Assessing Material Inventory Uncertainties in Integrated Fuel Cycle Simulations

Baptiste Mouginot, Kathryn Mummah, Paul P.H. Wilson

University of Wisconsin-Madison, Madison, WI
mouginot@wisc.edu, mummah@wisc.edu, paul.wilson@wisc.edu

INTRODUCTION

Fuel cycle simulations, as with any simulation process, do not produce results without uncertainties. Those uncertainties have two main sources: modeling uncertainty due to the simplifications and approximations built in to the simulator itself, and data uncertainty from the quantities provided by the user. This work focuses on a subset the data uncertainty related to the user input that defines the performance of the simulated facilities.

Such simulation uncertainties 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 characteristics 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 performed *N* times, with some input parameters randomly determined in each case. The distribution of each output metrics over the N trials of the simulation will be used to estimate their respective uncertainty.

THE EXPERIMENT

Method

To estimate the uncertainty of fuel cycle output metrics, a 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/nominal 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.

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
		LWR-UOX Fuel Enrichment

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.

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 have a constant maximum throughput, but may also be limited by the availability input material. The enrichment of the UOX is processed on demand. Buffer storage facilities (not shown in Figure 1) are present between all facilities with constant throughput.

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. The targeted burnup is a operational parameter and does not necessary related to the actual achieved burnup (computed from the real cycle length and the thermal power of the reactor). Therefore, the uncertainty of the fuel enrichment is not applied directly to the effective enrichment. It is instead applied to the targeted

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

burnup, resulting in a fuel enrichment uncertainty that is also close to 10%.

For each of the parameters in Table I, a set of 199 simulations was performed with only that parameter being randomly varied. An additional set of 199 simulations was performed in which all five parameters are randomly varied, using one-factor-at-a-time (OFAT) method. 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 (separated plutonium).

The total power generated in the simulation is reviewed to ensure that none of the compounded uncertainties result in material shortages substantial enough to cause long term facility shutdowns. For example, since SFR fuel is built from reprocessed used fuel, availability of that used fuel may impact the capability to build the required SFR-MOX fuel. While there may be studies in which this would be an interesting result, in the context of this work, such shutdowns would be well-documented in the operational histories of the facilities and should not be characterized as an uncertainty. Figure 3 shows that uncertainties in generated power are indeed very low.

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.

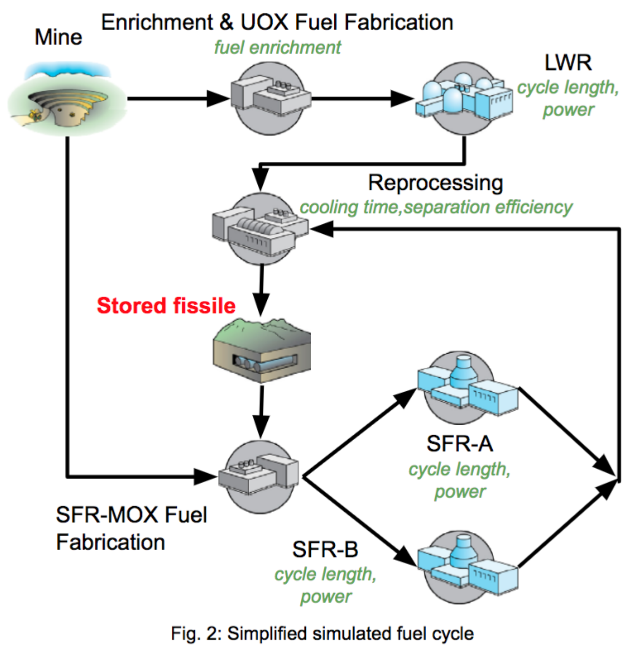

Fig. 1. Simplified representation of the material flow between the different facilities, with each operational parameter associated with an uncertainty labeled in green.

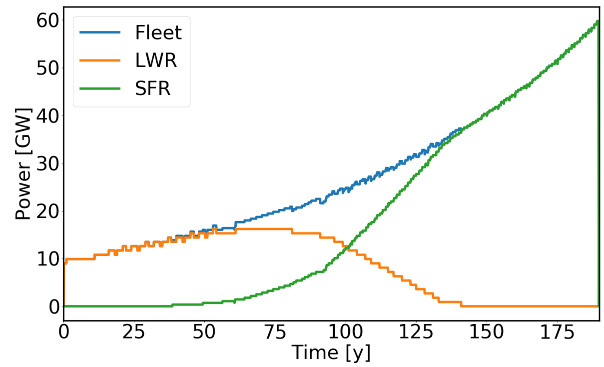

Fig. 2. Electric power generated over time, including contributions from each reactor type.

