CESAR5.3: AN INDUSTRIAL TOOL FOR NUCLEAR FUEL AND WASTE CHARACTERIZATION WITH ASSOCIATED QUALIFICATION - 12067

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ABSTRACT

CEA and AREVA_NC have developed and used a depletion code named CESAR for 30 years. This user-friendly industrial tool provides fast characterizations for all types of nuclear fuel (PWR / UOX or MOX or reprocess Uranium, BWR / UOX or MOX, MTR and SFR) and the wastes associated. CESAR can evaluate 100 heavy nuclides, 200 fission products and 150 activation products (with Helium and Tritium formation). It can also characterize the structural material of the fuel (Zircalloy, stainless steel, M5 alloy). CESAR provides depletion calculations for any reactor irradiation history and from 3 months to 1 million years of cooling time.

CESAR5.3 is based on the latest calculation schemes recommended by the CEA and on an international nuclear data base (JEFF-3.1.1). It is constantly checked against the CEA referenced and qualified depletion code DARWIN. CESAR incorporates the CEA qualification based on the dissolution analyses of fuel rod samples and the “La Hague” reprocessing plant feedback experience.

INTRODUCTION

Knowing the physical characteristics (material balance, activity, decay heat, radiation sources) is essential to cope with the problems related to the fuel cycle: biological shielding, decay heat removal, reprocessing, transport, basic nuclear facility classification, nuclear waste interim storage or disposal.

That is why, within the framework of collaboration between the CEA and the AREVA, CESAR (**S**implified **E**volution **C**ode **A**pplied to **R**eprocessing) has been developed to characterize as quickly and accurately as possible every fuel/waste elements covered by the validation studies.

The difficult part in the modeling is concentrated in the depletion code and in the cross section libraries (which need time and experimented engineering). This part is done by CEA scientific team before the industrial use at AREVA. So the use of CESAR became very easy and fast.

THE FUEL MODELISATION BY THE REFERENCE CALCULATION CODES

Before the use of CESAR, the fuel behavior in the reactor core needs to be evaluated by the CEA reference calculation codes for neutron physics: APOLLO [1] for the thermal spectrum

systems and ERANOS [2] for the fast spectrum systems. The calculation schemes are specific for both the fuel type and the reactor type (see Fig1).

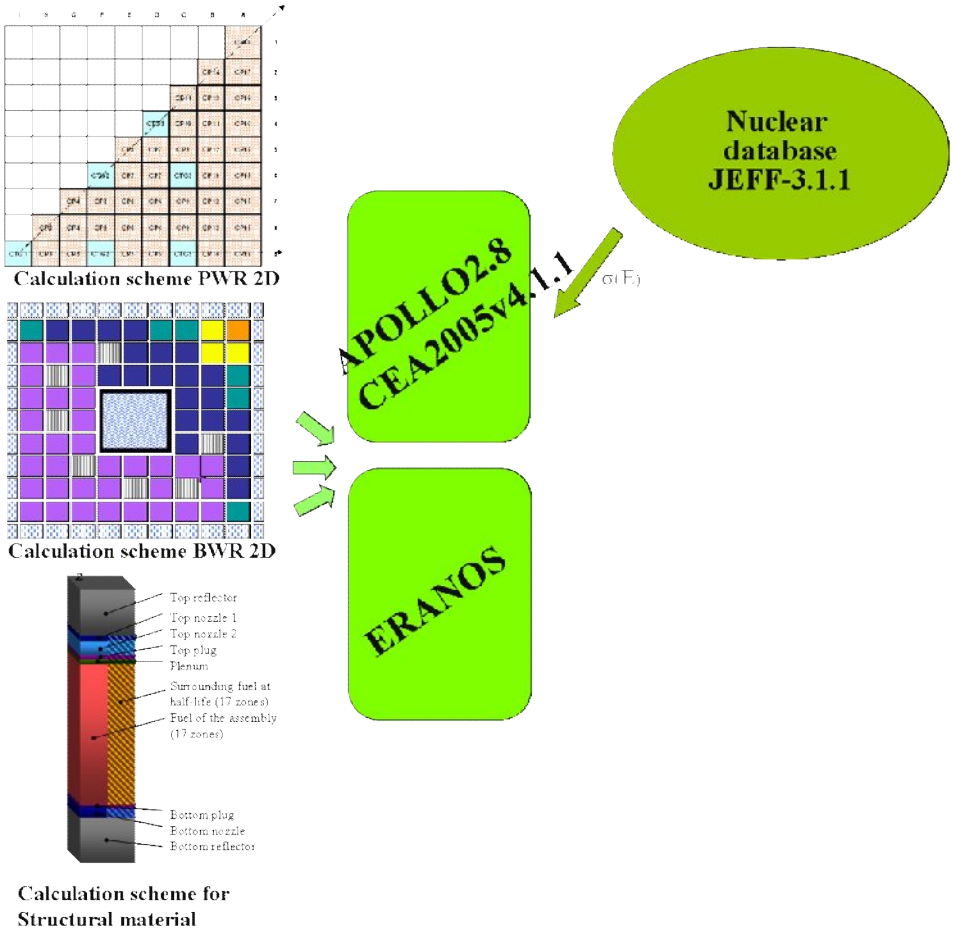


Fig 1. The reference calculation codes

The development and the validation of a calculation scheme need time and experienced engineers. For some type of fuels likes PWR, a calculation scheme in 2D is sufficient, for other likes BWR axial neutron physic behavior must be taken into account.

