CLASS, a new tool for nuclear scenarios: Description & First Application

B. Mouginot, J.B. Clavel and N Thiollière

Abstract—The presented work is motivated by a french law regarding nuclear waste management. In order to avoid the limitation coming with the usage of the existing scenario codes, as COSI, VISION or FAMILY, the Core Library for Advance Scenario Simulation (CLASS) is being develop. CLASS is an open source tool, which allows any user to simulate an electronuclear scenario. The main CLASS asset, is the possibility to include any type of reactor, even a complitely new concept, through the generation of its ACSII evolution database. In the present article, the CLASS working basis will be presented as well as a simple exemple in order to show his potentiel. In the considered exemple, the effect of the transmutation will be assessed on Minor Actinide Inventory produced by PWR reactors.

Keywords—electronuclear scenario, reactor, simulation, nuclear waste.

I. INTRODUCTION

IN France, the nuclear waste management R&D priority axes were established in the 1991 and 2006 laws, which should be studied by both academic and industrial research. The Accelerator Driven System (ADS) potential, for Minor Actinides (MA) transmutation, is being investigated in this framework. The ERDRE group at Subatech Laboratory, is involved in the study of double-strata scenarios, composed of first strata dedicated to electricity production and second strata devoted to MA transmutation using ADS reactor.

A new ADS concept (Fig. 1) has been developed at Subatech: the MUST ADS (MUltiple Spallation Target). The MUST ADS is composed of a sub-critical core ($k_{eff} \sim 0.97$) and three spallation targets. In order to produce the neutron flux needed to maintain a constant number of fission inside the core, a proton beam at high energy and high intensity (~ 30 mA) is divided into three secondary beams and send to the spallation target. This concept enables to deposit a high and regular energy inside the subcritical core. The ADS MUST is characterized by a high thermal power (up to 1.4 GWth) and volume specific power, and an increase the irradiation times during which minor actinides are burned (called cycle time) up to five years.

In order to estimate, the MUST ADS impact on the full inventory in Minor Actinide, "electro-nuclear fleat" simulation are needed. Because of the lack of scenario software allowing the implementation of non-common reactor (as ADS), we

B. Mouginot is with Subatech, Subatomic physics and associated technology laboratory, 4 rue Alfred Kastler La Chantrerie BP 20722 44307 Nantes cedex 3 (phone: +33 (0)2-51-85-85-64; fax: +33 (0)2-51-85-84-79; e-mail: mouginot@subatech.in2p3.fr).

J-B. Clavel is with Subatech (phone: +33 (0)2-51-85-84-63; fax: +33 (0)2-51-85-84-79; e-mail: clavel@subatech.in2p3.fr).

N. Thiollière is with Subatech (phone: +33 (0)2-51-85-86-42; fax: +33 (0)2-51-85-84-79; e-mail: thiollie@subatech.in2p3.fr)
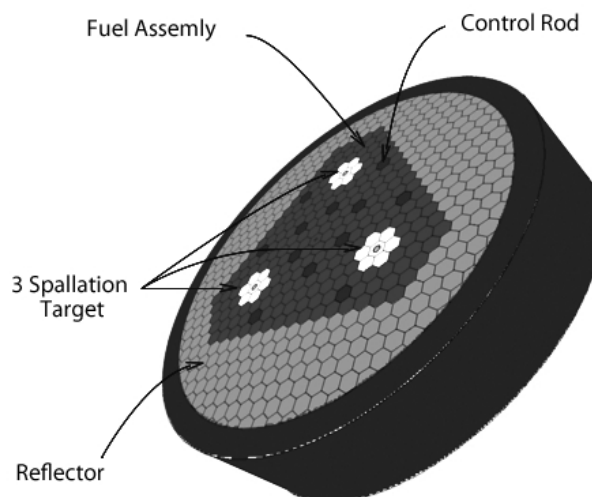
Fig. 1. Schematic representation of a three target MUST ADS.

are developing C++ library to simulate electro-nuclear scenario called Core Library for Advance Scenario Simulation (CLASS). The main goal of CLASS is to build, an open-source software, where the user will be able to control all the input parameters, to add new reactors, even new concepts, and to add any methods needed.

In the present work, the CLASS software will be presented, including the preliminary result of the first simulation.

