undergone a significantly different irradiation and cooling history, which means that the isotopy of the plutonium contained in it is unique. The construction of each new MOX assembly must take into account these particularities of the plutonium used. The average quantity of fissile isotopes in spent MOX is lower than in spent UOX, which poses many difficulties in the design of assemblies passing the various safety criteria. They are not recycled in the current French fuel cycle.

According to French law, "radioactive waste is radioactive material for which no further use is planned or envisaged". Spent MOX fuel that will be recycled in the future is therefore not considered as waste. Only vitrified packages from the reprocessing of spent UOX are currently considered as waste. These packages are made from materials that are not recovered, i.e., neither the uranium that can be re-enriched nor the plutonium that is used for MOX, so only the fission products and minor actinides. It is on this basis that the Cigéo project was designed. If spent MOX were to be added to this waste, the volume of the site would have to be multiplied by almost ten. This increase of an order of magnitude caused by assemblies that produce only 10% of the power is the transposition of reactor data to the scale of the fleet. Thus Figure 3 shows that the radiotoxicity of plutonium dominates the radiotoxicity of the materials present in the whole park for more than a million years.

This dominance of plutonium in the waste of the park makes its management the main question of the scenario studies. To be concerned with the other wastes without having a solution for the management of plutonium makes no sense from a physical point of view.

b. Plutonium status

For a long time, the strategy for the management of plutonium from spent MOX was based on the development of a fleet of SFRs that would allow this plutonium to be recycled as many times as necessary without the evolution of its isotopic composition or its variability ever being a problem. Until 2018, the start of construction of these SFR was expected for 2040. In this context, plutonium was not only a material that could be recovered, but a material present in limited quantities that had to be preserved and produced in quantity. Indeed, starting up enough SFRs to replace the entire French fleet would require about 1200 tons of plutonium, nearly three times the amount available in spent fuel, UOX and MOX, which is about 350 tons of plutonium. However, various technical, industrial and political difficulties have led to the abandonment of the SFR program in France, and no construction of an industrial-scale SFR is expected in France before the end of the 21st century, and is even questioned.

With the disappearance of this medium-term deployment plan for SFRs, the current strategy of monorecycling does not solve the problem of plutonium management with regard to its impact on waste. Indeed, without any planned or envisaged future use, the radioactive materials contained in MOX become waste. However, as shown in Figure 4, the use of MOX for mono-recycling has a very low impact on the waste produced. It is necessary either to recycle the plutonium continuously or to take it into account in the design of waste storage sites.

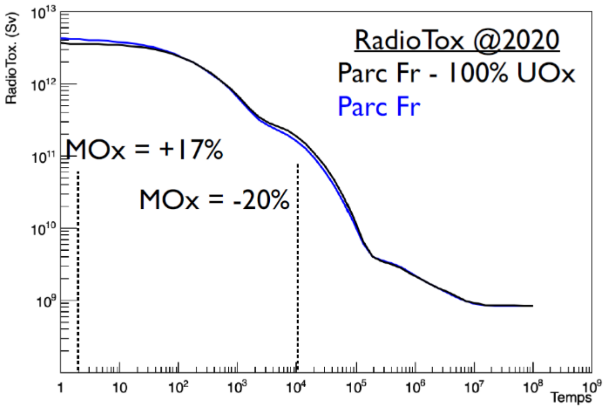

Figure 3:Effet du mono-recyclage sur la radiotoxicité des matières du parc

In order to multiply the plutonium, it is necessary to develop strategies for the recycling of spent MOX. Moreover, if spent MOX is not to be considered as waste, it must be recycled within a time frame that suits the legislators and safety authorities. A plan that is too far into the future will still force the resizing of storage sites.

However, if the deployment of SFRs is postponed to a relatively distant future, the design of the various plutonium management strategies cannot ignore it. Indeed, if this massive deployment of SFRs is to take place one day, large quantities of plutonium will be needed to do so. However, the French fleet has accumulated 350 tons of plutonium since its creation, so it will take more than 60 years to accumulate the rest of the 1200 tons needed for SFRs. The need for plutonium associated with a massive deployment of SFRs in 2100 cannot be forgotten when designing plutonium management strategies.

This tension between the status of plutonium as a valuable resource for a potential SFR deployment and as a major contributor of nuclear waste from existing PWR fleets is at the heart of the nuclear scenario studies we are conducting at IN2P3.

III. Tools and methods developed at IN2P3

a. Scenario study method

Scenario studies at IN2P3 are not dictated by the command of authorities or partners, but by a scientific question. For the reasons explained above, the question is, in most of our studies, linked to the question of the status of plutonium and to the capacity of certain strategies to provide an answer to the tension between its status as waste and as a resource.

In the past, we have, for example, carried out scenario studies to answer the questions: "Does the use of MOX fuel on an enriched uranium support in current French reactors allow for the incineration of plutonium?" and "Can strategies developed to allow for the deployment of SFRs be adapted to manage plutonium in reactors of current technology?

It is also important to specify the framework within which the study is being conducted. It determines the context of the study, in particular by determining the fleet used as a starting point. Most of our studies consider scenarios based on the French fleet, but other studies start with a newly created fleet. Defining this framework also involves determining the time horizon. It depends on the issue considered and can range from 70 to 300 years after the starting point. The framework of the study also determines which parameters of the cycle and their evolution are imposed, controllable or random. Approximations, such as the use of macro reactors or the mixing of stocks, may also be imposed or prohibited.

Once this framework is set, we translate it into technical choices compatible with our simulation tools. The imposed parameters are assigned numerical values. Ranges of possible values are determined for the controllable parameters and probability distributions for the random parameters. Approximations and physical models appropriate to the study are also chosen. The quantities and numerical criteria that will be followed in the study and on which the answer to the central question of the study will be based are also determined. In some studies, several options may be considered in parallel.