For one fuel type, it is necessary to proceed to many calculations with the reference code. Each calculation is different from another one on “important” criterion: For instance, the initial U-235 enrichment for UOX fuel or the initial Pu content for MOX fuel.

All of these calculation have to use the same referring nuclear data base: JEFF-3.1.1 [3]

THE CROSS SECTION DATA LIBRAIRIES CONSTRUCTION

The fuel isotopic behavior in the reactor core is described in the result file of the preceding calculations, by cross sections for every energy mesh. All of these cross sections are processed after within tree steps (see Fig2):

1. Collapsing operation to condense the cross sections in one energy group

2. Smoothing operation on each cross section to obtain a polynomial according to the burn-up and the initial U-235 enrichment (for example). Then, CESAR will be able to calculate a cross section for any value of the important criteria, not only for the specific values of the preceding calculations issued from the reference codes.

3. Formatting and ciphering operation. This latest step builds the Data Libraries (BBL). If some axial heterogeneity needs to be taken into account, it is in this step. Finally, the used fields are defined and the BBL are ciphered to prevent any alteration of the data and to ensure the quality of CESAR calculations.

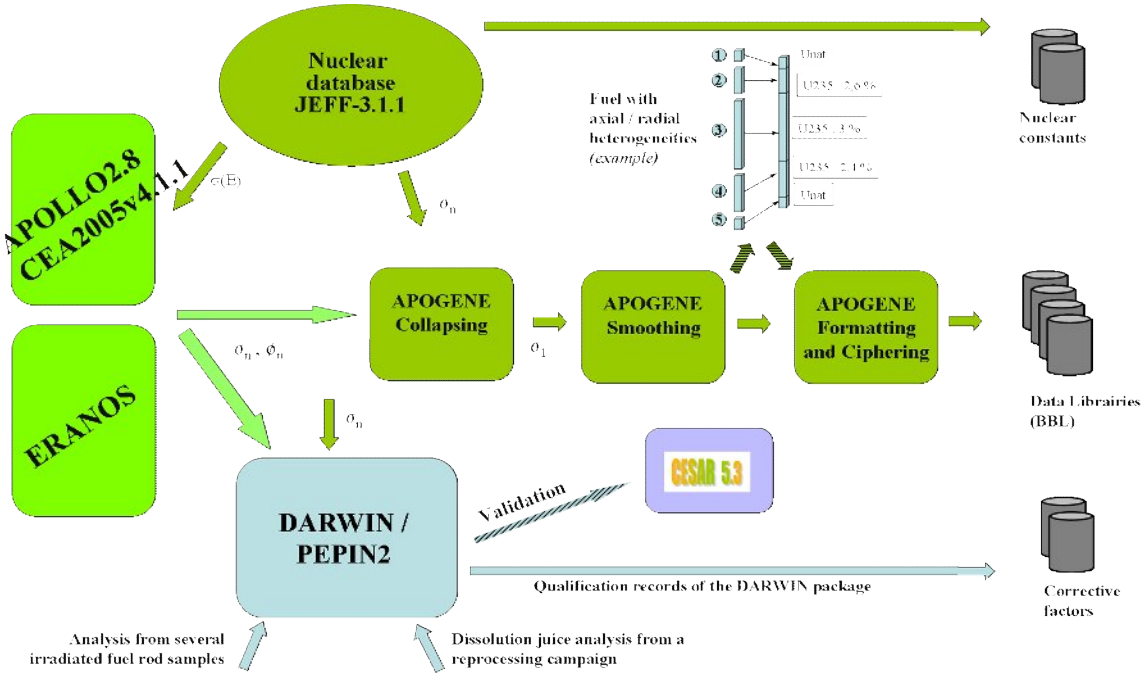


Fig 2. The cross section data libraries construction

All of these operations are done by a tool named APOGENE. At the end, the BBL is ready to be sent to CESAR. This part is a pre-processing operation for CESAR.

The validation from the reference codes to the result of a depletion calculation is insured by DARWIN. DARWIN is the CEA reference calculation package for the fuel cycle. It uses an experimental data based on chemical analysis measurements from fuel rod cuts irradiated in reactors and from full assembly dissolutions carried out at the AREVA/La Hague reprocessing plant. After the validation if some discrepancies are confirmed between experimental analysis and calculation results, the calculation results can be corrected in CESAR for industrial applications. This is done by the Corrective factor files (one for each fuel type where CEA have some experimental validation).

CESAR is in fact an industrial application of DARWIN. It uses the same data reference, the same mathematical models and the same neutron physics reference calculation codes.

All of these pre-processing steps, from the reference codes to CESAR through the qualification with DARWIN, are done with the JEFF-3.1.1 data base. An extract of nuclear data like the half-lives, the branching ratios, the decay energies, the fission yields, is performed for CESAR.

To reach a high performance level in an industrial environment like the “La Hague” reprocessing plant, CESAR uses different methodologies to characterize the fuel behavior under irradiation: the sensitivity to Pu isotopic composition for MOX, the consideration of void fraction profiles in the case of BWR, or the modeling of the structural material of the fuel element. Some algorithms have also been optimized for precision and fast calculations.

