3rd Technical Workshop On Fuel Cycle Simulation

FIAP Jean Monnet – PARIS – FRANCE

9-11, JULY 2018

PROGRAM

https://indico.in2p3.fr/event/16854/

Program – Monday 9th of July

- 09:00 – 09:30 – Welcome
- **09:30 – 09:40 – Introduction:** Reactor models in Dynamic Fuel Cycle Tools – *Xavier Doligez*
- **09:40 – 10:00 –** FITXS: A fast burn-up scheme based on the fitting of one-group cross-sections – *Máté Halász*
- **10:00 – 10:20 –** Multi-zoned fuel irradiation model for ASTRID-like SFR with the CLASS code – *Léa Tillard*
- 10:20 – 10:40 – COFFEE Break
- **10:40 – 11:00 –** Modeling MSRs in DYMOND – *Bo Feng*
- **11:00 – 11:20 –** Modeling a fast MSR with ORION – *Eva Davidson*
- **11:20 – 11:40 –** Molten salt reactor modeling and simulation – *Benjamin Betzler*
- **11:40 – 12:20--DISCUSSION--**

- 12:20 – 14:00 – LUNCH

- **14:00 – 14:20 – Introduction:** Fuel cycle simulators and data treatment – *Brent Dixon*
- **14:20 – 14:40 –** The Fuel Cycle Analysis Toolbox – *Brent Dixon*
- **14:40 – 15:00 –** Modeling fuel cycle events and advancing time in SITON v2.0- *Aron Brolly*
- **15:00 – 15:20 –** Improvements of Nuclear Fuel Cycle Simulation System (NFCSS) at IAEA – *Ki Seob Sim*
- **15:20 – 15:40 –** Development of an Advanced Nuclear Fuel Cycle Simulator (FANCSEE) with Graphical User Interface – *Wacław Gudowski*

- 15:40 – 16:00 – COFFEE break

- **16:00 – 16:20 –** Using Supply and Demand Curves to Determine Facility Deployment – *Robert Flanagan*
- **16:20 – 16:40 –** Regulus: Visual Analysis Exploration of High Dimensional Nuclear Fuel Cycle Simulations Data – *Yarden Livnat*
- **16:40 – 17:00 –** Implementation of a Modernized Transmutation Library Database- *Nicholas Brown*

- 17:00 – 17:40--DISCUSSION--

Program – Tuesday 10^{th} of July

- **09:00 – 09:10 – Introduction:** Economy and interdisciplinary applications of fuel cycle simulation – *Adrien Bidaud*
- **09:10 – 09:30** – Requirements of load following by nuclear power plant as a function of variable renewable energies developement – *Adrien Bidaud*
- **09:30 – 09:50** – Nuclear and Renewables in deregulated markets. Nuclear fuel cycle cost estimates with cross-disciplinary modelling – *Rodica Loisel*
- **09:50 – 10:10** – How can we anticipate the evolution of the uranium cost to define when Fast Reactors will become competitive against Light Water Reactors? – *Anne Baschwitz*
- **10:10 – 10:30** – Evaluation of non-nuclear material balance with the COSI software – *Philippe Miranda*
- 10:30 – 10:50 – COFFEE
- **10:50 – 11:10** – Economic Analysis of Alternative Transition Pathways to Improve Economic Considerations in Fuel Cycle Transition – *Brent Dixon*
- **11:10 – 11:50 --DISCUSSION--**
- **11:50 – 12:10 – Introduction:** Confidence and robustness in fuel cycle simulations – *Guillaume Krivtchik*
- **11:10 – 12:30** – Nuclear scenarios: an exercise of robustness analysis – *Guillaume Krivtchik*
- **12:30 – 12:50** – Strategies for the uncertainty quantification of fuel cycle scenarios – *Aris Villacorta Skarbeli*

- 12:50 – 14:20 – LUNCH

- **14:20 – 14:40** – Impact of Macro Reactor Approximation on Scenario: Modeling in C.L.A.S.S – *Abdoul-Aziz Zakari-Issoufou*
- **14:40 – 15:00** – Functionality Isolation Tests – *Nicolas Thiollière*
- **15:00 – 15:40 --DISCUSSION--**
- 15:40 – 16:00 – COFFEE
- **16:00 – 18:00 – Panel discussion with decision makers**

- 18:30 – 20:30 – COCKTAIL

Program – Wednesday 11th of July

- **09:00 – 09:20– Introduction:** Scenario studies and non-proliferation– *Paul P.H. Wilson*
- 09:20 – 09:40 – Modeling JCPOA breakout using Cyclus – *Paul P.H.* Wilson
- 09:40 – 10:00 – Nuclear diversion scenario within the functional uncertainties – *Baptiste Mouginot*
- 10:00 – 10:20 – Nuclear archeology: Reconstructing past fissile material production using measurements and fuel cycle simulations – *Malte Göttsche*
- 10:20 – 10:40 – COFFEE
- 10:40 – 11:00 – Integration Modeling to Decipher a fuel cycle – Romarie *Morales Rosado*
- 11:00 – 11:20 – Fuel Cycle Systems Scenario Analysis: Recycling LWR Plutonium in Thorium Fueled PT-HWRs – *Daniel Wojtaszek*
- 11:20 – 11:40 – Impact of Technology Characteristics on Transition to a Fast Reactor Fleet – *Ed Hoffman*
- 11:40 – 12:00 – On the use of plutonium burning fast reactors to reduce PWR irradiated assemblies' stockpile – *Timothée Kooyman*
- 12:00 – 12:40--DISCUSSION
- 12:40 – 12:50 – CONCLUSION

- 12:50 – 14:20 – LUNCH

WELCOME

- Dynamic fuel cycle simulation tool are used around the world for many different applications, future fuel cycle option assessment, economic and sociology studies, non-proliferation.... Over the past years different tools have been developed by the different communities, using different philosophies, different objects and different capabilities.

  This third dynamic nuclear fuel cycle workshop aims to connect those research efforts and to facilitate the development of international collaborations.

  The focus of this workshop is to provide the opportunity to scientists to present and exchange about their work with nuclear fuel cycle experts, to build collaborations and projects at national and international levels.

  Besides technical aspects, fuel cycle simulations have important, yet often implicit, political and social dimensions. This international workshop is also conceived as an opportunity for enhancing discussions between representatives of different social worlds involved in construction, evaluation or use of fuel cycle scenarios.

  This 2018 workshop is co-organized by CNRS/IN2P3, IRSN and CEA.

- **Organizing committee**
  - Clavel Jean-Baptiste
    Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
  - Doligez Xavier
    Institut de Physique Nucléaire d'Orsay, CNRS/IN2P3
  - Ernoult Marc
    Institut de Physique Nucléaire d'Orsay, CNRS/IN2P3
  - Krivtchik Guillaume
    Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA)
  - Mouginot Baptiste
    University of Wisconsin-Madison, U.S.A.
  - Thiollière Nicolas
    Subatech, IMTA-IN2P3/CNRS-Université, Nantes, France

09/07/18

Reactor models in dynamic fuel cycle tools

Xavier Doligez

Notes

FITXS: A fast burn-up scheme based on the fitting of one-group cross-sections

Máté Halász, Máté Szieberth
Budapest University of Technology and Economics, Institute of Nuclear Techniques – 1111 Budapest, Műegyetem rkp. 9., Hungary
halasz@reak.bme.hu

- ***Due to the high computational cost of detailed burn-up calculations, most scenario codes use burn-up tables or parametrized few group cross-sections to calculate fuel depletion in the reactors. As a special parametrization approach, a fast burn-up scheme called FITXS was developed at the BME Institute of Nuclear Techniques (BME NTI), which is based on the fitting of one-group cross-sections as polynomial functions of the detailed fuel composition.***

The atomic densities of 15-20 nuclides, including a wide selection of minor actinide isotopes and the total quantity of fission products were used as descriptive parameters to fit the one-group cross-sections and the *k*eff. The FITXS scheme was used to develop burn-up models for the Generation IV Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR) and Sodium-cooled Fast Reactor (SFR), as well as MOX fuel assemblies of the Generation III European Pressurized Reactor (EPR) and VVER-1200. In the case of MOX fuel assemblies, the atomic densities of 135Xe and 149Sm, and the boric acid concentration were used as additional fitting parameters. The burn-up models are able to calculate the spent fuel compositions of the reactors for a wide range of fresh fuel compositions, with less than one second computational time.

The accuracy of the fitted cross-sections and the burn-up models was verified with burn-up calculations using cross-sections calculated with the SCALE 6.0 code. Results showed that the fitted polynomials can describe the *k*eff and important cross-sections with typical errors in the order of 0.1%. The burn-up models showed high accuracy in the case of fast reactors and acceptable accuracy in the case of MOX fuel assemblies. The models were integrated into the nuclear fuel cycle simulation code SITON v2.0, developed at the Centre for Energy Research, as well as another simulation program developed at the BME NTI. A comparison between the applied polynomial fitting and neural network based fitting in terms of accuracy and computational cost is currently underway.