Several simulations are then launched within the space determined by the framework thus specified. Each collection of values thus obtained determines a strategy that can be implemented in our simulation tools which, after calculation, will give a representation of the associated trajectory that the park would follow if it were implemented.

Finally, different analysis techniques use the results of these simulations to provide elements of an answer to the central question of the study. The validity of this conclusion is limited to the scope of the study, but understanding the mechanisms at play in a particular scenario study advances the overall understanding of the behaviors of nuclear power scenarios.

b. Simulation of a trajectory for a nuclear fleet: the CLASS code

To carry out the simulations of the different trajectories, we have developed the CLASS code, for **C**ore **L**ibrary for **A**dvanced **S**cenario **S**imulation. The CLASS code is a dynamic fuel cycle simulation tool developed by the IN2P3 teams and which benefited at the beginning from a collaboration with the IRSN. CLASS is a collection of C++ classes that describes the installations of a nuclear fleet. The code was built around an object representing the reactor and manages the flow of nuclear materials from front-end to back-end of the cycle. It models complex nuclear fleets whose configuration may change over time. Within these fleets, it calculates the isotopic evolution of the material inventory at each moment, and in each unit (plants, reactors, cooling pools, stocks, ...).

These different units interact according to a rather generic process. From its start-up date until the end of its operating life, the reactor requests the manufacturing plant to build a fuel before each new load. This fuel must comply with the reactor's specificities. The new fuel is then subjected to decay in the plant during the time necessary for its fabrication. Then, the fuel is irradiated in the reactor during its cycle time. Then, the reactor discharges into the cooling pool where the spent fuel will be cooled during the cooling time characteristic of the pool. The pool can then discharge the cooled fuel into another pool, a storage facility or a separation plant that will separate the different materials (depending on its separation efficiency). Finally, all the materials end up in a stockpile. This type of unit is always the last link in the cycle and the materials can therefore reside there for an indefinite period of time and be taken from there by other units.

Among these processes simulated in CLASS, two are particularly complex and represent most of the development efforts: the model allowing to build a new fuel adapted to a reactor from the available materials and the one allowing to simulate the evolution of the isotopic composition of the fuel in the reactor. The first is called the equivalence model and the second the irradiation model. These models are specific to each type of reactor implemented in the CLASS code. The equivalence model most used in the CLASS code is based on artificial neural networks (ANNs) that predict the evolution of the multiplication factor k and use an iterative process to adjust the proportions between the different elements in the fuel to ensure that the reactor remains critical throughout the irradiation without having too much reactivity margin to avoid under-utilization of fissile material. The most common irradiation model is based on ANNs that predict the average cross sections in the reactor and their evolution over time and numerically solve the Bateman equations using them.

c. Limitation of scenario studies: managing uncertainties in scenario studies

Scenario studies seek to answer questions about situations in the distant future, several decades in the future, and complex systems that do not yet exist, such as reactors or innovative assemblies. And the studies are done with necessarily simplified models to be able to simulate these complex systems over long periods of time with a reasonable computing time. Under these conditions, the results obtained are necessarily subject to numerous uncertainties. In order to have an idea of the validity of the conclusions that are drawn from these studies, it is necessary to take these uncertainties into account during the analysis and the formation of the conclusions.

1. Different sources of uncertainty

The uncertainties that impact the results of our scenario studies are very diverse in terms of their sources and the quantities they impact.

Some of the uncertainties are related to the tools themselves and the models that are used. The physical models used in CLASS are numerical models or models trained on databases. However, the data on which these models are based are subject to uncertainties: the cross-section databases. Moreover, the efficiencies of industrial processes do not give exact values but estimates. The uncertainties on these basic data naturally generate uncertainties on the results given by the models using them. Moreover, these are simplified models that make many approximations, which generate biases on the results they give. Because of the small number of experiments available, especially when these models represent innovative systems or systems that have never existed, it is very difficult to evaluate these biases that have an impact on our results and this generates further uncertainties. When several models are available in the code, it is not always obvious which one is the most suitable for the current study and this choice of model, often made following an expert opinion that is not very well explained, therefore adds uncertainties.

The values associated with the operational parameters in the framework of a study, whether it is the single value that is imposed on them or the minimum and maximum values that they can take, are also subject to strong uncertainties. For example, the duration of an irradiation campaign for a reactor that will start in 2080 is not known today.

Moreover, the real possibilities may be very different from the predictions of external experts that we use in our studies. For example, the evolution of nuclear power, for which some studies use EPP predictions, may follow a completely different path in the future. Similarly, the dates of availability of the various technologies used to define the framework of our studies are also subject to uncertainties, technological locks could take longer to be lifted than expected or new ones could appear.

Finally, sudden events outside the scope of our studies can completely call into question the choices made when defining the framework. For example, a major nuclear accident on a sodium-cooled FR abroad can call into question the interest for this technology in the space of a few months, and a rapid and massive development of nuclear power in India, China and Brazil simultaneously can lead to a reconsideration of the assumptions made when the framework of our scenario studies was chosen. These are disruptions that subject the strategies we are studying to a profound uncertainty that is difficult to quantify, but is inevitable given the long periods we are looking at.

2. Studying operational uncertainties: The GSA methodology

Each form of uncertainty requires the use of a specific method. To take into account the uncertainties on the operational parameters of the future cycle, we have developed an original method adapted from the global sensitivity analysis (GSA) to the specificities of the nuclear power scenario. The value of these operational parameters used in the future is no longer considered as a variable that has a correct value and that is subject to uncertainty, but as a controllable lever that allows to orientate a fleet trajectory according to a strategy. The objective of the study is then no longer to propagate uncertainty on these variables, but to understand how these levers influence the results and towards which values they should be oriented. Their value is no longer an input parameter, a part of the study framework, but a result.

