DPA calculation in a stainless steel baffle of Chooz-A PWR using auto-dosimetry measurements

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Abstract. This paper presents a method dedicated to the calculation of DPA (displacements per atom) in a stainless steel element irradiated inside Chooz-A reactor core. This method is based on experimental results obtained in samples taken from the analyzed stainless steel element, and calculation results. Experimental results consist in the mass of ^{59}Co and the activity of ^{60}Co, both measured in 2018, i.e. 27 years after the final shutdown of Chooz-A reactor. Calculations are carried out with the TRIPOLI-4® 3D Monte Carlo particle transport code, and the DARWIN/PEPIN2 depletion code, with a simplified modelling of Chooz-A reactor. As explained in this paper, these simplifications are corrected by the use of measurement results. Due to a lack of information about the irradiated steel element (initial ^{59}Co quantity in particular), an iterative process was developed and used. It allows to evaluate missing information and to calculate corrected DPA results in samples. Besides, stress tests were carried out to check the robustness of the process and the uniqueness of DPA result for each sample. This work was carried out by CEA/SERMA with the financial support of EDF.

1 Introduction

Chooz-A Nuclear Power Plant was the first Pressurized Water Reactor built in France. It was operated by EDF (Electricité de France) and SENA (Société d'Énergie Nucléaire Franco-Belge des Ardennes) from 1967 to 1991. In the core of this reactor, some peripheral assemblies were separated by a stainless steel baffle, playing a merely mechanical role. During Chooz-A dismantling, one of these stainless steel elements was collected for the purpose of analysing changes in mechanical properties due to neutron irradiation. This component is shown inside Chooz-A reactor in Figure 1.

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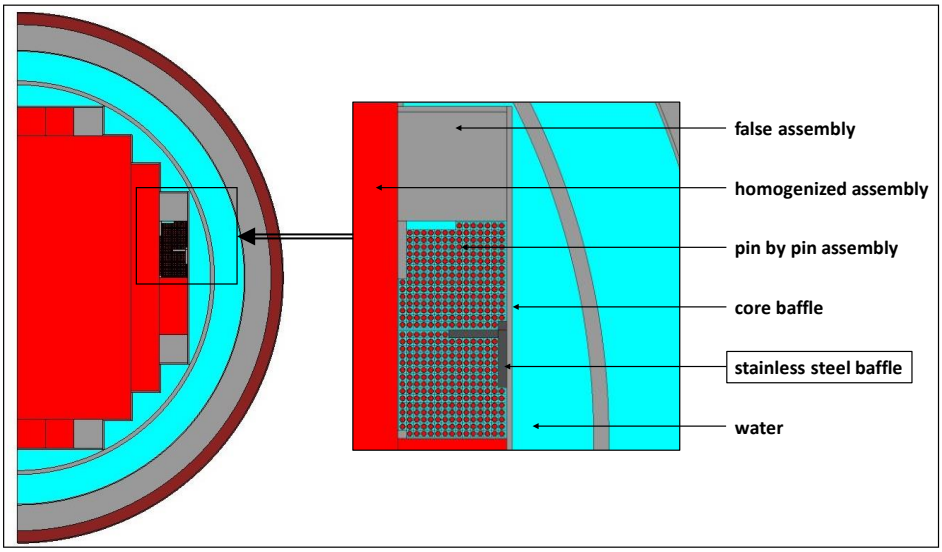


Fig. 1. Analysed stainless steel element in Chooz-A reactor.

This retrieved steel component was cut into several samples to be analysed. The number of displacements per atom (DPA) along the baffle was computed in earlier studies with two different methodologies, leading to significant differences at some locations. Moreover, preliminary Transmission Electron Microscope observations of the material showing the irradiation defects [1] yield some doubts about the computed DPA. Therefore, a new evaluation of DPA was decided.

The calculation of accurate results requires many precise modelling data concerning Chooz-A reactor and its operating history: the precise water temperature variations and distribution in the reactor, the precise neutron sources distribution in the core, the power history, etc. That would be cumbersome to consider all these parameters throughout the entire operating time of Chooz-A reactor.