Notes

Multi-zoned fuel irradiation model for ASTRID-like SFR with the CLASS code

Léa Tillard[1], Jean-Baptiste Clavel[1], Xavier Doligez[2], Marc Ernoult[2], Abdoul-Aziz Zakari-Issoufou[2], Eric Dumonteil[1]

1 - Institut de Radioprotection et de Sûreté Nucléaire

2 - Institut de Physique Nucléaire d'Orsay, CNRS/IN2P3

lea.tillard@irsn.fr

- ***Regarding the evolution of the electronuclear fleet for the next years, one strategy in France [1] considers the progressive deployment of "low void effect" Sodium-cooled Fast Reactor (SFR-CFV), a Generation IV reactor.***

Different options are considered regarding the deployment time of this kind of reactors, depending on the global nuclear energy development. In some options, the replacement of current PWR by those SFR is delayed after 2060, leading to a new issue: the plutonium stabilization in the fuel cycle, as a waiting strategy. In that case, some of these SFR-CFV may enable a dynamical management of the plutonium with the plutonium multi-recycling in few reactors. This option should be flexible as SFR may be operated as breeder, isogenerator or burner reactors.

The CFV core design used in this study is based on the 600 MWe French ASTRID concept developed by the CEA with industrial partners [2]. To reach a negative void coefficient, the core is divided in two radial parts: an inner and an outer core, which alternate different fertile and fissile zones.

The implementation of this heterogeneous reactor in the CLASS (Core Library for Advanced Scenario Simulation) software (a dynamic fuel cycle simulation code developed by CNRS in collaboration with IRSN), requires the development of a new dedicated model for the fuel irradiation in such a multi-zoned reactor. To calculate the depletion of fuel compositions, the model predicts, for each zone, actinides mean cross-sections and in addition the specific power, which are required to solve the Bateman equations. To do that, two separated Artificial Neural Network (ANN) are trained with the corresponding databank composed of many (1000) depletion Monte Carlo simulations [3] using VESTA (with MCNP as the transport solver) [4]. Each calculation differs from the other by the initial fuel composition that is sampled in the phase space associated to different scenarios for SFR-CFV fuel cycle.

These two predictors are used many times during the simulations, so they must be optimized on a criterion of computing time minimization while providing sufficiently accurate results. To check the accuracy of the ANN predictions, comparisons with the result of 200 Monte-Carlo depletion simulations are made. It shows that the actinide cross-section predictions are close to the Monte Carlo calculations, for instance the relative error on the 239Pu fission cross-section is around 2%. Then, the relative error on the power is on the order of 2% in fissile fuel zones but is much higher at this time in fertile zones, areas where the

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specific power represents less than 20% of the total power. The quality of the power prediction therefore degrades the estimation of isotopic compositions in fertile zones, however the global reactor representation is acceptable.

[1] CEA, " Avancées des recherches sur la séparation-transmutation et le multi-recyclage du plutonium dans les réacteurs à flux de neutrons rapides", CEA Report, 2015.

[2] O. Fabbris, "Optimisation multi-physique et multicritère des cœurs de RNR-Na : application au concept CFV", Thèse CEA - Université de Grenoble, 2014.

[3] F. Courtin and all, "Neutronic predictors for PWR fuelled with multi-recycled plutonium and applications with the fuel cycle simulation tool CLASS", Progress in Nuclear Ener

gy, 2017.

[4] IRSN, "VESTA USER'S MANUAL", IRSN Report.

Modeling MSRs in DYMOND

Bo Feng
Argonne National Laboratory
bofeng@anl.gov

- ***One of the US DOE-NE's Fuel Cycle Options Campaign's current research activities is assessing the differences in time-dependent fuel cycle behavior between different reactor technologies that fit in the same fuel cycle evaluation group. At Argonne, fuel cycle simulations were performed in DYMOND to model a system transition from the existing LWR-based fuel cycle in the US to a future fuel cycle that consists of only fast spectrum reactors that continuously recycle their TRU fuel.***

This future fuel cycle, as described, can be achieved using a number of different reactor, fuel, and recycling technologies. The two reactor technologies chosen for comparison in this specific study were a sodium-cooled fast reactor (SFR) and a fast-spectrum chloride molten salt reactor (MSR). These two reactors were selected for comparison purposes because of their differences in refueling approaches (batch-wise versus online refueling).

Most fuel cycle tools were developed with traditional batch-wise fuel management in mind, whether they are agent-based or fleet-based codes that use system dynamics, so the modeling of MSRs, which have very different characteristics, may require innovative modeling implementations and unique considerations.

For example, if the fuel salt is circulating outside of the core, the fuel in these loops, heat exchangers, processing facilities, etc. need to be accounted for. The simulation of continuous refueling may be easier for codes that already model loading and discharge at every time step. The concept of burnup (which is a primary input) is non-conventional since fresh fuel is continuously added. The fuel composition inside of the core may take decades to reach equilibrium so such evolution may need to be captured if this is a parameter of interest. The modeling approach used in DYMOND to address these unique characteristics will be shared to help the community think how different codes may be utilized.

Notes

Modeling a fast MSR with ORION

***Eva Davidson**[1], B. Betzler[1], R. Gregg[2], J. Peterson-Droogh[1],A. Worrall[1]
1- Oak Ridge National Laboratory - Bethel Valley Road-Oak Ridge, TN 37831- USA -
2 - National Nuclear Laboratory Preston Laboratory,
Springfields Works Salwick, Preston, PR4 0XJ United Kingdom,
davidsonee@ornl.gov

- ***Molten Salt Reactors (MSRs) are being pursued by several private companies as a viable technology that can enable a low-carbon future. These companies have invested heavily in the design of different types of MSRs leading to a response from the US Department of Energy (DOE) to provide assistance in furthering R&D in this area by fostering collaboration between the US national laboratories and the industry through the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative.***

This collaboration takes advantage of the resources available at all the institutions to bring MSRs to fruition in the near future. With the renewed interest in MSRs, the presentation will focus on analyzing a single-stage MSR in a systems dynamics fuel cycles tool, ORION, to understand the current capabilities of modeling MSRs and to identify any deficiencies in modeling an MSR accurately.

Oak Ridge National Laboratory (ORNL) has chosen ORION, a systems dynamics fuel cycles code developed and maintained by the National Nuclear Laboratory (NNL) in the United Kingdom, to model fuel cycle scenarios. A single-stage MSR was set up in ORION using (1) burnup-dependent cross sections and (2) an ORIGEN arplib file pertaining to the specific type of MSR under analysis in this paper. The two sets of ORION results will be presented along with the results from the reactor physics model to compare the trends in various output of interest.

The isotopic content of the salt evolves over time in an MSR. In the MSR design analyzed in this work, the isotopic content approaches equilibrium after 20 years of operation. Certain MSR designs never reach equilibrium and continuously evolve over the entire life of the reactor. During the process of setting up the ORION MSR model, it was found that several assumptions had to be made to input parameters in ORION due to the lack of current capability to account for certain behavior inherent to MSRs. The model and these assumptions will be discussed in further detail during the presentation.

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Molten salt reactor modeling and simulation

***B. R. Betzler,** E. E. Davidson, and J. J. Powers
Oak Ridge National Laboratory – 1 Bethel Valley Road – Oak Ridge, TN 37831– USA
betzlerbr@ornl.gov

- ***In a liquid-fueled molten salt reactor (MSR), the molten salt fuel is continuously circulated through the core, and undergoes irradiation, chemical treatments and separations, and feeds (fueling) simultaneously. This presents a challenge for modern neutron transport and depletion tools designed for analysis of solid-fueled systems, where the fission products, actinides, and activated isotopes physically remain within a fuel rod or assembly.***

In addition, liquid-fueled MSR analysis has largely focused on the state of the reactor at an equilibrium condition after fission products have built up in the fuel salt over years of operation. Little analysis has focused on the way the isotopic composition of the fuel salt changes from the startup of an MSR until this equilibrium condition.

While there is no established liquid-fueled MSR tool for neutronics and fuel cycle design and evaluation, there are existing products from universities and research institutions. The groundwork for these tools was laid during the early MSR programs at Oak Ridge National Laboratory (ORNL), which integrated neutronic and fuel cycle analysis tools into processing plant codes for MSR and processing system design work. These tools addressed the two main challenges unique to liquid fueled reactors: (1) the fuel material flows and (2) potential online separations or feeds of specific elements or isotopes.

Fuel flow is important due to delayed neutron emission. In a solid-fueled reactor, the fission product delayed neutron precursors remain very close to the fission site where they are created, later emitting delayed neutrons at that location with a softer energy spectrum than prompt neutrons. The precursors drift when the fuel flows, resulting in a different fission site and location of delayed neutron emission. From a fuel cycle perspective, precursor drift affects depletion calculations by augmenting the energy spectrum and strength of the neutron source within the core.

A liquid-fueled reactor is likely to have online separations and/or feeds, where material is moved to or from the core at all times (continuous) or at specific intervals (batch). The ability to perform online separations improves the potential neutronic performance of liquid-fueled systems (e.g., it is unnecessary to operate with excess reactivity if fissile material is continuously being fed into the core). There is also an additional neutronic benefit from removing highly absorbing fission products, but removal of each element from the liquid fuel presents a unique challenge in terms of storage and disposal of the separated materials.