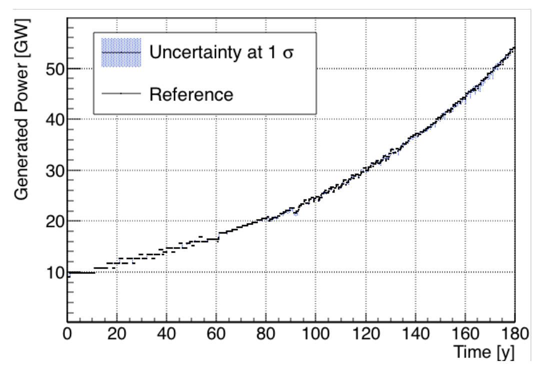

Fig. 3. Electric power generated as a function of time, with its uncertainty.

Natural Uranium Consumption Dedicated to LWR-UOX fabrication

Figure 4 represents the cumulative natural uranium consumption dedicated to LWR-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 for LWR-UOX fuel production. 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, and *vice versa*.

The relative uncertainty of the total uranium consumption starts at about 7%, slowly droping and stabilizing around 3%.

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 synchronized fuel cycles, reloading in the same time step. This phenomenon disappears with the gradual decommissioning of

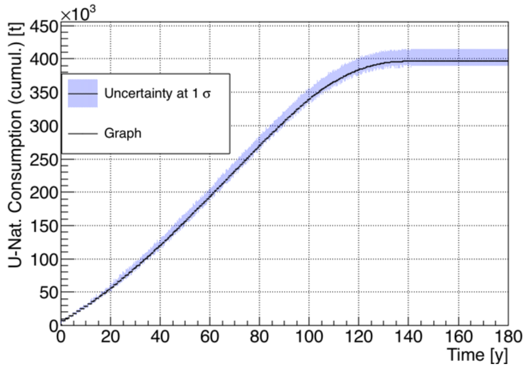

Fig. 4. Cumulative consumption of natural uranium as a function of time, with associated uncertainty.

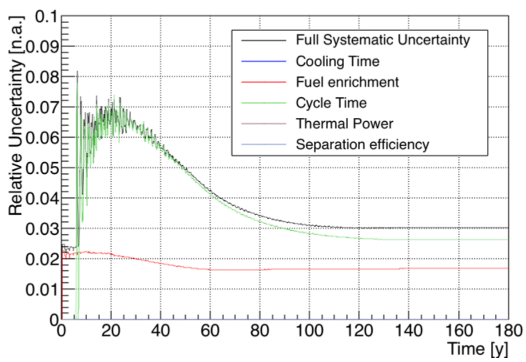

Fig. 5. Relative uncertainty of the cumulative natural uranium consumption, including individual contributions from each varied parameter.

the initial reactors, spread over 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 mean (reference) value, reducing its impact on the uncertainty on the total uranium consumption. This uncertainty contribution to the overall uncertainty decrease is proportional to the number of LWR reactors and stops with the decommission of the last one.

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 absolute 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

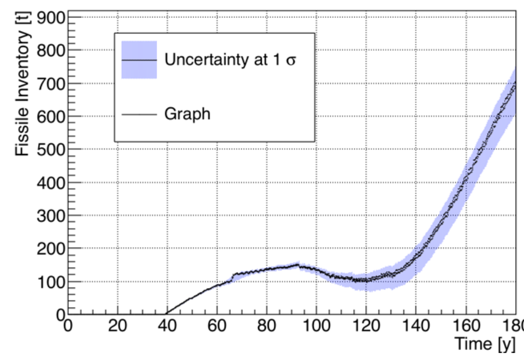

Fig. 6. Fissile (plutonium) inventory as a function of time, with associated uncertainty.

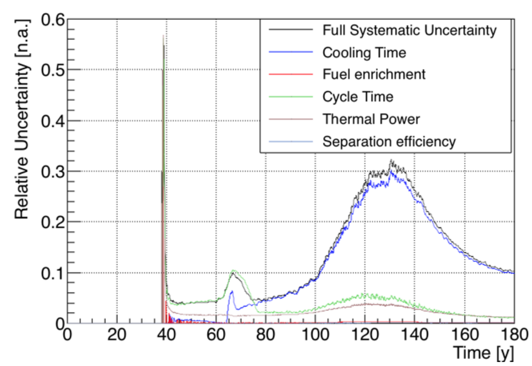

Fig. 7. Relative uncertainty in the fissile (plutonium) inventory, with individual contributions from each varied parameter.