For this, the operational parameters considered are no longer associated with their most probable value but with a range of possible values. Using this space of possibilities, a large number (several thousand) of collections of values are then randomly drawn by Latin hypercube sampling (LHS). Following the simulation of the strategies defined by these parameters, the corresponding trajectories can be used to understand the influence that the input parameters have on the results of interest, i.e. the amount of transuranium at the end of the simulated period for the example used here. For this purpose, Sobol sensitivity indices are calculated. Thanks to the first-order indices, we can determine which parameters have the greatest impact and the difference between the first-order and total indices indicates the importance of interactions with the other parameters. Thus, it can be seen that the burn-up of UOX fuel and the fraction of power supplied by MOX assemblies are the most impacting and can alone explain the variations in the plutonium and neptunium inventories. For Americium and Curium inventories the situation is more complex, with cooling time and MOX burn-up having a significant impact and with interacting variables.

Moreover, thanks to the LHS, the simulated trajectories can be reused in the rest of the analysis and by applying validity and performance criteria, it is possible to choose trajectories of interest as shown in figure 8 for the trajectories that stabilize the plutonium inventory and to have access to the values of the parameters for these trajectories of interest, thus obtaining the answer to one of the questions of the study, which was to determine the strategies that would allow the stabilization of the plutonium inventory in the cycle.

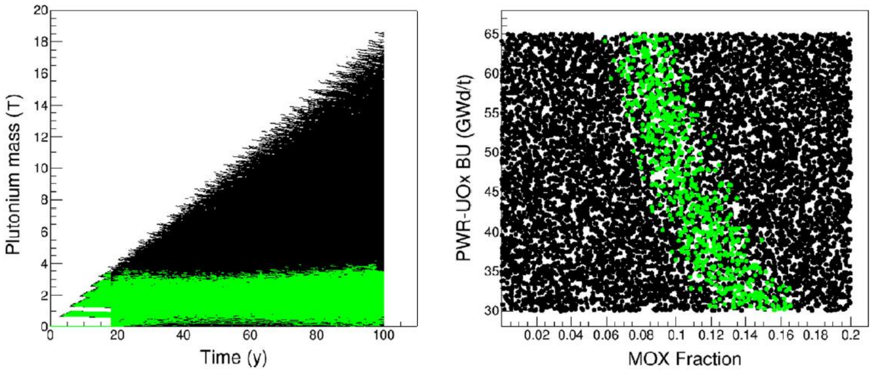

Figure 4: Selection of trajectories for plutonium stabilization and presentation of associated operational parameters

3. Study the uncertainties related to the choice of models: The FIT project

For the uncertainties related to the choice of models, IN2P3 has been a driving force in the FIT (Functionality Isolation Test) project dedicated to their quantification. This project is divided into several tests, each dedicated to a functionality of the dynamic cycle simulation codes, such as the ability to adapt the construction of fresh fuels during the simulation or to determine the dates at which to calculate the evolution and transport of materials, and allowing the quantification of the uncertainty in a simulation by the choice of a model over another to ensure this functionality.

Among the functionalities of interest, the first test focused on the ability of the fuel cycle software to adapt the fresh fuel to the isotopic qualities of the available material and the requirements of the associated reactor. Specifically, it focuses on the impact of using a fuel loading model (FLM) or a so-called "fixed fraction" (FF) approach. An FLM tailors the fresh fuel composition to the requirements of the reactor and the isotopic compositions of the available materials, whereas an FF model uses the same fissile fraction at each fresh fuel loading, regardless of the isotopic composition of the available fissile materials.

The FLM was used as a reference because it is expected to take more physics into account. The FF approach is the least expensive method to handle fresh reprocessed fuel fabrication, both in terms of development and computational time. The two fuel fabrication models will be compared within the same simulator, which will allow to evaluate the difference between two almost identical simulations: same simulator, same reactor description, same burnout algorithm, etc. The only difference being the method used to make the fresh fuel.

From the output data produced by the different simulators, estimators were designed to measure the impact of using an FF model versus an FLM. The first local estimator aims to measure the difference in plutonium enrichment in the MOX fuel between the FLM and the FF and represents the expected relative error on the ratio of the plutonium fraction given by this model. This estimator measures the local effect at each reactor loading that has a direct impact on the amount of plutonium present in the downstream fuel cycle. The second estimator is related to global effects. For PWRs, it is calculated from the evolution of the total mass of plutonium (F2), again measuring the relative error on the ratio. For SFRs, if the reactor is in equilibrium, the amount of plutonium may not change during the cycle. To take into account this behavior, a parameter inspired by the Fissile Inventory Ratio (FIR) is created.

For PWRs, the orders of magnitude for the local estimator are similar between fuel cycle simulators and range from 19% to 40%. This highlights the importance of the FLM by showing that between 20% and 40% of the average local deviation could be observed using an FF approach. The effect of using an FLM produces a difference on the relative plutonium consumption measured by the global estimator between 9% and 22%. This impact will be propagated in the fuel cycle calculation with each reactor fuel loading. For all codes, the smallest difference between the FF and FLM approaches is reached for a fraction of fissile plutonium in the fuel close to 65%, corresponding to a standard MOX fuel, which underlines the fact that the deviation of the FF approach increases with the exotic level of the plutonium composition.

The local estimator for SFRs ranges from 10% to 14%, lower values than for PWRs. This can be explained by the higher average plutonium content in SFRs at the beginning of irradiation, since similar absolute standard deviations are observed. For the overall estimator, the relative deviation is between 2 and 6% for the different fuel cycle simulators. While these deviations are not negligible, the effect is not significant for the cycle used in the test performed. Comparing the values of these estimators with those obtained for the PWRs, it is noted that the effect of using a FLM is thus less important and that a FF model may suffice in many studies.