The sensitivity to Pu isotopic composition for MOX

Generally, two of the fuel characteristics are sufficient to have a good smoothing:

- Burn up and the initial U-235 enrichment for UOX
- Burn up and the initial Pu enrichment for MOX

But in fact, for MOX fuel, the initial Pu isotopic composition has an influence on the sensitivity of the cross section of many isotopes. To have the best possible modeling, it’s necessary to introduce other smoothing parameters (one for each Pu main isotopes: Pu-238, Pu-239, Pu-240, Pu-241, Pu-242 and for Am-241). But the “initial enrichment of Pu” and the “initial value of the Pu isotope” are correlated parameters.

To separate the influence of each Pu isotope from the initial Pu enrichment, the number of the Pu main isotope to study is reduced from 6 to 5. The previous sixth parameters of the Pu isotope will be indirectly studied through the others 5.

So when the mass of one of the five parameters of the Pu isotope vector increases or decreases, the previous sixth one will counter the mass balance to maintain the initial Pu enrichment at the same value.

The Pu-240 is chosen as the Pu isotope which is not directly studied. Principally because:

- it is the Pu isotope which have the less influence on the cross section sensitivity,
- it has generally a sufficient initial mass composition to counter each mass variation on the mass of other Pu isotopes. (Each of the 5 Pu isotopes to study have a field of possible initial composition)

When all of these smoothing parameters are combined in a non specific MOX fuel composition, very few discrepancies are obtained when compared with reference calculation issued from a neutron physics code like APOLLO.

The values of the discrepancies introduced by this new smoothing methodology are:

- 0,4% on the Plutonium isotope
- 0,1% on the Uranium isotope

Before the implantation of this new smoothing methodology on a MOX fuel BBL, the discrepancies was nearly 6 times bigger (*between two MOX fuel calculations with the same initial Pu enrichment but with different initial Pu isotopes*).

This new methodology has also significantly reduced the number of MOX data libraries. Today, in the version 5.3 of CESAR, only 3 BBL are used to calculate all of the French MOX fuel (one for the oldest burning MOX fuel which are unload from core, one for the generation which are today in the core of the French reactors, and one for the next future generation with high Pu initial enrichment and high Burn up).

The consideration of void fraction in the case of BWR

For BWR fuel, the void fraction is an important parameter of the simulation. As the void fraction is not constant all along the fuel element, the BBL has to be divided in different axial zone. In addition, the initial compositions of the different fuel rods may be different throughout the sub-assembly. 10 axial zones provide a good compromise between a realistic material balance on the entire fuel element and the calculation time. Each zone is characterized by reference codes with its particular void rate.

This improvement of a BBL divided in 10 zones, has greatly increased the quality of the total fuel material balance estimated. However the value of the axial void rates is generally never given by customers. Accordingly, an axial profile of void fraction (such as an axial Burn up profile) is directly plugged in the BBL. Consequently, the CESAR users never directly "manipulate" void rates or instantaneous power of one zone.

In reality, for one axial height of the fuel, the void rate and the power are not constant. They depend on many parameters but some of them like the "final Burn up" and "the reactor control"[1], have been particularly studied.

For the axial void rate:

- The "reactor control effect" seems to lead to some differences between the beginning, the middle and the end of an irradiation cycle (This study of the "reactor control effect" on the void rate was in fact, coupled with a study of the "reactor control effect" on the fuel temperature). But, the lack of such data has prohibited the evolution of the void rate (idem fuel temperature) at each step of the simulation/calculation in CESAR.

For the axial instantaneous power:

- The "reactor control effect" has surely a great impact on the axial instantaneous power. But, the lack of such data has prohibited the evolution of the instantaneous reactor power at each step of the simulation/calculation in CESAR.
- Thanks to the measurement campaign at T1 station at La Hague reprocessing plant, the trends in profile power versus final Burn-up can be identified. Consequently different axial profiles of power have been stored in some BBL. CESAR automatically switches between them depending on the final fuel Burn up.

The structural material of the fuel element

This kind of BBL is also divided in different zones (generally 7). From the top to the bottom nozzle, through the plug, plenum and the cladding, each zone contains the comportment of the structural material present in the zone. As there is no actinides to evaluate the flux level in this BBL, a polynomial formula of the flux level in the structural material are plugged in each zone.

This flux level (as the flux spectrum) is issued from the reference calculation codes. It depends necessarily from the fuel rod type (UOX/MOX, initial U-235 enrichment, …) and from an attenuation coefficient issued from the assembly geometry. Consequently, a structural material BBL can generally not be generated before the fuel BBL associated. The generation of a

[1] The "reactor control" effect is understood like effects that are usually observed on the fuel during an irradiation campaign. Specific comportments of one reactor are not studied here but only generic comportments.

structural material BBL is more complex and takes more time than other BBL generation. Many reference codes must be chained.

The polynomial formula of the flux level in each zone depends on two parameters during the simulation: the average initial U-235 enrichment and the burn-up of the fuel assembly. These two parameters of the fuel assembly are generally the only known by CESAR users.

The initial chemical element compositions of the structural material of the fuel element are also introduced in the BBL. CESAR users can easily employ these default values or enter its specific ones. Some BBL even contain exotic or future structural material initial composition for studies.

GENERAL VIEW OF CESAR

The following flow-scheme gives a general view of the CESAR structure on a user computer (see Fig3).