An alternative to this complex calculation is to use a simplified Chooz-A reactor model combined with results from auto-dosimetry measurements carried out in the different steel samples. Information derived from experimental results are interesting in correcting imperfections of Chooz-A reactor modelling. In fact, this correction consists in applying an adjustment factor to DPA values calculated in steel samples with this simplified modelling.

This paper presents this alternative method and DPA results obtained for the different steel samples from Chooz-A reactor. This work was carried out by CEA/SERMA with the financial support of EDF.

2 Simplified Chooz-A reactor model

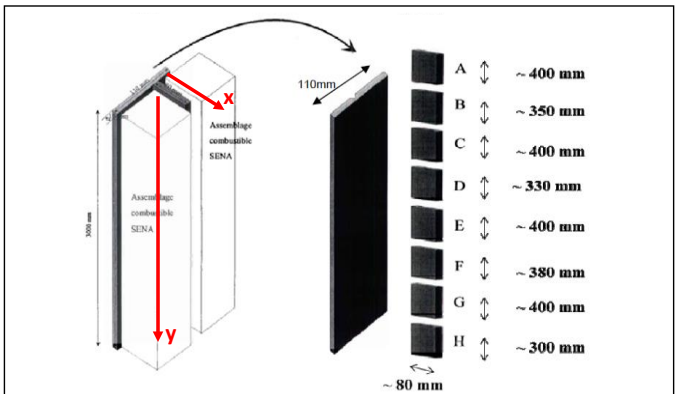
Neutron transport is simulated using the 3D TRIPOLI-4® [2] Monte Carlo code. This code provides many options and possibilities of modelling, and it is used by CEA, EDF, ORANO, and FRAMATOME as a reference tool for neutronics, shielding, and criticality problems. However, in our application, TRIPOLI-4® is used to model Chooz-A reactor with many approximations as described below. It will be explained further how these simplifications are compensated.

Fuel assemblies are homogenised except for the two assemblies surrounding the analysed stainless steel baffle. Water temperature is considered uniform out of the core (radially and axially) and it is supposed to be constant during the whole reactor operation. Inside the core,

the water is warmer and it remains constant. An overview of Chooz-A reactor modelling is shown on Figure 1.

Neutron source distribution is uniform radially inside each assembly. Axially, it corresponds to an average axial source distribution in Chooz-A reactor, and it is identical for each assembly. As in other parameters, radial and axial source distributions remain constant in this simplified model.

The analysed steel baffle has a simple shape and it is modelled without any approximations. It is sketched on Fig 2. This baffle was cut into eight pieces (A to H) but only six small samples were analysed in our application (P1 to P6), collected in the main pieces A, C and H. Information concerning these samples are detailed in the bottom of Figure 2.



sampling	steel piece	X (mm)	Y (mm)
P1	C	85	1060
P2	C	85	860
P3	C	2	950
P4	C	2	860
P5	A	3-13	340-380
P6	H	60-80	2660-2700

Fig. 2. Analysed steel baffle and location of the different steel samples.

Full power history of Chooz-A reactor from 1967 to 1991 is converted into 42 histograms as shown in Figure 3. Although the nominal power that was released by Chooz-A reactor is well known, the neutron source intensity that must be applied to correct simplifications made in the modelling of this reactor is not. The ratio between the neutron source intensity and the real nominal power is in fact the adjustment factor we are investigating for to calculate DPA in steel samples.

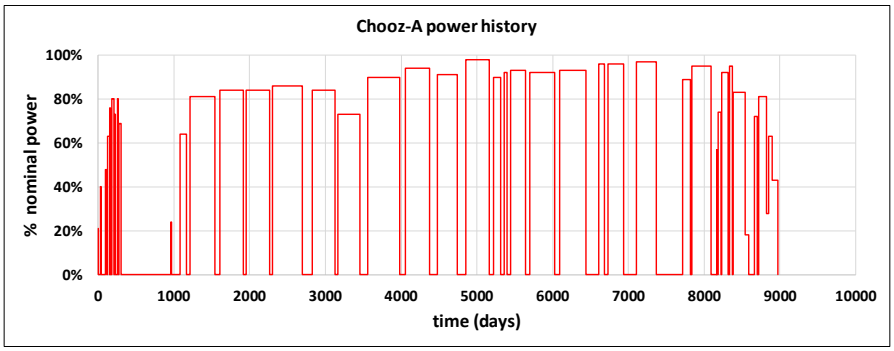


Fig. 3. Chooz-A power history.

