Uncertainty propagation on fuel cycle codes by means of Monte Carlo and Sensitivity Analyses

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Overview of TR_EVOL

TR_EVOL description

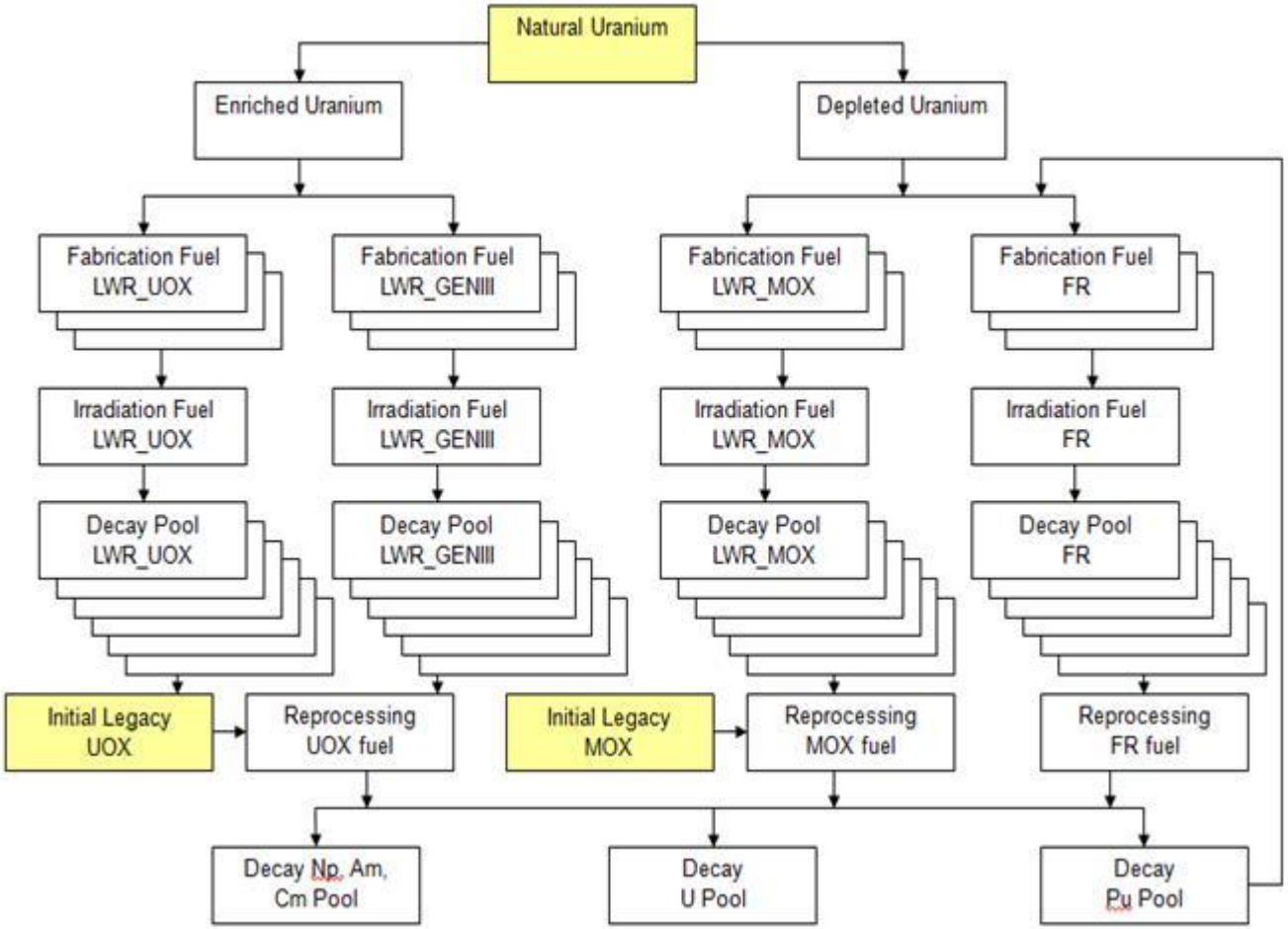
- The TR_EVOL data treatment is based on *buffers*: the isotopic vector and the total amount of material present in one particular storage. Each fuel cycle storage facility can be represented by one or several buffers.