II. THE CLASS LIBRARY

The CLASS software is developed in order to be simulate any electro-nuclear scenario, take into account all the key phases of a scenario study. In consequence, CLASS is composed by four main elements (Fig. 2) :

- the database, used to estimate the evolution of the isotopic vector [1] in time,
- the type of reactors, that changes the evolution of the fuel isotopic vector during the burning cycle,
- the treatment factory, which manages the cooling of the used fuel, the atomic separation of the cooled fuel to the ultimate waste or to the stock,
- and the CLASS main library, which makes the link between between the reactors and the treatment factory.
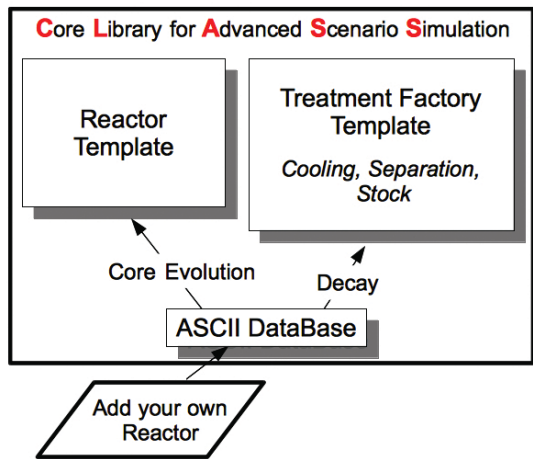
[1] Absolute isotopic composition of a material.

Fig. 2. Schematic representation of CLASS which include the Reactor, the Treat Factory and the associated ASCII database.

A. The Database

The conception of the CLASS database was constrained by two different aspects, firstly, the unlimited number of possibilities for the reactor implementation and, secondly, the minimization of computation time. An ACSII database has been request allowing any user to define any kind of reactor. Thus, to set up a new reactor, the user only needs to generate an Q_{ij} matrix (1), containing the evolution for the (n) steps of the (m) isotope quantity :

$$
\begin{pmatrix} \text{zai}_1 \\ ... \\ \text{zai}_i \\ ... \\ \text{zai}_m \end{pmatrix}
\begin{pmatrix}
(& t1 & ... & t_j & ... & t_n &) \\
Q_{1,1} & ... & Q_{1,j} & ... & Q_{1,n} \\
... & & ... & & ... \\
Q_{i,1} & ... & Q_{i,j} & ... & Q_{i,n} \\
... & & ... & & ... \\
Q_{m,1} & ... & Q_{m,j} & ... & Q_{m,n}
\end{pmatrix}
\tag{1}
$$

The management of the radioactive decay of any unstable isotope is exactly the same, each Q_{ij} matrix gives the isotopic normalized composition of the decay of a nuclei. Thus, this method allows to avoid the resolution of the Bateman equation, as it is already done in each Q_{ij} matrix. To get the isotopic quantity between two time steps, a simple interpolation is used.

B. The Reactors

As presented previously, the main element of a reactor is the database provided by the user, that gives the evolution of the fuel composition as function of time. In addition to the cycle duration (which can be provide in the database), two crucial information are needed : the incoming and the outgoing isotopic vectors. Indeed, if the reactor are fully recharged at the beginning of the cycle, the incoming and outgoing isotopic vector correspond respectively to the first and the last step of the reactor's Q_{ij} matrix. But when we are evaluating a charging plan[2], we have to consider partial refills of the reactor, where the incoming and outgoing isotopic vectors will

[2]A fraction $\frac{1}{n}$ of the reactor are change every $\frac{1}{n}$ cycle time.

not correspond to any step of the reactor's Q_{ij} matrix. In this case, the isotopic vectors must be set by the user.

C. The Treatment Factory

The treatment factories are in charge of all out-reactor phases : the cooling, the treatment and then the storage of the used fuel as reusable or as ultimate waste. In addition to the duration of each phase (cooling and treatment), all treatment factories will need a separation criteria to distinguish reusable material from waste. Finally, the decay of every isotopes during any out-reactor phases will be considered.

