CESAR: A Code for Nuclear Fuel and Waste Characterisation

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ABSTRACT

CESAR (**S**implified **E**volution **C**ode **A**pplied to **R**eprocessing) is a depletion code developed through a joint program between CEA and COGEMA. In the late 1980's, the first use of this code dealt with nuclear measurement at the Laboratories of the La Hague reprocessing plant. The use of CESAR was then extended to characterizations of all entrance materials and for characterisation, via tracer, of all produced waste. The code can distinguish more than 100 heavy nuclides, 200 fission products and 100 activation products, and it can characterise both the fuel and the structural material of the fuel. CESAR can also make depletion calculations from 3 months to 1 million years of cooling time. Between 2003-2005, the 5th version of the code was developed. The modifications were related to the harmonisation of the code's nuclear data with the JEF2.2 nuclear data file.
This paper describes the code and explains the extensive use of this code at the La Hague reprocessing plant and also for prospective studies. The second part focuses on the modifications of the latest version, and describes the application field and the qualification of the code. Many companies and the IAEA use CESAR today. CESAR offers a Graphical User Interface, which is very user-friendly.

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, nuclear waste interim storage or disposal.
That is why, within the framework of collaboration between the CEA and the COGEMA, and a Quality Assurance procedure, CESAR (**S**implified **E**volution **C**ode **A**pplied to **R**eprocessing) has been developed to answer these questions quickly for every fuel/waste covered by the validation studies.

A PRESENTATION OF CESAR

The following flow-scheme gives a general view of the CESAR structure.

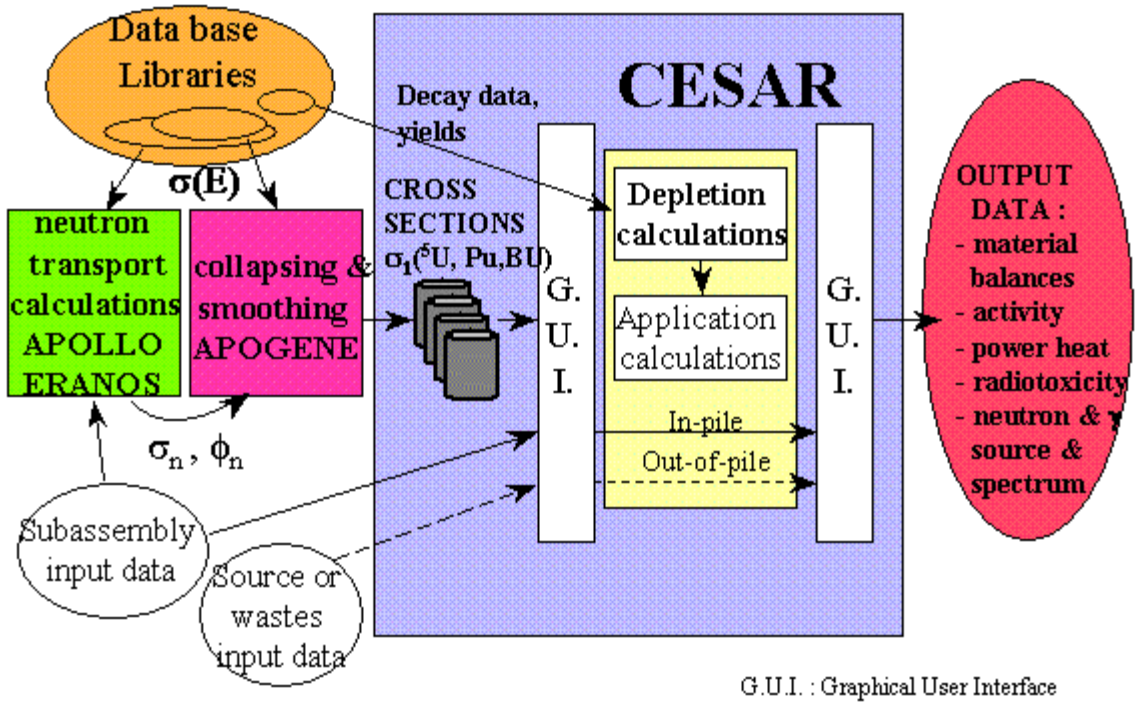

Fig. 1. CESAR flow-scheme

CESAR is composed of a calculation code, a Graphical User Interface, nuclear constants and neutron physics data libraries.