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Fuel cycle simulators and data treatment

Brent Dixon

Notes

The fuel cycle analysis toolbox

Brent Dixon
Idaho National Laboratory

- ***The first two fuel cycle workshops focused on scenario modeling tools, but also included some efforts to embed reactor core performance calculations (mainly depletion models) in the scenario tools. There was also some discussion on visualization of results. In reality, a much broader set of tools is needed to evaluate a nuclear fuel cycle.***

This presentation will provide an overview of the range of tools being utilized by the U.S. DOE Fuel Cycle Options Campaign, including:

- Reactor core performance tools and databases
- Fuel cycle analysis tools
- Market-based analysis tools
- Cost and financial risk analysis tools and data sets
- Technology and fuel cycle evaluation tools
- Collaboration and communication tools

The purpose of the presentation will be to generate a discussion on the different types of analyses and evaluations needed to assess the potential of a fuel cycle, the ways these analyses are coupled, the tools and data needed to support these analyses, and where there are opportunities to improve the process through embedding, linking, or otherwise integrating different types of tools. Important considerations include variations in time scale (from current day market analysis to century-long transition scenarios) and infrastructure scale (one facility or core batch to complete fleets), along with consideration of different objectives, opportunities, hazards, and audiences for the different analysis types.

Another expected outcome is discussion on the implications for automated optimization. Optimization involving parameters from only one or two discipline areas are likely to be sub-optimal when additional aspects are considered. The ability to include additional aspects in the optimization requires greater integration of what are currently mostly separate tools and analysis disciplines.

Notes

Modelling fuel cycle events and advancing time in SITON v2.0

Áron BROLLY
Centre for Energy Research, Hungarian Academy of Sciences Budapest, Hungary
brolly.aron@energia.mta.hu

- ***Treating the events of the nuclear fuel cycle and advancing time are key issues of dynamic fuel cycle modelling. The presentation covers how SITON v2.0—a dynamic, discrete facilities/discrete materials fuel cycle simulator—models these issues. Besides highlighting the advantages of the current modelling approach the presentation tries to address its limitations as well.***

In a discrete fuel cycle simulator information (e.g. request of material) and packages are transferred between facilities. In SITON such a transfer is called an event and series of events describes the operation of the fuel cycle. An event can trigger another event, e.g. when the reactor requests fresh fuel from the fuel fabrication plant. If the fabrication plant has processing time then this request in the present time of the simulation will trigger a request in the past: the fabrication plant requests enriched uranium from the enrichment plant.

To solve this problem, in SITON the survey of requests and the fulfilment of requests are decoupled. Firstly, in advance of the simulation during the phase called planning, facilities are surveyed and their requests are collected. This solution allows to track triggered requests in the past and ensures that all requests are taken into account at the proper time.

Secondly, in the phase called simulation, the collected requests are processed and fulfilled, i.e.: facilities work and packages are transferred between them.

Using events to describe the operation of the fuel cycle makes it possible to have variable length time steps since the times of the events can be used to advance time. Furthermore, there is no need for a simulation clock.

Notes

Improvements of nuclear fuel cycle simulation system (NFCSS) at IAEA

K.S. Sim[1], R. Yoshioka[2], H. Hayashi[3] and T.S.G. Rethinaraj[4]

1 – International Atomic Energy Agency

2 – International Thorium Molten-Salt Forum, Japan

3 – International Atomic Energy Agency (retired)

4 – National Institute of Advanced Studies, India

- ***Nuclear Fuel Cycle Simulation System (NFCSS) is a scenario-based computer simulation tool for fuel cycle, which enables users to carry out calculations using a given set of data. NFCSS provides answers to strategic questions related to fuel cycle year by year over a long period of time (200 years maximum): (a) what are the amounts of demanded resources at each stage of the front-end fuel cycle?; (b) what are the amounts of used fuel, actinide nuclides and high level waste to be stored?; (c) what is the impact of introducing recycling of used fuel on the amounts of resource savings and waste minimization?***

With the features of fast running and easy to use in addition to reliable fuel cycle assessments, NFCSS has been well recognized as a public tool that serves the interests of a wide range of professionals in academia, research and policy arena in Member States.

As described in the IAEA-TECDOC-1535, published in 2007, NFCSS applies to fuel cycle assessments forpresent fuels (i.e. UO2 fuel and Pu-blended mixed oxide fuel) and for 7 types of nuclear power plants (i.e. PWR, BWR, PHWR, RBMK, AGR, GCR and WWER).

Several improvements have been incorporated in NFCSS in the past decade based on users'feedbacks and requirements. Major improvements include: module for thorium fuel cycle assessments, radiotoxicity calculations and decay heat calculations, which need to be taken into account for safety assessments, although requiring complex calculations using computer codes. Simple and fast calculation methods have been adopted in NFCSS to evaluate the decay heat and the radiotoxicity of spent fuel when stored over hundreds years. Moreover, it is verified that NFCSS can be applied to innovative reactors such as FR/FBR.

This presentation introduces the overview of the NFCSS and recent key improvements.

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Development of an Advanced Nuclear Fuel Cycle Simulator (FANCSEE) with Graphical User Interface*

Błażej Chmielarz[1,3], **Wacław Gudowski**[1], Yuliia Hrabar[1], Alexander Bidakowski[4], Congjin Ding[1,2] and Jiali Zou[1,2]

1 – Royal Institute of Technology – KTH, Stockholm
2 – Tsinghua University, Beijing
3 – USNC Europe, Gif-sur-Yvette
4 – Uppsala University

- ***This paper describes development, benchmark and validation a nuclear fuel cycle simulator code – Fuel Advanced Nuclear Cycle Simulation Sweden Estonia (FANCSEE). The core physics of the code – solution of the burnup matrix exponential – is calculated using the state-of-the-art Chebyshev Rational Approximation Method. Libraries are separate for each fuel batch, fuel type as well as reactor type and are based on cross-sections calculated by Monte Carlo particle transport code Serpent 2.***

The idea behind *FANCSEE* is to create a user-friendly, easy to use, graphically controlled software which allows to quickly implement, change and simulate complex scenarios. It has the ability to track up to 1307 nuclides over up to 8599 years. The target users would include researchers, policymakers and students.

The code is controlled through pre-defined objects which represent facilities in a nuclear fuel cycle- reactors, mines, fuel factories, waste repositories, enrichment and reprocessing plants. Every object has a list of corresponding parameters – for example, reactor power, fuel or reactor type, enrichment, processing capacity, "First In First Out" or "Last In First Out" reprocessing order. Calculation timestep can be set between 1 and 120 days. Results of mass, radioactivity and radiotoxicity of sets of isotopes, selected by the user, can be plotted directly with *Grace* plotting tool or exported as *MATLAB* script files. Currently available libraries are for Boiling Water Reactor *ABB-III*, Pressurized Water Reactor (PWR) *Vodo-Vodyanoi Energetichesky Reaktor 440-213*, PWR Mixed Oxide and Uranium Oxide fueled reference Nuclear Energy Agency assemblies.

Current development is focused on implementation of new reactor types – Accelerator Driven System *Myrrha-like* (lead-bismuth cooled), Lead Fast Reactor *BREST*, Sodium Fast Reactor *Phenix* and a High Temperature Gas-cooled Reactor design. Next step of development will focus on implementation of new functionalities to the interface, benchmarking, validation and implementation of an economics module calculating costs of the entire nuclear fuel cycle with its back-end stage.

*Part of this project has been funded within the European Project "Brilliant", Grant Agreement: 662167

Notes

Using supply and demand curves to determine facility deployment

Robert Flanagan
University of South Carolina

- ***This work demonstrates the capability of the d3ploy [1] module for the Cyclus fuel cycle simulator [2]. D3ploy aims to predict the deployment of reactors (and the support facilities for these reactors) given a demand behavior set by a user. For the purposes of this work, the fuel cycle was simplified to three types of facilities; mines, enrichment facilities, and reactors.***

The reactors used for this experiment are CANDU reactors using slightly enriched uranium. Each time step for this simulation was set to 28 days and fuel is demanded by the reactors every time step. The reactors are deployed to match a 5% annual growth curve in electrical demand. The deployment of the support facilities is based on predicted demands from their downstream facilities. To perform the predictions two different time series prediction methods are used; autoregressive moving average (ARMA) [3,4], and autoregressive conditional heteroskedasticity (ARCH) [5,6].

This work compares these two predictive methods against each other as well as a demand response method. In the demand response model if demand exceeds supply new facilities will be built on the proceeding time step. The results show that both methods can deploy facilities to match demand curves and ensuring that all facilities in the scenario have the necessary supply of materials that they require. Of the two methods, ARMA producing superior results.

Additionally, it shows that using ARMA and ARCH improves the deployment of facilities by reducing the amount of time the system is under supplied with any commodities.

[1] https://github.com/ergs/d3ploy.

[2] Huff, K.D., Gidden, M. J., Carlsen, R. W., Flanagan, R. R., McGarry, M. B., Opotowsky, A. C., Schneider, E. A., Scopatz, A. M., Wilson, P. P.H. “Fundamental Concepts in the Cyclus Nuclear Fuel Cycle Simulation Framework.” Advances in Engineering Software, 2016.

[3] Li, K.; Principe, J.C., "The Kernel Adaptive Autoregressive-Moving-Average Algorithm," in Neural Networks and Learning Systems, IEEE Transactions on , vol.27, no.2, pp.334-346, Feb. 2016.