D. The CLASS main Library

The CLASS main is in charge to make the connection between each part/ The CLASS main library is linking the previously described parts together. Actually, this library adjusts the time step to perform a correct evolution, beginning/end of reactor cycle, of cooling, and to evaluate the material inventory at every print step. In a near future, the CLASS library will determine automatically the isotopic vector, as a linear combination of the isotopic vector present in any treatment factory storage, to fit the one needed for a reactor. When there is any significant differences between the IV needed and the modeled one, we will perform a new evolution of the corresponding reactor. A module should be developed in order to perform this kind of simulation, using the MURE software (MCNP Utility for Reactor Evolution) [1].

III. A SIMPLE APPLICATION, DESCRIPTION

In order to demonstrate the working mechanism of CLASS, a basic example is described. The results given herein has no purpose in deriving real physic conclusions. Although severe hypothesis are done, this simulation already gives the magnitude order of the inventory involved in the scenario.
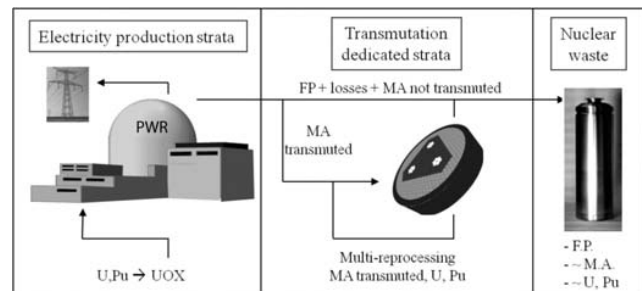

Fig. 3. Schematic double strata scenario, with from left to right, the electricity production, the Minor Actinide transmutation, ultimate nuclear waste.

A. The fleat description

In the following example, two case scenarios are taken into account. In the first case, with only a Pressured Water Reactor (PWR) in the scenario, we establish the evolution of the minor actinides inventory during 160 years. In the second case, we add a ADS strata (Fig. 3) in order to transmute the minor actinides produced by the PWR reactor. To keep realistic condition, the first ADS starts only 40 years after the beginning of the scenario.

B. The PWR Reactor

The simulated fleat is constituted with 9 Pressured Water Reactor (PWR) using Uranium Oxide (UOx) fuel at 1450 MW. The used database [3] shows the mean fuel evolution for a tree year cycle. Our PWR reactors use a fuel loading plan of one year : every year, one third of the fuel is replaced, thus each fuel assembly remains tree years in the reactor.

C. The ADS strata

The ADS strata is constituted with one ADS at 1.4 GW. This ADS is tuned in order to transmute the Minor Actinide flux produce by the PWR reactor strata. Its design is based on the study of our team, in term of power, dimensioning and macroscopical cross section. Nevertheless as the complete study have only been done with output fuel from WPR using Mixed OXides fuel (MOX) or from Fast Breeder Reactors (FBR), the database of this ADS evolution has been done with the simple evolution software, ACDC (Actinides Depletion Code).

This program computes the Bateman equation from the 21 most important nuclei parameters: proportions, cross sections, average number of neutrons emitted per fission and half-lives. It has been shown [2], that ACDC gives, for the evolution of a typical five years reactor, less than 10% deviation from an evolution simulated with the MURE [1]. The transmutation of all Minor Actinides coming from the PWR reactor strata has been consider to establish the ADS works. In our case, because the macroscopical cross section comes from the dimensioning of ADS using slightly different fuel, the 10% precision cannot be reached.

According the ADS simulation, an ADS of 1.4 GW can transmute the Minor Actinide flux of 560 kg per year, which corresponds to the production of 9 PWR reactors. Therefore, in every case scenario simulated, only a "single unit" will be taken into account : 9 PWR reactor or 9 PWR reactor and one ADS, depending on the case scenario.
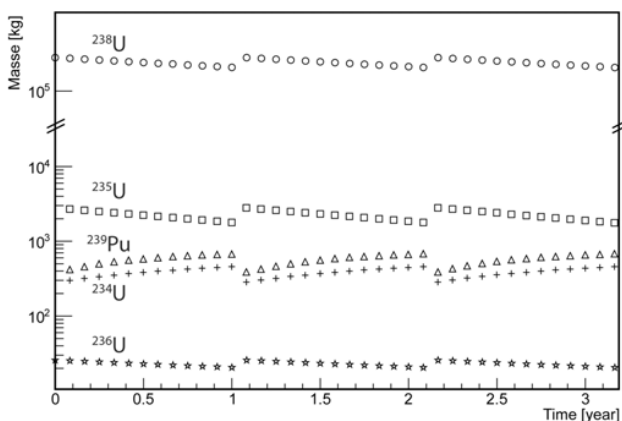
Fig. 4. Evolution of the masses of the most present isotopes inside a PWR reactor, ^{238}U in circle, ^{235}U in square, ^{239}Pu in triangle, ^{234}U in star and ^{236}U in cross.