- *Mass flows* are represented by connections between buffers. These can link one buffer to another, but can also be fed by more than one buffer, divided towards several buffers, or both.

- The operational parameters of the cycle facilities and the time-dependent interconnections are described in TR_EVOL using a series of basic instructions or *rules*. Each rule specifies a particular action that is applicable to a particular buffer (decay of stored material or fuel irradiation) or to a particular interconnection (fuel fabrication, reprocessing, etc.).

- A generic fuel cycle representation of buffers and mass flows in TR_EVOL is shown in the following slide.

Introduction: TR_EVOL code



TR_EVOL capabilities

- The mass and the isotopic composition balances of each stream defined in the fuel cycle are computed annually as averaged values.
- The number of isotopes that TR_EVOL can handle is only limited by the existence of database information for each particular isotope.
- Any kind of nuclear facility can be simulated in this code, since its operation can be described as a set of buffers plus a sequence of rules.
- Irradiation and decay through ORIGEN code. If ORIGEN input/output already exist, ORIGEN is not invoked.
- The fuel fabrication process can use the concept of equivalent Pu-239 (Baker and Ross formula).
- Reprocessing is simulated as a set of coefficients for the element recovery fractions.
- The introduction date in a cooling storage buffer of any spent fuel can be saved together with its material amount: reprocessing strategies allowed (FIFO, FILO, or homogenised).
- TR_EVOL allows the introduction of external material such as an initial spent fuel legacy from past generations or special material for fuel fabrication (possibly material for target matrices or natural uranium).
- The time spent in a common execution of a complex fuel cycle is smaller than half an hour.

TR_EVOL code mass balance

- Diverse nuclear power plants can be simulated (LWR, SFR, ADS, etc.) as a macro-reactor or individually.
- Diverse types of fuel (UO_2, MOX, etc.).
- Associated fuel cycle facilities (enrichment, fuel fabrication, reprocessing, interim storage, waste storage, geological disposal) can be assessed.
- New improvements:
  - Variable burn-up for a certain nuclear power plant.
  - First and last cores are taken into account.
  - Model for vitrified HLW generation.
  - Model for gallery requirements in the deep repository.
  - Management of fission and activation products, in addition to actinides.
  - Data management: improved robustness, debug-ability and efficient connection with the new economic module.

TR_EVOL code economic module

Its main objective is the estimation of the Levelised Cost of Electricity (LCOE) of the scenario and of the reactor technologies, by means of its four main contributors to the cost:

- **Investment cost**: Overnight cost, interest during construction and interest for the loan.
- **Fuel cost**: Front-end cost. Reprocessing cost included here if necessary. It also includes the cost of the new reactor cores.
- **Operation and Maintenance cost**: annual cost for the plant, as function of the installed capacity.
- **Decommissioning & Dismantling and Disposal Cost**: Decommissioning and dismantling as percentage of the overnight cost. Disposal cost includes interim and final disposal.

These four LCOE components are expressed by means of unit costs, taken from bibliography and applied as best-estimate values.

Economic module verification

- The economic module has been cross checked with references data when possible.
- A comparison with ARCAS EU project allowed checking the Investment cost, O&M cost and Fuel cost.
- A model has been developed for interim storage cost. No cross check yet.
- The model for the assessment of the Final Disposal cost for open cycle scenario and scenarios with partial reprocessing has been satisfactorily used to provide generic unit costs:
  - For some referenced costs for final disposal, the relative difference between the data and the model is around 3% for most of the studied cases with open cycle.
  - For scenarios with partial reprocessing, the relative difference is of the order of 10%.

Contents

Uncertainty propagation

Recent activities

The Nuclear Energy Agency (OECD/NEA), by means of the Expert Group on Advanced Fuel Cycle Scenarios, coordinates an effort for the study of transition fuel cycle scenarios, comparing reactor fleets, reprocessing and waste management strategies. Its main objectives are:

- Assemble, organise and understand the scientific issues of advanced fuel cycles.
- Provide a framework for assessing specific national needs related to implementation of advanced fuel cycles.

