DE LA RECHERCHE À L'INDUSTRIE

COSI6
A Tool for Nuclear Transition Scenarios studies

G. Krivtchik, R. Eschbach, G. Martin, M. Tiphine,
D. Freynet, R. Girieud, P. Miranda

Atomic Energy and Alternative Energies Commission
CEA, DEN, Cadarache, DER, SPRC

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COSI6 PRESENTATION

Purpose of COSI6:

- **Nuclear systems**, composed of reactors with varied fuel and cycle facilities (enrichment plant, fabrication plant, reprocessing plant …) are **complex and in constant evolution**.

- Decision makers need to have all the technical elements, based on **dynamic transition scenarios of nuclear fleet** :

  - To have a complete overview of nuclear systems, it is also required to **follow precisely material flows** at each step of the fuel cycle and at each date of the operation period.

  - The evolution in time and under flux of **materials isotopic composition** has to be taken into account, and gives access to other interesting values (activity, decay heat, toxicity …).

- **COSI: simulation software for scenarios studies**
  - simulates a pool of nuclear electricity generating plants with associated fuel cycle facilities,
  - allows to compare different options of evolution of a reactor fleet and different options of materials management,
  - allows to evaluate their sustainability.

- COSI simulates in continuous time (exact dates, no “steps”) the evolution of a discrete reactor fleet and the associated fuel cycle facilities over a defined period (#100 years).

- COSI has been developed by the **Nuclear Energy Direction** of the CEA (Cadarache center), during more than **25 years**.

International collaborations

- Current license agreements owner:
  - ENEA (Italy)
  - KIT (Germany)
  - IRSN (France)

- Benchmarks:
  - MIT Benchmark with CAFCA, DANESS and VISION (April 2009), MIT-NFC-TR-105
  - COSAC (AREVA NP) and TIRELIRE-STRATEGIE (EDF)
  - NEA Benchmarks:
    - Benchmark Study on Nuclear Fuel Cycle Transition Scenarios Analysis Codes (June 2012) : NEA/NSC/WPFC/DOC/2012/16 : VISION (DOE), FAMILI21 (JAEA), EVOLCODE (CIEMAT), DESAE2.1 (Kurchatov)
    - The Effects of the Uncertainty of Input Parameters on Nuclear Fuel Cycle Scenarios Studies (to be published)

COSI, reference code for French scenarios studies:

- CEA 2012 report to the French government (French Act for Waste Management, 2006):
  - Possible **evolutions** of the French reactor fleet and the **sustainability** of Sodium cooled Fast Reactors, interest of MA **transmutation** (homogeneous, heterogeneous).

- New R&D programme:
  Scenarios of **Pu multirecycling in SFR** with **industrial partners** EDF and AREVA.

M.Tiphine et al., « *Simulations of Progressive Potential scenarios of Pu multirecycling in SFR and associated Phase-out in, the French Nuclear Power fleet* » **GLOBAL 2015**

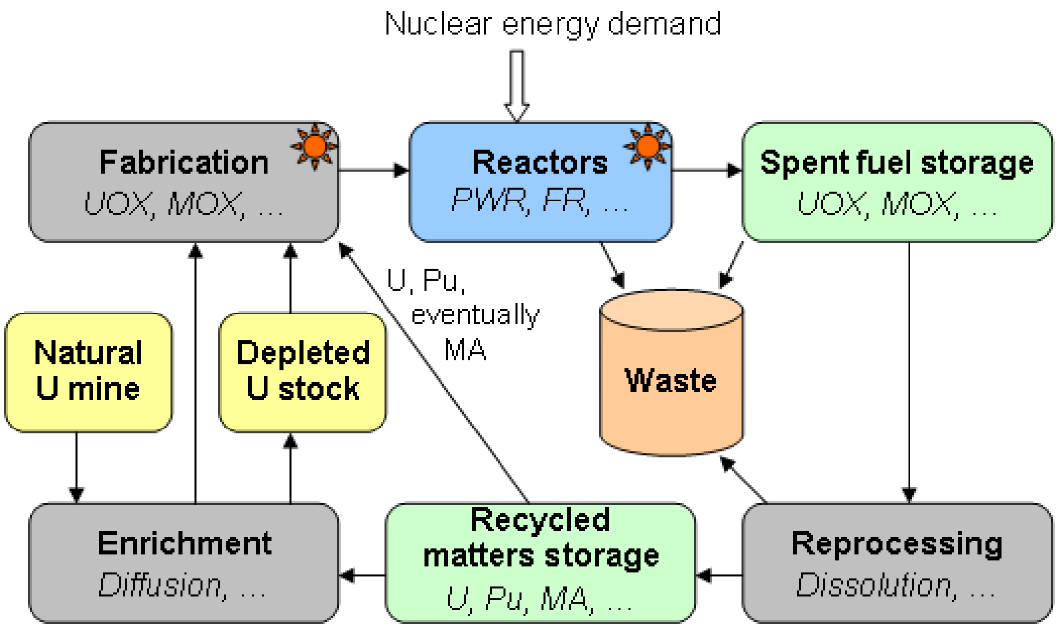
M.Tiphine et al., « *Sodium Fast Reactor: an Asset for a PWR UOX/MOX fleet* » **GLOBAL 2015**