3 DPA calculation method

3.1 General

The calculation developed by CEA is the following: first, using the simplified Chooz-A reactor modelling, a primary DPA result is calculated for each steel sample using TRIPOLI-4® Monte Carlo code. Then, adjustment factors must be determined to correct these primary DPA results. This adjustment is based on a comparison between auto-dosimetry results and calculated results.

Auto-dosimetry results consist of the measurement of the mass of ^{59}Co and the activity of ^{60}Co, both determined in each sample. These measurements were carried out in May 2018. ^{60}Co half-life is 5.271 years. These isotopes produced in steel on irradiation were therefore still present in samples 17 years after the final shutdown. ^{54}Mn produced by (n,p) reactions on ^{54}Fe could have been a good neutron fluence indicator, but ^{54}Mn half-life is 312 days. These isotopes were unfortunately no longer detectable in 2018.

Calculated results are as well the mass of ^{59}Co and the activity of ^{60}Co at the date of measurement (2018), in the same steel samples. They are calculated using DARWIN/PEPIN2 depletion code [3]. The main input data for these calculations are neutron spectra given by TRIPOLI-4® inside each sample.

The aim is to obtain consistent results between measurements and calculations. Adjustment factors (one per sample) that will make that possible will be directly applied to primary DPA values to give corrected DPA results. It should be noted that in this method, neutron spectrum shape inside each sample remains unchanged. Only the total intensity is adjusted.

The difficulty of this method is that the initial mass of ^{59}Co (in 1967) in samples is unknown and its variation during Chooz-A reactor lifetime was significant. It means that the measured ^{59}Co mass in 2018 is not the initial mass that was present in steel in 1967 before irradiation. This initial mass must therefore be determined in addition to the researched adjustment factor to calculate the mass of ^{59}Co and the activity of ^{60}Co when measurements were carried out (May 2018). To achieve this, an iterative process presented in the following paragraph was developed.

3.2 Iterative process

In this iterative process, source intensity and ^{59}Co initial mass are adjusted one by one, alternatively. In a first step, source intensity is the only adjusted parameter according to M/C (Measurement/Calculation) ratios on ^{60}Co activity (source intensity mainly affects ^{60}Co activity result and not ^{59}Co mass). Then, ^{59}Co mass value in 1967 is the only adjusted parameter according to M/C ratios on final ^{59}Co mass. Iterations are repeated until M/C ratios on ^{60}Co activity and M/C ratios on final ^{59}Co mass reach unity. Figure 4 gathers this iterative process. In practise, the process stops when $\varepsilon = 1\%$.

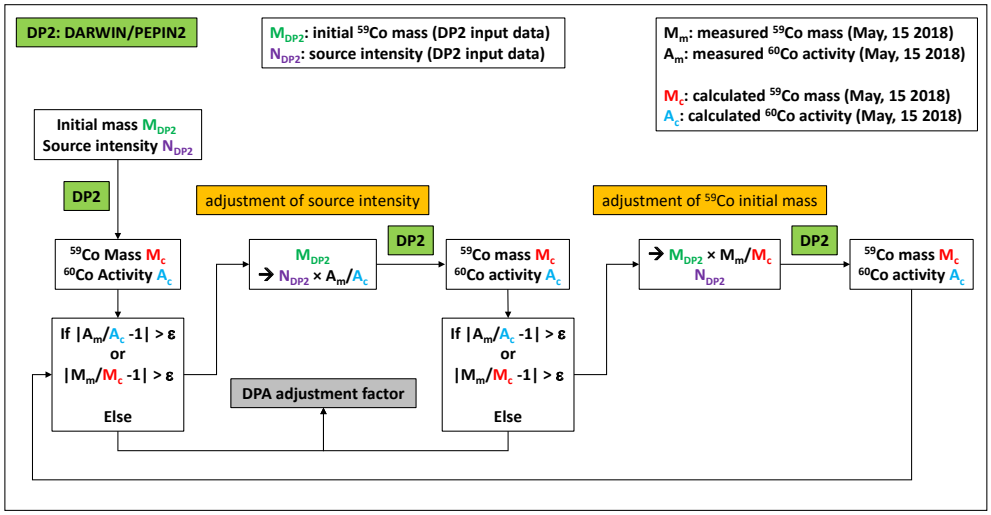


Fig. 4. Iterative process.