IV. Scenarios for Multi-recycling Pu in PWRs

Faced with the fact that SFRs will not be present in the French cycle in the next decades and that the current strategy of monorecycling does not solve the plutonium problem, many studies have been carried out to investigate the possibilities of multi-recycling of plutonium in current reactors and the associated performances.

a. Physics of plutonium recycling in PWR

Reconstruct the physical basis of the feasibility limits

In order to integrate the multi-recycling of plutonium in PWRs within our scenario studies, it was necessary to design and build suitable models to represent them in the codes. For the irradiation models, since the geometry of the different types of assemblies proposed is well known and the neutron spectra in these assemblies are close to those in current MOX, it was possible, after very little adaptation, to use the proven methods used for these standard MOX. For the fuel fabrication models, the similarity is much less direct. For these innovative assemblies, there is no reference plutonium content limit derived from historical studies and validated by the safety authorities. To determine the maximum acceptable content, it is therefore necessary to start from the beginning, to redo studies of reactor physics at the assembly scale to determine which physical observables are limiting the feasibility of an assembly.

Neutron studies inspired by the methods developed for the GSA have been set up and have made it possible to highlight the major role of the reactivity coefficient in case of draining. This safety coefficient is very strongly influenced by the total plutonium content in the assembly and by the fraction of even isotopes in the plutonium isotopic vector. When calculating the maximum plutonium content that guarantees an acceptable void coefficient, we find contents very close to reference limits. These studies have also shown that the enrichment of the uranium used as a support for MOX and the spatial distribution of the plutonium in the assembly considered have little influence on this limit.

Many assemblies proposed for multi-recycling mix plutonium and enriched uranium either by putting both MOX and conventional LEU rods in the assembly, or by mixing enriched uranium and plutonium in the same pellets. The creation of a new assembly then requires the determination of two independent fissile contents, and the usual equivalence models must therefore be adapted. For each design, it was necessary to establish an order of priority for the fissiles as well as minimum and maximum contents. These differences in priority and limits on grades during fabrication are notably the only differences between the MIX and MOXEUS assemblies.

Consideration of the core scale

This study of the physics of plutonium recycling in PWRs has made us realize the importance of having an accurate representation of the neutron spectrum, especially for the rods at the periphery of the assembly. However, until recently, our irradiation and equivalence models were designed only from assembly simulation, without taking into account the core scale.

To evaluate the impact of taking into account or not the core scale in our scenario studies, we decided to move towards a test inspired by the FIT philosophy and compare the results of the simulation of the same strategy with two different models, one taking into account the core scale and the other not. But for this study to be possible it was necessary to implement irradiation and equivalence models taking into account the core scale in CLASS. To make this development possible, a collaboration was set up with the Polytechnique Montreal team developing the core simulation code DONJON.

This study on the consideration of the core scale was first focused on standard LEU and MOX whose physics and industrial constraints are well known to focus on the difference of the models. Thanks to these studies at the core scale, we were able to evaluate the impact of the approximations we use in our models based on assembly calculations.

For the equivalence model, we could see that the calculation of the fissile content by models using only assembly data is clearly degraded, leading to differences of -8 to +12.5 % relative in the MOx cases and -5 to +2 % in the UOx cases. For the irradiation model, measured deviations are significantly higher in the UOx case than in the MOx. In particular, the error on the uranium 235 inventory is very poor, above 10%, which prohibits any precise study of uranium recycling with the assembly models. Whatever the nature of the fuel, the different isotopes of plutonium are simulated with errors of a few percent at most, which ensures that the assembly models can give usable results for plutonium management. In all cases, the simulation of minor actinides is particularly poor with deviations of the order of 10 to 30%. During this study, the importance of loading plans was also highlighted, as well as the difficulty of constructing these loading plans to obtain the most homogeneous burn-up possible on all the core assemblies. The performance of the loading plans from this point of view was evaluated via the core power factor which measures the ratio between the maximum power supplied by an assembly and the average power. This difficulty led to the establishment of reference loading plans designed with the core physics expertise of the Montreal researchers, which will be used for all irradiations.

A second study centered on heterogeneous cores including UOX and MOX assemblies was then carried out. The consideration of the core scale in CLASS for heterogeneous reactors required the development of an original dedicated fuel loading model. The one proposed here relies on the identification of the Pu content to ensure a minimum power peak factor. It differs from previous loading models based on considerations of infinite neutron multiplication coefficient. In this model, the core is first designed as if it contained only LEU assemblies, then MOX assemblies equivalent to the UOX assemblies they replace in terms of form factor are designed.

In terms of the impact on the scenario studies, the study with heterogeneous cores is very similar to that with homogeneous cores: the main source of divergence for the plutonium stockpile estimates is mainly due to the fuel loading model. The irradiation model was also found to be unsatisfactory for the prediction of the 235U inventory in the core as well as for the production of minor actinides, because 235U and minor actinides are much more sensitive to the effects induced by the neutron flux.

In the design of loading plans for mixed cores, the difficulty of creating them has become even greater. For the moment, it is necessary to rely on a small number of reference plans built by experts, making it difficult to take into account the core scale for reactor management that is too far from that currently known.

b. Scenarios for Multi-recycling Pu in PWRs

Based on this understanding of the physics of plutonium multi-recycling in PWRs, we launched the first scenario study related to this issue in the framework of Fanny Courtin's thesis. The aim of this study was to determine if it is possible to stabilize in the long term the total amount of plutonium contained in the cycle and the waste accumulated in a PWR-only fleet. In addition, a secondary question was studied on the possibilities of reducing this inventory. For this study of multi-recycling scenarios in PWRs, we focused on the MOXEUS (MOX on Enriched Uranium Support) assembly design because it is a homogeneous fuel that can be integrated into a traditional PWR, and therefore simpler to model than other concepts. It also has a high capacity for plutonium incineration.

Multiple simulations of MOXEUS at the assembly level have been performed using SMURE, the IN2P3 reactor simulation code, building a database. This database was used to train neural networks predicting the average cross sections on the assembly as a function of time and initial fuel composition in order to create an irradiation model. For the fabrication of the fuel, the first step is to create a MOX fuel based on depleted uranium, and if the plutonium content calculated in this way is higher than the maximum content fixed by the design, which can be as high as 16% in certain variants, the uranium is then enriched to be able to withstand the desired irradiation time.