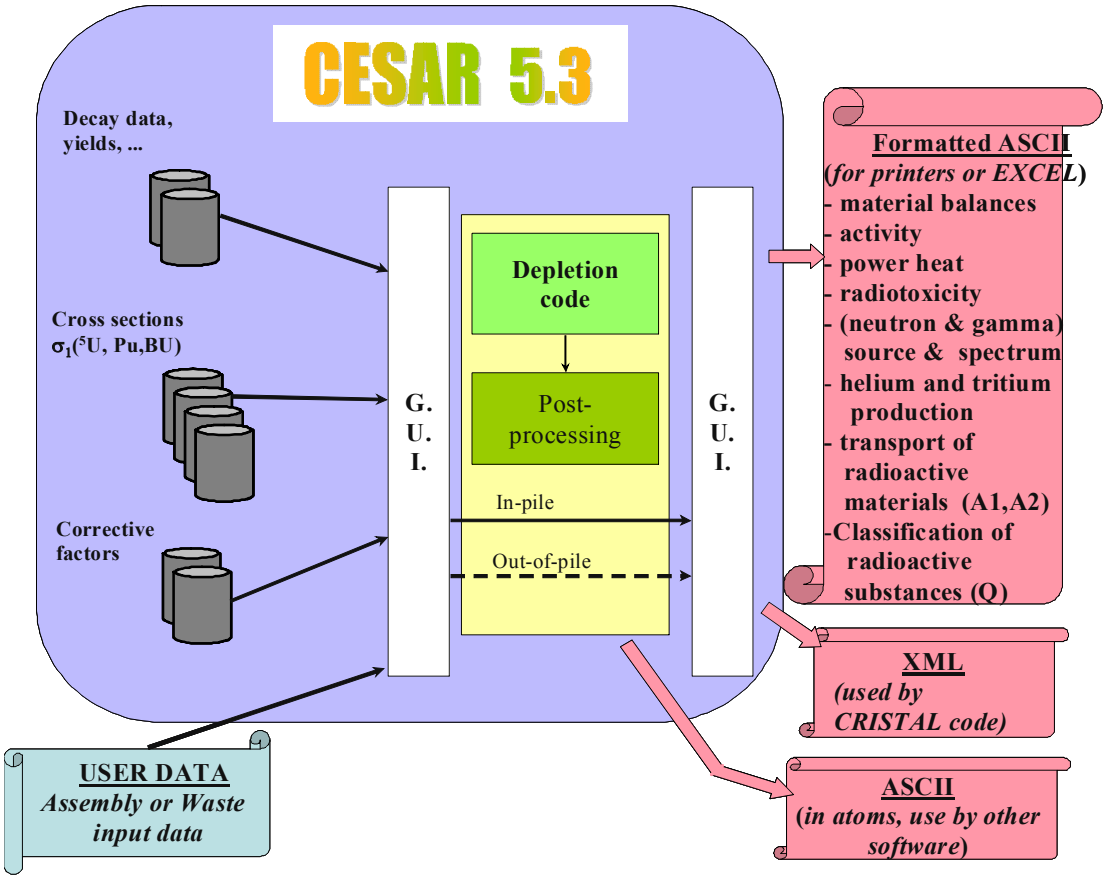


Fig 3. CESAR flow-scheme

CESAR is composed of a calculation code, a Graphical User Interface (GUI), nuclear constants and neutron physics data libraries (BBL). The latest version also integrates some corrective factors. These factors are based on the CEA validation feedback experience of some fuel rod dissolution analyses. BBL can be added or removed independently.

Many documentations (physics, mathematics, informatics, validation, …) exist. Installation and user guides for the two softwares (calculation code and the GUI) are included in the CD rom.

The input Data

The nuclear constants (half-lives, branching ratios, decay energies, fission yields,...) for actinides, fission products and activation products, come from the Joint Evaluated Fission and Fusion File (JEFF) version 3.1.1. [3]

The neutron physics data libraries (the cross sections sets) are supplied by the CEA reference calculation codes: the corrective factors are based on the CEA validation feedback experience of some fuel rod dissolution analyses. [4]

The depletion calculations

This part solves the differential equation system (see Eq.1) below that describes fuel evolution in and out-of-pile. Two solving methods are used: the RUNGE KUTTA method for the in-pile evolution and the matrix method for the out-of-pile evolution. These solving methods are best optimized for fast calculations:

- Double buffering,
- Carvings elementary matrices,
- Optimization according to the performance of the machine between matrix product and vector product.
- Evolution chains are fixed in the software source (loss of programming time, but save time when running)

We have as many equations as isotopes N(A, Z). For actinide calculation the system to solve is:

$$\begin{aligned}\frac{dN(t)}{dt}_{\left[\begin{smallmatrix}A\\Z\end{smallmatrix}\right]} &= \Phi(t).\left[\sigma_c(t).N(t)\right]_{\left[\begin{smallmatrix}A-1\\Z\end{smallmatrix}\right]} + \Phi(t).\left[\sigma_{n,2n}(t).N(t)\right]_{\left[\begin{smallmatrix}A+1\\Z\end{smallmatrix}\right]} \\ &+ \left[\lambda_{\beta^+}.N(t)\right]_{\left[\begin{smallmatrix}A\\Z+1\end{smallmatrix}\right]} + \left[\lambda_{\beta^-}.N(t)\right]_{\left[\begin{smallmatrix}A\\Z-1\end{smallmatrix}\right]} + \left[\lambda_{\alpha}.N(t)\right]_{\left[\begin{smallmatrix}A+4\\Z+2\end{smallmatrix}\right]} + \left[\lambda_{TI}.N(t)\right]_{\left[\begin{smallmatrix}A^m\\Z\end{smallmatrix}\right]} \\ &- \Phi(t).\left[\left(\sigma_c(t)+\sigma_f(t)+\sigma_{n,2n}(t)\right).N(t)\right]_{\left[\begin{smallmatrix}A\\Z\end{smallmatrix}\right]} - \left[\left(\lambda_{half-life}\right).N(t)\right]_{\left[\begin{smallmatrix}A\\Z\end{smallmatrix}\right]}\end{aligned} \quad \text{(Eq. 1)}$$

