5th Technical Workshop on Nuclear Fuel Cycle Simulation

June 28th – July 2nd 2021

PROGRAM

https://fcw2020.sciencesconf.org/

contact : twofcs.2020@gmail.com

Welcome

Dynamic fuel cycle simulators are developed to enhance the scientific knowledge related to nuclear fuel cycle physics. While those tools help to understand fuel cycle physics and to highlight drivers for nuclear inventories, they are also used as boundary objects for building interdisciplinary researches in link with sociology, economics, etc. Many different fuel cycle simulation tools are developed by nuclear engineering and research institutions.

Since 2015, an international effort has been made between fuel cycle simulators developers and users in order to connect stakeholders and facilitate the development of international collaborations. In this framework, workshops are organized in order to provide the opportunity for scientists to present and exchange about their work and to build collaborations and projects at national and international levels.

This workshop edition, organized by CEA, CNRS/IN2P3, IMT Atlantique, and IRSN, is also conceived as an opportunity for enhancing discussions between representatives of different parties involved in construction, evaluation or use of fuel cycle scenarios. Besides technical aspects, fuel cycle simulations have significant, yet often implicit, political and social dimensions.

Topics

Nuclear fuel cycle scenario studies
Fuel cycle simulation tools and physical models
Nuclear fuel cycle interaction with electrical and energy systems
Nuclear scenarios exploratory analysis

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Previous editions

2016: Institut d'Astronomie, Paris, France (link)
2017: University of South Carolina, Columbia, USA (link)
2018: FIPA Jean Monnet, Paris, USA (link)
2019: University of Illinois, Urbana-Champaign, USA (link)

Practical information

TWoFCS 2021 will be held **100% online** on a unique ZOOM session from Monday, June 28th to Friday, July 2nd, 2021. The link to access the ZOOM session will be sent to **registered participants** by email on Friday June 25th, 2021.

To connect to the ZOOM online conference, the best way is to use the dedicated client.

Download and install the client

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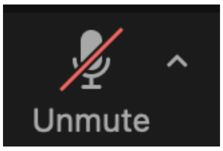

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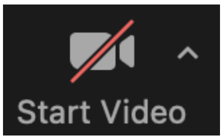

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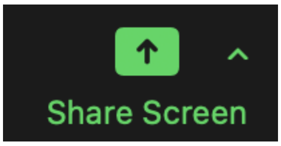


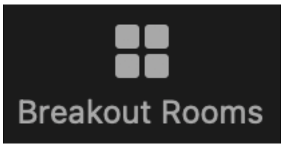
Recommendations for participants

Speakers should connect to the ZOOM meeting at the beginning of the session or at least **30 minutes** before their time slot and respect the time allocated to their presentation.

Please always keep your microphone and camera disabled if you are not involved in the current session.

At the end of each presentations, this will be possible to ask questions. Please use the chat to notice that you have a question and the session host will give you the floor.

At the end of each session, parallel discussions could be possible in dedicated rooms. To join a room, please click the following icon:



Use the pop-up window to select the room you want to reach by clicking the join button:

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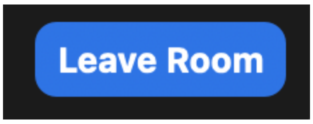

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Program

Monday June 28th

Fr Time

Afternoon session - 2:30pm to 5:30pm

2:30pm – 3:00pm: Welcome to TWoFCS 2021 - *Fanny COURTIN (CEA, France)*

3:00pm – 5:30pm
Topical Session: Nuclear fuel cycle scenario studies
Chair: Bo Feng (ANL, USA)

3:00pm – 3:15pm: INTRODUCTION

3:15pm – 3:45pm
Presentation of the fuel cycle related activities in the new European project PUMMA
Francisco ALVAREZ VELARDE (CIEMAT, Spain)

3:45pm – 4:15pm
Pu multi-recycling scenarios towards a PWR fleet for a stabilization of spent fuels inventories in France – *Camille LAGUERRE (CEA, France)*

4:15pm – 4:30pm: BREAK

4:30pm – 5:00pm
Modeling Material Requirements of the Transition to HALEU Fueled Reactors - *Amanda BACHMANN (University of Illinois, USA)*

5:00pm – 5:30pm: DISCUSSION

Tuesday June 29th

Fr Time

Morning session - 9:00am to 12:00pm

Topical Session: Fuel cycle simulation tool and physical models

Chair: Xavier DOLIGEZ (CNRS, France)

9:00am – 9:15am: INTRODUCTION

9:15am – 9:45am

Development of nuclear fuel cycle scenario code NMB4.0 for integral analysis from front to back end of nuclear fuel cycle - *Tomohiro OKAMURA (Tokyo Institute of Technology, Japan)*

9:45am – 10:15am

Simulation and validation of different nuclear fleets at equilibrium

Heddy BARALE (CEA, France)

10:15am – 10:30am: BREAK

10:30am – 11:00am

The CORAIL-A option for recycling plutonium in PWR: overview of the latest investigations at Framatome - *Barbara VEZZONI (Framatome, France)*

11:00am – 11:30am

Coupling fast reactor design and scenario calculations: a new methodology applied to scenario optimization - *Kévin TIREL (CEA, France)*

11:30am – 12:00pm: DISCUSSION

Afternoon session- 3:00pm – 5:30pm

Topical Session: Nuclear fuel cycle interaction with electrical and energy systems

Chair: Nicolas THIOLLIERE (IMT Atlantique, France)

3:00pm – 3:15pm: INTRODUCTION

3:15pm – 3:45pm

Electric transition in a fictitious emerging country - Impact of external constraints.

Sibylle MARTIN-LAUZER (CEA, France)

3:45pm – 4:15pm

First approach to the estimation of Levelized cost of Electricity in ANICCA code

Ivan MERINO (Universidad Catolica Del Maule, Chili)

4:15pm – 4:30pm: BREAK

4:30pm – 5:00pm

Impact of Fuel Supply Chain Disruptions on Energy Resilience: A case for Nuclear Energy

Guillaume L'HER (Colorado School of Mines, USA)

5:00pm – 5:30pm: DISCUSSION

Wednesday June 30th

Fr Time

Morning session - 9:00am to 12:00pm

Topical Session: Nuclear fuel cycle scenario studies

Chair: Guillaume MARTIN (CEA, France)

9:00am – 9:15am: INTRODUCTION

9:15am – 9:45am

Scenario study of optimization of disposal method to reduce the amount of waste and disposal area in MOX fuel use – *Eriko MINARI (Tokyo Institute of Technology, Japan)*

9:45am – 10:15am

Estimation of the vitrified canister production for a PWR fleet with the CLASS code
Léa TILLARD (ORANO, France)

10:15am – 10:30am: BREAK

10:30am – 11:00am

A Scenario Study on Transition to the Closed Nuclear Fuel Cycle Using the Nuclear Energy System Modelling Application Package NESAPP – *Andrei ANDRIANOV (MEPhI, Russia)*

11:00am – 11:30am: DISCUSSION

Afternoon session- 2:00pm – 4:00pm

International Panel Discussion – "Strategizing for the nuclear of the future"

Chair: Stéphanie TILLEMENT (IMT Atlantique, France)

Panelists:

Jeffrey R. Cooper
Director of Engineering, *Centrus, USA*

Alexey Lokhov
Deputy Director, *Rosatom Western Europe, Russia*

Daniel Mathers
Senior advisor, *NIRO, UK*

Jérôme Van Der Werf
Senior VP on Advanced Nuclear Energy Systems, *EDF, France*

Thursday July 1st

Fr Time

Morning session - 9:00am to 12:00pm

Topical Session: Nuclear scenarios exploratory analysis

Chair: Francisco Alvarez Velarde (CIEMAT, Spain)

9:00am – 9:15am: INTRODUCTION

9:15am – 9:45am

Impact of disruption between options of plutonium multi-recycling: in PWRs and in SFRs

Jiali LIANG (CNRS, France)

9:45am – 10:15am

Fuel cycle observables comparison from a UOX+MOX scenario based on irradiation libraries computed with different energy deposition models – *Augusto Hernandez Solis (SCK, Belgium)*

10:15am – 10:30am: BREAK

10:30am – 11:00am

Uncertainty and optimization: a coupled problem for scenario analyses

Aris V. Skarbeli (CIEMAT, Spain)

11:00am – 11:30am: DISCUSSION

Afternoon session- 3:00pm – 6:00pm

Topical Session: Fuel cycle simulation tool and physical models

Chair: Paul Wilson (UW-Madison, USA)