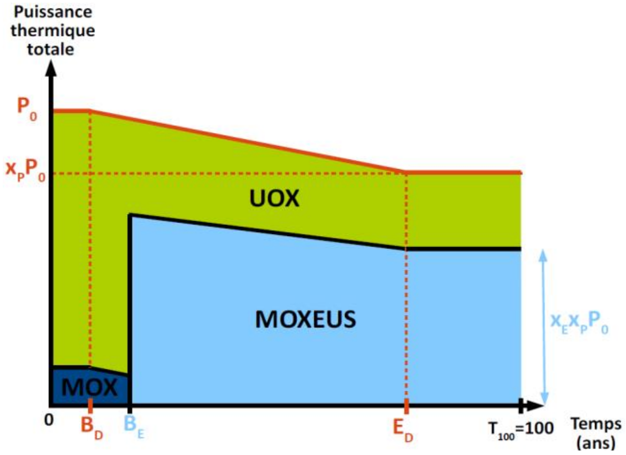

Figure 5: Scenario outline for a scenario study on multiply recycling plutonium in PWRs

Using this assembly and conventional UOX and MOX, a scenario framework, described in Figure 11, has been determined drawing a set of possible strategies characterized by 5 free parameters: the final power x_P, the start (B_D) and end (E_D) dates of the evolution of the total power, the start-up date of the MOXEUS (B_E) and the fraction of the final power provided by the MOXEUS assemblies (x_E)

Numerous simulations of multi-recycling of plutonium in MOXEUS were thus carried out following an LHS draw on the 5 variables in question. From these simulations, it was possible to calculate the Sobol indices mentioned above. With the exception of precision, the indices obtained in the case of LiFo management are identical to those obtained in the case of FiFo management. According to the sensitivity indices, only 4 variables have an impact on the total plutonium mass. These are x_E and x_P and to a lesser extent E_D and the burn-up of UOX fuel. Moreover, no second order sensitivity index is greater than its associated statistical error. This indicates that no interaction between the input variables has a significant effect on the output observables.

Once the behavior of the different strategies is understood thanks to this analysis, the trajectories whose behavior is dictated by the limitations of our models and not by the physics of the cycle can be removed from the set. And we can look for, among the valid trajectories, the trajectories of interest for the question of the scenario study, namely the stabilization of the total plutonium inventory. The trajectories that stabilize plutonium are represented in Figure 12 as a function of the two most impacting variables identified by the GSA: x_E and x_P. Three groups of trajectories can be distinguished: trajectories where stabilization is achieved by a nuclear phase-out (x_P close to 0), a group with a very high fraction of MOXEUS ($x_E > 0.5$) and intermediate situations with lower fractions of MOXEUS and a power around 30% of the current power.

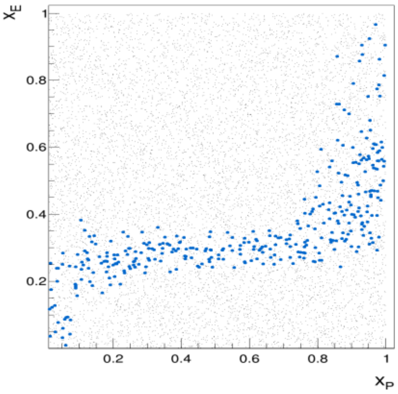

Figure 6: Plutonium stabilizing trajectories using multi-cycle Pu with MOXEUS

c. Dealing with deep uncertainties: Is multi-recycling of Pu in PWR a barrier to future SFR deployment?

Thanks to the study presented in the previous section, it has been shown that the use of fuels allowing multi-recycling of plutonium in PWRs allows the stabilization of the plutonium inventory, but imposes important constraints on the strategies to be undertaken, which must be spread out over a period of about 100 years. It is therefore possible that during this hundred-year period, the idea of starting up SFRs on a massive scale will again become a priority.

In order to know if the implementation of multi-recycling strategies in PWR still allows the change of direction in case of disruption due to an abrupt change of objectives and framework of the nuclear industry, we have carried out, during J. Liang's thesis, a study starting from a reference trajectory implementing plutonium multi-recycling in PWR and trying to see if it was possible to massively deploy SFRs at the beginning of the next century, if this was decided during its implementation.

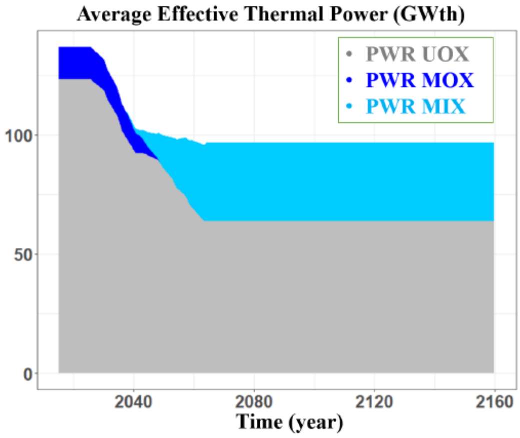

Figure 7: Reference trajectory for plutonium stabilization with MIX fuels

The starting strategy for this study is based on the current reference case and is presented in Figure 13. The EPR time horizon is chosen to cover both the initial transition from the current cycle to the cycle using the MIX and the possible development of SFRs in the next century. This implies a study period from 2015 to 2160.

The trajectory achieves stabilization of plutonium in the interim and total cycle inventories shortly after the transition in 2060, but has approximately the same consumption of natural uranium and accumulates the total cycle MA inventory faster than the current fleet. The amount of plutonium remaining unused in the inventory stabilizes at 250 tons. Because of this low level of inactive plutonium and the continuous recycling of that which is in the cycle, plutonium is without debate a resource.