To initialize this process, the first ^{59}Co mass in 1967 is taken equal to 365 ppm for each sample (this value was chosen to be in the order of magnitude of the average mass measured in 2018) and the initial source intensity corresponds to the nominal power of Chooz-A reactor.

Chapter 4 presents DPA results for Chooz-A application as well as stress test conclusions. These tests were carried out to check uniqueness of result for each sample, in particular for different initial ^{59}Co mass and source intensity values chosen to initialize the process.

4 Results and verification

4.1 DPA results

For the six analysed samples, Figure 5 shows evolution of M/C ratios for both ^{59}Co mass and ^{60}Co activity at the date of measurements (2018) after each iteration (black dashed lines). In this application, five iterations are necessary and sufficient to obtain M/C ratios lower than 1% (for ^{59}Co mass and ^{60}Co activity, for the six samples). Besides, evolution of adjustment factor of neutron source intensity is also plotted (bold red line). For each sample, the factor that must be applied to primary DPA results is last one (at the fifth iteration). These factors differ considerably from each other (they vary from 0.10 to 0.95). It probably means that the axial neutron source distribution and/or the axial water temperature is not correct in the simplified Chooz-A modelling used to carry out simulations, but the iterative process corrects these imperfections.

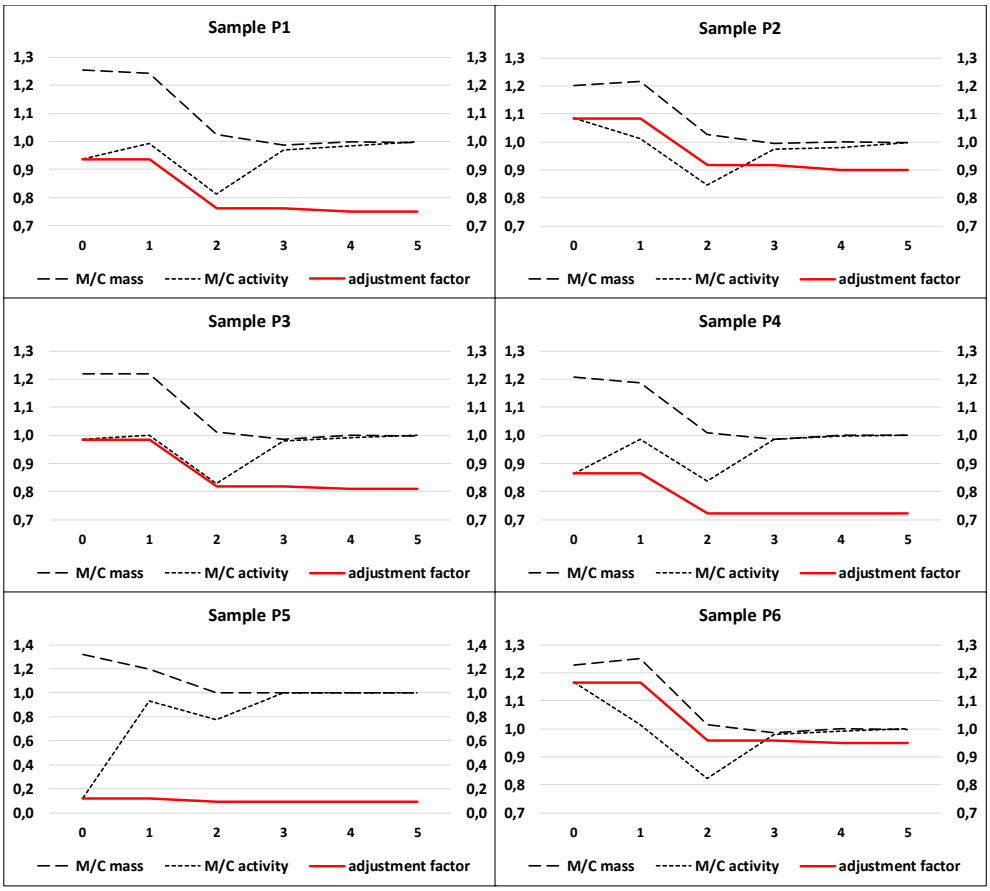


Fig. 5. Results of iterative process.

