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INTRODUCTION

Fuel cycle simulations, as with any simulation process, do not produce results without errors. Those errors have different sources: data uncertainties (from the simulator's reliance on previously estimated/measured metrics), modeling uncertainties (from simplifications made by the simulator) and the "operational" uncertainty (from the operation parameter uncertainties of different facilities).

Simulation errors are important in the context of treaty verification. Some scenarios require estimating historical fissile material production based on records of facility operation and material transfer. If the measurements of facility operation and material transfer are subject to uncertainty, the total production quantities will then also be uncertain, creating an opportunity for undetected diversion. This study seeks to understand which measures of facility operation have the most impact on the uncertainty of fissile material production across a complete fuel cycle. To accomplish this, a Total Monte Carlo methodology will be applied to the Cyclus fuel cycle simulator [1] to estimate the effect of individual facility uncertainties on the output metrics.

THE EXPERIMENT

Method

To estimate the uncertainty of fuel cycle output metrics, a Total Monte Carlo approach has been applied. In the following, output metric uncertainty corresponds to the standard deviation of the output metrics from 199 different simulations. For each deployed facility, the parameters are normally distributed with an artificially large standard deviation of 10%.

To pursue this work, both the Cycamore[2] package[1] and the CyCLASS[2] were updated[4, 5] to evaluate the uncertainty of several operational parameters in their associated facilities. Table I summarizes all uncertainty-tracking modifications implemented in the facilities of Cycamore and CyCLASS.

TABLE I. Summary of facility modifications according to their source package.

Package	Facility	Parameters
Cycamore	Separation Storage	Separation efficiency Residence Time
CyCLASS	Reactor	Cycle Length Power Fuel Enrichment (PWR-UOX)

[1]Low fidelity facilities package for Cyclus
[2]Reactor and fuel fabrication facility based on CLASS[3] models

The uncertainty of the different parameters in this study are systematic for each new deployed facility: each time a new facility is deployed (such as a reactor or a fuel fabrication facility) a new set of parameters are computed.

The Fuel Cycle Scenario

This work aims to assess the impact of the operational uncertainties of a simple transition, inspired from the EG23 fuel cycle of the Nuclear Fuel Cycle Evaluation and Screening Report[6]. Pictured in Figure 1, this is a transition from a light water reactor fleet loaded with uranium oxide fuel (UOX) fuel to a sodium fast reactor fleet loaded mixed oxide fuel (MOX) fuel, considering a 1%/y growth of the generated power (Figure 2).

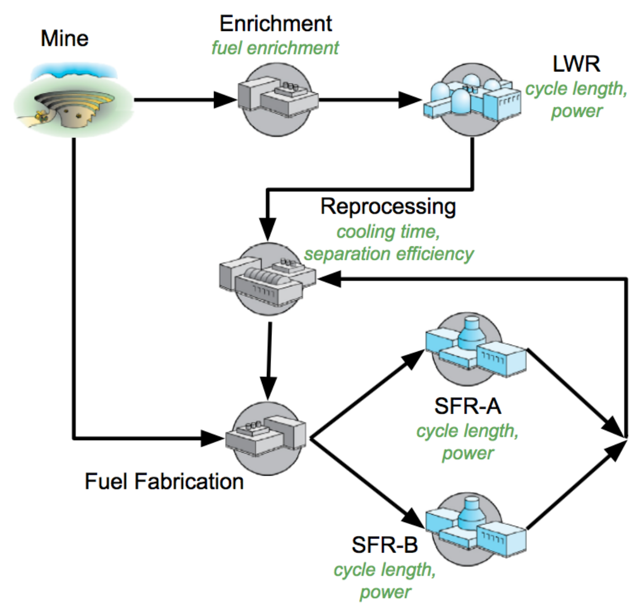

Fig. 1. Illustration of the material flow between the different facilities, with each operational parameter associated with an uncertainty labeled in green.