3:00pm – 3:15pm: INTRODUCTION

3:15pm – 3:45pm

Development of a MOX equivalence Python code package for ANICCA

Bart Vermeeren (Tractebel, Belgium)

3:45pm – 4:15pm

Molten Salt Sourdough Full Core Application

Alexander Wheeler (University of Tennessee, USA)

4:15pm – 4:30pm: BREAK

4:30pm – 5:00pm

IAEA's nuclear fuel cycle simulation tool- NFCSS and recent improvements

Kailash Agarwal (IAEA)

5:00pm – 5:30pm

Development progress and methodology of FANCSEE fuel cycle code

Blazej Chmielarz (KTH, Sweden)

5:30pm – 6:00pm: DISCUSSION

Friday July 2nd

Fr Time

Morning session - 9:00am to 12:00pm

Topical Session: Nuclear fuel cycle interaction with electrical and energy systems

Chair: Adrien BIDAUD (CNRS, France)

9:00am – 9:15am: INTRODUCTION

9:15am – 9:45am

Adaptations of a current nuclear reactor towards more flexibility in order to accommodate a power system with a high insertion of variable renewable energy sources

Anne-Laure Mazauric (CEA, France)

9:45am – 10:15am

Small Modular Reactor based solutions to enhance the grid reliability: identification of relevant criteria and preliminary assessment – *Charly Boudot (CEA, France)*

10:15am – 10:30am: BREAK

10:30am – 11:00am

A new PoweR histOry generaTor tOol (PROTO) for French nuclear power stations at IRSN

Miguel Macias (IRSN, France)

11:00am – 11:30am: DISCUSSION

Afternoon session- 3:00pm – 6:00pm

Topical Session: Nuclear scenarios exploratory analysis

Chair: Barbara VEZZONI (Framatome, France)

3:00pm – 3:15pm: INTRODUCTION

3:15pm – 3:45pm

Fuel Cycle Simulators for Nuclear Archaeology

Max Schalz (RWTH Aachen University, Germany)

3:45pm – 4:15pm

DONJON5/CLASS coupled simulations of MOX/UO2 heterogeneous PWR core

Maxime Paradis (Polytechnique Montréal, Canada)

4:15pm – 4:30pm: BREAK

4:30pm – 5:00pm

Application of Sensitivity Analysis in DYMOND/Dakota to Fuel Cycle Transition Scenarios

Scott Richards (ANL, USA)

5:00pm – 5:30pm: DISCUSSION

5:30pm – 6:00pm: TWoFCS 2021 Conclusion - *Fanny COURTIN (CEA, France)*

Nuclear fuel cycle scenario studies

Monday June 28th - Afternoon session

Chair: Bo FENG

Presentation of the fuel cycle related activities in the new European project PUMMA

Alvarez-Velarde Francisco [1], Blanc Victor[2], Hozer Zoltan[3], Van Til Sander[4], Boboridis Konstantinos[5], Maher Chris[6], Chauvin Nathalie[7]

[1] Centro de Investigaciones Energéticas, Medioambientales y Tecnologicas (Spain)
[2]Centre de recherche du Commissariat à l'Energie Atomique - CEA Cadarache (Saint Paul-lez-Durance, France)
[3]Magyar Tudomanyos Akademia Energiatudomanyi Kutatokozpont, Budapest (Hungary)
[4]Nuclear Research and Consultancy Group, Petten, The Netherlands (Netherlands),
[5]Joint Research Centre, Institute for Transuranium Elements (Germany),
[6]National Nuclear Laboratory Limited, Warrington (United Kingdom),
[7]Centre de recherche du Commissariat à l'Energie Atomique - CEA Cadarache (Saint Paul-lez-Durance, France)

The European project PUMMA (Plutonium Management for More Agility), which has started in October 2020, is dedicated to the study of different management options for the plutonium present in Generation IV reactor fuels. A wide range of Pu content (20 to 45%) can be found in these reactors and it would correspond to the highest concentration that can be encountered for plutonium multirecycling (~30-35% Pu to compensate degraded isotopic composition) and targeted plutonium burning (40-45%). This leads to the different strategies that can be chosen, given the flexibility of the fast neutron reactors: isogeneration, burning or breeding of plutonium.

In addition to experimental measures and theoretical studies on fuel behaviour under irradiation, material properties, spent fuel dissolution and partitioning, etc., the PUMMA project will also evaluate the fuel cycle scenarios associated with these different strategies, with the aim of evaluating the performance of the Generation IV reactors and their impact on different indicators such as fuel composition, facilities, transportation and economic criteria.

As part of this activity, a series of fuel cycle scenarios covering the wide range of different objectives regarding the Pu management will be defined and assessed. The detailed description of the scenario will include assumptions for parameters such as phases and associated timescales; PWR with or without Pu use in the initial phase; Gen-IV reactor deployment date and rate in the future phase; installed power and evolution; fuel cycle data regarding times in storage; and criteria for optimization among others. The output parameters list will include inventory of the main actinides; irradiated fuel and Pu stocks; waste production; etc.

The impact of the uncertainties in the input parameters will also be considered on the output indicators, since it can lead to underestimation or overestimation of the capacity of facilities or the inaccuracy to calculate the amount of wastes to manage.

22 participants will contribute to this 4-year project (11 to the particular Work Package dedicated to fuel cycle studies) with a total budget of around 7 M€.

Keywords: fuel cycle, Pu management, uncertainties

Pu multi-recycling scenarios towards a PWR fleet for a stabilization of spent fuels inventories in France

Fanny Courtin[1], Philippe Miranda[1], Camille Laguerre[1], Christine Chabert[1], Guillaume Martin[1]

[1]DES/IRESNE/DER/SPRC/LE2C, CEA Cadarache (Saint Paul-lez-Durance, France)

Nuclear scenario studies are performed to explore consequences of possible evolutions of nuclear fleets, in particular in France. The nuclear fuel cycle simulation tool COSI6 [1] developed by CEA, is used to model these dynamic scenarios and to evaluate them with respect to uranium and plutonium management, fuel reprocessing or waste production. In recent years, French scenarios have focused on transitions from the current nuclear French fleet to a deployment of SFR (Sodium Fast Reactor) [2]. However, the French Multi-annual Energy Planning (PPE) has recently stated that the deployment of this technology is not required before the second half of the 21st century [3]. Alternative solutions of plutonium management in PWR (Pressurized Water Reactor) are investigated [4] to stabilize total inventories of spent nuclear fuels. To allow for plutonium multi-recycling in PWR, fuel assemblies using enriched uranium along with recycled plutonium have been designed. PWR MIX assembly is considered in this study. MIX concept [4] is based on homogeneous fuel assemblies where fuel rods are composed of plutonium blended with enriched uranium. In this study, a transition from the current French fleet to an EPR™ fleet is simulated. Then, a progressive deployment of fuel multi-recycling in the EPR™ fleet is implemented to enable stabilization of all spent fuels and plutonium inventories. Compared with the previous scenarios elaborated [4], a more progressive MOX spent fuels resorption is considered. Natural uranium consumption is also minimized thanks to ERU fuel batches in EPR. In this paper, scenarios results will be presented and will be compared to the strategy of plutonium and uranium mono-recycling in PWR.

Acknowledgement:

This work was supported by EDF, ORANO and FRAMATOME.

References:

[1] C. COQUELET-PASCAL et al., “Cosi6: a tool for nuclear transition scenarios studies and application to SFR deployment scenarios with minor actinides transmutation”, Nuclear Technology 192 (2015) 91-110

[2] G. MARTIN et al., “French transition scenarios toward Sodium Fast Reactors in this century”, Proc. Of GLOBAL, Seoul, Korea (2017)

[3] Ministère de la transition écologique**,** “Stratégie française pour l’énergie et le climat, Programmation pluriannuelle de l’énergie 2019-2023, 2024-2028” https://www.ecologie.gouv.fr/

[4] G.MARTIN et al. "French scenarios toward fast plutonium multi-recycling in PWR." *MARTIN, Guillaume. ICAPP.: American Nuclear Society* (2018): 103-112.