CIEMAT uses its home-made fuel cycle scenario tool TR_EVOL in most of the activities included in this project.

Background for this work

Within this group, a special task is devoted to identify the sources of the uncertainty of input parameters on nuclear fuel cycle indicators, using sensitivity/parametric studies.

The possible sources of uncertainty have been investigated:

- Physics data.
- Global scenario parameters (energy demand, growth rate, etc.).
- Individual parameters (enrichment, tail composition, reprocessing efficiency, decay times, etc.).
- General model characteristics (isotopic U-nat versus U-recovered, breeding ratio, etc.).

Uncertainties in these parameters have been applied to a scenario consisting of the replacement of a LWR fleet by a SFR fleet. The scenario length is 200 years and the transition phase occurs between years 80 and 110.

This work has become the basis for the assessment of the uncertainty propagation developed here.

Methodologies

Sensitivity analysis

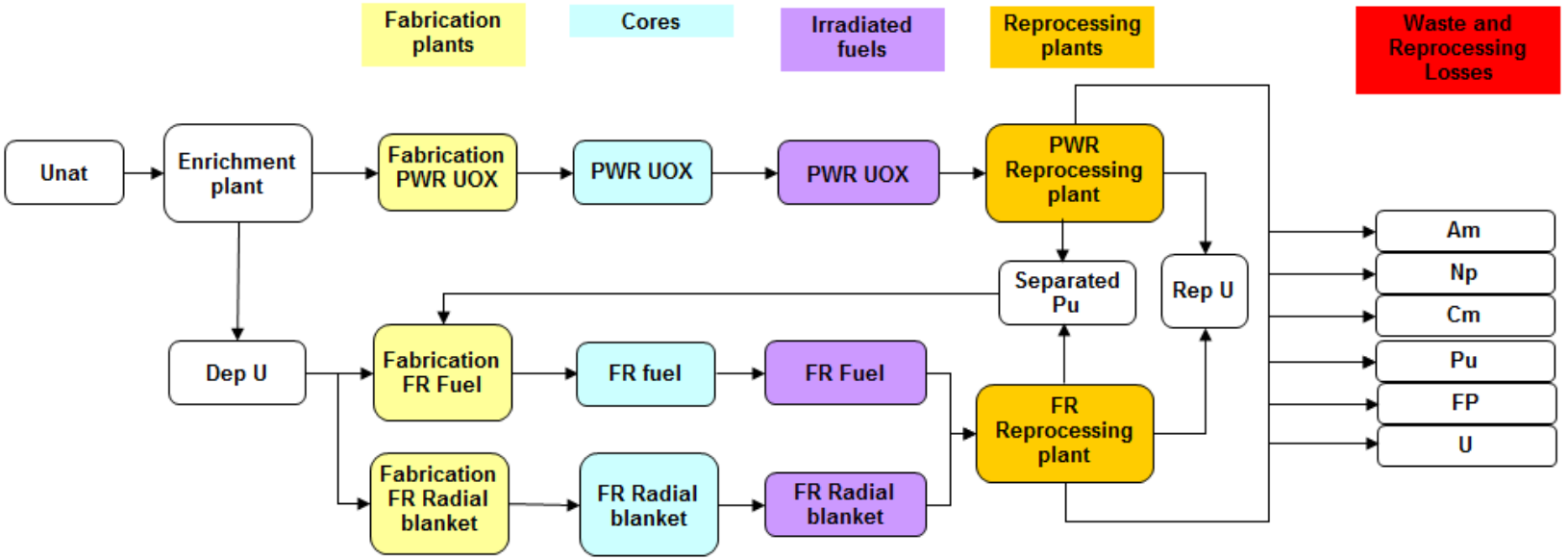
$$S_{kj} = \frac{p_j}{X_k}\frac{\partial X_k}{\partial p_j} \qquad \vec{X} = S\cdot\vec{p} + B \qquad \Delta X = \sqrt{S\cdot V\cdot S^T}$$