The Input Data

The nuclear constants (half-lives, branching ratios, decay energies, fission yields,...) for actinides and fission products comes from:

- the CEA library and the MEEK & RIDER library for version 4 of CESAR [**Error! Reference source not found.**]
- Joint European File (JEF) for version 5 of CESAR

The activation products come from the European Activation File (EAF).

The neutron physics data libraries (the cross sections sets) are supplied by the CEA reference calculation codes for neutron physics: APOLLO (see references) for the thermal spectrum systems and ERANOS (s.r.) for the fast spectrum systems.

After a collapsing and smoothing operation, these cross section sets are given as a function of burnup and initial 235U enrichment, or initial Pu content for MOX fuel. Moreover, for MOX fuel, version 5 of CESAR can take into account the influence of the initial composition of plutonium isotopes on cross sections. This improvement has greatly reduced the number of MOX data libraries.

For special fuel (BWR, …) and for the subassembly structures, cross section data libraries are divided into axial levels to take into account some axial heterogeneous characteristics (void rate, initial composition, …)

A specific neutron physics study is carried out for each type of fuel with an associated documentation.

The depletion calculations

This part solves the differential equation system 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 optimised for fast calculations.

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

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

For fission products and for some activation products, we can add a global fission yield, 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.

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

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

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

The application calculation
This part calculates the important downstream cycle physical parameters which vary with the cooling time: material balances, activity (alpha, beta, TI), decay heat (alpha, beta, gamma), neutron source and spectrum (spontaneous fission and (alpha,n) reactions), gamma and alpha source and spectrum and radiotoxicity source. For the radiation source, CESAR proposes the energy mesh of the MERCURE and TRIPOLI codes but the user can also create whatever energy mesh he wants. For a short cooling period (3 months) as well as for geological cooling time (10^6 years), the important physics parameters can be calculated for radioactive sources such as fuel and waste (glass, clads, grid hulls and nozzle casks and technological waste).

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)
- makes the calculation
- processes the resulting data by selecting and editing whatever type of results he is interested in.

Therefore, the user can easily make a calculation without knowing the neutron or fuel cycle physics.
An English version is available with the version 5 of CESAR.

THE USE OF CESAR

At the COGEMA la Hague reprocessing plant
CESAR version4 is today the reference code used at the COGEMA 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 COGEMA Software Approval Committee in 2002. CESAR is used to perform about 40,000 calculations per year at the COGEMA la Hague reprocessing plant.

The COGEMA la Hague uses CESAR for:

- Fuels physics characterisation. The objective is to control the data provided by customers.
- The "coming out" products characterisation (U, Pu, wastes and effluents). Non-measurable radionuclides are evaluated by correlation between measured radionuclides (tracer).
- Studies to verify that reprocessing safety criteria are respected
- Help programming of the reconditioning campaigns.
- Safety studies, waste reconditioning, dismantling and trading offer.

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 COGEMA 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 burnup control. CESAR is coupled with gamma and neutron spectrum acquisition sets for the determination of the fuel burnup [**Error! Reference source not found.**]
- The Process Nuclear Control Department which uses CESAR along with two tools. The first one is a data bank interface (called, "STAR"). It enables the control of nuclear material flows in the dissolver. The second use is made with the GB software (Gravimetric Balance). It adjusts/qualifies reactor data for the fuels with dissolving juice analyses for an entire dissolution campaign.
- For burnup credit applications (storage in pond or transportation) The new SMOPY burnup measurement system commercialized by CANBERRA and developed through a joint program between COGEMA-CEA and CANBERRA is a system using the CESAR code to minimize the uncertainty of the burnup evaluation. [**Error! Reference source not found.**,**Error! Reference source not found.**,**Error! Reference source not found.**].

Other applications

CESAR is also installed at:

- AREVA / COGEMA LOGISTICS for decay heat and radiation source evaluations of nuclear material transports.
- AREVA / SGN for acceptability studies (to verify some COGEMA la Hague reprocessing plant criteria : interim storage, transport, reprocessing, …).
- AREVA / CANBERRA. CESAR is installed in connection with gamma and neutron acquisition sets to determinate the fuel burnup.
- IRSN (Radioprotection and Nuclear Safety Institute) for criticality studies. In order to take into account the burnup credit for criticality-safety studies, the software "CRISTAL" uses CESAR [**Error! Reference source not found.**].
- 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)**Error! Reference source not found.**] to evaluate fuel mass balance for current or future type reactors (Sodium cooled Fast Reactors, Gas cooled Fast Reactors, minor actinides transmutations in PWR, …).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 JEFF3.1 decay data library for the Nuclear Energy Agency.