With:

- N(t) = concentration of an isotope $\left[\begin{smallmatrix}A\\Z\end{smallmatrix}\right]$ at time "t"
- ϕ(t) = neutrons flux at time "t"
- σ(t) = cross section at time "t"
- λ = half life decay constant

For fission products and for some activation products, this system is completed by using a global fission yield (see Eq.2), which is the sum of the fission rate of a fissionable actinide multiplied by the fission yields of the fission product for the fissionable actinide.

$$Y_{G\left[\begin{smallmatrix}A\\Z\end{smallmatrix}\right]} = \sum_{\substack{\text{fissionable}\\\text{actinides}\\j}} \gamma_{j\left[\begin{smallmatrix}A\\Z\end{smallmatrix}\right]} \tau_j \quad \text{(Eq. 2)}$$

With:

- τ_j = fission rate of the fissile nucleus "j"
- γ_j = Production yield of isotope $\left[\begin{smallmatrix}A\\Z\end{smallmatrix}\right]$ from fissile nucleus j

And for activation products, we also need to take into account some other reaction types [(neutron, alpha), (neutron, proton), …]

For long cooling times, CESAR uses a special depletion chain with a hundred actinides (from Pb-206 to Fm-257). For fission products, spontaneous fission yields are taken into account.

The latest version CESAR5.3 can switch between different periods of times for the solvers: days, hours or minutes. This is particularly adapted for research reactors.

The depletion calculation generates an ASCII output file in atoms. This file can be directly used by user's software (likes database or critical calculation software for example). But, these files are often reprocessed by the post-processing application of the Graphical User Interface.

The post-processing application

For a short cooling period (3 months) as well as for geological cooling time (10^6 years), this part calculates the important cycle physical parameters for fuel and waste:

- material balances,
- activity (alpha, beta, TI),
- decay heat (alpha, beta, gamma),
- neutron source and spectrum (spontaneous fission and (alpha,n) reactions in oxide fuel),
- gamma and alpha source and spectrum
- radiotoxicity source.
- coefficients used for the transport of nuclear material
- coefficients used for the classification of radioactive substances

For the radiation source, CESAR employs some energy mesh but the user can also create whatever energy mesh he wants.

The results could be in true values or in different normalizations according to user choice.

The Graphical User Interface

Using the Graphical User Interface, the user:

- prepares the input data for the calculations in a very user-friendly way. (The input data include the fuel type, the initial compositions and the irradiation history)
- runs the calculation
- processes the resulting data by selecting and editing whatever type of results he is interested in.

Therefore, the user can easily run a calculation without knowing the neutron of the fuel cycle physics. French or English versions are available.

The Graphical User Interface can produce file with special format for printers, for EXCEL or in XML. The XML format is used by CRISTAL V2 software which is a criticality calculation code.

The preceding version

CESAR 4 [5] which was the most used version had the greatest number of BBL. But it used data from different references and the oldest references codes was limited by theirs mathematics models/performances.

CESAR version 5.1 [6] based on JEF2-2, was the first version to use the new generation of reference codes [1][2]. But its data base was not totally sufficient and it is today replace with a new one based on JEFF-3.1.1 in CESAR version 5.3.

THE USE OF CESAR

At the AREVA la Hague reprocessing plant

CESAR is today the reference code used at the AREVA La Hague reprocessing plant to calculate the evolution of the spent fuel physical parameters in and out-of-pile quickly. These include the material balances, activity, decay heat, neutron and gamma source and spectrum. CESAR was the first code approved by the AREVA Software Approval Committee in 2002.