Keywords: Pu multirecycling, PWR, MIX, Spent fuels

Modeling Material Requirements of the Transition to HALEU Fueled Reactors

Bachmann Amanda[1], Huff Kathryn[1]

[1]University of Illinois, Urbana-Champaign (United States)

Current nuclear reactors employed in the United States use Low Enriched Uranium (LEU) fuel enriched to no more than 5%. New reactor designs, such as the Ultra Safe Nuclear Company (USNC) Micro Modular Reactor (MMR) TM, will require High Assay Low Enriched Uranium (HALEU) fuel enriched between 5-20%. To meet HALEU fuel requirements, the U.S. Department of Energy is considering recovery and down blending of High Enriched Uranium (HEU) fuel and enriching natural uranium to the required levels [1], with each of these methods containing their own limitations. The existing physical supply of HEU and down blending capacity limits the recovery and down blending method. Centrifuge capacity limits the enrichment of natural uranium method. This work aims to quantify the resource requirements of the current U.S. reactor fleet and of the transition to different reactors that require HALEU fuel. The fuel cycle scenarios are modeled using Cyclus, an agent-based fuel cycle simulator [2]. The scenarios model the current U.S. fuel cycle with each reactor unit modeled as a separate agent, from 1965 to 2090. The International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database [3] provided information about each Light Water Reactor (LWR) in the simulation. The first scenario modeled does not include the transition to an advanced reactor; is used to provide a baseline of resources required. The next scenarios modeled include the transition to either the USNC MMRTM[4] or the X-energyXe-100TMreactor[5] and model either a no-growth or 1% growth scenario. This creates five different scenarios. The advanced reactors were selected to provide a comparison between an advanced reactor with small cores and long cycle times and an advanced reactor with a large core that employs online refueling. The results of this work includes the rate of reactor deployment, the mass of enriched uranium, and the Separative Work Unit (SWU) capacity required for each scenario. These metrics inform the material requirements and provide insight into the best method to meet fuel requirements for these transition scenarios. Preliminary results show that for the no-growth transition, 5962 MMR reactors and 795 Xe-100 reactors are required to meet the energy demand, and MMR transition requires a greater mass of enriched uranium than the Xe-100 transition but requires less SWU capacity.

Keywords: HALEU, advanced reactors, transition scenarios

Fuel cycle simulation tool and physical models

Tuesday June 29th - Morning session

Chair: Xavier DOLIGEZ

Development of nuclear fuel cycle scenario code "NMB4.0" for integral analysis from front to back end of nuclear fuel cycle

Okamura Tomohiro[1], Oizumi Akito[2], Kenji Nishihara[2], Masahiko Nakase[3], Kenji Takeshita[3]

[1]Tokyo Institute of Technology (Japan)
[2]Japan Atomic Energy Agency (Japan)
[3]Tokyo Institute of Technology (Japan)

Nuclear Material Balance code (NMB code) has been developed in Japan Atomic Energy Agency for evaluating the mass balance of nuclear fuel cycle. The analysis target of the conventional NMB code was mainly actinides, and it was specialized in front-end mass balance analysis. However, quantitative scenario analysis of radioactive waste management has been recently required to consider future research and development, and nuclear energy policies. In order to evaluate the scenario or mass balance of radioactive waste generated in the nuclear fuel cycle, an integrated analysis of nuclear fuel cycle, including reactor operation, reprocessing, vitrification, interim storage, and geological disposal, is required. In this study, we developed NMB 4.0, which enables integrated analysis of whole of nuclear fuel cycle. The features of NMB4.0 were shown below.

The mass balance of each process of nuclear fuel cycle is analyzed given the operating conditions of the reactor and reprocessing as inputs.

Operated by Microsoft Excel.

179 nuclides (26 actinides and 153 FPs) selected from the view point of burn-up chain, and required nuclides for mass balance of waste management, are calculated.

The burn-up calculation method is conducted by first-order approximate solution of matrix exponential method. The accuracy of burn-up calculation and mass balance of nuclear fuel cycle differs from ORIGEN, which is a code system for calculating the production, decay and mass flow of radioactive materials, by about 1%.

The nuclear data library obtained from the core analysis can be utilized with the nuclear data library editing function. Light water reactors, CANDU reactors, gas reactors, sodium-cooled FBR, and ADS are available. Each core can be combined with UO2, MOX, nitride fuel, etc.

The condition of immobilization including vitrification, sodalite and cement solidification can be set flexibly.

Disposal of spent nuclear fuel, vitrified and TRU wastes can be calculated.

Nuclide migration in geological disposal can be calculated using GoldSim as an external cord connection.

As described above, NMB4.0 have been developed for integral scenario analysis from front to back end of nuclear fuel cycle. In my presentation, in addition to details of above contents, other functions and results of scenario analysis will be discussed.

Keywords: Nuclear fuel cycle simulation code, Mass balance analysis, NMB, Waste management

Simulation and validation of different nuclear fleets at equilibrium

Barale Heddy[1], Laguerre Camille[1], Sabatini Paul[1], Courtin Fanny[1], Martin Guillaume[1]

[1]DES/IRESNE/DER/SPRC/LE2C, CEA Cadarache (Saint Paul-lez-Durance, France)

Scenario simulations are the main tool for studying the impact of a nuclear reactor fleet on the related fuel cycle facilities. Scenario studies can be used to explore future options of the nuclear energy development, investigating advantages and disadvantages, technological constraints, costs and overall attractiveness of different fuel cycles and reactor fleet developments. Different types of scenario simulation tools have been developed for these aforementioned scopes, this study focuses on dynamic and equilibrium codes. Dynamic fuel cycle simulation code models the ingoing at outgoing material flow in all the facilities of a nuclear reactor fleet as well as their evolutions through the different nuclear processes over a given period of time. Equilibrium fuel cycle simulation code models advanced nuclear fuel cycles at equilibrium conditions, i.e., in conditions which stabilize selected nuclear inventories such as spent nuclear fuel constituents, plutonium, or some minor actinides. This represents a theoretical situation which do not correspond to the realistic industrial situation. Nevertheless, equilibrium codes can be seen as a complementary tool to the dynamic codes. This equilibrium preliminary study has the goal to compare advantages and drawbacks of different strategies that will be simulated with more details dynamically. In this study, the equilibrium tool SEPAR (Simulation d'Equilibres de Parcs Avancés de Réacteurs) is used to investigate these aspects. SEPAR has been recently developed at the Department of Reactor Studies (IRESNE/SPRC/DER) at CEA Cadarache. It relies on a neural network approach to estimate the equilibrium material composition and fluxes for each isotope to and from reactors, enrichment, reprocessing facilities. This paper focuses on the SEPAR modeling, optimization and analysis of a variety of new advanced nuclear fuel cycles at equilibrium. The principle of this work is to analyze different nuclear reactors (PWR, EPR, SFR) and several fuel types (UOX, MOX, ERU, MIX) to simulate advanced nuclear fleet with partial and fully plutonium and uranium multi-recycling strategies at equilibrium. The results are compared to the reference dynamic code COSI6, developed by CEA since 1985. Equilibrium scenario simulation is a new research area that comes along with fundamental milestones and several incertitudes. Future developments of SEPAR are the addition of environmental, technical and economic index and constraints in the fuel cycle evaluation, as well as the modeling of transmutation systems.

Keywords: Scenario, Fuel cycle, Equilibrium, Plutonium management

The CORAIL-A option for recycling plutonium in PWR: overview of the latest investigations at Framatome

Terrazzoni Claire[1], Spaggiari Roberto[1], Vezzoni Barbara[1], Graziano Laurent[1], Rugama Yolanda[1]

[1]FRAMATOME (France)

For achieving the objective of a long term use of nuclear energy, several strategies on reactor and fuel types needs to be investigated. Feasibility analysis of those strategies remains an interesting subject to be investigated by coordinated R&D projects involving academics and industrial partners. Beyond the well-established UO2 fuel assembly recycling process through MOX fuel, energy is still available in the used MOX fuel and an improved use could be considered. While working on GEN-IV solutions, it has been decided to investigate a shorter term option based on PWR type for used MOX fuel. This intermediate solution may allow assuring a transition on current or future PWRs. In order to have a long term fuel cycle strategy, investigations need to be fed by physical analyses (e.g. on the fuel behavior during the scenario, on plutonium consumption, etc.) and the developments and testing of new fuel concepts dedicated to plutonium multi-recycling and/or to the design and construction of new fuel cycle facilities (e.g. reprocessing facilities). In this paper, an overview of the latest Framatome investigations is presented focusing on studies carried out at assembly as well as at core level. The CORAIL-A fuel, characterized by UO2 and MOX fuel rods in the same assembly, has been investigated. This fuel concept is only one solution among others to multirecycle Pu on a PWR. The fuel assembly optimization options are analyzed for taking into account the variability of the Pu vectors during the multi-recycling generations. The impact of parameters like the Pu content, Pu isotopical vector, time between generations, blending strategies, etc. have been quantified with respect to safety and performance criteria. Those indicators have been chosen for giving a picture of the assembly Pu consumption performances as well as of the main safety parameters. Among all, parameters like Doppler and void effects and power distribution have been compared for different strategies. The most relevant results will be presented in the paper. The assembly investigations are used for designing the fuel assembly concepts and provide first sensitivities but core level analyses are mandatory to investigate the behavior of those fuel types under representative 3D core conditions. Therefore, core analyses have also been carried out at Framatome on the basis of the so-called CORAIL-A1 case (characterized by a specific Pu vector). A short overview of the main achievements, and the comparison with respect to the assembly calculations, will be presented in the paper as well.