COSI6 FLOW SCHEME

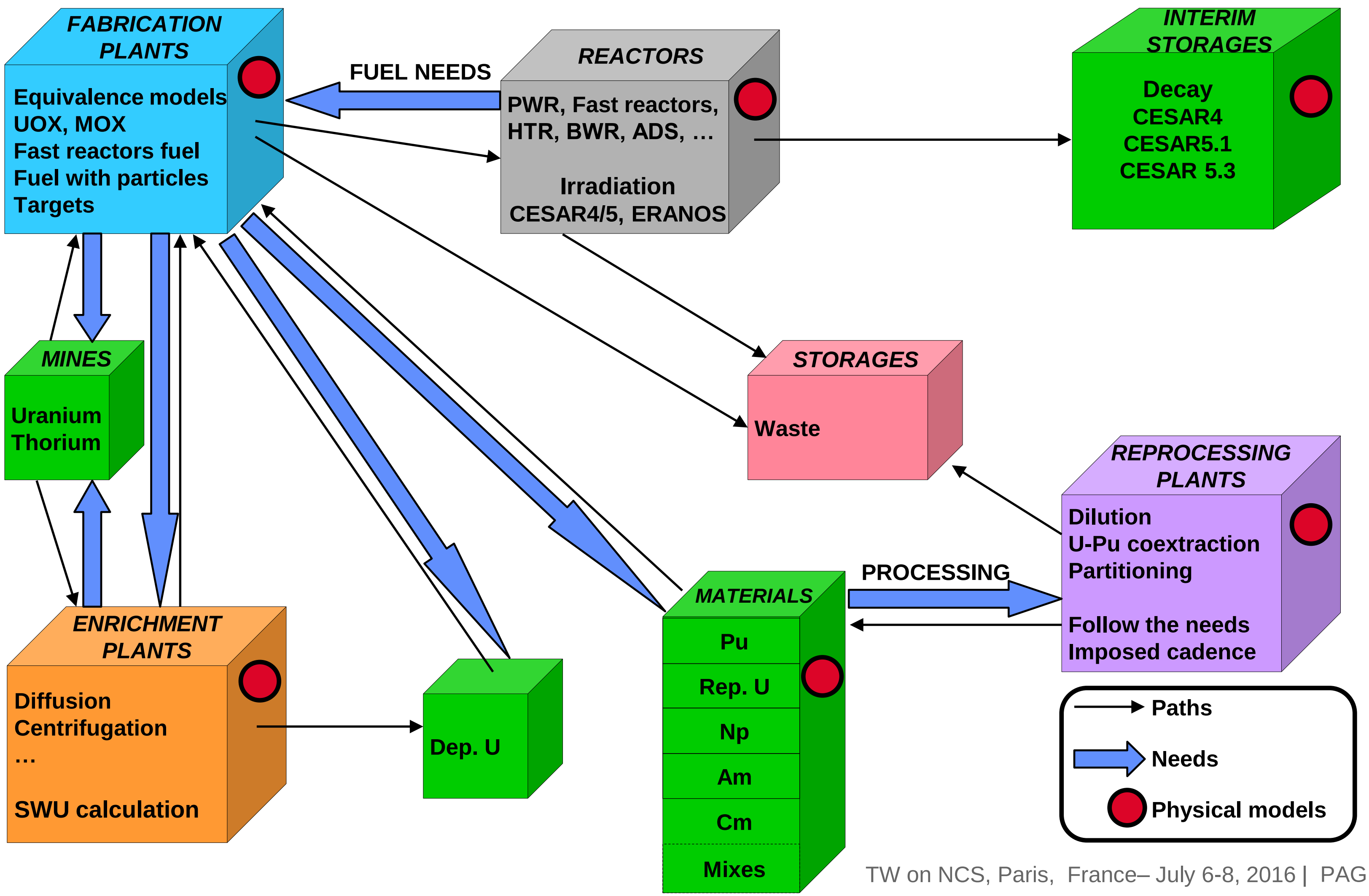
Data Flow in COSI

- The **reactors** drive the front-end (pull) and the back-end cycles (push)
- The **reprocessing plants** close the cycle (to produce fissile materials required for fuel fabrication)
- COSI can model any arbitrarily complex / large scenario

- Two main physical models:
  - Equivalence model in fabrication plant (compute the enrichment as a function of isotopy)