[4] Woodard, D. B.; Matteson, D. S.; Henderson, S. G. Stationarity of generalized autoregressive moving average models. Electron. J. Statist. 5 (2011), 800—828.

[5] Baillie, R. T., Bollerslev, T., Mikkelsen, H. O. Fractionally integrated generalized autoregressive conditional heteroskedasticity. Journal of Econometrics 74(1996) 3-30.

[6] Lei Shi, Md. Mostafizur Rahman, Wen Gan & Jianhua Zhao (2015) Stepwise local influence in generalized autoregressive conditional heteroskedasticity models, Journal of Applied Statistics, 42:2, 428-444.

Notes

Regulus: Visual analysis exploration of high dimensional nuclear fuel cycle simulations data

Yarden Livnat, Di Wang, Dan Maljovec, Valerio Pascucci
Scientific Computing and Imaging Institute, University of Utah

- ***Nuclear fuel cycle analysis spans a wide range of systems and processes from modeling and analysis of combustions processes to understanding the nuclear industry and ecosystem at a macroscopic level. Understanding the behavior and finding optimal designs are a major challenge due to the high-dimensionality and the non-linear behavior of these complex systems and processes.***

Earlier works relied on hand crafting simulations and fine tuning using expert knowledge. A more efficient approach is to define an objective function and sample the multi-dimensional simulation space using iterative optimization techniques. While this approach can reduce the number of sample required, the solution may only be a local optimum and the samples may not be adequate for other objective functions. The optimal solution may also be sensitive small perturbations in the input. Sensitivity analysis has been used in some cases to guide optimization processes using a simple linear regression models. Yet, such global sensitivity analysis may fail to capture intrinsic local behaviors when the system is highly nonlinear.

We designed a framework for analysis and visualization of multi-dimensional nuclear simulations data using a partition-based topological and geometric approach. We first segment the parameter space using an approximate Morse-Smale complex over the cloud of sample points, where each point represents a scalar measure from one of the simulation runs. We use Morse-Smale regression to identify regions of approximate monotonic behavior within the system response and construct hierarchal representation at multiple level of details relative to a persistence measure. A local regressions and sensitivity analysis is then applied on these hierarchical regions. Using our visualizations, scientists can explore the identified regions at various levels of detail and examine and compare their characteristics. The system facilitates understanding of: i) extreme (optimal) output values such as how many there are and where are they located ii) the inverse relationships between the output and the input parameters that describes which combination of input values lead to the set of output in each region iii) the topology of the high-dimensional space that can be used in sensitivity analysis and identifying regions with unique behavior characteristics iv) identifying under-sampled areas that require additional simulations to improve fidelity.

This work is based on collaboration with nuclear engineers at the University of Wisconsin-Maddison and South Carolina University, and leverages our earlier works on visual exploration of high-dimensional scalar functions with collaboration with scientists at Idaho National Lab.

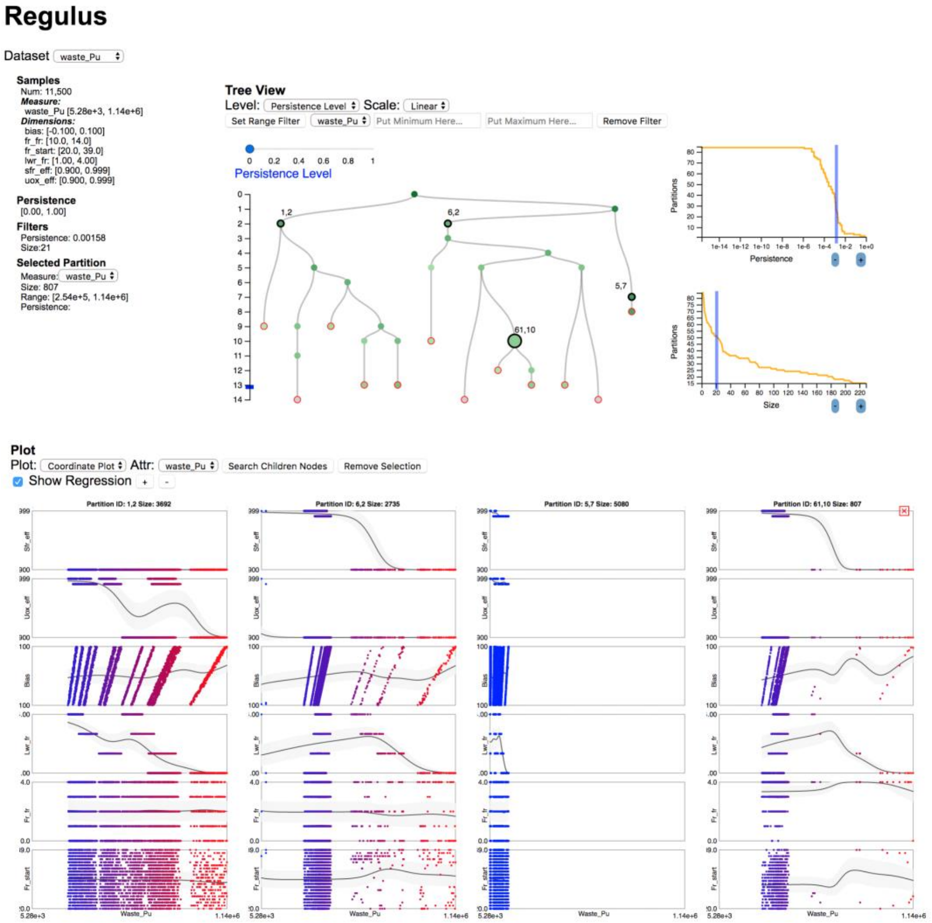

Figure 1 A screenshot of Regulus visual display during an interactive investigation of 11,000 simulations of an LWR to FR transition scenario using the Cyclus fuel cycle simulator.

Notes

Implementation of modernized transmutation library database

Adrian Leandro[1], Mark Ambrose[1], Joshua L. Peterson[2], **Nicholas R. Brown**[1,3], Michael Todosow[3]

1 – Pennsylvania State University, University Park, PA USA

2 – Oak Ridge National Laboratory, Oak Ridge, TN USA

3 – Brookhaven National Laboratory, Upton, NY USA

- ***The Fuel Cycle Options (FCO) Campaign of the U.S. Department of Energy, Office of Nuclear Energy (DOE – NE) is organizing a source of technical data for various fuel system analyses and/or evaluations. Current legacy Excel files or raw data files are not sufficient for all of the recent data and applications, and consequently, a new, updated, centrally hosted database will serve as an essential fuel cycles research asset. Most importantly, this database will have the flexibility to accommodate new data while preserving existing information.***

The first step in creating a modernized transmutation library database is to form an interface between the raw data and the database called an importer template. The importer template is composed of Excel spreadsheets that capture fuel cycle parameters and isotopics for a variety of reactor technologies. The fuel cycle parameters are mainly composed of information found in raw data files known as the Fuel Cycle Data Package (FCDP) from the Nuclear Fuel Cycle Evaluation and Screening (E&S) study. It is also composed of information derived from data in the FCDP (average specific power per zone, for example). This information is given for both whole core and core regions (e.g., the driver and blanket zone) or as regional averages. Charge and discharge information has been entered into the importer template, but region-wise information has also been demonstrated. The importer templates contain information from both the Nuclear Fuel Cycle Evaluation and Screening (including the 40 evaluation groups and handful of non-representative options) and the legacy transmutation library.

An initial version of a database that encompasses the information in the importer templates has been generated and demonstrated. This is a MySQL database, an open-source relational database which is structured to demonstrate how different pieces of information correlate to one another. The database serves as an efficient resource where the user can easily pull information that was previously only available in multiple locations. At this time, an initial version of the MySQL database has been developed and importation of fuel cycle data has been demonstrated. This work includes automatic importation of the draft importer templates into the database via Python scripts. Specific information has been queried from the database. Basic data quality assurance checks and unit testing are presently being implemented. By the end of Fiscal Year 2018, the database will contain the majority of transmutation information from the E&S and several other cases that demonstrate additional capabilities.

Notes

10/07/18

Economy and interdisciplinary applications of fuel cycle simulation

Adrien Bidaud

Notes

Requirements of load following by nuclear power plant as a function of variable renewable energies's developpement

A. Bidaud[1], G. Mantulet[2], S. Mima[2], L. Lemiale[3], R. Loisel[3], G. Mathonnière[4], S. Dautremont[4]

1 – Laboratoire de Physique Subatomique et Cosmologique, Université Grenoble Alpes, Grenoble Institute of Technology, CNRS/IN2P3, (Grenoble, France)

2 – Grenoble Applied Economics Laboratory, Grenoble, France

3 – Laboratoire d'Economie et de Management de Nantes-Atlantique, Nantes, France

4 – I-tésé, CEA/DEN/DANS, Université Paris Saclay

bidaud@lpsc.in2p3.fr

- ***Thanks to massive subsidies, variable renewable energies (VRE) have become a major industry. Their impressive cost reductions make them competitive in more and more places. Because VRE have zero marginal costs, even without regulated higher priority on the grid, they will reduce the load factors of dispatchable technologies.***

Nuclear energy's low variable cost makes it a base load technology. It is expected to be among the last ones to see its working hours reduced. Nevertheless, with higher VRE penetration, nuclear energy should adapt to changes in demand and variable energy production, in particular in regions with high nuclear energy shares such as France.

