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INTRODUCTION

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 operation parameters of the different facilities).

Some treaty verification 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. An approaching using Total Monte Carlo methodology will be applied to the Cyclus fuel cycle simulator [1] to estimate output metrics uncertainty caused by individual facility uncertainties.

THE EXPERIMENT

Method

To estimate the uncertainty on 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 over about 200 different simulations. For each deployed facilities, the uncertainty associated parameters have been a normally distributed with an artificially large standard deviation of 10%.

To pursuit this work, both the Cycamore[2] package[1] and the CyCLASS[2] have been updated[4, 5] to deal with uncertainty in several operational parameters of their associated facilities. Table I summarizes all modification implemented in the range of facilities present in Cycamore and CyCLASS.

TABLE I. Summary of facility modification per source package.

Package	Facility	Parameters
Cycamore	Separation	Separation efficiency
	Storage	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

It must be noted that for this work, the fuel enrichment was determined by a fuel fabrication model[6] which calculates the fissile fraction required in the fuel to reach a target burnup at the end of irradiation. In this study, the uncertainty on the fuel enrichment is not applied directly on the effective enrichment but on the target parameter (the burnup), which leads to to a fuel enrichment uncertainty close to 10%.

The Fuel Cycle

This work estimates the impact of the operational parameters uncertainty on a simple transition (see Figure 1) inspired from the EG23 of the Screening And Evaluation Group[7]: a transition from light water reactors fleet loaded with uranium oxide fuels (UOXs) fuel to a sodium fast reactors fleet loaded mixed oxide fuels (MOXs) fuel, considering an 1%/y grows of the generated power (Figure 2).

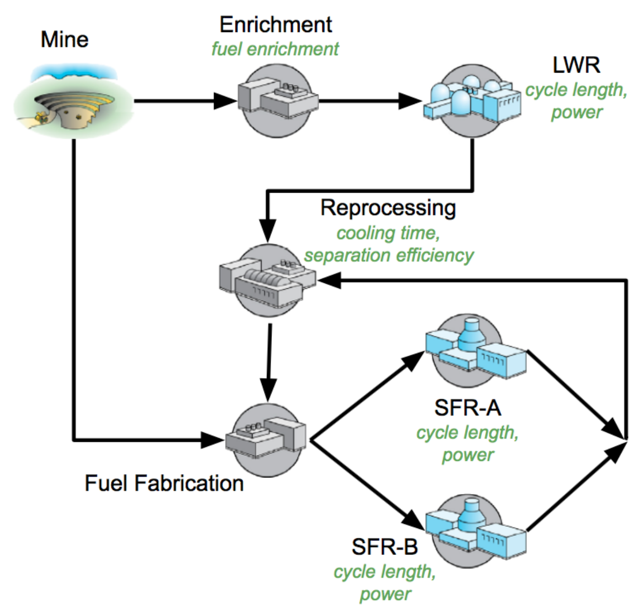

Fig. 1. Illustration of the material flow between the different facilities, with in green each operational parameters associated with an uncertainty.

As illustrated on Figure 2, the transition starts with a fleet fully composed by light water reactors (LWRs) loaded with enriched UOXs fuel. The actual transition starts around year 35, with the deployment of fast breeder reactors (FBRs), loaded with Mixed oxide fuel (MOX), consisting of plutonium blended with natural uranium.

The plutonium, required for the MOXs fabrication, is reprocessed from all used fuel, at first only used UOX, then used MOX fuel as they start to be available for reprocessing.

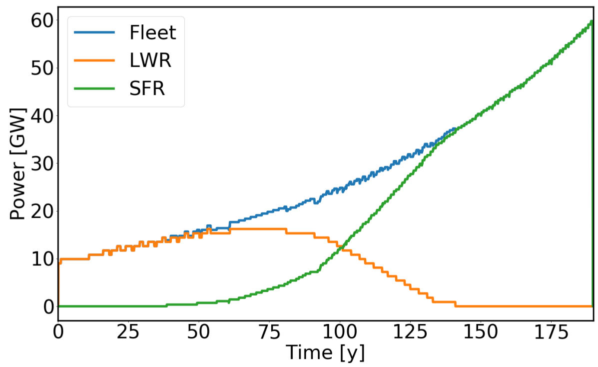

Fig. 2. Electric power generated over time, with in blue the full production, in orange the LWRs contribution, in green the FBRs.