  - Evolution calculations, generally performed with **CESAR**



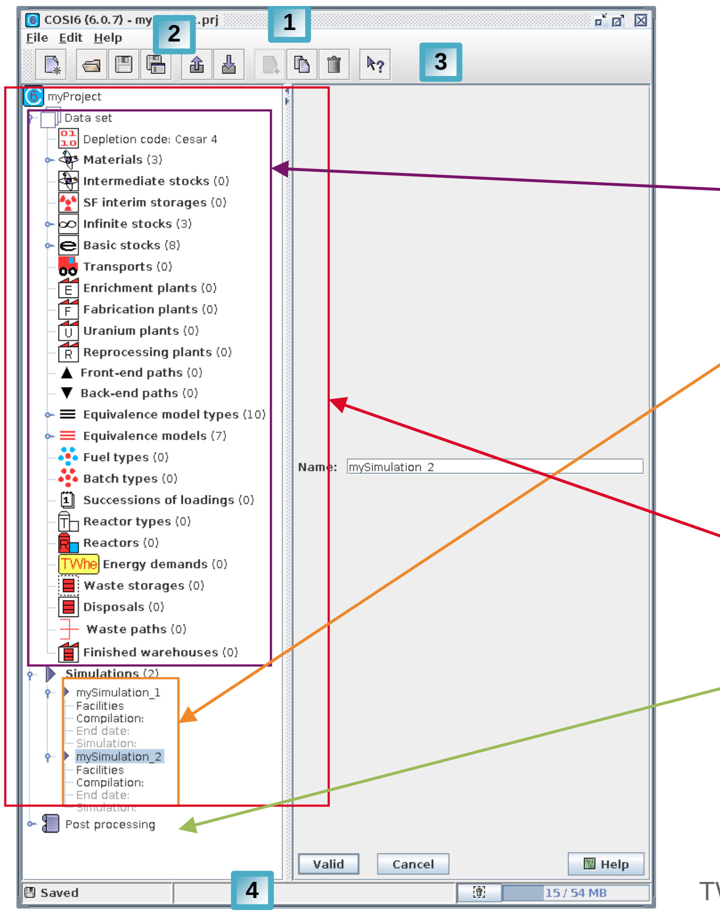
COSI6 FLOW SCHEME (OBJECT-ORIENTED FRAME)



HOW TO USE COSI

Graphical User Interface

- Standard COSI6 utilization is based on a **graphical user interface** which represents a data set in the form of a tree display and some simulations, included in a project. It also gives access to the post-processing tools.