We will present some results of a benchmark of technology dispatching tools: MAEL from CEA/ITESE, OPTIMIX from CEA/IRSN, EUCAD from CNRS/ University Grenoble Alpes and EcoNUK from CNRS/University of Nantes. The models aimed at reproducing the hourly production of France during year 2012. The total demand as well as the actual productions of wind and solar energies are known and common assumptions for variable and ramping costs as well as technology efficiencies are taken. The compared outputs are agreggated costs, CO2 emissions, average load factors for the different technologies.

Then we will present some simulation results for the 2030 horizon. Assumptions of demand and installed capacities are taken whether from energy prospective tools (Prospective Outlook for Long Term Energy Supply, POLES), or extrapolated from the French Transport System Operator RTE. Variations in the average load factors as well as distribution of daily load reductions are computed. These results allow complementary studies, such as those presented by R. Loisel et al. at the same workshop which are assessing the evolution of the business model of nuclear energy as well as the technical requirement in term of load following capacity of future nuclear reactors.

Notes

Nuclear and renewables in deregulated markets. Nuclear fuel cycle cost estimates with cross-disciplinary modelling

R. Loisel[1], L. Lemiale[1], N. Thiollière[2], X. Doligez[3], S. Mima[4], A. Bidaud[5]
1- Université de Nantes, IEMN-IAE, LEMNA, France,
2 - IMTA, Subatech, CNRS
3 - IPNO, CNRS, (5) GAEL, CNRS,
4 - Phelma, LPSC, CNRS
rodica.loisel@univ-nantes.fr

- ***Empirical evidence shows that power systems with high shares of nuclear and renewables make flexible nuclear reactors cycling more often and would push them to retire earlier. This paper analyses the French power system by 2050 and estimates the way the nuclear power plants operating load-following affects the dynamics of the uranium cycle under cost-efficiency considerations.***

We first formalize the problem and identify the market factors affecting the nuclear fuel cycle such as the capacity factor, the technical lifetime and the license transient budget, the operational cost and the frequency of safety measures due to excessive cycling. A cost calculation methodology is developed based on physics, economics and regulation with the aim of assisting policy makers and industry. The contribution to the literature is the integration of the nuclear load-following operating mode into the overall nuclear cost calculation, with a deep understanding of the operation of a nuclear flexible reactor and its upstream material flow inventory.

First, a physical tool (CLASS, *Core Library for Advanced Scenario Simulation*) describes the dynamics of a complete fuel cycle of a representative PWR kind reactor and gives insights into the material flow under the constraint of the capacity factor, i.e. the share of the fuel burned to match the nuclear power market demand. In general, the lower the nuclear power output, the lower the share of the uranium burned, the longer the cycle and the lower the fuel cost.

Secondly, a technical-economic model (POLES, *Prospective Outlook on Long-term Energy Systems*) integrates the cost of the uranium cycle calculated with physics criteria and simulates the French power system in 2030 and 2050 under carbon emissions constraint.

Thirdly, Poles' outputs, such as renewables installed capacities and flexibility provided by nuclear power plants, are integrated into a sectoral economic model (EcoNUK, *Economic dispatching of NUClear reactors*). It is assessed on an hourly basis the operation of the nuclear power fleet over the complete fuel cycle. Model results allow assessing the number of cycles performed with nuclear power reactors, the market demand for nuclear power and a new value of the capacity factor, which can be different from timely aggregated models. The hourly loop shows that punctually nuclear reactors are cycling excessively triggering down the load factor, while eventually they can substitute flexible gas-fired units instead of operating base-load improving therefore the capacity factor.

Notes

Iterations among disciplines allow finding stable results in terms of uranium cycle cost and reactors' capacity factors, to ultimately compute the nuclear power generation cost, e.g. the LCOE indicator.

Preliminary results show that a limited number of iterations is needed due to robust results from the model Poles in terms of nuclear plants' capacity factors. That is, for a large range of the uranium cycle costs, the nuclear power keeps stable its position in the merit order curve that is deregulated market-specific. Two indicators are instead subject to cost cycle variation, namely the system cost to operate the nuclear power plants and the nuclear generation cost.

How can we anticipate the evolution of the uranium cost to define when Fast Reactors will become competitive against Light Water Reactors?

Anne BASCHWITZ, Gilles MATHONNIERE
CEA, Université Paris Saclay, GSI/DAS/I-tésé
F-91191 Gif-sur-Yvette, France

- ***The nuclear enables to access to energy while being environmentally responsible, at an acceptable cost, and with reasonable security of supply. This technology should thus continue to be deployed in a large scale in the future decades.***

However, the uranium needed by the current light water reactors is a finite resource and will not always be available at the current cost.

The need to exploit deeper deposits or those with lower contents will increase the price of this raw material. Although the cost of uranium only represents today a small share of the levelised cost of electricity produced by a nuclear power plant, in order to maintain and increase nuclear electricity production for the long term it may be necessary to design and develop reactors that make better use of this resource and avoid uranium price tensions

In this context, Fast Reactors (FRs) are promising.

Their competitiveness against LWRs and when it could occur is a key question for planning long term nuclear policies.

We propose a new methodological approach to compare the expected levelised kWh costs of FR and LWR technologies. We take into account the investment, operation, maintenance and fuel cycle costs, and in particular long term uranium cost trend.

We will present how we determine the possible evolution of the uranium cost over time and also how we define a model for anticipating the cost of all the reloads for the reactor's lifetime.

We will then give a few qualitative results concerning the competitiveness of FRs according to various parameters. The key factors affecting the economic time frame for a quantitative development of FRs are, in decreasing order of impact:

- The uranium supply curve
- The extent of deployment of the nuclear fleet, the existing backend of the fuel cycle in
- the countries being considered and the discount rate,
- The additional investment cost of FRs in comparison with LWRs,
- The reactor construction times.

Notes

Evaluation of non-nuclear material balance with the COSI software

Ph. MIRANDA
CEA - DEN/DER/SPRC, bât. 230, 13108 Saint-Paul-Lez-Durance Cedex, France

- ***Since 1985, the CEA has been developing the simulation software COSI to study different trajectories of nuclear fleet evolution and provide technical elements to decision makers, particularly fuel flows and waste production.***

An evolution of the COSI6 scenario code was carried out in 2013, in order to compute, by proportion with nuclear materials, the flow of non-fissile materials (also called critical or strategic). A first application of the new COSI post-treatment was achieved in 2015, on all non-nuclear materials present in the ASTRID demonstrator, during its whole lifetime.

The optimized version of COSI post-processing, achieved in 2016, enables to study the whole French fleet which includes, in addition to the current 58 units of PWRs, the future EPR reactors, ASTRID in its Basic Design version and the SFR 1000 MWe in its most recent version. After presenting the critical materials topic, the assessment of non-nuclear materials flow in the French fleet will be presented since 1977 until 2090.

Among the dataset necessary to use this post-processing, we can note the great amount of data (number, material, mass and reload frequency) needed to define accurately the assemblies loaded in PWR and SFR reactors (EPR, ASTRID and SFR 1000 MWe).

The diversity of fuel batches in PWR reactors made this inventory work more complex. The loading of new assemblies, involving various building materials, during the whole reactors life, has a significant impact on the material balance of steels and critical materials. This computation requires a accurate knowledge of the history of the succession of loadings for each new type of assembly.

Finally, some approximations must be noted. The operation of the future fleet is evaluated by considering constant load factors. In this scenario, the new assembly technologies that will emerge in the coming years are obviously not accounted for. With these restrictions, we provide the overall material balance for non- nuclear materials until 2090.

These results will enable to assess potential supply problems (resources, costs, production capacity) caused by the production of strategic materials by a single country and the rising prices due to the increasing demand.

This situation has caused some concern and the European Commission carried out several assessments of the vulnerability risk and proposed an action plan to minimize its impact.

The CEA participates in this research effort particularly by its work on the recycling of Rare Earths elements by process developed for the separation of actinides.

Notes

Economic Analysis of Alternative Transition Pathways to Improve Economic Considerations in Fuel Cycle Transition

Brent Dixon and Jason Hansen
Idaho National Laboratory

- ***This presentation will highlight the results of a case study analysis to identify the least cost alternatives for transitioning to a nuclear fuel cycle.***

The analysis is based on assumptions applicable to the civilian nuclear industry in the United States and a transition from the current once-through light water reactor (LWR) low enriched uranium (LEU) oxide-based fuel cycle to a new, closed fuel cycle based on fast spectrum break-even reactors or fast breeders and thermal burners. The target fuel cycle is based on high breeding ratio sodium fast reactors (SFR) that start up on 19% enriched uranium (with no recycle of the legacy LWR spent fuel). SFR spent fuel is recycled, with the recovered Pu and LEU used to fabricate U/Pu fuel. Fission products are discarded as high level waste and depleted uranium (DU) is used as makeup material. Through successive recycles, the fuel evolves to an unenriched U/Pu composition that is approaching isotopic equilibrium. At that point, the fast reactor breeding ratio can be reduced to a break-even level, or alternately the excess bred Pu can be used to convert remaining legacy LWRs to operate on U/Pu mixed oxide fuel. In both cases, the enrichment required for SFR startup generates an inventory of depleted uranium that can be used as makeup material for hundreds or years without any additional enrichment or uranium mining.