As illustrated in Figure 2, the transition starts with a fleet composed of only light water reactors (LWRs) loaded with enriched UOX fuel. The actual transition starts around year 35, with the deployment of fast breeder reactors (FBRs). The FBRs are loaded with MOX, which consists of plutonium blended with natural uranium.

The plutonium, required for MOX fabrication, is reprocessed from all used fuel. At first, it is sourced only from UOX, then used MOX fuel as it becomes available for reprocessing.

Both fuel reprocessing and fabrication are done at a constant rate (constrained by the feed material availability). The

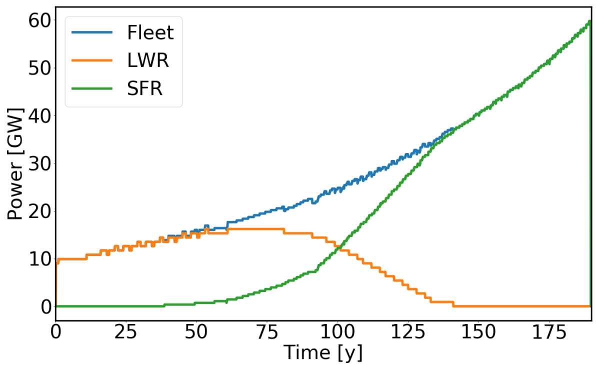

Fig. 2. Electric power generated over time, with the full production, the LWR contribution, and the FBR contribution labeled in blue, orange, and green, respectively.

enrichment of the UOX is processed on demand. Buffer storages (not shown in Figure 1) are present between all facilities with constant processing rates.

In this work, a time step of 1 month has been considered, i.e., each output metric is reported once per month. Additionally, decay processes have not be taken into account.

It must be noted that for this work, the fuel enrichment was determined by a fuel fabrication model[7] which calculates the fissile fraction required in the fuel to reach a target burnup at the end of irradiation. Therefore, the uncertainty of the fuel enrichment is not applied directly to the effective enrichment. It is instead applied to the burnup, which leads to a fuel enrichment uncertainty close to 10%.

RESULTS

The main interests of nuclear archaeology involve highly enriched uranium production and fissile inventories, so this study mainly focuses on the uncertainties of the total quantity of natural uranium used and the total unused fissile inventory (unused reprocessed plutonium). Generated power is also briefly being investigated to ensure the overall uncertainty is not contaminated with a missed fuel loading, which could be interesting but is not the focus of this work.

For this study, the 199 simulations were performed six times, and a reference calculation was also computed. With the five parameters in Table I (separation efficiency, residence time, UOX fuel enrichment, reactor cycle length, reactor thermal power) being tracked, the six sets are divided as follows: five sets where a single parameter is varied and the four others remain fixed, and one with all five parameters being varied. The reference calculation is a single simulation with all five parameters fixed at the mean value.

In the following, each total uncertainty is reported at $\pm 1\sigma$ around the mean values of the corresponding uncertainty set at each time step. The time-dependant relative uncertainties are computed as the standard deviation of a single set over its mean value at the corresponding time.

Generated Power

By construction, the very low uncertainty (Figure 3) on the generated power is expected.

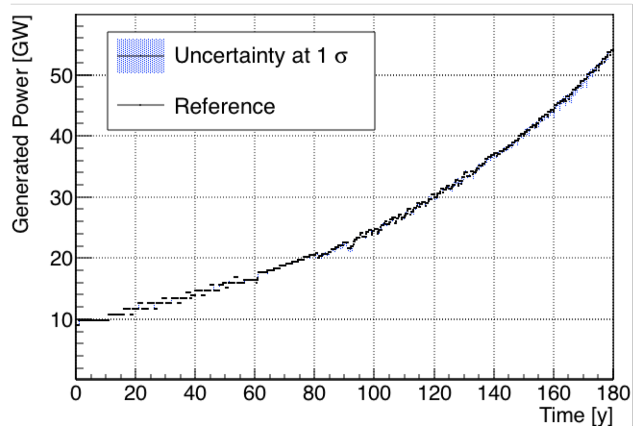

Fig. 3. Electric power generated as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