Keywords: Pu multi-recycling, PWR, CORAIL-A

Coupling fast reactor design and scenario calculations: a new methodology applied to scenario optimization

Tirel Kévin[1], Kooyman Timothée[2], Coquelet-Pascal Christine[2], Merle Elsa[3]

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There is currently a sequential relation between reactor design studies and scenario studies. Generally speaking, it goes as follows: after establishing a set of objectives for the nuclear fleet, reactor concepts are designed to meet constraints and performance criteria coming from reactor physics (safety and efficiency aspects) and scenarios (minimizing plutonium inventory, minimizing natural uranium consumption...). Once the design phase is over, numerical models of the reactors are generated. The purpose of these numerical models is to simulate the irradiation by adapting the flux and the cross sections for given fresh fuel compositions, without accounting for reactor performances. In scenario calculations, these models are considered as fixed entries whereas scenario parameters such as reprocessing strategy, deployment dates or batch composition are adjustable. This sequential logic may not be optimal from both reactor design and scenario calculations points of view. From reactor design perspective, it is known for example that plutonium isotopy has an impact on reactor performances such as reactivity loss per cycle or maximum linear power which can lead to limitations on core parameters like cycle length or reactivity control system dimensioning. Taking into account the data of plutonium evolution coming from scenario calculations would enable a better dimensioning of reactivity control systems and a better monitoring of safety estimators. From a scenario perspective, using set reactor models may prevent the access to optimized results regarding given criteria. By considering an adaptive reactor which design can be modified online as an optimization lever, it is expected to get access to new optimized scenarios, while making sure that reactor safety indicators are acceptable at every moment of the simulation. The main goal of this paper is to present a new methodological approach that consists in using adaptive reactor design in scenario calculations in the case of sodium-cooled fast reactors (SFR). The construction of the adaptive fast reactor design using artificial neural network is presented as well as an explanation of the optimization loop that makes the link between the adaptive fast reactor and the scenario calculation. Then, this methodology is applied to an example: the minimization of plutonium inventory in a mixed fleet PWR-SFR.

Keywords: Sodium cooled fast reactors, SFR, artificial neural network, ANN, plutonium stabilization

Nuclear fuel cycle interaction with electrical and energy systems

Tuesday June 29th – Afternoon session

Chair: Nicolas THIOLLIERE

Electric transition in a fictitious emerging country - Impact of external constraints.

Martin-Lauzer Sibylle[1], Cathalau Stéphane[1]

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This paper presents a study of scenarios related to the electric transition of a fictitious country that decided to transform its old-fashioned electricity grid into a more efficient and more environmentally friendly grid. This country, called Ladonia, is an average natural resource enriched country possessing industrial minerals and hydrocarbons. Over the past three decades, Ladonia had pursued a national development agenda that seeks to achieve the long-standing objective of becoming a middle-income economy. Ladonia's growth target for this year is 6.5 % mainly to be driven by the industrial sector, especially the mining and oil and gas sectors. Reducing the economy's dependence on oil and gas is also a key long-term objective.

Ladonia government has been working towards developing a policy framework that integrates adaptation, mitigation and other climate related policies within broader development policies. In the energy sector, the objectives set in the plan are the following:

- To adopt, starting from 2030, a carbon tax of 30 $ per tCO2eq,
- To improve, by 20 %, energy efficiency in power plants and industrial facilities by 2030, To increase the share of carbon-free electricity to 33% (minimum) by 2040,
- To limit the carbon intensity of the produced electricity to 100 gCO2eq per kWh or less.

The current electricity power fleet involves mainly coal and gas plants, but none nuclear neither hydro plants. Two wind onshore and photovoltaic plants are under construction. Ladonia plans to increase its electric consumption starting from 20 TWh up to 40 TWh, in thirty years.

The study presents several scenarios related to the Ladonia electric transition when involving large nuclear power plants, offshore and onshore wind farms and photovoltaic plants. The impact of Small Modular Reactors on costs is also analyzed and environmental constraints are taken into account. The study involves several software such as Excel for simple models and LEAP or EPS for more sophisticated models.

We show that, if it is easy to find satisfactory solutions in terms of low costs and low environmental impacts, when we examine the starting and the final points, the “good” solution which satisfy the whole constraints (electric demand, costs, GHG emissions, land occupation, water consumption, etc.) all along the period of transition, is not trivial.

A first solution could be an energy mix that would rely mostly on onshore wind. The installed capacity in 2040 is 68% wind, 13% NGas CCGT, 7% Coal, 6% Nuclear SMR, 5% NGas OCGT. This scenario has the advantage of meeting the demand with the lowest cost, considering the constraints stated above. The production cost in 2040 is 3900 M$ (4% of the GDP of 2040 considering a GPD's average growth of 7% every 3 years). However, this scenario must be rethought in terms of land use, which is consequent for wind farms. Moreover it is not optimal to meet the 2021 demand. The final paper will give additional results and the “best” solution depending on which criteria they have been determined.

Keywords: Electric transition, Scenarios

First approach to the estimation of Levelized cost of Electricity in ANICCA code

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The Levelized Cost of electricity (LCOE) is one of the most useful economic indicators to compare between different sources of energy and types of strategies to obtain it. In this work, we show the first approach to this indicator by implementing an economic module in ANICCA code. The method implemented considers dividing the LCOE into four main costs: Investment, Fuel, Operation and Maintenance (O&M) and Back-end. For the first one, investment, we took into account the overnight cost, the construction time and the financial cost. In case of fuel, the natural uranium, its enrichment and conversions costs were considered. The O&M cost was related to the overnight cost. Lastly, for Back-end, the cost was set as a fixed value per unit of stored material. For this study, a set of updated data obtained from different sources were used as unit costs. Aware of the high uncertainties of the nuclear costs, we also performed a Monte Carlo analysis to reflect the uncertainty involved in these calculation. To test the module, we performed a simulation of a nuclear fleet with an open fuel cycle strategy. Results showed that the module is fully operative for open cycle scenarios, however more improvements need to be made for advanced scenarios studies and uncertainty analyses.

Keywords: Nuclear fuel cycle simulation, Nuclear economics, Uncertainty Analysis, Levelized Cost of electricity

Impact of Fuel Supply Chain Disruptions on Energy Resilience: A case for Nuclear Energy

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Natural hazards are often the cause of energy network disruptions in affected areas. Most developing countries do not have a resilient power infrastructure despite often being located in high risk regions. Such countries also happen to predominantly use fossil fuels to power their infrastructure. An imported fuel supply chain consequently becomes a critical factor in the system resilience. Fossil fuel is transported by trucks via roads or by train. Disruptions to the road network during a natural event such as a hurricane or an earthquake can consequently limit the fuel supply chain and even strand the assets for a prolonged period of time. Common renewable energy sources (hydropower, wind turbines, or solar panels) are also vulnerable to natural hazards such as flooding or high winds. Nuclear energy is resilient to external events and can strongly mitigate their impact on the power grid by notably eliminating the need for frequent refueling.

A stochastic method is developed to assess the resilience of existing power infrastructures in a country based on a road network analysis along the supply chain and considering its exposure to natural events. This analysis is then combined with a small nuclear reactor siting algorithm which highlights the benefit of developing nuclear energy.

A demonstrative case study is performed on a Carribean island to determine the amount of energy generation at risk during and after natural hazards, combined with an automated siting analysis for nuclear reactors. Climate change will have an impact on the frequency and intensity of future natural hazards. The importance of non fossil energy fuel sources and improved grid resilience cannot be overstated. This study demonstrates the benefits that nuclear energy, especially with small modular reactors, can bring to emerging power grids.