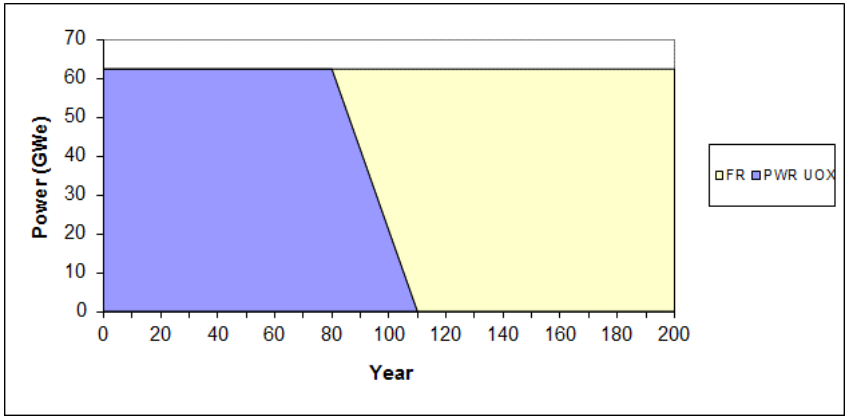
- Valid for linear dependencies.
- 100 parametric calculations performed varying one input parameter at a time.
- Random generation sampling.

Monte Carlo approach

- Monte Carlo perturbation strategy.
- Multiple execution of the problem for different sets of input parameters (10000 executions), whose values have been stochastically generated.
- Analysis of outputs in terms of frequency.

Scenario description





Input parameters: Uncertainties

Input parameter	Units	Sensitivity analysis		Monte Carlo	
		Nominal value	Parametric studies	Central value	Relative uncertainty
LWR burn-up	GWd/tHM	60	40, 50	50	± 20%
FR fissile burn-up	GWd/tHM	136	100	133	± 3%
UO_2 enrichment	% U-235	4.95	Adjusted with burn-up	4.25	± 20%
UO_2 enrichment tails	% U-235	0.25	0.15, 0.35	0.25	± 40%
MA in MOX	% MA	0	1, 2	1.25	± 50%
UO_2 reprocessing capacity	tHM	850	700, 1000	850	± 12%
MOX reprocessing capacity	tHM	600	400, 800	600	± 33%
U and Pu reprocessing efficiency	%	99.9	99.8, 99.99	99.88	± 0.075%
MA recuperation rate	%	0	99, 99.9	99.45	± 0.45%

Reference values are sometimes the boundary limits of the Monte Carlo interval!

Results: Sensitivity analysis

- A selected group of output indicators is shown.
- Dependence of each output indicator on each input indicator can also been obtained (sensitivity coefficients).
- Uncertainty should be considered carefully due to hypothesis of linear dependence.

Input parameter (tHM)	Reference scenario value	Relative uncertainty
PWR fabricated fuel	8.4E4 ± 6E3	± 7%
Total amount of depleted U	7.7E5 ± 8E4	± 10%
Maximum amount of separated Pu	740 ± 230	± 31%
Maximum amount of separated MA	175 ± 27	± 15%
Total mass in final repository	6300 ± 600	± 8%
Pu content in final repository	4.0 ± 2.0	± 50%
MA content in final repository	32 ± 13	± 40%
Total amount of Pu generated in PWR	1220 ± 120	± 10%

Results: Monte Carlo approach (1/4)

- The same selected group of output indicators is shown.
- Central value has been obtained as the mean value of the outputs.
- Linear and not linear dependencies can be considered with this methodology.