Indeed the transition scenario has been designed to allow all the reactors to receive the fuel as needed allowing them to be producing power all the time. This ensures that the uncertainty measured any other parameters is not influenced by the reactors miss-loadings. As FBRs fuel is built from reprocessed used fuels, the availability of those used fuels may impact the capability to build the required MOX-FBR fuel. Having reactor miss-loads, may impact more miss-loading later during a simulation and lead to a snow-ball effect. Having a small uncertainty on the power generation ensures large miss load effects are not to be considered here.

Natural Uranium Consumption dedicated to PWR-UOX fabrication

Figure 4 represents the cumulative natural uranium consumption dedicated to PWR-UOX fuel fabrication as a function of time. The uncertainty on the cumulative uranium consumption grows as expected with the time and the loading of the LWRs. The increase stops around year 125y with the decommissioning of the last LWRs.

As expected, cooling time, separation efficiency and thermal power don't affect the natural uranium consumption. The uncertainty on the natural uranium consumption is dominated by the LWRs cycle length: shorter the cycle length is, the more fuel will be loaded.

The relative uncertainty of the total uranium consumption starts at about 5.5% a slowly drops and stabilise around 3%.

Uncertainty fluctuation of the full relative uncertainty can be observed before year 50. Those fluctuation are induced by the fuel loading: all reactors at the beginning of the simulation have synchronised cycle, this phenomenon disappears with the gradual decommissioning of the initial reactors, spread on 50 years.

The decrease of the cycle time uncertainty contribution,

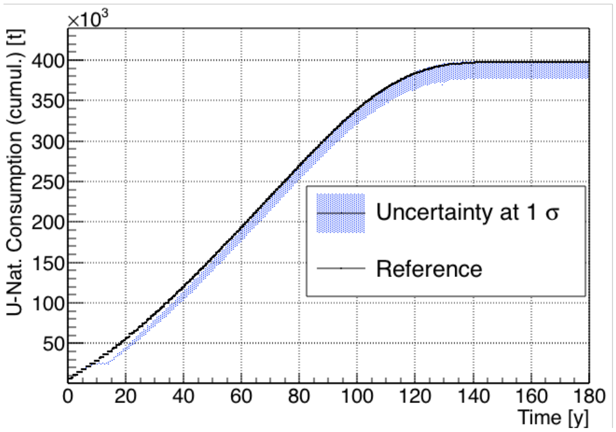

Fig. 4. Cumulative consumption of natural uranium as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

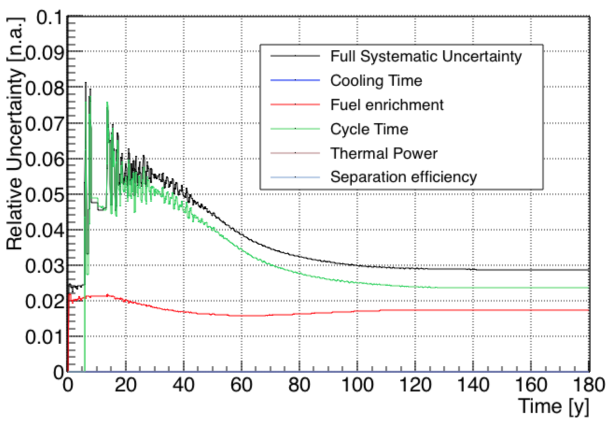

Fig. 5. Cumulative natural uranium consumption relative uncertainty, with in black the total uncertainty at 1σ, and in color the uncertainty contribution of each parameter: cooling time (blue), fuel enrichment (red), cycle time (green), thermal power(brown), separation efficiency (light blue).

from year 30 to year 90, can be understand as an averaging effect. As the uncertainty are considered as systematic per deployed facility, each reactor will have a different cycle length value, so a different number of loaded batches per year.With the increase of deployed reactors, the number of batches of LWRs fuel loaded converges to the references one, reducing its impact on the uncertainty on the total uranium consumption.