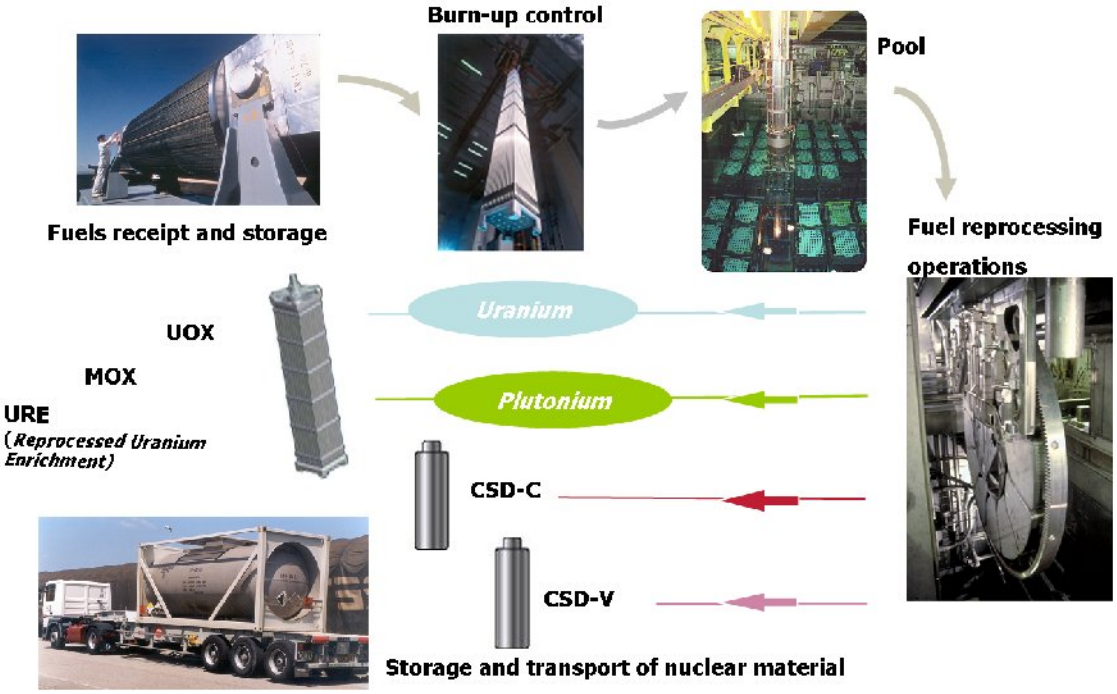


Fig 4. Industrial use of CESAR at AREVA reprocessing plant

The AREVA la Hague uses CESAR for (see Fig4):

- Technical and economic studies
- Fuel acceptance or Fuels physics characterization. The objective is to control the data provided by customers.
- The “coming out” products characterization (U, Pu, wastes and effluents). Correlations to nuclear control process: Non-measurable radionuclides are evaluated by correlation between measured radionuclides (tracer).

- Permission requests to receive and process. Studies to verify that reprocessing safety criteria are respected
- Criticality studies: use of burn-up credit
- Help programming of the reconditioning campaigns.
- Safety and biological protection assessment
- Guaranteed and additional parameters of CSD-C and CSD-V: waste reconditioning, dismantling and trading offer.
- Power heat studies
- Records knowledge for ANDRA (French Agency for Radioactive Waste Management)

CESAR is implanted in different parts of the reprocessing plant. These include the following:

- Nuclear fuel acceptance : To accept a fuel with its attached data from AREVA customers. Each fuel is characterized before shipping to La Hague to verify safety criteria and for quality insurance purposes.
- The T1 station (shearing and dissolving) for burn-up control. CESAR is coupled with gamma and neutron spectrum acquisition sets for the calculation of the fuel burn-up [7]
- The Process Nuclear Control Department which uses CESAR along with two tools. The first one is a data bank interface (called, "STAR"). It allows the calculation of a lot of fuel from an associated data base. It gives: correlations fuel by fuel, referring spectrum and correlations between measured and non measured isotope. The second one allows experimental feedback by comparing the calculations and the dissolving juice analysis.
- For burn-up credit applications (storage in pond or transportation) The new SMOPY burn-up measurement system commercialized by CANBERRA and developed through a joint program between AREVA-CEA and CANBERRA is a system using the CESAR code to minimize the uncertainty of the burn-up evaluation [7][8][9]

AREVA reprocessing plant use CESAR to perform about 150,000 calculations per year.

Other applications

CESAR is also installed at:

- AREVA / LOGISTICS for decay heat and radiation source evaluations of nuclear material transports.
- AREVA / SGN for acceptability studies (to verify some AREVA la Hague reprocessing plant criteria : interim storage, transport, reprocessing, …).
- AREVA / CANBERRA. CESAR is installed in connection with gamma and neutron acquisition sets to estimate the fuel burn-up.
- IRSN (Radioprotection and Nuclear Safety Institute). In order to take into account the burn-up credit for criticality-safety studies, the software “CRISTAL V2” uses CESAR [10].
- EDF to control / calibrate their own depletion codes for: Research & Development, criticality studies, burn-up credit or safety analysis.
- IAEA (International Atomic Energy Agency). CESAR helps inspectors of the Safeguards Department to control all country’s declarations.
- many CEA research laboratories to help, to control, to calibrate installation with data cross section sets for “real” fuel or for “reference” fuel.
- CESAR is also integrated into the software COSI (SImulation COde for nuclear strategy studies) [11] to evaluate fuel mass balance for current or future type reactors (Sodium cooled Fast Reactors, Gas cooled Fast Reactors, minor actinides transmutations in

PWR, …). The KIT (Karlsruher Institut für Technologie) and the ENEA(Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile) built their own BBL for CESAR to be used in COSI.
- Moreover, CESAR is a tool used in the French fast reactor PHENIX to calculate the material balance and linear power.

CESAR was also used to validate the processing of the JEFF-3.1 decay data library files for the Nuclear Energy Agency.

CESAR VERSION 5.3

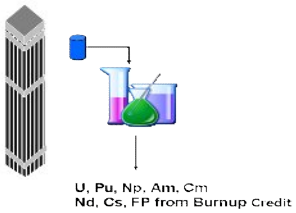
The principal modification of this version of CESAR is the harmonization of the nuclear data with JEFF-3.1.1[3] and the use of the CEA reference calculation codes for neutron physics:
- APOLLO2 [1] for thermal spectrum systems.
- ERANOS [2] for fast spectrum systems.