Keywords: resilience, SMR, siting

Nuclear fuel cycle simulation studies

Wednesday June 30th - Morning session

Chair: Guillaume MARTIN

Scenario study of optimization of disposal method to reduce the amount of waste and disposal area in MOX fuel use

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The issue of radioactive waste management is becoming increasingly important. To provide a safe and acceptable environmental load for disposal of high-level radioactive waste (HLW), it is necessary to examine the future fuel cycle system that intends to use the mixed oxide (MOX) fuel based on plutonium. This approach has not been considered until now from the viewpoint of establishing an acceptable disposal method. If such fuels are reprocessed and vitrified in the near future, the thermal properties of the vitrified waste will have significant impact on disposal strategies including an increase in the disposal area of HLW deep underground. In addition to the thermal properties of the waste, the number of vitrified waste packages is also a major influencing factor that determines the disposal area of the repository. The impact of disposal of MOX fuel from light water reactors (LWRs) has been considered for both the number and the thermal properties of the vitrified waste for various conditions of the nuclear fuel cycle. In this study, the amount of waste and the disposal area in the direct disposal scenario and the reprocessing scenario of spent MOX fuel were evaluated by setting a model. In direct disposal, the influence of heat generation from uranium and plutonium isotopes is large, and it is necessary to set a cooling period of 300 years in consideration of the buffer material restricted temperature of 100. In the reprocessing scenario, an area reduction effect of 50% or more was obtained compared to direct disposal. Focusing on the reprocessing scenario, it is possible to further reduce the area by introducing technical options such as MA separation and mixed vitrification compared to the single vitrified waste. Based on the above results, when disposing of spent MOX fuel, it is necessary to build a back-end system that considers the heat generation characteristics peculiar to spent MOX fuel. The introduction of technical options in the reprocessing scenario is effective in reducing the amount of waste and the waste occupied area at the disposal site and is necessary for rational disposal. If it assumes the spent MOX fuel will be directly disposed without any further burning as resources, it has high impact on repository design and waste management policy. In other words, it is desirable to reuse spent MOX fuel for minimization of waste volume and toxicity.

Keywords: MOX, LWR, radioactive waste management, Vitrification, Geological disposal

Estimation of the vitrified canister production for a PWR fleet with the CLASS code

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To evaluate possible futures for the nuclear energy and the electronuclear industry, scenario studies is of great interest. The CLASS code (Core Library for Advanced Scenario Simulation) [1], a dynamic fuel cycle simulation tool developed by CNRS/IN2P3, can be used to perform such scenario simulations by describing the evolution of the reactor fleet and the associated fuel cycle. Many criteria are relevant to compare the different trajectories simulated up to the end of the century, such as natural uranium consumption, spent fuel recycling capability or waste production. One output of interest to characterize nuclear wastes and compare trajectories is the number of vitrified canisters generated in one of the last spent fuel reprocessing stages. This quantity is used among others to estimate the future storage needs for geological disposals. Those canisters are designed to confine nuclear wastes over several ten thousand years. The number of produced canisters depends not only on minor actinides and fission products masses but also on alpha radiations and decay heat of materials to be vitrified, hence it is linked to spent fuel reprocessing strategies. The minimization of vitrified container production may be an important target while analyzing electronuclear scenarios. New features have been developed in the CLASS code to model the outline of a waste vitrification facility with adjustable mass and time buffers. This new CLASS unit evaluates the number of canister produced all along the scenario, canisters that must respect different physic limitations chosen by the user. The calculation of the corresponding physic values at each vitrification step is based on artificial neural network predictors. Besides, time and mass buffers allow the mix of different spent fuel type to be reprocessed and may lead to a decrease in the container production by optimizing the different criteria. These new capabilities will be presented and illustrated with the analysis of the vitrified containers production in a Pressurized Water Reactor (PWR) fleet multi-recycling plutonium [2]. In this multi-parametric scenario, MIX fuel is loaded in PWR to multi-recycled the plutonium [3]. This study shows the strong links between the number of produced containers, the fuel cycle choices and reprocessing strategies. It aims at highlighting some levers, at the global fleet level or at the vitrification level, which would minimize this quantity.

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[3] F. Courtin et al., Neutronic predictors for PWR fuelled with multi-recycled plutonium and applications with the fuel cycle simulation tool CLASS, Progress in Nuclear Energy (2017)

Keywords: CLASS, Pu multi recycling, MIX fuel, Vitrified nuclear waste, Canister production

A Scenario Study on Transition to the Closed Nuclear Fuel Cycle Using the Nuclear Energy System Modelling Application Package NESAPP

Andrianov Andrei[1], Andrianova Olga[1], Kuptsov Ilia[1], Svetlichny Leonid[1], Utianskaya Tatiana[1]

[1]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute) (Russia)

The paper presents the results of a case study on evaluating performance metrics for Russian nuclear energy deployment scenarios with thermal and sodium-cooled fast reactors in the closed nuclear fuel cycle. Ten possible scenarios are considered which differ in the shares of thermal and sodium-cooled fast reactors, including options involving the use of mixed uranium-plutonium oxide (MOX) fuel in thermal reactors. The evolution of the following performance metrics is estimated for the period from 2020 to 2100 based on the considered assumptions: annual and cumulative uranium consumption, needs for uranium enrichment capacities, fuel fabrication and reprocessing capacities, spent fuel stocks, radioactive wastes, amounts of plutonium in the nuclear fuel cycle, amounts of accumulated depleted uranium, and the levelized electricity generation cost.

The models for assessing material flows, needs for nuclear fuel cycle services and economic performance metrics were elaborated using the nuclear energy system modelling application package NESAPP. NESAPP is a set of codes to support nuclear energy planning and nuclear fuel cycle transition scenario studies, including Nuclear Data Processing Spreadsheets (NUDAPS), Nuclide Evolution Exploring Tool (NUCLEX), Nuclide Composition Adjustment and Blending Tool (NUCAB), Material Flow Analysis Data Integration Tool (FANES), Economic Assessment Tool (ECNES) as well as a local reactor database including an atlas of one-group neutron cross-sections and neutron production/destruction rates. The elaborated nuclear energy system model considers the expected growth rates of electricity production and describes the main components of the industrial infrastructure, including nuclear reactors and fuel cycle facilities with specified technical and economic parameters. At various stages, the considered scenarios include thermal reactors with uranium oxide fuel, thermal reactors with partial loading of MOX fuel and sodium-cooled fast reactors with MOX fuel.

The presented results show that the sustainability of the Russian nuclear energy system can be significantly enhanced through the intensive deployment of sodium-cooled fast reactors and the transition to the closed nuclear fuel cycle. It is highlighted some issues for further considerations, which will lead to more rigorous conclusions regarding the preferred options for the development of the national nuclear energy system.

Keywords: scenario analysis, nuclear energy system, closed nuclear fuel cycle, thermal reactors, sodium, cooled fast reactors, performance metrics

International Panel Discussion
Strategizing for the nuclear of the future

Wednesday June 30th – Afternoon session

Chair: Stéphanie Tillement

International Panel Discussion:

Strategizing for the nuclear of the future

Wednesday June 30th – 2pm to 4pm (Fr Time)

Panelists:

Jeffrey R. Cooper, Director of Engineering, Centrus, USA

Alexey Lokhov, Deputy Director, Rosatom Western Europe, Russia

Daniel Mathers, Senior advisor, NIRO, UK

Jérôme Van Der Werf, Senior VP on Advanced Nuclear Energy Systems, EDF, France

Moderator:

S. Tillement, Assistant Professor, IMT Atlantique, France

Introductory Remarks – Aim of the Panel Discussion

Current “grand challenges” or “big issues” such as the "energy transition" has rekindled debate about the possible contribution of nuclear power to the electricity mix. Yet, the organizations in charge of defining strategies are confronted to major uncertainties, which can be technical or socio-political and are complex and hardly manageable. In the field of strategy-making, techniques related to forecasting, planning and prospective studies have become prevalent devices to inform decisions, and consequently, the associated tool, i.e. the scenario, plays an increasingly important role to frame problems and decisions. Yet, little is known about the way industrials can manage these uncertainties when building strategies for the future. In particular, can scenarios help in doing so?

With this fundamental issue in mind, the **objective of this panel discussion is twofold**:

1) To better identify and qualify the types of uncertainties to which strategy makers are confronted to, notably in the industrial field and depending on the national context;
2) To better understand how prospective studies and scenarios can help in taking into account these uncertainties when building their industrial strategies.

Key Themes & Questions (1h15)

Opening remarks – S. Tillement
Introduction by each panelist

<u>Theme 1</u> – Nuclear strategies and associated challenges: France, Russia, USA, UK

<u>Theme 2</u> –Taking into account (deep) uncertainties in scenarios for strategy-making: stakes & specificities?

The panel discussion will be followed by 45 minutes of open discussion with attendees.