Both fuel reprocessing and fabrication are done at a constant rate (constrained by the feed materials availabilities). The enrichment of the UOX is processed on demand. Buffer storages (not shown on Figure 1) is present between all facilities with constant processing rates.

RESULTS

In this specific study, one will only focus on the uncertainty on the produced electric power as a function of time, on the total quantity of natural uranium used and on the total unused fissile inventory (unused reprocessed plutonium). In order to estimate the total uncertainty on those 3 parameters as well as the individual contribution of the operational parameters several set of (199) simulations have been completed. All uncertainty are computed as the standard deviation over over all the calculations in the set.

In addition to the set with all parameters are sampled according to their uncertainty, a set a have been computed for each parameter, with all the other remaining fixed to the reference value.

Generated Power

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

Indeed the transition scenario has been design to allow all the reactors to receive the fuel as needed allowing them to be producing power all the time. This ensure that the uncertainty measured on other parameters are not influence by the reactors miss-loadings.

Natural Uranium Consumption

Figure 4 represents the cumulative natural uranium consumption 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.

The fluctuation of the full relative uncertainty at low time are because of the sensitivity to the fuel loading: all reactors

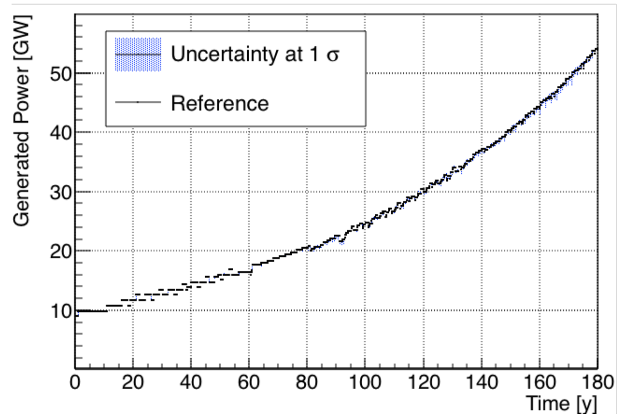

Fig. 3. Electric power generated as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

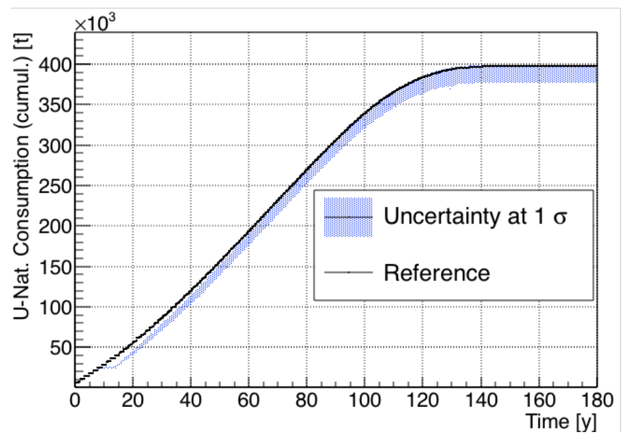

Fig. 4. Cumulative consumption of natural uranium as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

at the beginning have synchronised cycle, this phenomenon disappears with the gradual decommissioning of the initial reactor, spread on 50 years.

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

As expected, cooling time, separation efficiency and thermal power does not 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.

As the number of deployed LWRs reactors increases, as each parameters is sampled once for each facilities, the average length of the cycle (as well as the number of loaded batches) converges to the reference value. The fuel enrichment contribution follow a smoother behavior, so as the total relative uncertainty decrease, their contribution increases over time.

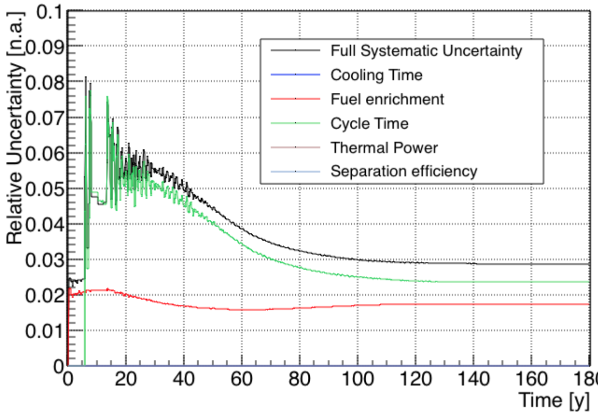

Fig. 5. Cumulative natural uranium consumption relative uncertainty, with in black the total uncertainty at 1σ, and in color the uncertainty contribution of each parameter: cooling time (blue), fuel enrichment (red), cycle time (green), thermal power(brown), separation efficiency (light blue).

