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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. A "Total Monte Carlo" approach will be applied to the Cyclus fuel cycle simulator [?] to estimate output metrics uncertainty caused by individual facility uncertainties.

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 uncertainty associated parameter, an artificially large uncertainty of 10% have been Normally distributed.

To pursuit this work, both the Cycamore[?] package and the CyCLASS[?] have been updated to deal with uncertainty in different operational parameters of their different facility. Table I summarize all the modification implemented in the different facilities present in Cycamore and CyCLASS.

TABLE I. Summary of facility modification per source package.

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

THE EXPERIMENT

The Fuel Cycle

This work aims to assess the impact of the functional uncertainties of a simple transition (see Figure 1) inspired from the EG23 of the Screening And Evaluation Group[?]: 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).

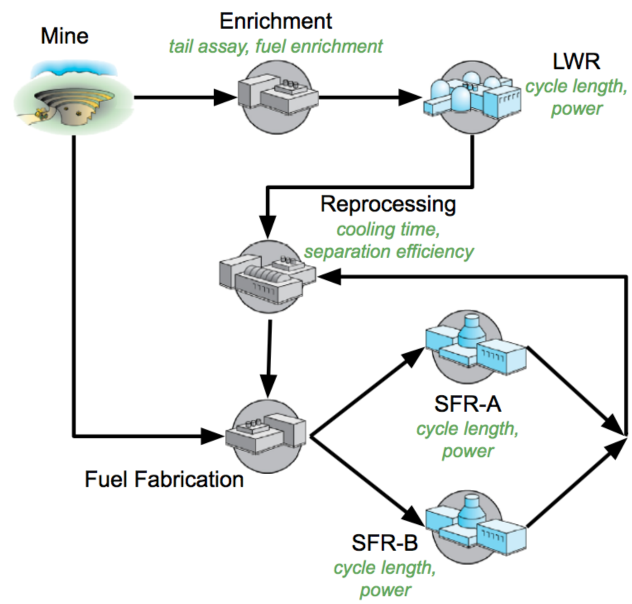

Fig. 1. Illustration of the material flow between the different facilities, with in green each operational parameters associated with an uncertainty.

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. Once the transition to a full FBRs fleet is completed, the FBRs fleet is slowly replaced with FBRs with a lower breeding ratio.

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.

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.

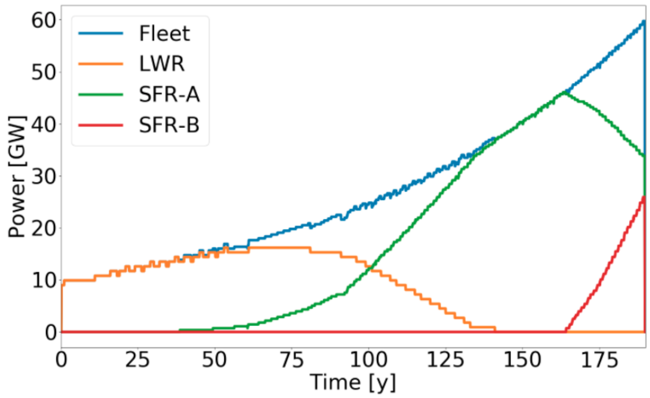

Fig. 2. Electric power generated over time, with in blue the full production, in orange the LWRs contribution, in green the hight breeding ratio FBRs and in red the low breeding ratio FBRs.

Uncertainty Measurements

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.

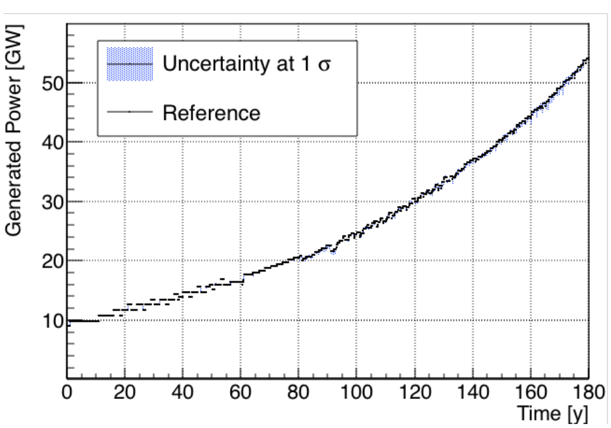

Fig. 3. Electric power generated as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

Indeed the transition scenario has been 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.

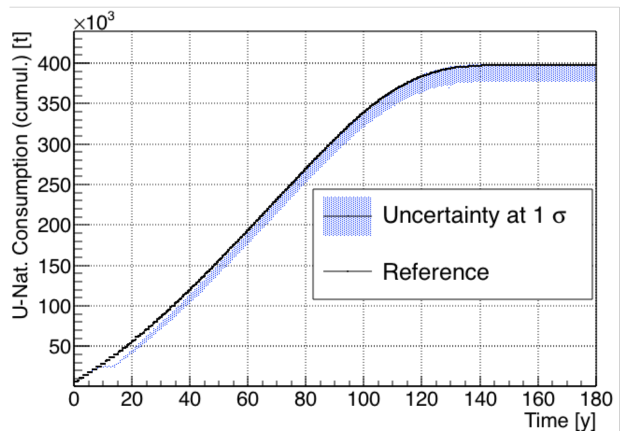

Fig. 4. Cumulative consumption of natural uranium as a function of time. The black line represents the reference calculation and the blue zone represents the 1 σ uncertainty distribution.

The fluctuation of the full relative uncertainty at low time are because of the sensitivity to the fuel loading: all reactors at the beginning have synchronised cycle, this phenomenon disappear with the gradual decommissioning of the initial reactor, spread on 50 years.

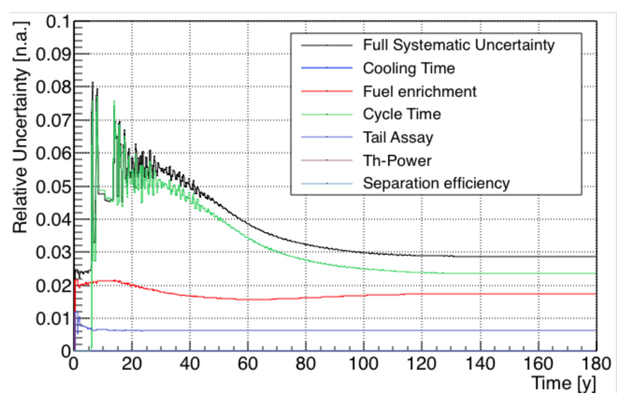

Fig. 5. Cumulative natural uranium consumption relative uncertainty, with in black the total uncertainty at 1σ, and in color the uncertainty contribution of each parameter: cooling time (blue), fuel enrichment (red), cycle time (green), thermal power(brown), separation efficiency (light blue).

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 and the tail assay contribution follow a smoother behavior, so as the total relative uncertainty decrease, their contribution increases over time.

ACKNOWLEDGMENTS

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