Nuclear scenarios exploratory analysis

Thursday July 1^{st} – Morning session

Chair: Francisco Alvarez Velarde

Impact of disruption between options of plutonium multi-recycling: in PWRs and in SFRs

Liang Jiali[1], Ernoult Marc[1], Doligez Xavier[1], David Sylvain[1], Thiollière Nicolas[2]

[1]Laboratoire de physique des 2 infinis - Irène Joliot-Curie (France)
[2]Laboratoire de physique subatomique et des technologies associées (France)

After the Fukushima nuclear accident, the estimation of future demands of uranium has changed greatly, and SFR competitiveness is called again into question. In this context, the planning of multi-recycling of plutonium in PWRs for the near-term decades has been announced in France, which replaces the objective of future SFR deployment. However, the mid-term policy concerning the future reactor system is always uncertain, and the demand for SFR deployment may re-increase significantly. This study looks at this possibility and analyze the consequences of such back and forth between different plutonium multi-recycling strategies, particularly in terms of the timing of SFR deployment.

The newly developed method of robustness assessment presented in [1] is applied to the problem. Two reference prior trajectories of multi-recycling of plutonium, one involving the use of MIX fuel in PWR and the other considering the deployment of SFR, are analyzed first. The trajectory of SFR indicates a reference schedule of the original deployment planning. Disruption to the trajectory of MIX is then supposed, aiming to readopt the objective of SFR deployment. To quantify the impacts on deployment timing, the earliest achievable time of the total replacement of PWR fleet with SFRs is investigated. This new schedule of SFR deployment and other outputs are compared with the reference ones.

To supplement, one may also investigate the impacts on the decision of multi-recycling of plutonium in PWRs if SFRs have been already deployed. Disruption to the reference trajectory of SFR is also supposed. In this case, a dedicated strategy to future SFR deployment is firstly implemented. But due to some problems not well anticipated, the deployment is interrupted and no new SFR can be built after. The multi-recycling of plutonium in new-built PWRs, regarded as adaptive strategy, aims to minimize the idle plutonium. The minimal achievable time-average inventory of plutonium in interim stocks and other relevant outputs are then compared with the reference ones.

In the analysis of these disruptions to the multi-recycling of plutonium in PWR and in SFR with the method of strategy robustness assessment, numerous outputs of interests are analyzed, and thus a global quantification and evaluation of consequences of these disruptions can be given.

References
[1] Jiali LIANG, Marc ERNOULT, Xavier DOLIGEZ, Sylvain DAVID, Sandra BOUNEAU, Nicolas THIOLLIERE, Guillaume KRIVTCHIK, Fanny COURTIN, Weifeng ZHOU, Stéphanie TILLEMENT. Assessment of strategy robustness under disruption of objective in dynamic fuel cycle studies. Annals of Nuclear Energy, 2021.

Keywords: multi-recycling of plutonium, disruption, robustness assessment, nuclear fuel cycle simulation

Fuel cycle observables comparison from a UOX+MOX scenario based on irradiation libraries computed with different energy deposition models

Hernandez Solis Augusto[1], Merino Rodriguez Ivan[1], Van Den Eynde Gert[1]

[1]Centre d'Etude de l'Energie Nucléaire (Belgium)

SCK-CEN has developed the ANICCA fuel cycle code for the general simulation of the front- and back-end of advanced scenarios. It is a modular code where the reactor core model, which represents the irradiation stage along fuel cycles studies, it is based on pre-computed libraries that include burnup-averaged one group microscopic cross-sections. This form the basis for solving the Bateman equations, with the objective of computing the evolution of the initial isotopic vector composition of the fuel during depletion and up to a certain discharge burnup. This is internally done by the code by applying the matricial CRAM method.

Pre-computed one-group irradiation libraries are created by a complete depletion calculation, where the proper flux spectra and the induced reaction rates are computed for the further solution of the Bateman equations. Assuming a base initial fuel composition and a discharge burnup, such depletion calculation is performed, in practical terms, by means of the Monte Carlo SERPENT2 code. In the end, the objective is to obtain one-group microscopic cross-sections as a function of burnup for each formed isotope within the depleted material of interest. In general, this type of calculation has been performed assuming that all the fission released energy is being deposited in the fuel. However, it has been observed that, if a more proper depletion computation is done based on a model that deposits the energy around the materials of the domain of study in a correct way (i.e. coupled neutron-photon transport), then the associated one-group cross-section as a function of irradiation will differ compared to the original case of local energy deposition. In this work, the aim is to study how two different base-irradiation libraries, coming from depletion calculations based on different energy deposition models affect the final observables in fuel cycle scenarios involving a UOX+MOX closed case. In the end, two scenario calculations in ANICCA, utilizing the same parameters but two different irradiation libraries, will serve as basis to study the effect on the amount of spent fuel in final repositories, as well as different stocks related to U and Pu utilization. This work will then give a measure on the impact that improving the irradiation model has in the final computation of fuel cycle scenario observables.

Keywords: ANICCA, SERPENT2, energy deposition, irradiation models

Uncertainty and optimization: a coupled problem for scenario analyses

V. Skarbeli Aris[1], Alvarez-Velarde Francisco[1], Becares Vicente[1]

[1]Centro de Investigaciones Energéticas, Medioambientales y Tecnologicas (Spain)

Nuclear fuel cycle simulators have become an essential tool for researchers and policy makers for studying and evaluating different electronuclear strategies in the mid and long term. In order to improve their versatility and to reduce the user interaction, in the recent years the codes have been upgraded for performing optimization analyses. In this way, the desired outcomes of the simulation (i.e. the functions to be optimized) are firstly defined instead of being a result of the calculation. Therefore, given a relaxed set of initial conditions, the best scenario matching the chosen objectives is automatically obtained without previous knowledge of the user.

Nevertheless, although best-case scenarios can be obtained with these methods, in practice they may not be the desired ones because of the lack of robustness. This happens because certain quantities can be pushed to the limit during the optimization process. Hence, if small perturbations occur, the scenario will break, and the simulation will not be completed. This is of special interest in uncertainty analyses in which some input parameters are not characterized by a reference value but by a probability density function. If the scenario has been optimized for the expected values of the input parameters, when different samples are randomly drawn there is no guarantee that the scenario remains stable.

In this work, the problem of optimization under uncertainty in fuel cycle simulations is discussed. The evolutionary algorithm implemented in TR_EVOL for performing multiobjective optimization is firstly shown, and after that, the extension used for addressing the uncertainties will be presented. This methodology has been applied to a test case based on an advanced European transition scenario in which an initial fleet of LWR is replaced by a burner one with the objective of reducing as much as possible TRU inventories while keeping the economic costs low.

Keywords: optimization, robustness, uncertainty

Fuel cycle simulation tool and physical models

Thursday July 1st – Afternoon session

Chair: Paul WILSON

Development of a MOX equivalence Python code package for ANICCA

Vermeeren Bart[1], Druenne Hubert[1]

[1]Tractebel (Belgium)

The production of MOX (Mixed OXide) fuel assemblies for nuclear power plants finds its place in a fuel cycle closure strategy that optimizes the use of the fuel resources by reprocessing the fissile contents of spent UOX (Uranium OXide) fuel assemblies (FAs) discharged from the light water reactor (LWR).

In the current industrial scheme, MOX fuel is recycled in LWRs, where the fraction of MOX FAs loaded in the core is typically limited to 30 to 40% of the fresh feed, balanced by an enriched UOX fuel complement. When replacing a UOX FA by MOX, the operator prefers to keep the cycle length (=amount of produced energy) and feed size (=number of fresh FAs) unchanged; this is the basis of the energy equivalence principle. MOX equivalence is obtained by tuning the Pu content in the MOX fuel, considering the specific Pu isotopic vector (and Pu-241 decay into Am-241 between the reprocessing and the MOX fuel utilization), to obtain a crossing of the reactivity curves of UOX and MOX at the end-of-cycle core average burnup.

When the decision for spent UOX fuel reprocessing is taken after a long period of once through operating mode, the reprocessing strategy, e.g., FIFO (First In, First Out) or LIFO (Last In, First Out), will be a defining parameter in the evolution of the spent fuel inventory by determining the number of FAs to be reprocessed per year to match the given MOX equivalence, leading to identify the possible need for interim storage buildings and associated capacity dimensioning. This analysis may become very complex as the difference in origin (different reactors) of the spent fuel, the irradiation history (burnup), and cooling time all introduce an additional dispersion to the plutonium vector.