CESAR VERSION 5

The principal modification of the 5th version of CESAR is the harmonisation of the nuclear data with JEF2.2[**Error! Reference source not found.**] and the use of the CEA reference calculation codes for neutron physics :

- APOLLO2 **Error! Reference source not found.**] for thermal spectrum systems.
- ERANOS **Error! Reference source not found.**] for fast spectrum systems.

CESAR 5 calculates the isotopic depletion of

- 109 actinides (from Tl-207 to Fm-257)
- 209 fission products (from Zn-72 to Ho-166m)
- 146 activation products for fuel impurities and subassembly structures (from H-1 to Gd-160)

Application field

The cross sections data libraries currently built for CESAR5, allow the calculation of the following types of reactors:

Table I. Type of fuel/reactor and range of calculation of the current cross-section sets of CESAR5

Fuel / Reactor	Initial enrichment	Maximum burnup	Note
PWR 17x17 UOX	1.4%<U-235<5%	0<bu<100 GWd/t	
PWR 17x17 UOX with reprocessing Uranium	3.7%<U-235<4.5%	0<bu<70 GWd/t	
PWR 17x17 MOX	4.5%< Pu <12% U-235 = 0,25%	0<bu<70 GWd/t	The effects of initial composition of plutonium isotopes on cross section sets are taken into account.
subassembly structures of PWR 17x17 UOX	3.25%<U-235<4.95%	0<bu<100 GWd/t	This data library is divided into different parts: Top nozzle, spring plug, plenum, clads and grids, bottom end plug, bottom nozzle
subassembly structures of PWR 17x17 MOX	4.5%< Pu <8% U-235 = 0,25%	0<bu<70 GWd/t	This data library is divided into different parts : Top nozzle, spring plug, plenum, clads and grids, bottom end plug, bottom nozzle

Table II: Type of fuel/reactor and range of calculation of the cross-section sets of CESAR4

Fuel / Reactor	Initial enrichment	Maximum burnup	Note
PWR UOX	1.4%<U-235<5%	0<bu<60 GWd/t	17x17 but also 14x14, 15x15, 16x16, 18x18, and URT fuel, etc …
PWR MOX	Punctual value of Pu from 4.5% to 12% U-235 = 0,25%	0<bu<60 GWd/t	17x17 but also 14x14, 15x15, 16x16 …Effects of initial composition of plutonium isotopes on cross section sets aren't taken into account.
subassembly structures of PWR 17x17 UOX	1.4%<U-235<5%	0<bu<60 GWd/t	This data library is divided into different parts: Top nozzle, spring plug, plenum, clads and grids, bottom end plug, bottom nozzle
subassembly structures of PWR 17x17 MOX	Pu =[5.3%; 7.5%; 10%, 12.5%] U-235 = 0,25%	0<bu<100 GWd/t	This data library is divided into different parts: Top nozzle, spring plug, plenum, clads and grids, bottom end plug, bottom nozzle
BWR UOX	1<U-235<3,6 %	0<bu<60 GWd/t	SVEA-96, SVEA-64, 9x9-9Q, 8x8
Heavy Water	85%<U-235<99 %	0<bu<440 GWd/t	French experimental old reactor, ANSTO/HIFAR
Fast Reactor	0.1%<U-235<0.3% 20%< Pu <25 %	0<bu<200 GWd/t	Phenix
GGR	0,7%<U-235<1,7%	0<bu<11	metallic fuel

		GWd/t	
MTR	U-235 ≈ 93 %	0<bu<440 GWd/t	SILOE, plate experimental reactors

Qualification: Experimental validation

The qualification of CESAR5 is based on the qualification of DARWIN**Error! Reference source not found.**], 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 as 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.

So CESAR5 profits from the DARWIN2 validation programmes based on the dissolution analyses of fuel pin samples or aliquots of entire assembly sets. DARWIN benefits from the feedback provided by CESAR's intensive use at the COGEMA la Hague reprocessing plant.

Experimental data is based on chemical analysis measurements from fuel rod cuts irradiated in French PWR reactors and from full assembly dissolutions carried out at the COGEMA/La Hague reprocessing plants. This enables us to cover a large range of UOX fuels having various enrichments in U-235, 3.1% to 4.5%, associated with burnups 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 burnup of 45 GWd/t. Uranium, Plutonium, Americium and Curium isotopes were analysed in the PWR samples. Furthermore, the fission products involved in the Burnup Credit studies were measured.