Definitions

- Data set : set of COSI objects
- Simulation : [included data set + results of a scenario]
- Project: current data set + 0 to n simulations
- Post-processing: post-processing of the results of 1 simulation

All reactors type can be integrated

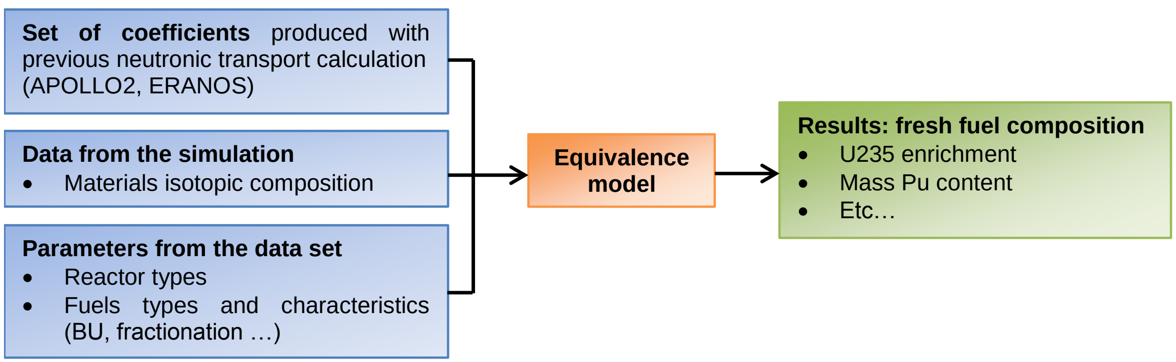
- Standard PWR: UOX fuel, MOX fuel, reprocessed U fuel
- PWR with High Conversion Ratio
- HTR
- CANDU: natural uranium, Th-233U
- SFR: MOX fuel with or without minor actinides, thorium fuels, metal fuel, breeding blankets
- Gas Fast Reactor
- ADS
- …

Typical results

- Needs in natural uranium and fissile materials
- Separative work units, needs in fabrication and reprocessing
- Storages of materials, waste and spent fuel
- Evolution of the inventories in Pu, MA etc. in all the fleet
- Isotopic composition of fuels and materials
- Decay heat, toxicity, activity and neutron sources
- Waste packages evaluation
- …

Equivalence models

- Used to determine the initial fuel fissile content according to the isotopic composition of the available materials:
  - Thermal reactors (PWR MOX, MOX EU IMR...): specific models
  - Fast reactors with or without minor actinides (Baker and Ross formula, neural networks…)
  - Ongoing validation/improvement work on equivalence models