It is proposed in this work to extend ANICCA (Advanced Nuclear Inventory Cycle Code), a fuel cycle analysis tool developed at SCK CEN (Belgium) to monitor the flow of nuclear material between facilities, with a MOX equivalence Python code package, which automatically governs the demand and supply flows related to the plutonium content required to obtain a given MOX equivalence. This MOX equivalence package can determine the reactivity evolution for any given Pu vector by means of a multidimensional interpolation on a mesh of pre-calculated data tables generated by Wims10, thereby covering the physically accessible Pu vector space. An assessment will be made for a typical evolution of the Pu vector inventory in the available irradiated UOX fuel throughout time, and thereby defining the storage building dimensional requirements for different reprocessing strategies such as FIFO, LIFO,...

Keywords: MOX equivalence

Molten Salt Sourdough Full Core Application

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Molten salt fuel possesses unique characteristics allowing a rethink of refueling and spent fuel management. In many proposed molten salt reactor (MSR) concepts, refueling results in volumetric growth of the fuel salt. This expansion will eventually double the original amount of the fuel salt in the reactor. At this point, another reactor of the same design can start up using the excess fuel, much like a sourdough starter. At the same time, soluble fission products remain suspended in the salt. Previous research has shown that the primary factor in calculating the refueling rate and corresponding volume expansion is the enrichment of uranium in the refuel salt. In this work, we apply the sourdough methodology to a 3D core model of a Thorcon-inspired low-enriched uranium fueled MSR. Adopting a defined reactor design concept allows us to expand the applicability of this methodology to specific projections of reactor units, doubling times, salt volumes, and uranium needs for a postulated clean energy growth scenario. We also discuss how this approach presents a significant step toward eliminating the spent nuclear fuel issue.

Keywords: Molten Salt Reactor, Waste Management, Online Refueling

IAEA's nuclear fuel cycle simulation tool- NFCSS and recent improvements

Agarwal Kailash

[1]International Atomic Energy Agency (Austria)

The website of the integrated-Nuclear Fuel Cycle Information System (iNFCIS) of the International Atomic Energy Agency (IAEA) hosts a nuclear fuel cycle simulation tool (Nuclear Fuel Cycle Simulation System: NFCSS) since 2005 which is freely available to all users of IAEA nucleus. The NFCSS is a scenario-based computer simulation tool that can model various nuclear fuel cycle options in different types of nuclear reactors. NFCSS is very efficient and accurate in answering questions such as: the nuclear mineral resources and technical infrastructure needed for the front end of the nuclear fuel cycle; the amounts of used fuel, minor actinides, fission products and high level waste generated for a given reactor fleet size; and the impact of introducing recycling of used fuel on mineral resource savings and waste minimization. NFCSS is a fast running tool that requires only a few input data and parameters for execution. The studies of the International Project on Innovative Nuclear Reactors and Fuel Cycles (IAEA/INPRO) on the sustainability of nuclear energy were carried out using this tool.

Based on the requests from Member States, IAEA improved NFCSS and uploaded the revised version on its web-site in 2019, together with a technical document. Now, any users can utilize it with free of charge by registering their names on IAEA nucleus. NFCSS has a built-in burn-up engine, which was offered by Japan, together with cross section data. So, it can perform fuel cycle evaluation without reactor core design codes. Main improvements of the revised version are; thorium cycle capability for PWR/BWR, expanded number of actinides from 14 to 18, fuel cycle capability for FBR besides previous 7 reactor types, a user friendly manual, and an added module linked to NFCSS for decay heat and radiotoxicity of PWR/BWR spent fuels.

The presentation will cover the new features of the simulation tool, recent improvements with some results from benchmarking exercise and case studies.

Keywords: nuclear fuel cycle simulation, NFCSS

Development progress and methodology of FANCSEE fuel cycle code

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[3]Lund University (Sweden),
[4]Tsinghua University (China),
[5]Uppsala University (Sweden)

This work describes recent developments and methodology of a nuclear fuel cycle simulator code - Fuel Advanced Nuclear Cycle Simulation (FANCSEE). The idea behind FANCSEE is to create a user-friendly, graphically controlled software which allows to quickly implement, change and simulate complex scenarios. The target users of the code would include researchers, policymakers and students. FANCSEE enables to calculate mass, radioactivity and radiotoxicity of up to 1307 nuclides from the front to the back-end of the fuel cycle in user-defined scenarios spanning up to ten thousand years with timesteps of one day or more. Scenarios containing large nuclear fleets and reprocessing can be handled by modest hardware in short runtimes, typically spanning minutes to an hour, due to the use of the computationally efficient Chebyshev Rational Approximation Method to solve the burnup matrix exponential. Analysis of scenarios and influence of different reactor types on waste radiotoxicity can be done on automatically generated MATLAB output files or plotted directly by the software. The plotting functionality, visual nature of the code and short runtime create an opportunity to show environmental advantages of closed fuel cycles. The code can lead to a more sustainable energy management through better comprehension of nuclear fuel cycles. A set of libraries for different reactors were calculated with Monte Carlo particle transport code Serpent 2. The reactor libraries include Pressurized Water Reactors, Boiling Water Reactor, Sodium-cooled Fast Reactor, Lead-cooled Fast Reactor and a High Temperature Gas-cooled reactor. Reactor inventory can be customized - mass, type of fuel, enrichment, number of batches and fuel cycle time. Reprocessing can be done in both FIFO and LIFO order. A limit can be set on the number of times Pu vector can be reprocessed as well as how long does fuel need to cool down before reprocessing.

Keywords: radiotoxicity, CRAM, reprocessing, GUI, Monte Carlo

Nuclear fuel cycle interaction with electrical and energy systems

Friday July 2nd – Morning session

Chair: Adrien BIDAUD

Adaptations of a current nuclear reactor towards more flexibility in order to accommodate a power system with a high insertion of variable renewable energy sources

Mazauric Anne-Laure[1], Sciora Pierre[1], Droin Jean-Baptiste[1], Pascal Vincent[1], Bésanger Yvon[2], Hadjsaïd Nouredine[2, 3], Tran Quoc Tuan[4]

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Power system ensure a balance between electricity production and consumption at all times. This balance is constrained by the load variations over the day and the year. The massive penetration of renewable energy sources (RES), such as wind and photovoltaic that are variable and not "dispatchable", may weaken this supply-demand balance. Furthermore, the ultimate removal of thermal power plants in favor of the increasing integration of these variable RES reflects French and European strategies to reduce CO2 emissions. Nuclear power plants contribute in part to this daily and seasonal balance thanks to the "load-following" mode, but there are still limits to their use. These limits prevent a nuclear power modulation as efficient and quickly as the conventional thermal power plants, which are preferred during strong disturbances of the network and for rapid stability control.

Previous studies presented an approach which highlighted the need in terms of power ramps for nuclear in a constrained power system, in order to compensate for the removal of thermal power plants. The possibility that nuclear reactors can achieve power ramps of significant values (>5%Pn/min) is put forward and could make it possible to replace the services currently provided by thermal power plants.

The objective of the study is then to use these power system requirements as the main input parameter for the design of a nuclear reactor with high flexibility. So that nuclear can participate more actively in the permanent balance of electricity supply and demand, frequency control (especially primary control), and in the integration of variable RES on the grid.

A simple modeling of a current reactor of the French 1300 MW PWR fleet is carried out. This model is then validated on a reference transient imposed by the power system, i.e. a power variation of +/-5%Pn/min, which is currently the technical limit of current NPPs.

Parametric studies are carried out in order to reveal technical and technological constraints. The study suggests ways of design in order to improve flexibility of nuclear. Several solutions may be considered for the reactor design to be more resilient and capable of accommodating high RES penetration. A relationship between power system challenges, nuclear power ramp requirement and impact on reactor design is proposed.

Keywords: Nuclear reactor design, Flexibility, Generator power ramp, variable Renewable Energy Sources, RES

Small Modular Reactor based solutions to enhance the grid reliability: identification of relevant criteria and preliminary assessment

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In the current renewable energies expansion framework, the increasing part of intermittent electricity production sources (solar or wind farms) in the mix may lead to a source of grid vulnerability in the next decades. Indeed, on the one hand, thermal power stations that are nowadays useful to ensure the grid stability will tend to disappear because of their too high greenhouse gases emissions, and on the other hand, the share of variable renewable energies (VREs) in the energy mix will increase, adding a source of unpredictability in the power production.

Nuclear energy, which is carbon-free and dispatchable, may be a sustainable solution to this grid reliability issue if it is adequately designed and implemented on the grid. Several solutions aiming at improving the future nuclear power production and distribution are currently under investigation at CEA, mostly based on Small Modular Reactor plants. In order to demonstrate their potential ability to stabilize electric grids, it is necessary to perform electrical dynamic simulations taking into account a spatial and temporal discretisation of the grid.