Fissile Inventory

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.

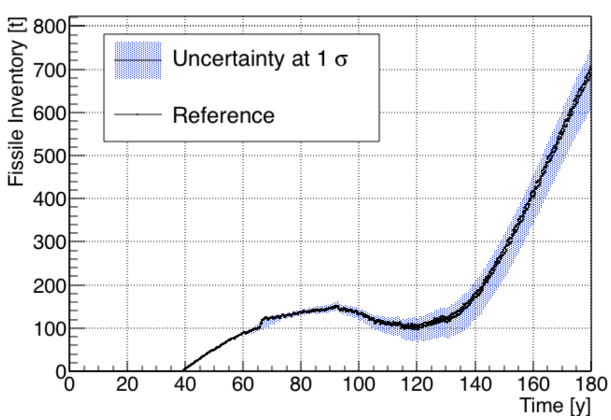

Fig. 6. Fissile (plutonium) inventory as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

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 will reach an equilibrium between 5 and 10%... 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

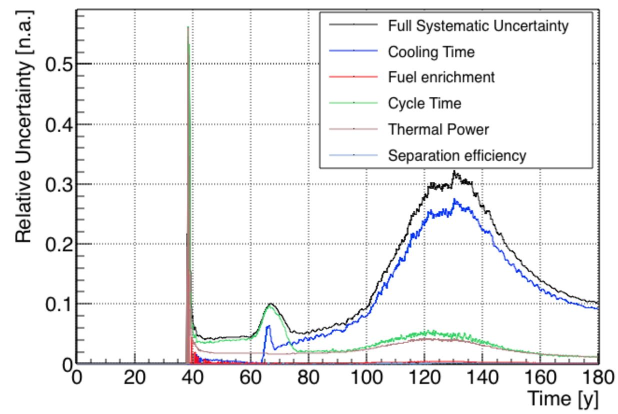

Fig. 7. Fissile (plutonium) inventory relative uncertainty, with in black the total uncertainty at 1σ, and in color the uncertainty contribution of each parameter: cooling time (blue), fuel enrichment (red), cycle time (green), thermal power(brown), separation efficiency (light blue).

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.

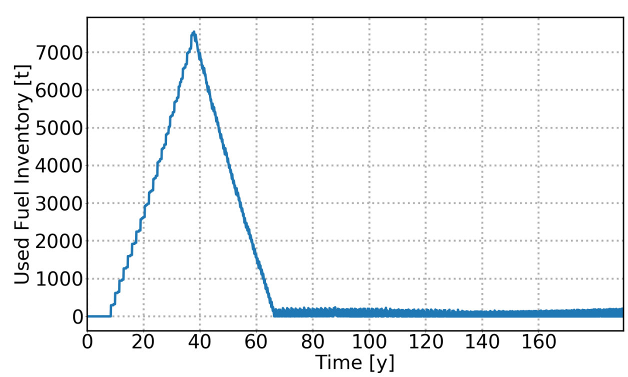

Fig. 8. Used fuel inventory.

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 are conversion toward the power contribution, such as the increase of fuel loads effect tends to vanish and let its place to a discharge burnup effect (the power uncertainty only affects the burnup of the fuel at discharge).

Discussion

Even if for the two output metric analysed there is no surprise such as the identified uncertainty contributions, it is very interesting to be able to measure them and rank them.

In this study, we can estimate than the cycle length uncertainty of 10% varies from 3% to 5% on the total uranium needs uncertainty, where $\approx$ 10% on the enrichment implies a almost flat uncertainty of 2%, and the enrichment tails uncertainty have an even lower contributions of 1%.

It is also very interesting to observe that while the plutonium inventory uncertainty reach a pick at 30%, lead by the cooling time uncertainty contribution, the reactor parameters seems to have a lower contribution, the cycle time contribution picking at 10% and stabilizing with the power contribution around 1%

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. As the cycle length impact 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 a large uncertainty. Those kind of uncertainties will need a special treatment on further uncertainty analysis.

This study aims to be a proof-of-principle for uncertainty propagation in potential commercial fuel cycle transition and will to be extended to random uncertainty.

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 archeology works, which aims to precisely estimate past fissile production by the different nuclear countries.

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