For each of these cases a scenario of possible build profiles for separations facilities are imposed. The base scenario builds separations facilities such that as soon as demand for services arrive, the facility is present to provide services. This results in a low utilization factor until enough SFRs are built to fully utilize each new facility. The alternative scenario delays construction of separations facilities while building an inventory of cooled used fuel such that the facilities go online just in time to reach both a near 100 percent utilization factor and depletion of the inventory of cooled used fuel, at the cost of some additional uranium mining and enrichment. Delayed separations is enabled by the use of a relatively unlimited supply of enriched uranium for reactor startup instead of a limited supply of Pu in LWR spent fuel. This also makes the system less sensitive to fuel cooling and recycle time.

These scenarios and cases lead to four alternatives in the analysis. These are evaluated using an economic model designed to evaluate the system costs of each alternative. The cost data for the model come from the Advanced Fuel Cycle Cost Basis Report. The data on the material flows and mass balance are generated using the VISION model for simulating fuel cycle possibilities. Results suggest that the economically optimized scenarios have better cost performance than a system optimized on material flow alone.

Notes

Confidence and robustness in fuel cycle simulations

Guillaume Krivtchik

Notes

Nuclear scenarios: an exercise of robustness analysis

G. Krivtchik[1], A. Bidaud[2], B. Carlier[3], J.-B. Clavel[4], F. Descamps[5], X. Doligez[2], M. Ernoult[2], D. Lecarpentier[5], N. Thiollière[2], Y. Richet[4], L. Tillard[4], W. Zhou[1], A.-A. Zakari-Issoufou[2]
1- CEA, 2- CNRS, 3- Framatome, 4- IRSN, 5-EDF,

- ***Nuclear fuel cycle scenarios give access to a wide range of data, such as mass balances, material flows, natural resources consumption, spent fuel and separated materials inventories, etc. Their ability to make projections of industrial strategies makes them a powerful decision-making tool. As such, they are widely used by the utilities, industrials and academics in order to help deciding the feasibility, relevance and performance of scenarios.***

As any simulation, scenarios are subject to uncertainty, generated, inter alia, by nuclear data, industrial processes and decisions, economics and politics. The impact of known uncertainties on scenarios can sometimes be assessed using conventional methods, such as Monte-Carlo sampling, often coupled with the use of depletion surrogate models in order to speed-up the computation. Previous studies have shown that in the case where the constraint on facilities, such as separated material stockpiles, is strong, the feasibility of the scenario is impacted by uncertainties.

The principle of the robustness methods is to identify policies (or levers) that can be adapted throughout time in order to counter the effect of perturbations, or to adjust the scenario into a different but still desirable trajectory. In that case, the robustness does not describe the inertia of the scenario, but quantifies its flexibility and reorganization capabilities when addressing perturbations, which seems more convenient given the secular timeframe of fuel cycle scenario studies.

In this work, we provide a methodological analysis of straightforward uncertainty propagation techniques and robustness. We first define a scenario simple enough to bear a predictable behavior, while still being representative of scenarios of interest in the case of the French fleet. The variables are defined, and the scenarios deemed satisfactory are characterized. Then, a perturbation is applied and its impact on the objective is evaluated using straightforward techniques. Finally, a set of levers are identified among the parameters, and a robustness strategy is tested, and the results are compared with the straightforward method.

- This study was performed simultaneously using two distinct nuclear fuel cycle scenario codes:
  - COSI6, developed by CEA ;
  - CLASS, developed by CNRS and IRSN.

Notes

Strategies for the uncertainty quantification of fuel cycle scenarios

A.V. Skarbeli and F. Alvarez-Velarde
CIEMAT, Avd. Complutense 40, 28040, Madrid
aris.villacorta@ciemat.es

- ***Fuel cycle simulators tools are fed by a large number of variables with a non-trivial mathematical relationship between them. When an electronuclear scenario is defined, the uncertainties in the input parameters are propagated through the simulation so at the end of the scenario, their impact on the studied outputs can be strong.***

Uncertainty quantification addresses for the study of the dependence of the input variables uncertainties in the simulation results. Two different approaches can be differentiate: local methods, where a small region of the input domain is mapped (Sensitivity coefficients, a first order approximation), and global methods, where the whole domain is perturbed (Sobol variance decomposition). The second ones are desirable since they can provide more information (like the interaction between input parameters or the existence of non-linear effects).

Moreover, as they make no assumption on the underlying distribution of the input uncertainties, the theory can be applied directly to discrete variables.

The main drawback of the global sensitivity analysis is the excessive computational costs. The Sobol indices estimators are integrals defined in a multidimensional space that grows with the number of parameters considered. Intuitively, the first approach for solving these problems is Monte Carlo sampling since its convergence does not depend on the problem dimension. However, when the execution time of the fuel cycle simulator is taken into account, the convergence can be not fast enough.

In this paper, other approaches for the calculation of the Sobol indices are presented. They include different sampling techniques that speed up the convergence, or the build of a surrogated method from whose the desirable information can be derived with no extra computational cost.

Notes

Impact of Macro Reactor Approximation on Scenario Modelization in C.L.A.S.S

A.-A Zakari-Issoufou, M. Ernoult, X. Doligez
Institut de Physique Nucléaire d'Orsay, CNRS/IN2P3

- *Typical nuclear scenarios usually consist in describing the power share over time between different reactor generations or fuel types. In CLASS, simulating such scenarios mostly relies on defining one big (macro) reactor by technology or by fuel usage with respect to the scenario path. Following this principle, we are assuming for example that all reactors (in one macro) start at the same moment and with the same cycle time before discharge.*

While this simplifies the simulation, it can prevent a complete overview on what a scenario implies, especially in term of fuel supply : we might be rejecting scenarios because of a lack of fissile but only because the refueling of a macro reactor artificially demands more fuel.

In order to evaluate the approximation of macro reactor model, we propose to assess a simple nuclear fleet with reactors using UOx and MOx fuel.

Firstly by simulating macro reactors and then with a more detailed description by reflecting single reactors with an independent starting time or cycle time. The result of this analysis regarding available fissile or mis-loadings effects will be presented at this workshop.

Notes

Functionality Isolation Tests

N. Thiollière[1], B. Mouginot[2], X. Doligez[3], B. Feng[4], E. Davidson[5], R. Hays[6]
1 – Subatech, IMTA-IN2P3/CNRS-Université, Nantes, France
2 – University of Wisconsin-Madison, U.S.A.
3 – Institut de Physique Nucléaire d'Orsay, France.
4 – Argonne National Laboratory, U.S.A.
5 – Oak Ridge National Laboratory, U.S.A.
6 – Idaho National Laboratory, U.S.A.

- ***Fuel cycle simulators are used worldwide to provide scientific assessments of future fuel cycle strategies. These tools help analysts and stakeholders understand the fuel cycle physics and the most impactful drivers on a system level. A lot of different fuel cycle simulation tools are developed by nuclear engineering and research institutions [1,2,3,4,5,6,7].***

The level of detail of these available tools ranges from the simple spreadsheets to complex coupled codes. Verifications among these tools have been attempted through numerous benchmarks [8,9], which generally involved complex/realistic scenarios in which the exact causes of differences were difficult to pinpoint.

The proposed Functionality Isolation Tests aim to aggregate the international fuel cycle simulator community in order to build an easily-accessible online mechanism for detailed verification effort. By specifying very simple unit tests (e.g., single reactor instead of fleet, one event instead of several) and detailed accounting for all differences between results from participating codes, the FIT project will allow the community to better understand the potential impact of specific modeling choices on the fuel cycle output metrics. Some of these choices include modeling of fleet-based reactors versus agents, continuous mass flows versus discrete, use of fuel recipes versus coupling with depletion, etc.

The first of the proposed unit tests within FIT has been completed. These tests are based on models of a single PWR or SFR. The exercise has been designed to test various Fuel Loading Models (FLMs) used to predict the plutonium content required in MOX fuel loaded in such reactors. A focus is made on the comparison for output calculated from complex FLM versus using a constant fissile fraction.

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Notes

Panel Discussion (Re)thinking the future of nuclear energy – How to design and use energy scenarios to better inform policy decisions?

Moderators: Stéphanie Tillement & Benoit Journé

Panelists: Christian Bataille, Peter Lyons, Jacques Repussard

Notes

Panel Discussion
How to design and use energy scenarios to better inform policy decisions?

Moderators: **Stephanie Tillement & Benoit Journé**
stephanie.tillement@imt-atlantique.fr

Panelists: **Christian Bataille (French Parliament, OPECST), Peter Lyons (US Senate, NRC) & Jacques Repussard (IRSN, ETSON)**

- INTRODUCTORY REMARKS – AIM OF THIS PANEL DISCUSSION
- In the current context of "energy transition", one conclusion emerges: forecasting, planning and prospective studies become more prevalent to inform decisions, and consequently, the associated tool, i.e. the scenario, plays an increasingly important role. Yet, little is known about the real contribution of scenario in decision-making processes: do they really inform decisions? Do politicians really have access and consult scenarios? Do they support discussion and cooperation, as well as the development and enhancement of expertise, among the different groups involved?
- With these fundamental issues clearly in mind, the **objective of this panel discussion is twofold**: 1) confront the first results of social sciences researches conducted on the link between scenarios & political decisions to Experts involved in decisions related to nuclear energy; 2) going further by engaging international discussions and first comparison between France and USA on these topics.