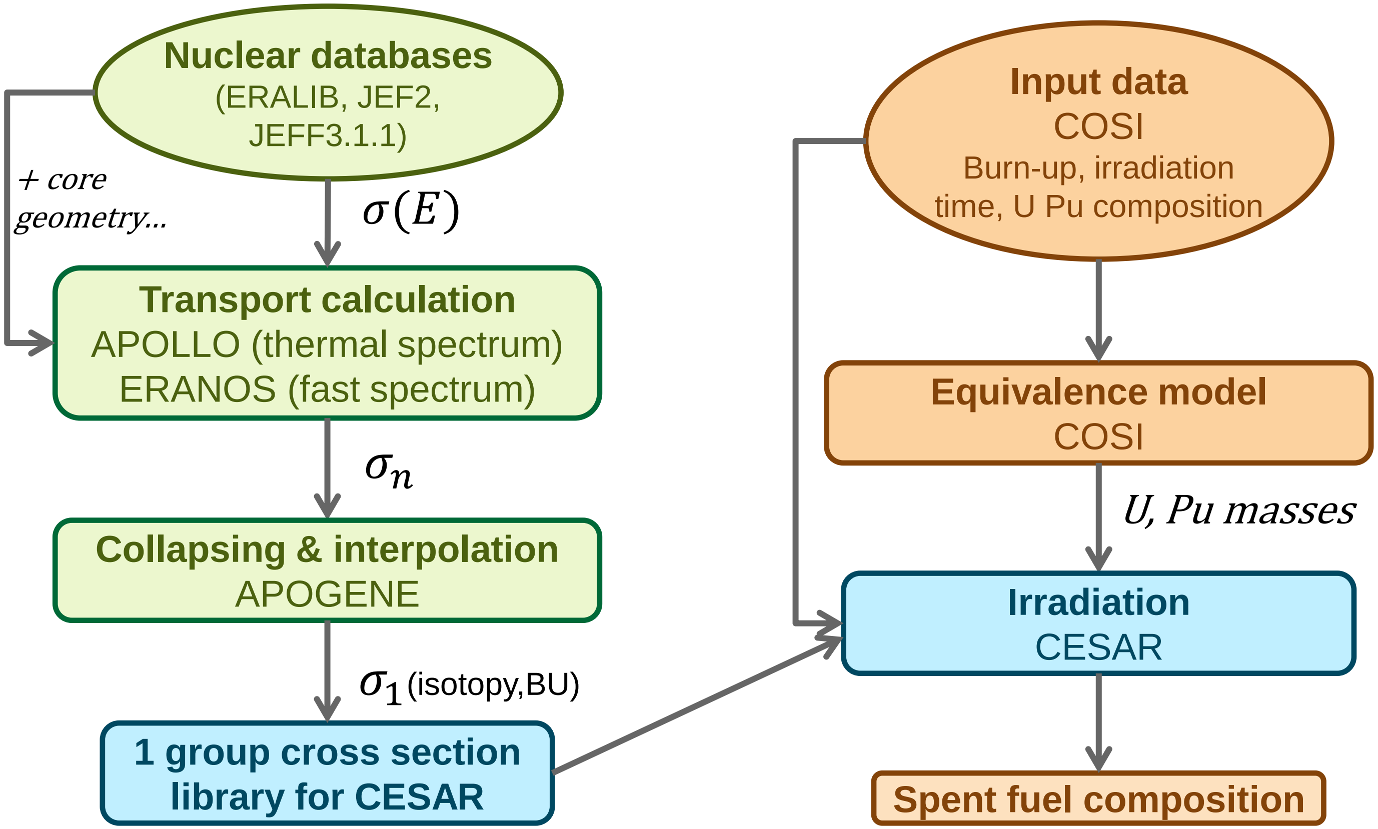
Evolution during irradiation

- The depletion of the fuel during irradiation can be evaluated by coupling COSI with **CESAR** or with **ERANOS** (see next slides), including:
  - CESAR4 (CEA86), restricted to heavy nuclides: 21 heavy nuclides
  - CESAR5.1 (JEF2.2) with more isotopes and fission products: 109 heavy nuclides, 209 fission products and 80 activation products.
  - CESAR5.3 (JEFF3.1.1), the reference code at the AREVA NC La Hague reprocessing plant.

COSI-CESAR

Creating CESAR libraries

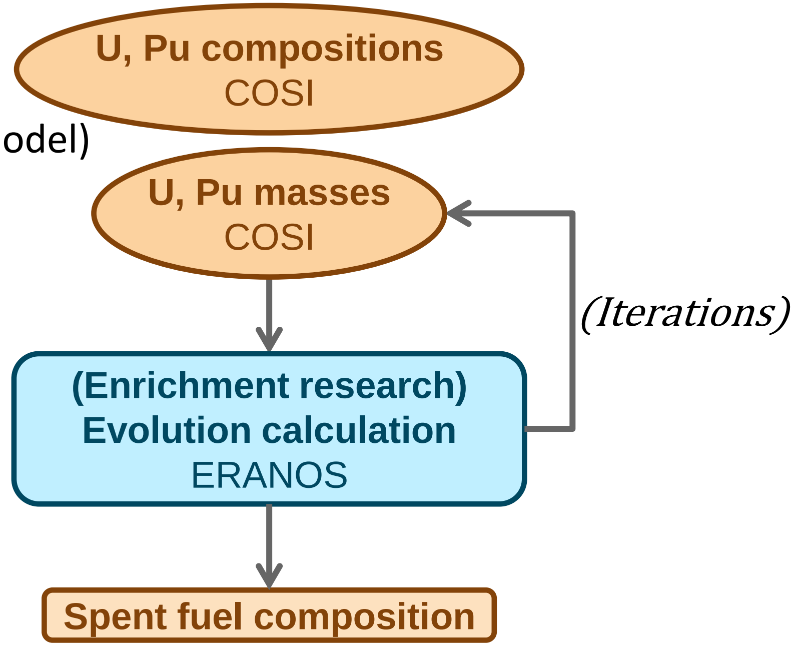
COSI-CESAR coupling



- Any reactor or fuel type can be modeled with COSI once the appropriate cross section library is available.
- Physical models from reference validated **CEA/DEN neutronic codes and data** (APOLLO, ERANOS, CESAR, JEFF3.1.1).

Coupling between **COSI** and **ERANOS**.