Table III. Qualification on actinides for DARWIN / CESAR5 for UOX (→60GWd/t) and MOX (→45GWd/t)

	UOX	MOX
U-234, U-235, U-236	< ± 5% ± 3 % (URE U-236 ± 1%)	
Pu-239, Pu-240, Pu-241	< ± 3 % ± 3 %	
Pu-242	-7 % ± 4 %	-4 % ± 1 %
Pu-238	-11 % ± 5 % URE –3 % ± 3.6 %	-7 % ± 0.5 %
Np-237	-4% ± 6%	-11 % ± 2 %
Am-241	-4% ± 3%	2 % ± 2 %
Am-242m	-25 % ± 4 %	
Am-243	-10 % ± 8 %	-7 % ± 2 %
Cm-243	-30 % ± 8 %	-20 % ± 2 %
Cm-244, Cm-245, Cm-246, Cm-247	-20 % ± 10 %	-8 % ± 3 %

Table IV. Qualification on fission products for DARWIN / CESAR5 for UOX (→60GWd/t) and MOX (→45GWd/t)

	UOX	MOX
Nd-143, Nd-144, Nd-145, Nd-146, Nd-148	< ± 2% ± 2%	
Cs-133, Cs-135, Cs-137	< ± 5 % ± 3 %	< ± 3 % ± 2 %
Cs-134	< ± 10 % ± 4 %	
Sm-149	< ± 11 % ± 10 %	

Sm-147, Sm-150, Sm-151, Sm-152	< ± 5 % ± 3 %	
Mo-95, Tc-99, Ru-101, Rh-103, Ag-109	< ± 10 % (insoluble chemical problem)	30 % < x < 80 % (insoluble chemical problem)
Eu-153	14 % ± 2 % (60GWd/t)	10 % ± 2 % (40 GWd/t)
Eu-154, Gd-154	40 % < x < 100 %	10 % < x < 50 %
Eu-155, Gd-155	< 15 %	20 % < x < 30 %

For CESAR version 4, the qualification for the REP UOX17x17W was based on the analyses of the Gravelines fuel spin sample dissolutions and the La Hague reprocessing plant feedback[**Error! Reference source not found.**].

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 environment: IBM, SUN, HP and DEC alpha. CESAR is also available on PC/Windows with an electronic key.
The calculation time is approximately 15 seconds for a standard UOX fuel.

THE FUTURE DEVELOPMENTS

A newer version based on JEFF3**Error! Reference source not found.**] will be created within the next two years. This period of time is necessary for:

- an internal validation of the JEFF3 cross section data bank for the CEA reference calculation codes for neutron physics APOLLO2,
- an adaptation of the depletion chain of CESAR to JEFF3,
- a new qualification of DARWIN / CESAR based on the CEA experimental data bank,
- reprocessing all CESAR's neutron physics data libraries (cross sections sets).

A new, more polyvalent calculation scheme for the BWR, is also being developed at the CEA.

CONCLUSION

CESAR is a depletion code developed through a joint program between the CEA and the COGEMA. It provides the required characterisation data for different types of irradiated fuels (UOX and MOX) taken from PWRs, BWRs and FRs. CESAR is also be able to characterise all waste and nuclear materials from the reprocessing plants.

CESAR is the reference code used at the COGEMA to calculate quickly the material balances, the activity, the decay heat and the radiation sources of the assemblies reprocessed in the La Hague plants. CESAR is used directly or indirectly with other software, data bank or special equipment in many parts of the La Hague plants

CESAR version 4 has already been installed in 20 nuclear sites in FRANCE and at the IAEA

CESAR version 5 uses the CEA reference calculation codes for neutron physics with the JEF2.2 nuclear data set. CESAR5 is now entering its distribution phase.

Owing to its user-friendly GUI, it is very easy to use the CESAR5 code and it does not require much knowledge of fuel cycle physics. An English version is available.

For the principal isotopes of U and Pu, CESAR5 benefits from an experimental validation for the PWR UOX fuels, up to a burnup of 60 GWd/t and for PWR MOX fuels, up to a burnup of 45 GWd/t.
This experimental validation process is ongoing and its scope will be extended to other types of fuel and to a more complete range of isotopes.

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