D. The PWR Evolution

As shown in (Fig. 4), CLASS is able to determine the evolution of the fuel composition as function of time. The one year equilibrium can be clearly seen, corresponding to the loading plan. The normal production of ^{239}Pu is observed during the cycle of about 500 kg per year, as well as a production of about 60 kg of Minor Actinides every year (Fig. 5), which includes the production of ^{241}Am from the relatively fast decay of the ^{241}Pu ($\tau_{1/2} = 14, 4$ y).
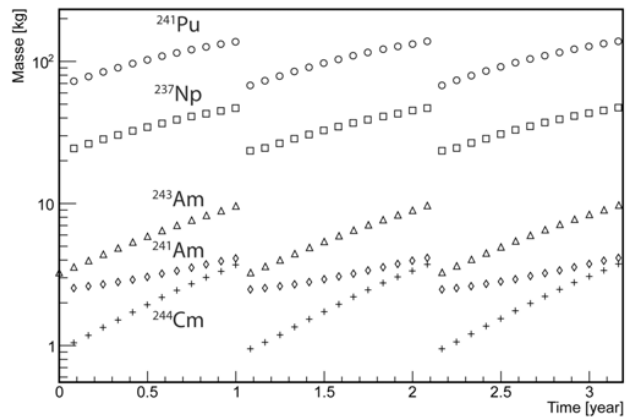
Fig. 5. Main contribution in Minor Actinide inside the PWR reactor, ^{241}Pu in circle, ^{237}Np in square, ^{243}Am in triangle, ^{241}Am in diamond and ^{244}Cm in cross.

E. The ADS Evolution

The basic ACDC evolution gives us access only to the 21 most important isotopes (^{232}Th, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{242}Am*, ^{243}Am, ^{242}Cm, ^{243}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm and ^{247}Cm). In TABLE I, the composition of the fuel inside the ADS at the beginning and the end of the five years cycle has been reported.

TABLE I
COMPOSITION OF THE ADS FUEL

Isotope	Fuel Composition		Burning Rate
	Start Cycle	End Cycle	
^{234}U	0.082	0.071	13.6%
^{235}U	0.014	0.014	0.1%
^{236}U	0.013	0.013	0.5%
^{238}Pu	0.196	0.201	-2.5%
^{239}Pu	0.059	0.058	0.2%
^{240}Pu	0.087	0.077	10.6%
^{237}Np	0.229	0.133	41.2%
^{241}Am	0.188	0.103	44.9%
^{243}Am	0.068	0.043	36.7%
^{244}Cm	0.036	0.065	-2.4%

As it can be seen on TABLE I and Fig. 6, uranium and plutonium isotopes in the ADS fuel are at the equilibrium (or
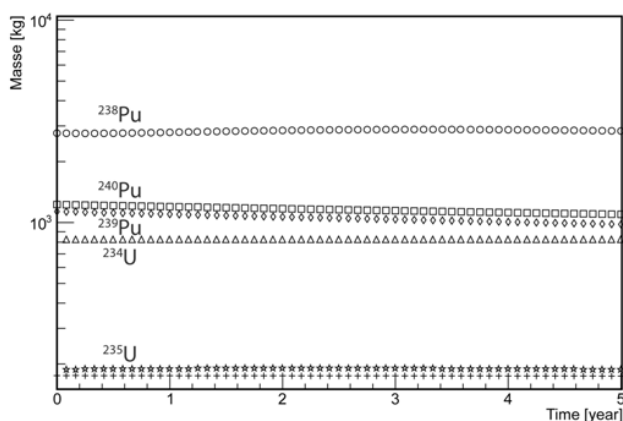
Fig. 6. Evolution of the principal masses of Uranium and Plutonium isotope inside the ADS reactor, ^{238}Pu in circle, ^{240}Pu in square, ^{239}Pu in triangle, ^{234}U in diamond, ^{235}U in star and ^{236}U in cross.

almost) : the mass at the end and beginning of the cycle is almost the same as the one.