- KEY THEMES & QUESTIONS (1H)
- *At the beginning of the panel discussion, the participants will have a dedicated time to introduce themselves and explain how they have faced the question of scenario in their professional career. (10 min)*
- **Theme 1 – The organization of nuclear related decision-making processes: France & USA (15')**
- **Theme 2 – Evaluation process and use of energy scenario to support policy decisions (15')**
- **Theme 3 – Decision-making processes & the nuclear field: what specificities & challenges? (15')**
- *The panel discussion will be followed by 45 minutes of open discussion with attendees.*

Notes

Scenario studies and non-proliferation

Paul P.H. Wilson

Notes

Modeling JCPOA breakout using Cyclus

Baptiste Mouginot, Kathryn Mummah, **Paul P.H. Wilson**
University of Wisconsin-Madison

- ***While most of the actual fuel cycle simulator usages are dedicated to the simulation of prospective scenarios, aiming to evaluate different fuel and reactor technologies against/with one another, fuel cycle simulators could be used as well on non traditional research, such as non proliferation safeguard. Fuel cycle simulation software can indeed be used to explore possible nuclear material diversion paths, and help to define new safeguard against nuclear proliferation.***

This works take advantages of the recently development high fidelity enrichment cascade[1] and the Dynamical Resource Exchange (DRE)[3] built-in the Cyclus fuel cycle simulator[2] to compare different ways to produce HEU in Iran.

The Cyclus DRE, allows the exchange of material/commodities between the different facilities inside the simulation, resolving the market problem of offers and request issued by the facilities. In addition to the DRE, the Cyclus fuel cycle simulator is designed to support the dynamic addition novel facility models into fuel cycles. The CascadeEnrich archetype was developed to model gas centrifuge enrichment cascades at a high fidelity relying on individual centrifuge and cascade design parameters to build an ideal cascade configuration. Once a CascadeEnrich facility is deployed, it may be asked to participate in the fuel cycle at a variety of flow rates and enrichments over time, constrained by the initial design of the cascade.

Since 2015, the Joint Comprehensive Plan of Action (JCPOA)[4] limits the Iranian nuclear program in exchange for a lift on some of the economics sanctions placed on Iran. The JCPOA agreement allows Iran to use only 5060 centrifuges (from the 19000 theoretically available) in no more than 30 cascades and to keep its level of uranium enrichment at up to 3.67%.

This work will study the possibility and the rate of HEU production, while only using enrichment cascade designed with in the agreement (i.e. product enrichment with natural uranium feed up to 3.67%, with multiple cascade using between 167 and 5060 centrifuges), aiming to highlight potential fast path for high enrich uranium production.

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Notes

Nuclear diversion scenario within the functional uncertainties

Baptiste Mouginot, Kathryn Mummah, Paul P.H. Wilson
University of Wisconsin-Madison

- ***Fuel cycle simulations, as any simulation process, do not produce results without errors. Those errors have different sources: data uncertainties (when the simulation relies on previously estimated/measured metrics), modeling uncertainties (produced by the simplification made by the simulator) and the "functional" uncertainty (uncertainty on the input parameters and/or metrics).***

While all of them need to be precisely accounted, the present research aims to assess the impact of the functional uncertainty to the different output metrics, specifically focuses on metrics related to non-proliferation. The work aims to estimate the possibility and the speed of material undetected diversions within the error due to those functional uncertainty, determining to which extend nuclear countries/organisations could conduct undetected material diversion. Ultimately this should allow to define a list of observables and associated uncertainty required to detect potential nuclear material diversions.

This specific work try to assess the impact of the functional uncertainties of a simple transition inspired from the EG23 of the FCO campaign: a transition from light water reactors fleet loaded with UOX fuel to a sodium fast reactors fleet loaded MOX fuel, considering an exponential grows of the generated power. The functional uncertainty considered here are: cooling time, burnup, UOX enrichment, tail assays and separation efficiency.

This work will be performed within the Cyclus framework, taking advantage of the cyCLASS module allowing the usage of the CLASS model for fuel fabrication and on-the-flight burnup calculation, as well as some archetypes from the Cycamore modules. All Cycamore and CyCLASS archetypes have been updated to deal with functional parameter uncertainties.

Notes

Nuclear archaeology: Reconstructing past fissile material production using measurements and fuel cycle simulations

Malte Göttsche, Antonio Figueroa
Aachen Institute for Advanced Study in Computational Engineering Science (AICES) RWTH Aachen University Germany

- ***Today, there is a lack of methods to verify baseline declarations of fissile material holdings. This would for instance be relevant for new states joining the Non-Proliferation Treaty with existing nuclear programs. One method is the attempt to reconstruct the past fissile material production. This approach is called nuclear archaeology.***

If a state provided detailed operational records to inspectors, they could be checked for consistency and plausibility using fuel cycle simulations. Measurements in shut-down nuclear facilities and radioactive wastes could yield additional information. With regard to plutonium production for example, neutron activation assessments of permanent reactor components in or near the core could be used to calculate the reactor's neutron fluence, which is related to the amount of produced plutonium. Measurements of the volume/mass and isotopic concentration of high-level waste can provide further information on reactor operations. Such measurements could be useful in the case where information from provided records are insufficient or not trust-worthy. They could also be useful in combination with provided records, by enabling additional consistency-checks.

To make best use of the various sources of information, including from records and measurements, new models and tools are needed to integrate them into an overall fissile material assessment. Such models and tools should be designed in such a way that they use the available information to minimize the uncertainty of the overall estimate. One approach may be a combination of forward-simulations of fuel cycle operations and inverse analysis based on measurement results, perhaps in an iterative manner. While uncertainties of several percent may remain, such an approach may help inspectors to at least understand and perhaps even reduce uncertainties that fissile material-producing states declare to have.

Notes

Integration Modeling to Decipher a fuel cycle

Romarie Morales Rosado, David Vermillion, Jereme Haack, Matthew Oster, Siddharth Manay, Ryan Goldhahn, Braden Soper, and Paul Whitney

- *The objective of this project is to evaluate methods for nuclear non-proliferation assessments – in particular, detect undeclared nuclear facilities using computational models of the nuclear fuel cycle that integrate information from multiple characteristics. Some key questions we aim to address are: Can we produce a mechanism that identifies facilities of interest? Can disparate observations from different characteristics or facility associations be combined to create data products with superior information content?*

What methods quantify relative confidence that a suspect facility is a 'facility of interest'? What methods quantify the relative value of characteristics and collections?

To this end we used several model case scenarios that included the phases of uranium production facilities. Inside each facility we have information on the input, if the facility is operational (on/off), resources needed for production, product output, and waste material. In order to address one of our key questions we labeled some of the facilities as unknown. Known and unknown facilities had similar production information. We used Netlogo for an initial visualizations and transportation displays between facilities. We used Python software to simulate the production movement within the facility and connections with other facilities.

To this end we implemented computational modeling and inference methods to integrate sparse remote sensing information across a manufacturing chain to draw stronger inferences about the activities at unknown facilities.

We applied machine learning and deep learning tools in order to classify the location of origin of the facilities of interest. For the facility classification we used two sequences of a three component parallel model. We omitted the information of the first two components of one of the sequences. We obtain an accuracy higher than 0.9. Some natural next steps will be to expand to other model sequences, understand the impacts of misspecifications for the models, and quantify the impacts of incomplete data.

Facility classification was also performed using hidden Markov models (HMM) to model the time-dependent observables of an exhaustive set of possible facility types. Bayesian inference methods are presented to select the model and state sequence that best explains the observed data from the unknown facility. The effect of missing data, and model uncertainty will be quantified for several test cases.

Notes

Fuel Cycle Systems Scenario Analysis: Recycling LWR Plutonium in Thorium Fuelled PT-HWRs

D. Wojtaszek*, A.V. Colton, B.P. Bromley, G.W.R. Edwards, A. Levinsky
*Canadian Nuclear Laboratories, 286 Plant Road, Chalk River, ON, Canada, K0J 1J0

- ***Thorium-based fuel cycles offer many potential benefits, including improved long-term energy sustainability, and improved waste management characteristics, relative to uranium-based fuels.***

The purpose of this study was to assess the impact of two plutonium-thorium (Pu,Th)O2 fuel concepts on the electrical energy that could be generated by recycling plutonium from the spent UO2 fuel from a fleet of one hundred 900-MWe-class Light Water Reactor (LWR) into a fleet of 700-MWe-class Pressure Tube Heavy Water Reactors (PT-HWRs). The impact on the inventory of plutonium in the fuel cycle, and the stockpile of 233U (and 235U) that is produced are also presented. The fuels that were analyzed include a low-burnup option using 3.5 wt% PuO2/(Pu,Th)O2, giving an exit burnup of 23.6 MWthd/kg, and a high-burnup option using 4.5 wt% PuO2/(Pu,Th)O2, giving an exit burnup of 36.4 MWthd/kg.