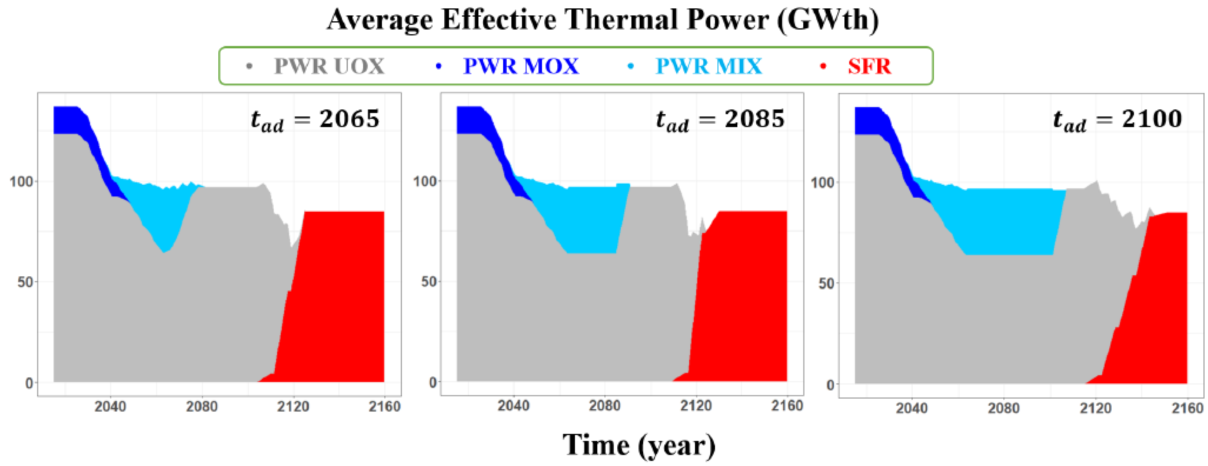

Figure 8:strategy adapting the reference MIX trajectory to allow the mass deployment of SFRs. At 3 adaptation times

In the case of a sudden change of industrial strategy with respect to plutonium recycling, calling into question recycling in PWRs in favor of SFRs, the reference strategy does not allow for the rapid deployment of SFRs because of a lack of available plutonium. The plutonium inventory is stabilized at only 550 tons, which is less than the 800 tons necessary for the deployment of SFRs. Thus, in this new framework, in order to meet the objective of plutonium management, which must now be carried out in the SFRs, the strategy used must be adapted. Using the Nelder-Mead algorithm, the optimal adaptation strategies that minimize the time at which the SFRs are deployed in the whole park are identified for three adaptation times: 2065, 2085 and 2100 and presented in Figure 14.

The regret of the use of MIXs in regard to the deployment of SFRs is mainly due to the decrease in available plutonium. Under a rapid fuel cycle change before the year 2085, the delay in plutonium accumulation can be well compensated and absorbed, and the deployment of SFRs can be completed in time. Otherwise, it will take longer to replace the fleet.

Regardless of the adaptation performance, the demand for natural uranium is definitely higher and the production of minor actinides in the total cycle is higher in all adaptation trajectories than in that of an SFR deployment trajectory followed from the beginning. This can be explained by the need to enrich uranium in the MIX and by their higher production of minor actinides. Moreover, a much higher reprocessing flow is necessary if the deployment of SFR is not anticipated sufficiently in advance. This clearly shows that the MIX strategy is not naturally going to allow massive deployment of SFR at the beginning of the 22nd century, but that it can be adapted to allow it if the adaptation is made sufficiently in advance.

V. SFR in scenarios studies

a. Symbiotic scenarios between PWRs and SFRs

If the multi-recycling of plutonium in PWRs is at the heart of most of the scenario studies carried out at IN2P3, we have also carried out studies about the contributions of SFRs for plutonium management. The study carried out in the framework of the NEEDS PERMIS project on the REP-SFR symbiotic parks has given important results in this respect. The objective was to study a fleet including LEU PWRs, MOX PWRs and SFRs, allowing cross-recycling of plutonium.

The first part of the study allowed the determination of strategies that would allow the stabilization of plutonium inventories. This search for equilibrium fleets was carried out both by an exploratory method sampling the parameters and filtering a posteriori the valid trajectories and by a constrained optimization method. By analyzing 5 input parameters of the selected trajectories, the space leading to the equilibrium was identified with spaces, slightly different but of the same shape, obtained with both techniques. In all cases the SFR fractions in the obtained parks were several tens of percent. One of the important characteristics observed on these equilibrium spaces was that they were not convex or dense.

In order to see if these equilibrium spaces remained valid when uncertainties are taken into account, the second part of this study has perturbations on parameters fixed in the study but subject to uncertainties such as the burn-up of the LEU PWRs. The application of these perturbations led in most cases to the loss of equilibrium of the perturbed scenarios even if some scenarios were more resistant than others. However, some non-equilibrium scenarios reach equilibrium after the application of the perturbations and these are all scenarios close to the non-perturbed equilibrium space.

This study has thus shown that a significant part of the fast reactors in the fleet can stabilize the plutonium. However, the strategies allowing equilibrium are very close to those not allowing it, and small perturbations can take a trajectory out of equilibrium. Such perturbations do not, however, drastically change the zone in which the strategies leading to equilibrium are found.

b. Multi recycling of Pu in generation 4 reactors

As part of the NEA expert group, we have been involved in a study of long-term transuranic management and the ability of a strategy to absorb excess transuranics from a neighboring country going nuclear. In this very exploratory study, a large number of fast neutron reactor concepts are used to multi-recycle plutonium or transuranics in the framework of three-stage scenarios: first, a fleet entirely composed of UOX PWRs, then a stage of transuranic stockpile reduction, and finally the implementation of a stabilized fleet multi-recycling plutonium. In this study, each organization has focused on different types of scenarios and reactors that are of major interest to it. This led to the exploration of the use of gas- or sodium-cooled SFRs, with oxide or metallic fuels, and as critical reactors or ADSs.

