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INTRODUCTION

Fuel cycle simulations, as with any simulation process, do not produce results without uncertainties. Those uncertainties have different sources: data uncertainties (from the simulator's reliance on previously estimated/measured data), modeling uncertainties (from simplifications made by the simulator). This work we will be focused a part of the data uncertainty related to the expected behavior of the facilities being simulated.

Simulation errors could be 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. Any uncertainty in fissile production quantities poses a material accounting challenge, possibly 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. Uncertainty propagation using a Monte Carlo method will be applied to the Cyclus fuel cycle simulator [1] to estimate the effect of individual facility uncertainties on the output metrics. The same simulation will be simulated *N* times, for each simulation parameters affected with an uncertainty will be randomly determined, the distribution of each output metrics over the N iterations of the simulation, will be used to estimate their respective uncertainty.

THE EXPERIMENT

Method

To estimate the uncertainty of fuel cycle output metrics, a Total Monte Carlo approach has been applied. In each of 199 independent simulations, some of the parameters that define facility behavior are randomly selected from Normal distributions with standard deviations that are 10% of the mean value. This artificially large standard deviation is selected for the purpose of demonstrating the methodology. The mean and standard deviation of some output metrics are calculated from the simulation output, as a function of time.

To pursue this work, both the Cycamore[1] [2] and the CyCLASS[2] [4, 5] packages were updated 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.

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 sampled, and those parameters are used throughout the life of that facility.

TABLE I. Summary of facility modifications according to their Cyclus archetype package.

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

The Fuel Cycle Scenario

For demonstration purposes, a simple commercial fuel cycle transition is used, 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 (LWR) fleet loaded with uranium oxide fuel (UOX) fuel to a fast breeder reactor (SFR) fleet loaded mixed oxide fuel (MOX) fuel, considering a 1%/y growth of the nuclear generated power (Figure 2).

As illustrated in Figure 2, the transition starts with a fleet composed of only LWRs loaded with enriched UOX fuel. The actual transition starts around year 35, with the deployment of SFRs. The SFRs 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 enrichment of the UOX is processed on demand. Buffer storage facilities (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 given 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%.

For each of the parameters in Table I, a set of 199 simulations was performed with only that parameter being randomly

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

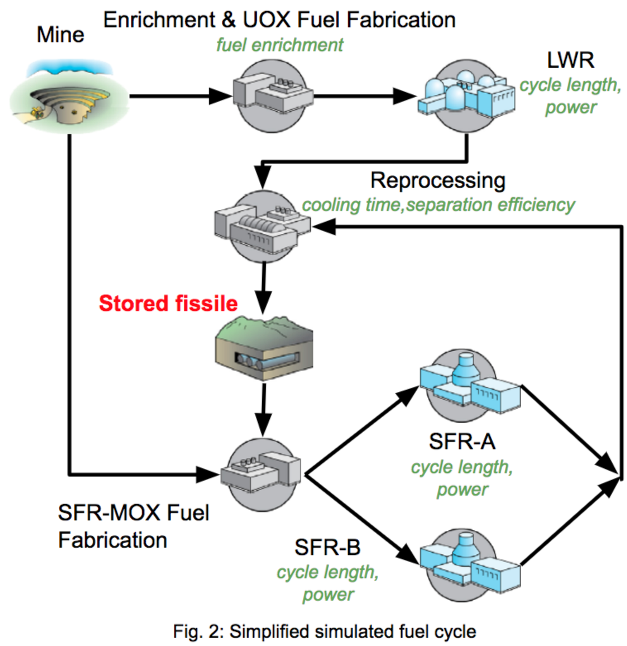

Fig. 1. Simplified representation of the material flow between the different facilities, with each operational parameter associated with an uncertainty labeled in green.

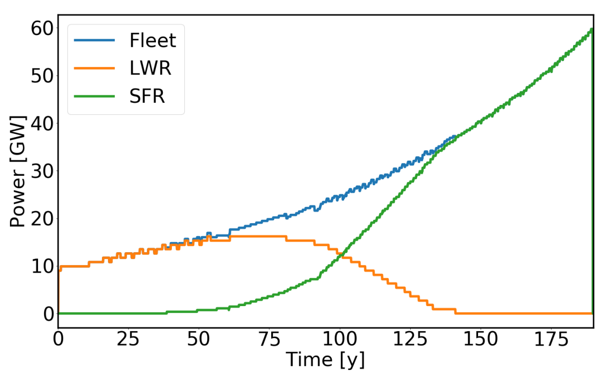

Fig. 2. Electric power generated over time, with the full production, the LWR contribution, and the SFR contribution labeled in blue, orange, and green, respectively.

varied. An additional set of 199 simulations was performed in which all five parameters are randomly varied. A reference simulation was performed with all five parameters fixed at the mean value.