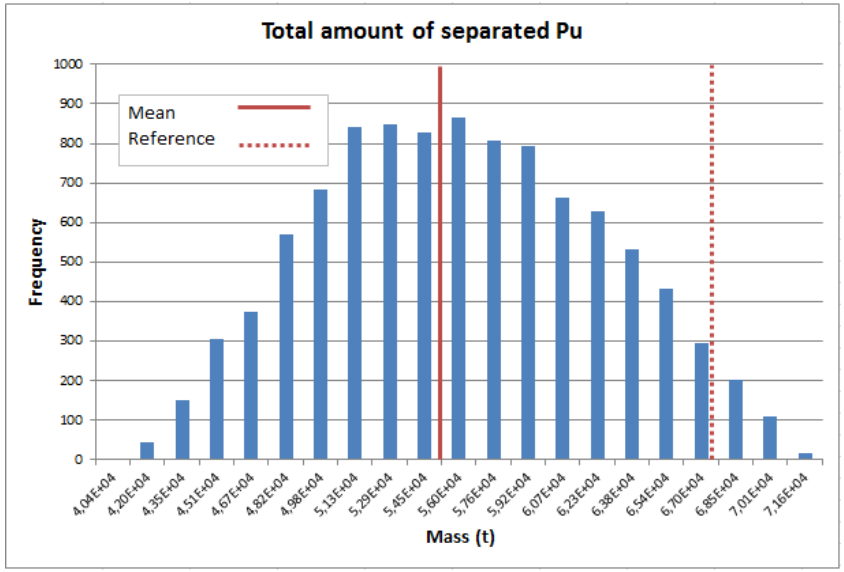
Input parameter (tHM)	Central value	Relative uncertainty	ity analysis	
				Rel. Uncert.
PWR fabricated fuel	80510 ± 50	< ± 1%		± 7%
Total amount of depleted U	6.3E5 ± 1.1E5	± 19%		± 10%
Maximum amount of separated Pu	516 ± 40	± 8%		± 31%
Maximum amount of separated MA	170 ± 50	± 30%		± 15%
Total mass in final repository	5400 ± 400	± 8%		± 8%
Pu content in final repository	4.6 ± 1.6	± 35%		± 50%
MA content in final repository	120 ± 50	± 42%		± 40%
Total amount of Pu generated in PWR	1050 ± 60	± 6%		± 10%

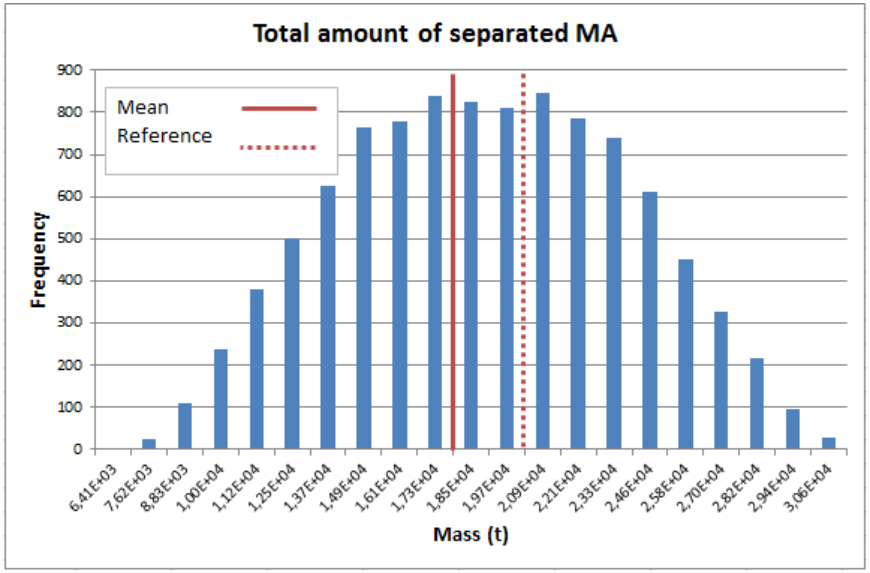
- Special interpretation of the results, depending on the magnitude and its relation with the input parameters.

Results: Monte Carlo approach (2/4)

Gaussian curve

- Linear dependence.
- For large number of samples, final results are distributed around a central value (Gaussian). Simultaneous random perturbations cancel each other in the less probable regions.
- Both methods can be compared.
- However, central and reference values between methods may not coincide due to different hypotheses between methods.