After initial simulations to help guide the discussion, the framework of the study was refined to a study starting with a new fleet followed over a period of 300 years in order to compare the different options for long-term multi-recycling in fourth generation reactors. The only variations between the different strategies are the fast reactor technology used, the power ratio between the different types of reactors and fuels, and the organization of the material flows between the cycle plants. The simulated trajectories could be analyzed with regard to numerous observables such as the inventories of the different elements in the different units of the cycle and the needs in quantity of manufactured or reprocessed fuel.

The analysis of these results is still in progress, but the first conclusions show a much greater impact of the cycle parameters, such as the priorities of reprocessed or reused stocks, the power ratios or the choice of recycled materials, than of the reactor design. Thus, the two trajectories using an SFR design very close to the

SFRv2B are less close to each other than to other trajectories using metal-fueled reactors and a very heterogeneous core or small fast neutron SMRs but using more similar cycle options.

c. Contribution of some SFRs for plutonium management

The most accomplished scenario study that we have carried out on the contribution of SFRs to plutonium management was carried out during the thesis of L. Tillard. This study analyzes the impact of the deployment of ASTRID-type reactors, in the form of two variants, break-even and plutonium burner, in fleets comprising PWR-type reactors, on the dynamic management of plutonium.

Building models for SFRs in CLASS

In order to perform the simulations necessary for this study, it was necessary to model in detail the concepts of interest for the final study, i.e. two ASTRID-type SFR-Na, a plutonium break-even configuration and an burner configuration. These two configurations of interest present axial and radial heterogeneities. The analysis of the two systems, in their respective reference configurations, allowed the identification of the dominant modeling biases, due to the non-accounting of core reloading. However, the errors induced by these modelling assumptions on the plutonium inventories at the end of the cycle are less than one percent, which is sufficiently low for their exploitation in scenario studies.

A new multi-zone manufacturing model for new SFR fuels dedicated to ASTRID-type reactors had to be developed in the CLASS code. This new model builds the fuels by adapting the two plutonium contents to the material available in the repositories, and is based on a criticality condition at the beginning of the cycle and an initial power distribution. For these two target criteria, all the batches of fuels manufactured, whatever the isotopy of the plutonium available, induce, at the scale of the reactor, the same initial power distribution and the same neutron multiplication coefficient at the beginning of the cycle.

In addition, to calculate the evolution of the fuels during irradiation, and thus to solve the Bateman equations by zone, a prediction of the evolution of the local cross sections and a prediction of the local mean flux, or of the local mean power, has been implemented. As the evolution of the physical quantities of interest for the resolution of the Bateman equations by this model is not simply related to the compositions of the new fuels and to the effective neutron multiplication coefficient, this model also uses several predictors. The errors induced by their coupled use, on the plutonium inventories at the end of the cycle, are a few percent, i.e. lower by a factor of about 10 than in the case where the single-ozone model is used.

Scenario study

Using the new multi-zone models, dedicated to ASTRID-type reactors, a set of strategies has been simulated.

The first family of trajectories analyzed deploys break-even SFR-Na in PWR fleets. These scenarios last 120 years and the SFRs are integrated after 70 years. The study of this first family of scenarios shows the very important impact of the quality of the plutonium used to manufacture new SFR-MOX fuels on the behavior of ASTRID-type reactors. Indeed, the plutonium content of the new SFR fuels, adapted to the isotopy available in the repositories, influences the mode of operation of these reactors. For a high content, and thus a degraded isotopy, the ASTRID-type reactor incinerates the plutonium but improves the fissile quality of the plutonium. Conversely, a low content induces the overgeneration of plutonium but a decrease in its quality. The break-even reactor thus seems resilient to the isotopic quality of the plutonium, but this modifies its operation. At the cycle scale, these effects are not very visible. Indeed, the main factors determining the quantities of plutonium in the cycle remain, with or without SFR, the behavior of PWRs. However, the operation of PWRs is strongly influenced by the recycling of spent SFR-MOX fuel during the fabrication of new PWR-MOX fuel. The plutonium content of the fuels increases significantly and can exceed the limit of 12% often quoted in the literature. The conditions of integration of ASTRID break-even SFR-Na are thus potentially very influential on the operation of the symbiotic fleets. Moreover, the inclusion of ASTRID-type reactors leads to a significant increase in the reprocessing of spent fuel and thus in the sending of minor actinides to the waste, although, apart from the reprocessing stages, the production of minor actinides in SFRs is comparable with that of PWRs. This observation could call into question the potential implementation of transmutation strategies for minor actinides in the longer term. Moreover, the stabilization of plutonium inventories is never reached in the framework of the study. Only the complete shutdown of PWRs leads to the stabilization of inventories at a level directly correlated to the burn-up of LEU PWRs before their shutdown.

The second family of trajectories focuses, this time, on the deployment of SFRs of the ASTRID plutonium burner type. In this case, the stabilization of plutonium inventories in the cycle in symbiotic plants is possible if the SFRs provide at least 20% of the power of the plant. In the case of an out phase, the significant reduction of the total inventory requires the deployment of a large number of burners SFRs, over a period of at least 50 years.

VI. Conclusion

In conclusion, here is a quick summary of the different perspectives drawn in the previous sections. These prospects are in the continuity of the current work. Thus, we are planning a major work on the quantification and propagation of uncertainties and their influence on the conclusions of our scenario studies. This will require a differentiated management of the different types of uncertainties with the implementation of methods specifically adapted to each of them, quantifying the effect of each on the observables produced by the dynamic modeling tool of the CLASS cycle. Then, by correlating the size of these effects with the sensitivities of the conclusions to the observables, we will be able to establish protocols for the design of studies and analyses that take them into account throughout, from design to conclusion.

In continuation of the work done in FIT and in the collaboration with Montreal, the first specific effort is planned on the impact of the chosen models and their approximations. This will involve a stronger connection with the reactor simulation studies underlying these models to study their uncertainties and the transfer of these into our models.