RESULTS

Because the main interests of nuclear archaeology involve highly enriched uranium production and fissile inventories, 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 investigated to ensure the overall uncertainty is

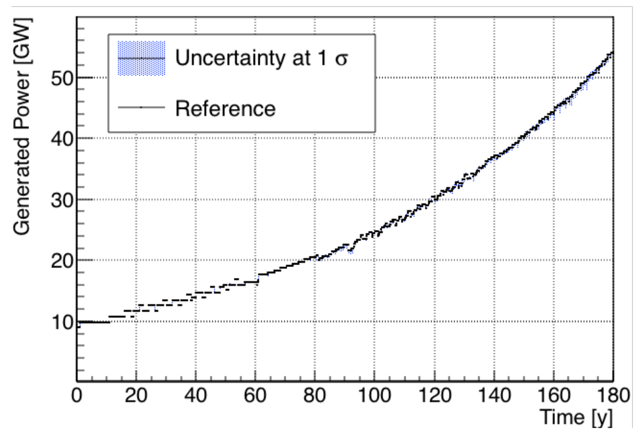

Fig. 3. Electric power generated as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

not contaminated with a missed fuel loading, which could be interesting but is not the focus of this work.

At each time step, the $\pm 1\sigma$ uncertainty due to the full set of varied parameters is reported. In addition, the relative contribution to the total uncertainty from each of the parameters is calculated as the ratio of the 1σ uncertainty due to that parameter over the total uncertainty.

Generated Power

By design, the very low uncertainty (Figure 3) on the generated power is expected. 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 measured uncertainty is not affected by a facility disruption that has an outsized impact on material flows. As SFR fuel is built from reprocessed used fuel, the availability of that used fuel may impact the capability to build the required MOX-SFR fuel. Facility disruptions may cause material shortages that can lead to snow-ball effect of more disruptions later in the simulation. While such disruptions are interesting in some analyses, they are outside the scope of this study.

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 do not affect the natural uranium consumption. The uncertainty on the natural uranium consumption is dominated by the LWR cycle length: shorter the cycle length is, the more fuel will be loaded.

The relative uncertainty of the total uranium consumption

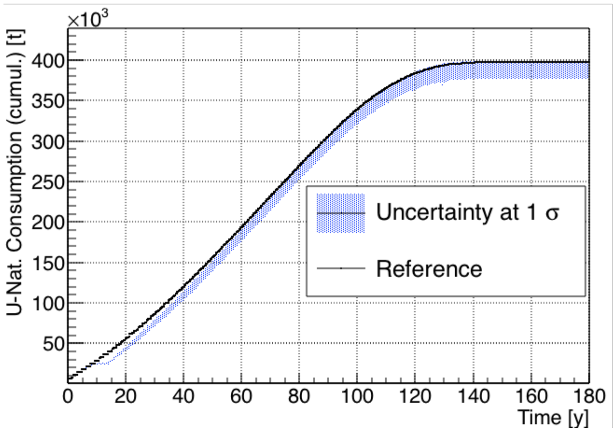

Fig. 4. Cumulative consumption of natural uranium as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

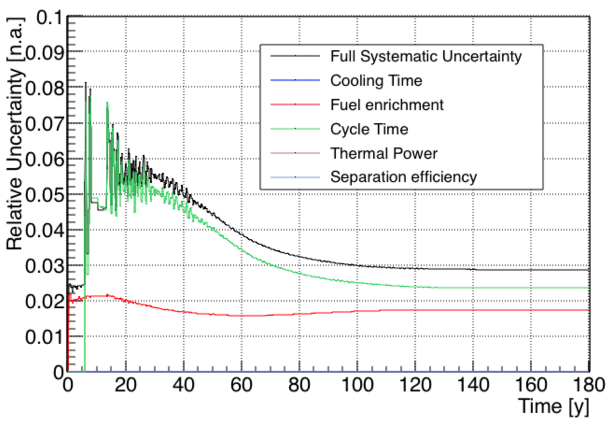

Fig. 5. Cumulative natural uranium consumption relative uncertainty, with in black the total uncertainty at 1σ, and in color the uncertainty contribution of each parameter: cooling time (blue), fuel enrichment (red), cycle time (green), thermal power(brown), separation efficiency (light blue).