The scenario involved the deployment of plutonium recycling facilities (i.e., a UOX separations plant, and a (Pu,Th)O2 fabrication plant), each with a 25-year lifetime and sufficient maximum throughput to reprocess all spent UOX fuel from a fleet of LWRs and to produce fuel for the fleet of PT-HWRs. These plutonium recycling facilities and the PT-HWR fleet were deployed as early as possible in order to minimize the decay of plutonium (Pu-238 to U-234, and Pu-241 to Am-241) prior to recycling, and thus maximize the energy generated by the PT-HWRs.

The scenario was implemented using the CYCLUS fuel cycle simulation toolset, in which there were two separate cases: 1) all PT-HWRs were fuelled with the lower burnup (23.6 MWthd/kg) (Pu,Th)O2 fuel, and 2) all PT-HWRs were fuelled with the higher burnup (36.4 MWthd/kg) (Pu,Th)O2 fuel. The fleet of 100 LWRs producing spent fuel had a total life-time generation of 1080 TWe-days. In this scenario, the following results were observed for the two cases.

The higher burnup (Pu,Th)O2 fuelled PT-HWR fleet produced more electricity (183 TWe-days from 34 reactors) and burned more plutonium (69% reduction in Pu inventory) than the fleet with lower burnup fuel (156 TWe-days from 26 reactors, and 61% reduction in Pu inventory). The lower burnup (Pu,Th)O2 fuelled PT-HWR fleet produced 226,079 kg of fissile uranium (235U, and 233U with 233Pa precursor), whereas the higher burnup fuel produced 209,738 kg of fissile uranium.

Notes

Impact of Technology Characteristics on Transition to a Fast Reactor Fleet

Edward Hoffman
Argonne National Laboratory
ehoffman@anl.gov

- *Under the Evaluation and Screening study, the continuous recycle of uranium and transuranics in fast reactors was identified as one of most promising nuclear fuel cycles in the United States. The transitions to the most promising fuel cycle from the current nuclear fleet deploying a fleet of solid-fueled sodium-cooled fast reactors (SFRs) and liquid-fueled molten-salt-cooled reactors (MSRs) under the same conditions and designed for the same objectives have been evaluated, and the transition performance related to the fuel form characteristics in fast spectrum critical reactors was compared in this study.*

The availabilities of the technologies and required fissile materials are the two general constraints on transition. Both must be satisfied in order to transition as desired. The availability of the technology will likely be a major factor. Informing on timing of availability of different technologies is beyond the scope of this analysis.

The focus of this study is on technology characteristics that are likely to be impacted by the choice of SFR or MSR. Specifically those characteristics that will have the biggest impact on the supply of and demand for fissile material. There are three factors that are likely to have the most significant impact on the time-dependent supply and demand of fissile material. These are the amount of fissile material required to deploy a given capacity, the additional material needed to transition from the deployment of that new capacity to its steady-state average system inventory, and the maximum practical fissile material net breeding rate that is achievable.

Each factor is a combination of physics and practical design choices. With little practical experience to reference, a range is considered for each factor and performance was evaluated over a range of possible future scenarios. This will help inform on the importance of different approaches and design choices within the range of anticipated technology options allowing designers to factor in these considerations.

The results show how important design considerations can impact transition behavior. The range of designs that seem plausible at this stage of development for each reactor technology (whether SFR or MSR) will yield larger differences than those between a consistent comparison between MSRs and SFRs. The apparent best designs, in terms of transition, for both MSR and SFR-based systems give comparable performance, but they may imply potentially costly design decisions to achieve that performance. If a large fleet is to be deployed, these considerations could play a major role. The impacts over a range of scenarios will be summarized.

Notes

On the use of plutonium burning fast reactors to reduce PWR irradiated assemblies' stockpile

Timothée Kooyman
DEN/DER/SPRC, Bat 230 CEA Cadarache 13108 Saint Paul lez Durance CEDEX
timothee.kooyman@cea.fr

- ***Plutonium recycling as currently implemented in the French nuclear fuel cycle leads to the storage of irradiated MOX fuel assemblies. Deploying a limited number of fast reactors (SFR) by the end of the century may limit the growth of this stockpile while a further increase in the number of SFRs would lead to the stabilization of the plutonium inventory and then the closure of the fuel cycle.***

Considering the flexibility of fast reactors in terms of plutonium loading and consumption, this paper investigates the possibility of replacing the initial fast reactors by so-called CAPRA cores, which are designed to consume significantly more plutonium than breeder reactors. This deployment would allow a faster reduction of the PWR spent fuel stockpiles and a lower total plutonium inventory stored in spent fuel. It is shown here that compared to the current approach in which the stockpile level is merely stabilized by 2090, a reduction by 1000 to 1900 t of spent PWR assemblies can be achieved by the same date by deploying 2 SFR CAPRA by 2065. However, this reduction is achieved at the cost of a significant increase in the fuel reprocessing and manufacturing capabilities which must be further characterized. The total amount of plutonium stored in PWR and FR assemblies is only slightly modified compared to a reference case (-1 %). This however has a positive impact on the minor actinides inventory, which decreases by 8 to 13 %.

In a second step, various equilibrium situations where plutonium produced in thermal reactors is consumed in CAPRA cores are analyzed. It is shown that using such a symbiotic fleet with PWR and SFR CAPRA, it is possible to achieve a stabilization of the plutonium inventory between 572 and 643 t of plutonium with between 12 to 18 fast reactors to be deployed along UOX-fueled PWR. The performances achieved depends on the plutonium consumption of the CAPRA core considered (-24 kg/TWhe to -55 kg/TWhe). Current industrial scenarios consider the deployment of 16 fast reactors to stabilize the plutonium inventory, but with a PWR fleet operating with around 34 % of MOX fuels. However, as this inventory is significantly lower that the inventory associated with a complete fleet of fast reactors operating in a closed fuel cycle (around 1260 t), conversion of the burner cores would be required to allow deployment of additional fast reactors. It is concluded here that no significant reduction of the number of SFR necessary to stabilize the plutonium inventory in the fuel cycle can be achieved by using CAPRA cores.

Notes

Practical information

- **Website**
  https://indico.in2p3.fr/event/16854/overview

- **e-mail:**
  fuelcycle.workshop.2018@gmail.com

- **Wifi connection:**
  - WIFIAP18
  - internet

Participants list

Last Name	First Name	Affiliation
Akdag	Yasar	Université de Nantes, LEMNA
Baschwitz	Anne	CEA I-tésé
Bataille	Christian	French Parliament
Bernard	Franck	IRSN
Bidaud	Adrien	CNRS/IN2P3
Brolly	Aron	Centre for Energy Research, Hungarian Academy of Sciences (MTA EK)
Brovchenko	Mariya	IRSN
Brown	Nicholas	Pennsylvania State University
Chmielarz	Blazej	KTH, USNC Europe
Cissokho	AHMET	Ecole Technique de Tambacounda
Clavel	Jean-Baptiste	IRSN
Courtin	Fanny	CEA
David	sylvain	CNRS
Davidson	Eva	ORNL
Ding	Congjin	Royal Institute of Technology - KTH, Stockholm
Dixon	Brent	Idaho National Laboratory
Doligez	Xavier	IPNO-IN2P3-CNRS
Druenne	Hubert	Tractebel Engineering S.A.

Participants list

Last Name	First Name	Affiliation
Dumonteil	Eric	IRSN
Ernoult	Marc	CNRS/IN2P3 – IPNO
Eschbach	Romain	CEA
Evo	Stéphane	IRSN
Flanangan	Robert	University of South Carolina
Göttsche	Malte	AICES Graduate School, RWTH Aachen University
Gudowski	Waclaw	Royal Institute of Technology
Halász	Máté	Budapest University of Technology and Economics
Hoffman	Edward	Argonne National Laboratory
Hrabar	Yuliia	Participant
Jacqmin	Robert	CEA
Journe	Benoit	Université de Nantes
Kieta	Pa Modou	Gambia Technical Training Institute
Krauth	Mihael	French Parliament
Krivtchik	Guillaume	CEA
Lemiale	Lionel	LEMNA – Université de Nantes
Livnat	Yarden	University of Utah
Loisel	Rodica	Université de Nantes, LEMNA

Participants list

Last Name	First Name	Affiliation
Lyons	Peter	US Department of Energy
Mang	Florian	IRSN
Mantulet	Gabin	LPSC IN2P3
Mima	Silvana	CNRS-GAEL
Miranda	Philippe	CEA
Morales Rosado	Romarie	Pacific Northwest National Lab
Mouginot	Baptiste	University of Wisconsin-Madison
Philippe	Marc	IRSN
Repussard	Jacques	Former IRSN
Senentz	Gérald	Orano
Sim	Ki Seob	IAEA
Thiollière	Nicolas	IMTA - CNRS
Tillard	Léa	IRSN
Tillement	Stéphanie	Université de Nantes
Timothée	Kooyman	CEA Cadarache
Tkaczyk	Alan	University of Tartu
Vermeeren	Bart	Tractebel Engineering S.A.
Viette	Arthur	

Participants list

Last Name	First Name	Affiliation
Villacorta Skarbeli	Aris	CIEMAT
Wilson	Paul	U. Wisconsin–Madison
Wojtaszek	Daniel	Canadian Nuclear Laboratories
Zakari-Issoufou	Abdoul-Aziz	CNRS

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