- Possibility to track new parameters:
  - Initial equivalent ^{239}Pu content re-evaluated by ERANOS.
  - Reactivity at the beginning and the end of cycle.
  - Safety parameters: void coefficient, Doppler, βeff.
- ERANOS can be used to evaluate:
  - The fresh fuel enrichment (as an equivalence model)
  - Or both the fresh and spent fuel composition (enrichment research + irradiation iterations)



COSI6 POST-PROCESSING

All COSI6 post-processing are available in excel and .txt format.

Physical characteristics

- Gives access to the **mass fluxes and isotopic compositions** of materials at any point of the scenario and at any time.

Waste evaluation

- COSI6 can evaluate:
  - the number of **High Level Waste packages**,
  - their characteristics (mass, thermal power, toxicity, neutron sources, …).

Economy

- Can be used to evaluate economical aspects of a nuclear reactor fleet simulation.
- This post-processing requires economical inputs data such as the unit costs.

Activities and **Strategic Materials** post-processing are described in the next slides.

COSI6 EVOLUTIONS SINCE 2012

- Post-processing “**Activities**”:
  - Calculation of neutron sources, activity, toxicity and decay heat.
  - Per fuel assembly or per tons of initial heavy nuclides.

- Option “**Final imposed content**”:
  - Possibility to fix the fuel composition after irradiation and avoid the CESAR calculation (as well as the building of CESAR libraries)
    - Useful for fuel with constant initial composition and constant final composition

- Possibility to limit the decay heat at reprocessing.

- **New calculation scheme: CESAR5.3HN restricted to the heavy nuclides.**
  - **Fission products are regarded as a global mass.**
  - **Implementation of a Runge-Kutta solver for HN cooling computation.**

- It is now possible to add “**recommended data”** to a database (restricted to COSI with CESAR5.3 and CESAR5.3HN)
  - Reference reactor models can be loaded automatically

- Compatibility with java 7

COSI6 EVOLUTIONS SINCE 2012

- New post-processing “**strategic materials**”:
  - Objective: assessment of the required quantities for the deployment of new reactors
  - Possibility to associate “non-nuclear” materials to the fuel assemblies or the reactors of the simulation.
  - The materials are only defined by their name and their mass or quantity.
  - For the moment, activation calculations are not possible.
  - Currently being applied to study the deployment of Sodium Fast Reactors in the French Context

COSI6 EVOLUTIONS SINCE 2012

- Introduction of **parallelism**
  - For irradiation / cooling computations
  - Loosely based on the **lazy evaluation** principle:
    - Computations are performed when the result is needed
    - Or when a CPU is available
  - Average **computation time** ÷5→10

- **Irradiation surrogate models**
  - Surrogate model = “simple” model (ex: statistical estimator) modeling the output of a code in function of its input data
  - Sub-model approach implemented in COSI: the irradiation code can be replaced with surrogate models
  - New computation scheme based on irradiation surrogate models (artificial neural networks) and analytical solutions of Bateman cooling equation
  - Average computation time ÷50 or more
  - Useful in GUI mode (parameter space exploration, manual optimization) as well in batch mode (uncertainty propagation, optimization)

COSI6 EVOLUTIONS SINCE 2012

- Code **memory efficiency** improved: reduction of RAM load (÷10)
  - Rethinking the **data storage process**
  - Save data in ***libraries*** shared between the objects, and not in objects themselves

- New function: scenario ***rewind***
  - Efficient method to modify quickly a scenario: parts of the scenario already computed are not computed again
  - Strong improvement of the iterative scenario construction

First run: everything is computed

Second run: The section is already in the memory, no need to compute it again

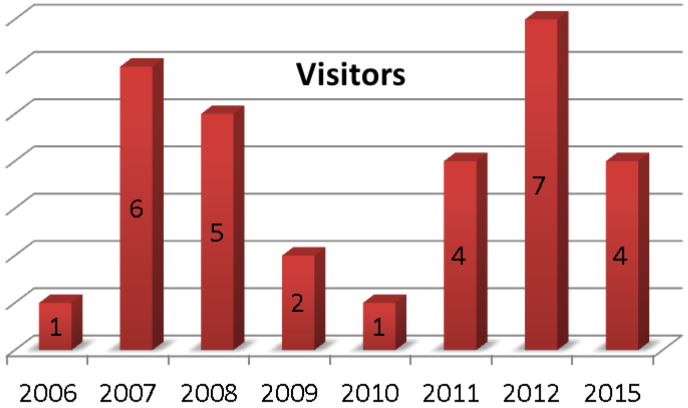
COSI6 user guide and methodology

- A user guide is now available.
- A publication in **Nuclear Technology:** detailed description of the code with some examples of studies carried out with COSI6.