In this paper, such calculations are performed using the PowerFactory software. This tool can reproduce electrical grids thanks to models of turbo generators, lines, transformers, loads, I&C systems, etc. The objective is to assess to what extent SMR may enhance the control of the voltage of a grid, of its frequency and of its machines synchronism, which are the three keys of the grid stability. For this purpose, some criteria are firstly identified based on a literature review. Then tested on a simple and aggregated network modelling, the meaning of these criteria within the framework of a dynamical approach instead of a prospective one is discussed. The relevance of implementing small modular reactors instead of large power plants on such stability indicators on a larger grid modelling is finally assessed, in order to understand about the possible contribution of small reactors to the future grids sustainability.

Keywords: SMR, energy mix, grid stability

A new PoweR histOry generaTor tOol (PROTO) for French nuclear power stations at IRSN

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The operating power of French reactors is usually adjusted according to the electricity demand and the availability of other sources of production. The power fluctuation has an impact on the reactor core operations, especially on the fuel composition. For example, it affects the time between fuel unloading, loading of fresh fuel, and assemblies redistribution in the reactor core.

To investigate the power fluctuation effect on the core, the neutronics and criticality safety assessment division of the Institute for Radiological Protection and Nuclear Safety (IRSN) has developed a Monte Carlo tool (named PROTO) to provide realistic power histories in order to simulate the power fluctuation request for a typical French nuclear reactor. The first application of this tool is the determination of isotopic inventory of the reactor core. These variations are an important input for major accident assessment, for instance, to estimate the release of radioactive elements in the atmosphere. Other possible uses of this tool could be in the topics of the energy transition scenarios.

The Monte Carlo tool is composed of two stages: firstly, the analyses of a database information from the French nuclear power stations obtained in the last seven years. Power frequency distribution, amplitude power fluctuations, shutdowns distribution, periodicity and duration, and power patterns are some pieces of information extracted from the database to define probability distributions used in the second stage of PROTO. Secondly, PROTO uses the Monte Carlo method to sample the probability distributions to generate realistic power histories. The routine implemented is notably able to reproduce the fuel management cycles, taking into account shutdown and maintenance periods from the realistic data. The power histories generated between two shutdowns are able to reproduce a realistic reactor load demand, including frequencies and fluctuation probabilities, for different reactors and different bins (hours, days, and MW*d/kg).

The success of the results carried out with PROTO motivated its developers to improve and enhance the capability. A third stage of the code has been designed to adapt and provide the input results in a format of the well-known reactor core simulation codes like CASMO and VESTA.

Keywords: Nuclear power history generator, power fluctuations, Monte Carlo tool

Nuclear scenarios exploratory analysis

Thursday July 1st – Morning session

Chair: Barbara VEZZONI

Fuel Cycle Simulators for Nuclear Archaeology

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To enable deep cuts towards a world without nuclear weapons, states will need to submit baseline declarations listing their fissile material inventories. Provided records of the historical operation of fuel cycle facilities could be checked for consistency. Based on these records, then, inspectorates could perform forward simulations of the nuclear fuel cycle in question to reconstruct the fissile material production and compare it to the declared inventories. This is called nuclear archaeology. Such simulations could also help determine fuel cycle-specific signatures that can be measured, allowing for additional consistency checks. With regard to HEU, one such signature could be the composition of the enrichment tails. In this presentation, the approach is illustrated in a case study using Cyclus. For this purpose, an enrichment facility prototype tracking minor uranium isotopes, such as U-234 and U-236, has been implemented in Cyclus. Based on this study, we examine how existing fuel cycle simulators would need to be adapted to make them better suited for nuclear archaeology. After all, they are typically optimized to study future scenarios, such as energy transitions, while nuclear archaeology simulators should recreate the past as precisely as possible. This conceptual difference and possible arising problems are discussed. Lastly, the inverse problem is introduced: can it be possible to directly reconstruct aspects of the operational fuel cycle history based on measured signatures such as tails compositions?

Keywords: nuclear archaeology, multicomponent isotope enrichment, disarmament, Cyclus

DONJON5/CLASS coupled simulations of MOX/UO2 heterogeneous PWR core

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Most fuel cycle simulation tools are based either on fixed recipes or assembly calculations for reactor modeling. Due to the high number of calculations and extensive computational power requirements, full-core computations are often seen as not viable for this purpose. However, this leads to additional hypotheses and modeling biases, thus limiting the physics realism of the resulting fuel cycle. For several applications, the current modeling method is sufficient, but precise calculations of discharged compositions may require further refinement.

CLASS (Core Library for Advanced Simulation Scenarios) is a dynamic fuel cycle simulation code developed since 2012 with reactor models based on neural networks to produce nuclear data and physical quantities. Past work [1] has shown a first coupling between CLASS and DONJON5 to quantify neural networks approach biases. This work assesses the applicability of 3D full-core calculations using a deterministic calculation code coupled with nuclear scenario simulations to allow realistic simulation of a full PWR core at equilibrium cycle conditions. The deterministic calculation is provided by the chaining of DRAGON5 and DONJON5. DONJON5 enables interpolation of burnup dependent diffusion coefficients and cross sections [2] generated beforehand by DRAGON5, a deterministic lattice calculation tool [3].

Whereas [1] considered only homogeneous reactors (i.e. homogeneous assembly in terms of composition and enrichments as well as homogeneous core), the present contribution focuses on the integration of full-core calculations in CLASS for fuel cycles involving a MOX/UO2 PWR core (i.e. 1/3 MOx - 2/3 UOx). The DONJON5 model considered in this work is for a core with critical boron concentration at equilibrium cycle conditions loaded partially with MOx heterogeneous assemblies composed of three enrichments. In fuel cycle calculations, the main issue is to adapt, in the fabrication stage, the fresh fuel composition for the reactor with regards to the isotopic composition of the available stocks. This work presents a fuel loading model based on power-peaking factors minimization that respects cycle time reloading scheme, 235U enrichment as well as Pu concentration and fissile quality, hence, ensuring a more uniform power distribution about the core.

The full paper will provide an illustration as to the viability and robustness of this new multiparameter fuel loading model. Also, results obtained via our deterministic approach for homogeneous and heterogeneous rectors will be discussed.

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Keywords: CLASS, DONJON5, Full core calculations, Fuel loading model, MOX

Application of Sensitivity Analysis in DYMOND/Dakota to Fuel Cycle Transition Scenarios

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The nuclear fuel cycle is a complicated system with many feedback mechanisms that can have unintuitive effects when transitioning between fuel cycles. Successfully analyzing a potential change in a fuel cycle, either due to policy or emergence of a new technology, requires a nuclear fuel cycle simulator (NFCS). However, NFCSs require many free parameters to allow the flexibility to model the large range of potential fuel cycles and facilities, with many of these parameters being left to the judgement of the user as there have been no real-world equivalent of the potential reactors or facilities described. This freedom also creates parametric uncertainties - uncertainty that is the result of the assumptions of the parameter's values. To better understand the models that are being simulated and the results of these uncertainties, sensitivity analysis and uncertainty quantification (SA&UQ) is incorporated into the NFCS calculations. These approaches reveal how the system performance changes in response to changes of a single or group of uncertain parameters. This relationship is studied through sampling methods and surrogate models to calculate a distribution on system performance measures (i.e., response metrics) and to understand which parameters contribute most to the variance of the response and the synergistic relationships between parameters. To perform this analysis a framework based on the Design Analysis Kit for Optimization and Terascale Application (DAKOTA) was developed and interfaced with the NFCS DYMOND. DYMOND allows for accurate representation of the dynamic changes in nuclear fuel compositions through its coupling with ORIGEN for depletion calculations and direct critical fuel composition calculations. This analysis framework reveals both the parametric and the synergistic effects between four free parameters and four response metrics of significance in an example nuclear fuel cycle transition scenario. The free parameters in this study were chosen based on experience of the limiting factors in the transition from the current U.S. once-through nuclear fuel cycle to a closed cycle with reprocessing - when reprocessing is begun, the annual reprocessing capacity, the growth of energy demand, and the rate at which advanced fast reactors are deployed. The response metrics were chosen to be in line with several of the evaluation criteria chosen for the U.S. Nuclear Fuel Cycle Evaluation and Screening Report - natural uranium required, annual enrichment capacity required, mass of nuclear waste that requires disposal, and the levelized (in 2020 US$) cost of the fuel cycle transition as estimated by the Advanced Fuel Cycle Cost Basis Report.

Keywords: Sensitivity Analysis, Surrogate Models, Sobol Indices, DYMOND