CESAR 5 calculates the isotopic depletion of
- 109 actinides (from Tl-207 to Fm-257)
- 212 fission products (from Zn-72 to Ho-166m)
- 165 activation products for fuel impurities and subassembly structures (H-1 to Gd-160)

Qualification: Experimental validation

The qualification of CESAR5 is based on the qualification of DARWIN[4], the CEA reference calculation package for the fuel cycle. A code validation was made between isotope results of CESAR and DARWIN. This validation was easy because they use the same data reference, the same mathematical models and the same neutron physics reference calculation codes. In fact, we might qualify CESAR as an industrial application of DARWIN.

Table II: Experimental database



Experimental database for DARWIN qualification on PWR and BWR fuel

Reactor	Enrichment	up to Burnup
BUGEY UOx	3.1% (U_{235})	40 GWj/t
FESSENHEIM UOx	3.1% (U_{235})	50 GWj/t
GRAVELINES UOx	4.5% (U_{235})	60 GWj/t
CRUAS URE	3.5% (U_{235})	40 GWj/t
ST LAURENT B1 MOx	4.5% (Pu)	45 GWj/t
DAMPIERRE MOx	5.3% (Pu) / 6.7% (Pu)	60 GWj/t
GUNDREMMINGEN	3.95% (U_{235})	40 GWj/t
CRUAS UOx	4.5% (U_{235})	68 GWj/t
MALIBU UOx	4.5% (U_{235})	68 GWj/t
CRUAS UOx	4.3% (U_{235})	70 GWj/t
GRAVELINES ALIX UOx	4.5% (U_{235})	85 GWj/t

Experimental data (see Table II) is based on chemical analysis measurements from fuel rod cuts irradiated in reactors and from full assembly dissolutions carried out at the AREVA/La Hague reprocessing plants. This enables us to cover a large range of fuels having various enrichments in U-235, up to 4.5%, associated with burn-ups ranging from 10 GWd/t to 60 GWd/t. Recently, MOX fuels have also been investigated, with an initial Pu amount in the central zone of 5.6 % and a maximum burn-up of 45 GWd/t. Uranium, Plutonium, Americium and Curium isotopes were analyzed in the samples. Furthermore, the fission products involved in the Burn-up Credit studies were measured.

So CESAR5.3 profits from the DARWIN2.3 validation programs based on the dissolution analyses of fuel pin samples. DARWIN benefits from the feedback experience provided by CESAR's intensive use at the AREVA reprocessing plant.

Discrepancies between experimental and calculated values with their uncertainties are in Table III

Table III: Qualification on actinides and fission products for DARWIN2.3 / CESAR5.3 for UOX (→60GWd/t) and MOX (→45GWd/t)

	UOX	MOX
U-234, U-235	< ± 5% ± 3 %	
U-236	-1 % ± 1 %	-3 % ± 1 %
Pu-238	-7% ± 4 %	-3 % ± 1 %
Pu-239	≤ ± 3 % ± 3 %	
Pu-240	≤ ± 2 % ± 2 %	≤ ± 2 % ± 1 %
Pu-241	-3 % ± 3 %	-3 % ± 1 %
Pu-242	-3 % ± 4 %	-2 % ± 1 %
Np-237	-6% ± 4%	-4 % ± 4 %
Am-241	-5 % ± 3 %	
Am-242m	≤ ± 15 % ± 5 %	
Am-243	-6 % ± 7 %	-6 % ± 3 %
Cm-243	-20 % ± 8 %	-17 % ± 3 %
Cm-244, Cm-245, Cm-246, Cm-247	-15 % ± 10 %	-5 % ± 4 %
Nd-143, Nd-144, Nd-148, Nd-150	≤ ± 2% ± 2%	
Cs-133	- 4 % ± 2 %	< ± 2 % ± 2 %
Cs-134	- 5 % ± 4 %	
Cs-135	≤ ± 3 % ± 3 %	≤ ± 5 % ± 2 %
Cs-137	- 7 % ± 2 %	- 2 % ± 2 %
Sm-147	- 3 % ± 2 %	
Sm-150, Sm-152	- 5 % ± 3 %	
Sm-151	- 9 % ± 3 %	
Eu-153	4 % ± 2 % (60GWd/t)	2 % ± 2 % (45 GWd/t)
Eu-154, Gd-154	7 % ± 3 % (60GWd/t)	2 % ± 3 % (45 GWd/t)
Eu-155	-1 % ± 3 % (60GWd/t)	-3 % ± 3 % (45 GWd/t)
Gd-155	1 % ± 3 % (60GWd/t)	-7 % ± 3 % (45 GWd/t)
Ru-106	≤ ± 6 %	

Data processing and performance

The programming language is Fortran 90 for the calculation code and C++ for the Graphical User Interface. The development is carried out within a Quality Assurance framework. CESAR 5 can be installed on all computers that have the UNIX or PC/Windows environment.

The software, the BBL and the nuclear data take few spaces on a CD rom. The calculation time is approximately 15 seconds for a standard UOX fuel.