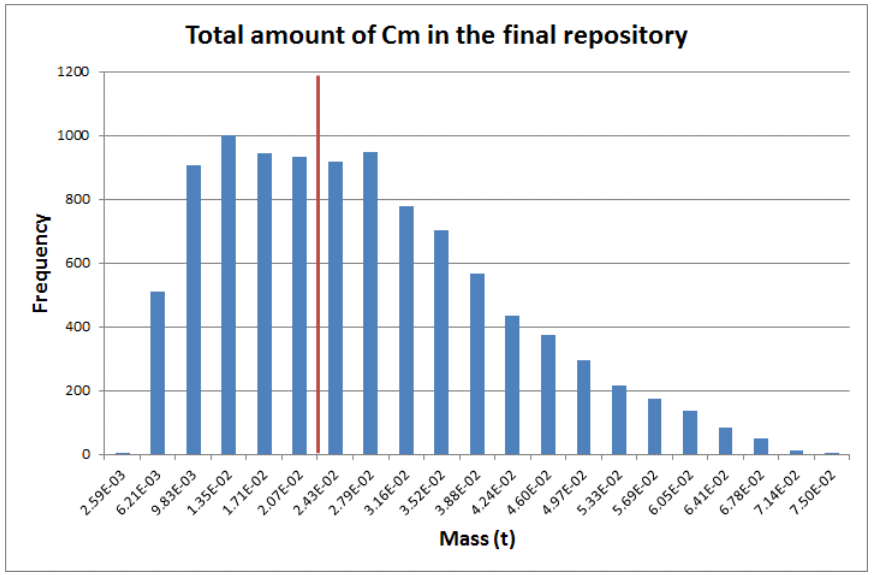


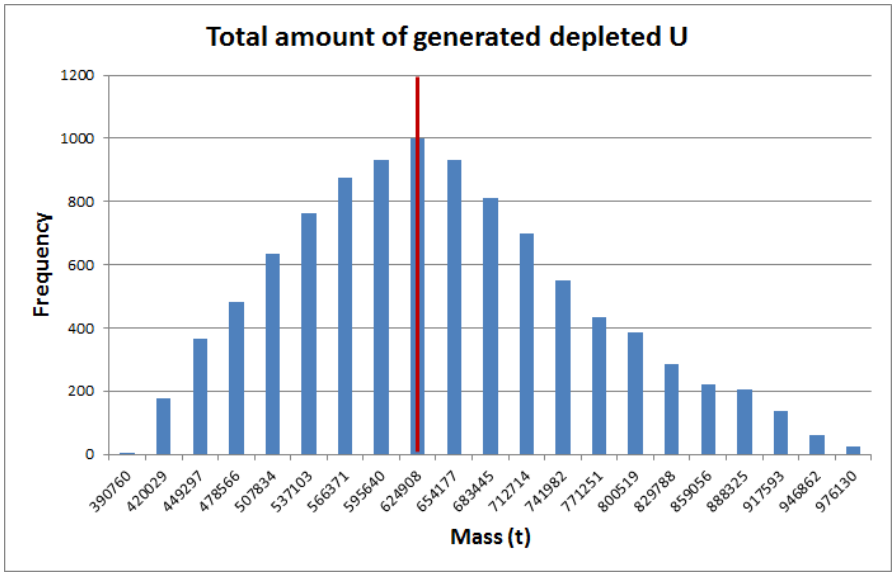


Results: Monte Carlo approach (3/4)

Asymmetric shape

- Certain bias in the shape of the curves.
- Non-linear behavior.
- Only MC can be considered as good estimation.
- Not clear in some cases.