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, from year 30 to year 90, can be understood as an averaging effect. As the uncertainty are defined once per deployed facility, each reactor will have a different cycle length value, so a different number of batches loaded per year. With the increase of deployed reactors, the number of batches of LWR 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, it has a growing shared of the total uncertainty over time.

Fissile Inventory

The fissile inventory corresponds to the amount of separated fissile material waiting to be blended with natural uranium in order to produce the SFR MOX fuel.

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

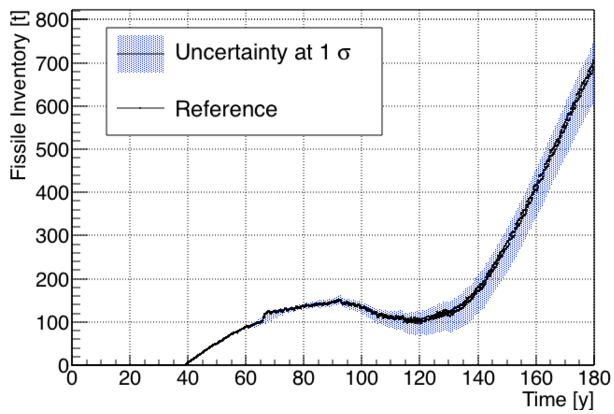

Fig. 6. Fissile (plutonium) inventory as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

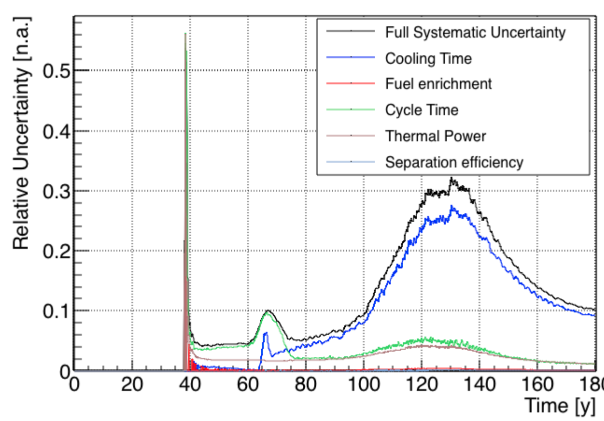

Fig. 7. Fissile (plutonium) inventory relative uncertainty, with in black the total uncertainty at 1σ, and in color the uncertainty contribution of each parameter: cooling time (blue), fuel enrichment (red), cycle time (green), thermal power(brown), separation efficiency (light blue).

Regarding the uncertainty, disregarding the artefact of a very low mean inventory observed at the onset of fissile material production, 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 with 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 becomes small enough to start limiting producton of fissile material. The uncertainty weight is then slowly transferred from the cycle length to the fuel cooling time.

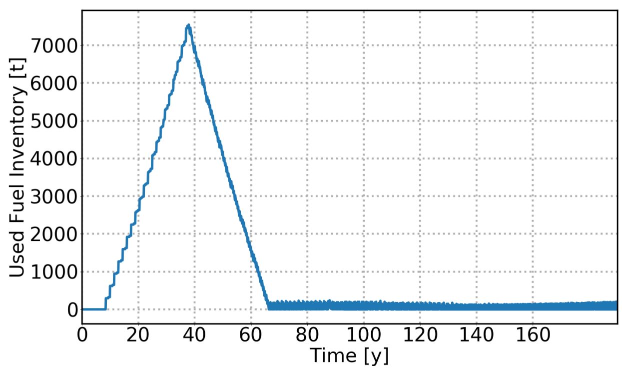

Fig. 8. Used fuel inventory, corresponding to the amount of used LWRs and SFRs fuel, cooled and waiting to be reprocessed.

Between year 90 and 120, the SFR 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 SFRs starts to be sufficient to sustain the new SFRs 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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