The fuel enrichment contribution follow a close to constant uncertainty contribution of 2%, so as the total relative uncertainty decrease, its relative contribution increases over time.

Fissile Inventory

The fissile inventory corresponds to the amount on separated fissile waiting to be blend with natural uranium in order to produce the FBRs MOX fuel.

As observed on Figure 6, the fissile inventory starts to grow on year 40, with the deployment of the first reprocessing facility. It grows during the first period of the LWRs to FBRs-A transition until year 90, then decrease slightly as the last LWRs are decommissioned. When he steady state is reached (full FBRs fleet), the plutonium inventory starts to increase, as the breading ratio of the FBRs is higher than the deployment needs.

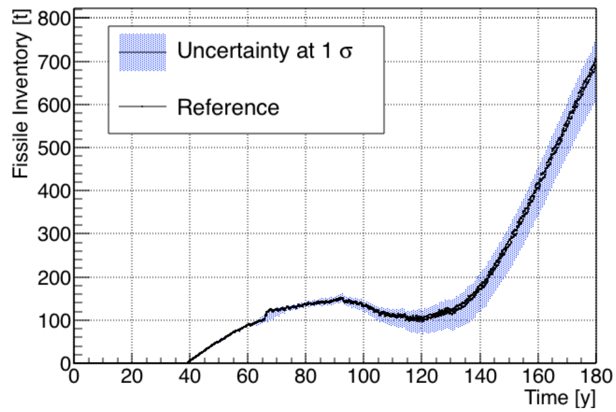

Fig. 6. Fissile (plutonium) inventory as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

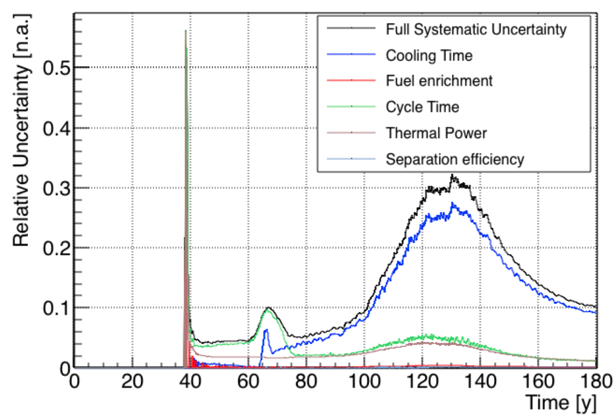

Fig. 7. Fissile (plutonium) inventory relative uncertainty, with in black the total uncertainty at 1σ, and in color the uncertainty contribution of each parameter: cooling time (blue), fuel enrichment (red), cycle time (green), thermal power(brown), separation efficiency (light blue).

Regarding the uncertainty, beside the low inventory artefact observable around year 40, the relative uncertainty starts at about 5%, and grows until year 125 to decrease up to 10% at the end of the simulation time (180y), it seems it would have reached an equilibrium between 5 and 10% with longer simulations... Between year 40 and 70, the main contributor to the fissile inventory uncertainty is the cycle length, as for the uranium needs, lower cycle length implies more fuel loads.

Never the less, around year 65 (see Figure 8), the stock of used fuel available for reprocessing starts to lack, and the availability of the used fuel starts to dictate the evolution of fissile in storage. The uncertainty weight is then slowly transferred from the cycle length to the fuel cooling time.