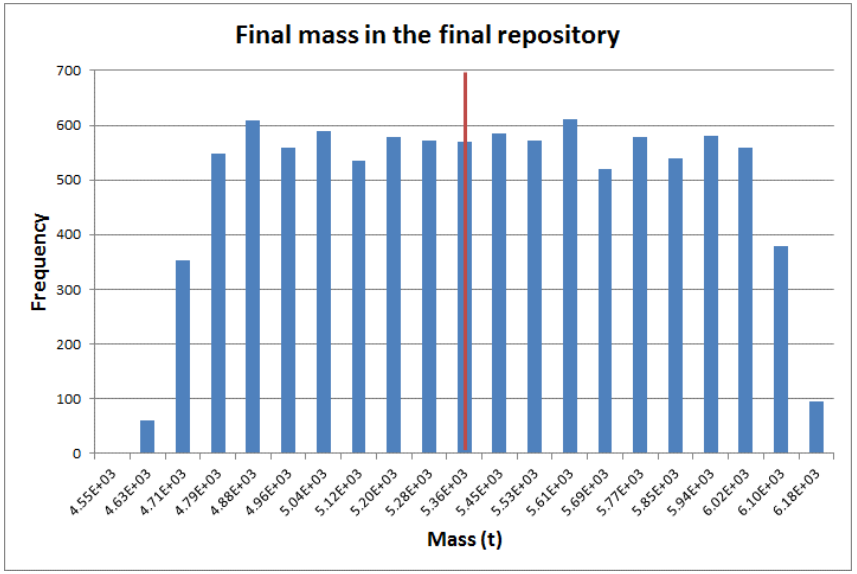


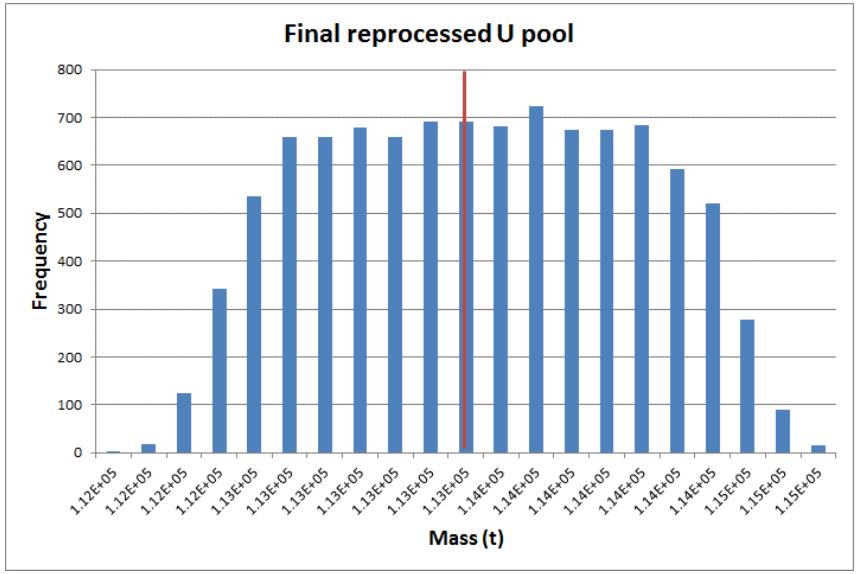


Results: Monte Carlo approach (4/4)

Uniform distribution

- Input parameters have very large uncertainties.
- It is possible to give an averaged value and an uncertainty.
- A reduced uncertainty for the input parameter is desired to understand the effect in the output.
- Possible bias cannot be identified.





Conclusions

- This work includes the analysis of the uncertainty propagation in a fuel cycle scenario using two methodologies: Sensitivity and Monte Carlo methods.
- Sensitivity analysis allows estimating the dependence of each input parameter in a given output parameter, but it is only valid with linear dependencies.
- Monte Carlo methodology allows estimating the propagation of the uncertainties in the input parameters to the output parameters, no matter if the dependencies are linear or not.
- Both methodologies have been successfully applied to a generic fuel cycle scenario where the light water reactors are replaced by sodium cooled fast reactors at a steady rate in the intermediate stage of the scenario.
- Uncertainties obtained in this work, for both the sensitivity/parametric studies and MC, are large enough to explore the most significant dependencies.

Future work

- Analysis of the input parameters causing the uncertainties with the Sensitivity method.
- Assessment of these methodologies for scenarios with other objectives.
- Implementation of correlations between variables.
- Development of a link between uncertainties in the mass balance and uncertainties in costs, for cost assessments.

Thank you for your attention!