Application field

Each data libraries has a technical notice that describes the calculation scheme, the reactor and the fuel data used and the validation field. Their calculation schemes are archived in a CEA data bank. The BBL allow the calculation of the following types of reactors (see Table I):

Table I: Type of fuel/reactor and range of calculation of the current cross-section sets

Fuel / Reactor	Initial U-235 or Pu enrichment Maximum burnup	Note
PWR UOX *(fuel)*	Up to 5% Up to 100 GWd/t	17x17 but also 14x14, 15x15, 16x16, 18x18, and URT fuel, etc …
subassembly structures	Up to 5% Up to 100 GWd/t	This library is divided into different parts: Top nozzle, spring plug, plenum, clads and grids, bottom end plug, bottom nozzle
BWR UOX	Up to 4.5 % Up to 72 GWd/t	SVEA-96, SVEA-64, 9x9-9Q, 8x8 These BBL are divided into different parts to take into account axial heterogeneity (void fraction or initial composition). Ended burn-up have also an influence on axial power level.
PWR MOX *(fuel)*	Up to 12% Up to 100 GWd/t	17x17 but also 14x14, 15x15, 16x16 Effects of initial composition of plutonium on cross section sets are taken into account.
subassembly structures	Up to 12% Up to 100 GWd/t	This library is divided into different parts : Top nozzle, spring plug, plenum, clads and grids, bottom end plug, bottom nozzle
BWR MOX	Up to 6.1 % Up to 50 GWd/t	These BBL are divided into different parts to take into account axial heterogeneity (void fraction or initial composition).
Heavy Water	Up to 94 % Up to 440 GWd/t	French and foreign experimental old reactors
Fast Reactor	Up to 25 % Up to 200 GWd/t	Phenix
GGR	Up to 1,7% Up to 11 GWd/t	metallic fuel
MTR	Up to 94 % Up to 1000 GWd/t	plate or cylindrical experimental reactors

THE FUTURE DEVELOPMENTS

The future version of CESAR will integrate:

- A new post-processing application for the calculation of dose rate.
- The reduction of the lower limit of 90 days to 1 day for the minimal cooling time,
- The rebuild of the GUI with new informatics technologies,
- New nuclear data and BBL for Fast Reactor and other new reactors studied.

CESAR IN FOUR WORDS

CESAR in four words, is **RIGHT, FAST, SIMPLE, SECURE**

CESAR is right

- Nuclear constants are issued from international data bank (JEFF-3.1.1)
- Calculation schemes for the generation of cross sections libraries are based on CEA referenced codes.
- Irradiation chains are validated against a CEA reference code (DARWIN)

- The calculation results are validated in relation to analysis of irradiated fuel rod sample and the feedback experience of the La Hague AREVA_NC reprocessing plant. In addition, correction factors are used to correct some discrepancies still observed.
- Solvers used and smoothing methods should introduce the minimum uncertainty calculation.
- The BBL may reflect axial fuel heterogeneities (like BWRs).

CESAR is <u>fast</u>

- All the very long part of calculating neutron cross sections (via reference codes) has already been obtained/performed by the CEA. The cross sections are tabulated and ready for use.
- Two algorithms are used to solve the differential equations system (Runge-Kutta under radiation flux, matrix for cooling times). CESAR optimizes the benefits of each of these two solvers. They are directly coded in CESAR (no use of generic external functions)
- Irradiation chains are fixed in the software source (loss of programming time, but save time when CESAR is running)
- Each solver is optimized to be faster by mathematical or computer algorithms.

CESAR is <u>simple</u>

- All the difficult part of the construction has already been made by the CEA.
- A single input file with simple but strict format, describes all the user data. A single output file is produced by the code. A user manual details all formats. The coupling with other codes or databases is therefore very easy.
- The reprocessing of old output files for irradiation or cooling calculations is possible.
- Some Graphical User Interfaces can be added to the depletion code to make it more "accessible". These are very user-friendly. The user is guided step by step. Many post-processing can target exactly the information sought.
- The code is portable across many computers: no libraries needed, all files are in ASCII.

CESAR is <u>secure</u>

- Before any calculation, the user data are validated against the used ranges of the BBL. More than 250 error messages simple but precise, can be returned to the user.
- Nuclear data libraries (BBL) are encrypted. Each has its own used area.
- The BBL development is described in a technical note (calculation scheme, data used)
- The CEA provides the durability / archiving of all BBL (A protocol was signed by AREVA, CEA and SGN, but applies to IRSN, ENEA and FZK. Today all the BBL are archived with their calculation scheme)
- All the software was developed under Quality Assurance. Code maintenance has been provided for 20 years by the CEA.

CONCLUSION

CEA and AREVA_NC have developed and used a depletion code named CESAR for 30 years. This user-friendly industrial tool provides fast characterizations for all types of nuclear fuel (PWR / UOX or MOX or reprocessed Uranium, BWR / UOX or MOX, MTR and SFR) and the wastes associated. CESAR calculates the material balances, the activity, the decay heat, the radiation sources, the radiotoxicity sources, and useful coefficients for transport and radioactive substances classification.

AREVA_NC uses CESAR intensively at “La Hague” plant, not only for prospective studies but also for characterizations at different industrial facilities all along the reprocessing process and waste conditioning (near 150 000 calculations per year). CESAR is the reference code for AREVA_NC. CESAR is used directly or indirectly with other software, data bank or special equipment in many parts of the La Hague plants.

The great flexibility of CESAR has rapidly interested other projects. CESAR became a "tool" directly integrated in some other softwares. Finally, coupled with a Graphical User Interface, it can be easily used independently, responding to many needs for prospective studies as a support for nuclear facilities or transport. An English version is available.

For the principal isotopes of U and Pu, CESAR5 benefits from the CEA experimental validation for the PWR UOX fuels, up to a burnup of 60 GWd/t and for PWR MOX fuels, up to 45 GWd/t. CESAR version 5.3 uses the CEA reference calculation codes for neutron physics with the JEFF-3.1.1 nuclear data set.

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