On the contrary, the inventory of Minor Actinides inside the ADS core, is decreasing. As shown in Fig. 7, almost 50% of the major Minor Actinide (as ^{237}Np and ^{241}Am) and about 34% of the total masses of them are burned inside the ADS.

IV. A SIMPLE APPLICATION, RESULTS

Both studied case scenario have been simulated during 150 years.
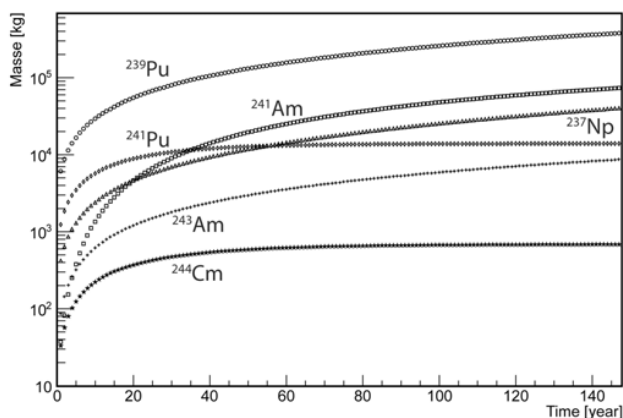
A. PWR-only Case Scenario

Fig. 7. Comparison of the evolution of masses of the major Minor Actinide between the two case scenario, ^{239}Pu in circle, ^{241}Am in square, ^{243}Am in cross, ^{237}Np in triangle, ^{241}Pu in diamond and ^{244}Cm in star.

In this case scenario, we can observe an increase of all nuclear wastes during the "reactor phase". The asymptote reached by the ^{241}Pu is due to the relative short lifetime of this isotope, which decays by β decay on ^{241}Am. The different evolution of this isotope (for small time) can be explained with

the same argument, the main production of ^{241}Am comes from the 241Pu decay.

We can also note that the evolution of ^{249}Pu masses is linear, which suggests that CLASS is working well.

B. PWR-ADS Case Scenario

As expected, in this case scenario we can clearly observed a stabilization of the amount of Minor Actinide (Fig. 8). Nevertheless, a increase amount of 241Am can be observed. The increase comes from the production of ^{241}Pu of the PWR
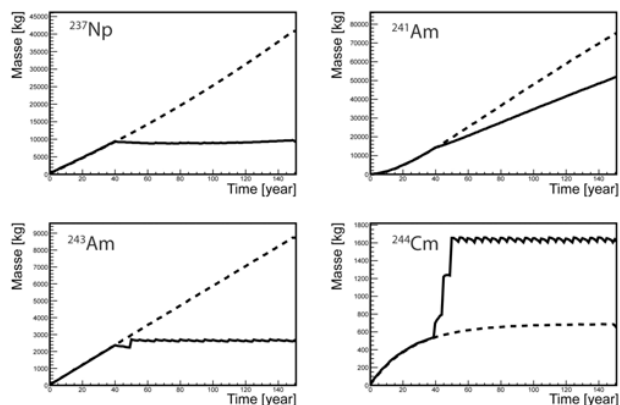

Fig. 8. Masse evolution of the major Minor Actinide between the two case scenario, where dashed line correspond to the pure PWR scenario and plain line to the PWR+ADS scenario, on the top left one find 237Np, with the top right 241Am, on the bottom left 243AM and on the bottom right 244Cm.

reactor. Indeed, the ADS was built in order to take directly the PWR reactor used fuel after the seven years of treatment (which includes the cooling and the separation between waste or storage). The small discontinuity on the ^{243}Am is due to the insufficient storage capacity. So at the 45 years mark, we would need to get some ^{243}Am from outside the fleat.

V. CONCLUSION

Despite the fact that both scenario presented herein were basics, they already show the great potential of the CLASS code to simulate an electronuclear scenario using any type of reactor. Nevertheless, to be able to compute realistic comprehensive scenario, improvements are still needed. In particular, a new module dealing with the transition is being developed in order to build properly the equilibrium fuel composition of new reactor. The ERDRE groups is also initiating new collaboration to add economical and social aspect to the CLASS simulation software. The CLASS simulation will have far-reaching implications for the prediction of the nuclear waste evolution.

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