LWRs are decommissioned. When the 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.

At the onset of fissile material production, very low mean inventories lead to unreliable artifacts in the relative uncertainty. After that, the relative uncertainty starts at about 5% and grows until year 125, then decreases to 10% at the end of the simulation time (180y). Between year 40 and 70, the main contributor to the fissile inventory uncertainty is the cycle length. As with the uranium needs, different cycle length implies different number of fuel loads, so different amount of resources used. Nevertheless, around year 65 (see Figure 8), the stock of used fuel available for reprocessing becomes small enough to start limiting the production of fissile material. The dominant contribution to the uncertainty then slowly transitions from the cycle length to the fuel cooling time.

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 growing power demand. During this period the needs in plutonium are higher than its production, explaining the observed decrease of the total amount, and the increase associated relative uncertainty.

As the transition ends, the plutonium bred from the SFRs starts to be sufficient to sustain the new SFR deployment to follow the power demand.

The uncertainty contribution from the cycle length be-

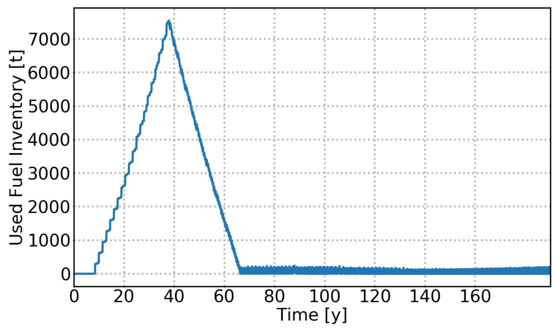

Fig. 8. Used fuel inventory, corresponding to the amount of used LWRs and SFRs fuel, cooled and waiting to be reprocessed.

tween year 40 and 70 comes mainly from fuel batch loading frequencies (Figure 7. After 70 years this contribution follows the thermal power contribution closely, suggesting that fuel discharge burnup (*i.e.* fuel discharge composition) is the mechanism of this contribution, the variation of cycle length being driving a direct variation of the burnup as the thermal power is held constant. UOX Fuel enrichment and separation efficiency showed a relative contribution smaller than 0.4%.

Around the year 70, the relative uncertainty related to cycle time is slightly bigger than the overall relative uncertainty. This effect is related to the OFAT method used to estimate the individual uncertainty contribution. While allowing a quick access to the individual contribution, the OFAT method does not capture coupling effect between the different parameters.

Discussion

Uranium consumption and separated fissile inventory are two important metrics related to non-proliferation and nuclear archaeology. In this study, we have been able to estimate that the cycle length uncertainty of 10% implies a variation of 3% to 5% on the total uranium needs uncertainty, whereas about 10% uncertainty on the enrichment implies an almost constant uncertainty of 2%.

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

This preliminary study may suggest that the most important contributions to natural uranium consumption and fissile inventory come from the parameters that govern the exchange of material between facilities, and not from the physical parameters that describe those facilities, such as thermal power or fuel enrichment. Moreover such conclusions might change in a different scenario with different hypothesis: not considering radioactive decay remove the decay of ^{241}Pu during cooling and considering a transition to fast reactors reduce the effect of composition change induced by the cycle length variations.

CONCLUSION

Three main points can be deduced from this work. First, in a transitional fuel cycle, uncertainty contributions to output metrics can vary over time depending of various factors: deployment schedule artifacts or material flow constrictions.

Second, 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. While some of those time related parameters will, to first order, only impact material availability (as the cooling time will do), others, like cycle length, will also have a impact as physical parameters such as fuel enrichment or thermal power.

Finally, Figure 7 shows the limit of the OFAT method to assess the individual contribution of each parameter, missing all the coupling effects between each of them...

Cycle length impacts the discharge fuel burnup and the frequency of the fuel loads. When they combine to produce in uncertainty of the material availability, this could result in variations related to time delays that may contribute to the final uncertainty in ways that are not relevant to some analyses. That is, a simple time lag in a particular output that otherwise follows an identical history could manifest itself as a large variation at any particular time. Those kind of time related uncertainties will require a further analysis to understand and measure accurately their contributions to the total uncertainty. I

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. This kind of study will to be extended to random uncertainty (new parameter values as a function of time) and completely systematic uncertainty (shared by all the facilities of a kind). Additionally more sophisticated methods needs to be used to assess precisely each parameter contributions..

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

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