These activities focused on the physics of the cycle will naturally be accompanied by the continuation of the interdisciplinary collaborations born and supported in the successive NEEDS projects.

Appendix: Scientific production since 2017

Publications in peer-reviewed journals

Guillet, M., Doligez, X., Marleau, G., Paradis, M., Ernoult, M., & Thiollière, N. (2021). Coupled CLASS and DONJON5 3D full-core calculations and comparison with the neural network approach for fuel cycles involving MOX fueled PWRs. *Annals of Nuclear Energy*, *152*, 107971.

Tillard, L., Doligez, X., Senentz, G., Ernoult, M., Liang, J., & Thiollière, N. (2021). Estimation of the vitrified canister production for a PWR fleet with the CLASS code. *EPJ Nuclear Sciences & Technologies*, *7*, 21.

Liang, J., Ernoult, M., Doligez, X., David, S., Tillard, L., & Thiollière, N. (2021). Robustness Study of Electro-Nuclear Scenario under Disruption. *Journal of Nuclear Engineering*, *2*(1), 1-8.

Ernoult, M., Doligez, X., David, S., Liang, J., Tillard, L., & Thiollière, N. (2021). Systematic Analysis of Multivariate Scenarios Using Advanced Clustering Methods. In *EPJ Web of Conferences* (Vol. 247, p. 13002). EDP Sciences.

Liang, J., Ernoult, M., Doligez, X., David, S., & Thiollière, N. (2021). Impact of disruption between options of plutonium multi-recycling in PWRs and in SFRs. *EPJ N-Nuclear Sciences & Technologies*, *7*, 20.

Liang, J., Ernoult, M., Doligez, X., David, S., Bouneau, S., Thiollière, N., ... & Tillement, S. (2021). Assessment of strategy robustness under disruption of objective in dynamic fuel cycle studies. *Annals of Nuclear Energy*, *154*, 108131.

Courtin, F., Thiollière, N., Doligez, X., Ernoult, M., Leniau, B., Liang, J., ... & Zakari-Issoufou, A. A. (2021). Assessment of plutonium inventory management in the french nuclear fleet with the fuel cycle simulator CLASS. *Nuclear Engineering and Design*, *377*, 111042.

Ernoult, M., Doligez, X., Thiollière, N., Zakari-Issoufou, A. A., Bidaud, A., Bouneau, S., ... & Somaini, A. (2019). Global and flexible models for Sodium-cooled Fast Reactors in fuel cycle simulations. *Annals of Nuclear Energy*, *128*, 69-76.

Thiollière, N., Clavel, J. B., Courtin, F., Doligez, X., Ernoult, M., Issoufou, Z., ... & Somaini, A. (2018). A methodology for performing sensitivity analysis in dynamic fuel cycle simulation studies applied to a PWR fleet simulated with the CLASS tool. *EPJ Nuclear Sci. Technol.*, *4*, 13.

Courtin, F., Leniau, B., Thiollière, N., Mouginot, B., Doligez, X., Somaini, A., ... & Clavel, J. B. (2017). Neutronic predictors for PWR fuelled with multi-recycled plutonium and applications with the fuel cycle simulation tool CLASS. *Progress in Nuclear Energy*, *100*, 33-47.

Doligez, X., Bouneau, S., David, S., Ernoult, M., Zakari-Issoufou, A. A., Thiollière, N., ... & Capellan, N. (2017). Fundamentals of reactor physics with a view to the (possible) futures of nuclear energy. *Comptes Rendus Physique*, *18*(7-8), 372-380.

Zakari-Issoufou, A. A., Doligez, X., Somaini, A., Hoarau, Q., David, S., Bouneau, S., ... & Sogbadji, R. (2017). Americium mono-recycling in PWR: A step towards transmutation. *Annals of Nuclear Energy*, *102*, 220-230.

Invited Talks

Thiollière, N. (2021, November) The FIT project. In *PUMMA European workshop on Fuel Cycle Scenarios*

Ernoult, N. (2021, November) Uncertainties and Optimization in fuel cycle studies. In *PUMMA European workshop on Fuel Cycle Scenarios*

Ernoult, N. (2021, November) Dealing with disruptions in fuel cycle studies. In *PUMMA European workshop on Fuel Cycle Scenarios*

Doligez, X. (2021, November) Artificial neural networks in fuel cycle studies. In *PUMMA European workshop on Fuel Cycle Scenarios*

Thiollière, N. (2018, November). Fuel cycle simulations at CNRS/IN2P3. In *Seminar at Budapest University of Technology and Economics*.

Thiollière, N. (2017, January). Fuel cycle simulations: Limitations and Sensitivity Analysis. In *Seminar at Madison-Wisconsin University*.

Talks in international conferences

Liang J. (2021 July) Impact of disruption between options of plutonium multi-recycling: in PWRs and in SFRs. In 5th *Technical Workshop on Fuel Cycle Simulations*.

Paradis M. (2021, July) DONJON5/CLASS coupled simulations of MOX/UO2 heterogeneous PWR core. In 5th *Technical Workshop on Fuel Cycle Simulations*.

Tillard L. (2021 July) Estimation of the vitrified canister production for a PWR fleet with the CLASS code. In 5th *Technical Workshop on Fuel Cycle Simulations*.

Thiollière, N. (2019, JulyThe Fit Project: Improving confidence in fuel cycle model. In 4th *Technical Workshop on Fuel Cycle Simulations*.

Doligez X., Ernoult M., Liang J. Thiolliere N., Tillard L. (2019 July) Potentialities of SFR Pu burners for the reduction of in-cycle fissile inventories. In 4th *Technical Workshop on Fuel Cycle Simulations*.

Guillet M., Doligez X., Marleau G. (2019 July) Coupled class and Donjon5 3D full core calculations and comparison with the neural net approach for fuel cycles involving MOX fueled PWRs. In 4th *Technical Workshop on Fuel Cycle Simulations*.

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