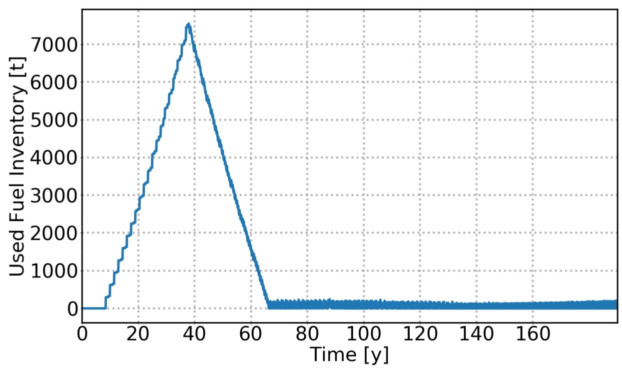

Fig. 8. Used fuel inventory, corresponding to the amount of used LWRs and FBRs fuel, cooled and waiting to be reprocessed.

Between year 90 and 120, the FBRs deployment speed increases, it has to compensate the non replacement of the decommissioned LWRs as well as follow the power demand. During this period the needs in plutonium are higher than its productions, explaining the observed decrease of the total amount, and the increase associated relative uncertainty.

As the transition ends, the plutonium breed from the FBRs starts to be sufficient to sustain the new FBRs deployment to follow the power demand.

It is also interesting to note that, the uncertainty contribution from the cycle length is between year 40 and 70 comes mainly from fuel batch loading frequencies, and after it relative contributions follows closely the thermal power one, suggesting a contributions through fuel discharge burnup (i.e. fuel discharge composition).

Discussion

Uranium consumption and separated fissile inventory are two important metrics regarding to non proliferation and nuclear archaeology. In this study, we have been able to estimate than the cycle length uncertainty of 10% implies a variation of 3% to 5% on the total uranium needs uncertainty, where $\approx$ 10% on the enrichment implies a almost flat uncertainty of 2%.

Regarding the reprocessed fissile inventory, this study has shown the limited impact of the reprocessed fuel compositions (through burnup variations) it limited to 5%, where fuel availability constrains, fuel loading frequency (cycle time), or fissile materials available for fuel fabrication (cooling time) can lead to higher uncertainties, respectively up to 10% and to 30%. Moreover it is very interesting to observe the pressure transition from one to the other around year 70.

This preliminary study may suggest that the most important contribution to natural uranium consumption and fissile inventory is coming from the time when occurs the different material exchange between facilities, and not necessary from the physical parameters such as thermal power or fuel enrichment. Further analysis should allow us to confirm or denies it.

CONCLUSION

Two main points can be deduced from this work. Firstly, in a transitional fuel cycle, the uncertainty contributions to an output metric can vary over time depending of various factors: deployment schedule artifact or pressure point in the material flows.

Secondly, it is important to note the special character of the time related parameters uncertainty in a fuel cycle study, such as cooling time and cycle length. Where some of those time related parameter will on the first order only impact material availability (as the cooling time will do), some other, like cycle length, will also have a impact as physical parameters such as fuel enrichment or thermal power.

Cycle length impacts the discharge fuel burnup, it also affects the frequency of the fuel loads, this, as well as the cooling may imply a uncertainty on the material availability, which could lead to an artificially large uncertainty. Those kind of time related uncertainties will require a careful analysis on further uncertainty analysis, in order to understand and measure accurately their contributions on uncertainties.

This study aims to be a proof-of-principle for uncertainty propagation in potential commercial fuel cycle transition. While it has demonstrated the capability to measure the uncertainty on output fuel cycle metrics and their relative contributions, it has only been applied to systematic uncertainties per facilities (parameters randomly generated at each new facility deployment). This kind of study will to be extended to random uncertainty (new parameter values at each occurrence) and completely systematic uncertainty (shared by all the facilities of a kind).

While the parameters contributing to natural uranium needs and fissile inventory uncertainties might be obvious, such study allows to estimate each parameters contribution, it could be less obvious for other parameters, such as plutonium quality, waste compositions. Such studies could also provide research guidance for nuclear archaeology works, which aims to precisely estimate past fissile production by the different nuclear countries.

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