> **C. Coquelet-Pascal** et al., "*COSI6: a Tool for Nuclear Transition Scenarios Studies and Application to SFR Deployment Scenarios with Minor Actinides Transmutation*", ***Nuclear Technology***

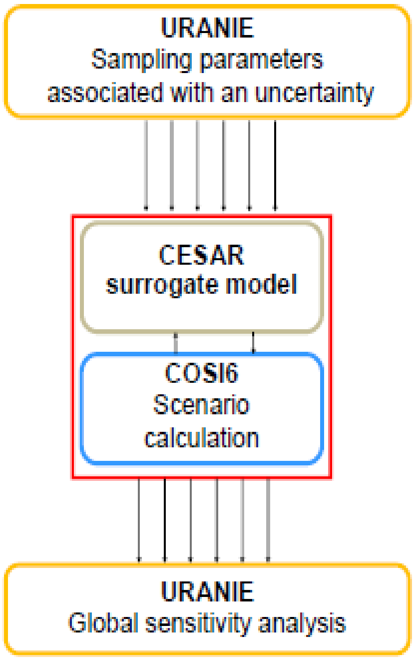
COSI user group

- COSI user group and training every year



Evaluation of the uncertainty

- New methodology based on a **stochastic** approach and **surrogate models** of CESAR in COSI
  - Using CEA/DEN uncertainty platform URANIE
  - Input parameters associated with uncertainty:
    - fuel parameters (burnup, cooling/fabrication time, enrichment, etc.),
    - core parameters (efficiency and load factor, heavy masses, breeding gain, cycle length, etc.),
    - reprocessing plants parameters (annual capacity, losses, recovery rate of MA, etc.),
    - nuclear data (1-group cross sections)



- Results
  - **Uncertainty** (variance, correlations)
  - Global **sensitivity analysis** (part of variance: which parameters contribute to uncertainty?)
  - **Probabilistic** assessment of feasibility

G. Krivtchik et al., « *Analysis of Uncertainty Propagation in Scenario Studies: Surrogate Models Application to the French Historical PWR Fleet* » **GLOBAL 2015**

Multiobjective Optimization using COSI

- COSI is currently simulated chronologically, without **decision making**, scenarios whose parameters are wholly defined by the user. As the interactions among reactors and fuel cycle facilities can be complex, and the ways in which they may be configured are many, the development of **stochastic optimization methodology** could help scenario studies.

- A multi-objective optimization capability is developed around the COSI nuclear fuel cycle simulation code to allow for the automated determination of optimal deployment scenarios and the associated objective trade-off surfaces.

D. Freynet et al., « *Multiobjective Optimization for Nuclear Fleet Evolution Scenarios Using COSI* » **GLOBAL 2015**

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CONCLUSIONS

- COSI, reference code for French scenarios studies.
- Has been developed by the **Nuclear Energy Direction** of the CEA (Cadarache center), during more than 25 years.
- COSI: **physical models from reference validated CEA/DEN neutronic codes and data** (APOLLO, ERANOS, CESAR, JEFF3.1.1).
- COSI: **validated on the French nuclear fleet** (GLOBAL 2013).
- COSI **benchmarked with the main international other codes** (AEN,…).
- COSI **results used for technology requirements of fuel cycle facilities**, economic criteria (estimation of cost) , transport,… with other tools of CEA/DEN.
- COSI **still actively developed** to improve physical models, user convenience, uncertainty propagation, multiobjective optimization.

Thank you for your attention

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Cadarache | 13108 Saint-Paul-lez-Durance Cedex
T. +33 (0)4 42 25 31 30 | F. +33 (0)4 42 25 48 49

Etablissement public à caractère industriel et commercial | RCS Paris B 775 685 019

Direction de l'énergie nucléaire
Département d'étude des réacteurs
Service de physique des réacteurs et du cycle