Table 1 gathers primary DPA results calculated with TRIPOLI-4® and the simplified Chooz-A reactor model, as well as corrected DPA values obtained with the iterative process.

Table 1. DPA results.

Sample	Primary values	Corrected values	Corrected/Primary
P1	29.6	22.2	0.75
P2	28.3	25.5	0.90
P3	17.9	14.5	0.81
P4	17.1	12.4	0.72
P5	11.9	1.1	0.10
P6	17.0	16.1	0.95

In general, corrected DPA results are lower than primary results. It shows that the simplified modelling of Chooz-A reactor overestimates calculated damage to the steel baffle.

Corrected result for sample P5 is surprisingly low, compared to DPA attached to other samples. However, this sample was irradiated in the top of the core (see Figure 2), where neutron flux is very low compared to the neutron flux at mid-plane of the core for instance. Besides, the measured ^{60}Co activity associated to this sample is also ten times smaller than

activity of others samples. The corrected DPA and measured activity of ^{60}Co are thus consistent.

An uncertainty associated to corrected DPA values can be estimated. It includes uncertainty on measurement (mass of ^{59}Co and activity of ^{60}Co), Monte Carlo uncertainty, convergence criterion ($\varepsilon = 1\%$), uncertainty linked to an imprecision in the exact location of sampling in the steel baffle, and uncertainty on calculated neutron spectra. This total incertitude is 17% (1σ) for all samples except for sample P5 for which it is 20% (1σ). Imprecision in the exact location of sampling is slightly higher for this sample.

4.2 Verification

4.2.1 Verification of initial ^{59}Co mass

The mass of ^{59}Co in steel in 1967 was chosen more or less arbitrarily equal to 365 ppm to initialize the iterative process. As a result, it should have converged to similar values for the six samples. Indeed, the whole stainless steel baffle was built from a unique steel melt, with homogeneous impurities (cobalt in particular). In our application, the average initial mass of ^{59}Co (in 1967) obtained for the six samples at the last iteration is 440 ± 8 ppm. The low dispersion value (1.8%) enhances the robustness of the developed iterative process.

4.2.2 Verification of the uniqueness of results

Uniqueness of adjusted DPA results is checked by running the iterative process with different initialisation values (mass of ^{59}Co in 1967 and neutron source intensity). Table 2 presents different cases carried out to achieve that. The reference case corresponds to the application presented in this paper (paragraph 4.1).

Table 2. Initialisation values for iterative process to check uniqueness of DPA results.

Cases	Mass of ^{59}Co in 1967 (ppm)	Neutron source intensity (× nominal power)
Reference	365	1.00
Test #1	100	0.23
Test #2	100	2.30
Test #3	1000	0.23
Test #4	1000	2.30
Test #5	10	0.023

These stress tests were performed for sample P1, but results obtained hereafter are also valid for all samples. For each test, Table 3 gathers adjusted results (mass of ^{59}Co in 1967 and neutron source intensity) providing consistent M/C ratios for the mass of ^{59}Co and the activity of ^{60}Co, both determined in 2018. The number of iterations necessary to reach a good convergence (lower than 1%) is also indicated.

Table 3. Stress test results.

Cases	Calculated mass of ^{59}Co in 1967 (ppm)	Calculated neutron source intensity (% nominal power)	Number of iterations
Reference	448	75.0%	5
Test #1	447	75.4%	8
Test #2	447	75.1%	8
Test #3	443	76.1%	4
Test #4	444	75.4%	5
Test #5	450	74.9%	13
Average	447 ± 2	(75.3 ± 0.4) %	-

These tests show that the iterative process leads to the same adjustment factors, whatever initialisation values are. In particular, the discrepancy on the calculated neutron source intensity (0.4%) is lower than the convergence criterion (1%). Only the number of iterations to reach convergence vary, but these numbers remain reasonable.

5 Conclusion

Experimental results associated to a simplified modelling of Chooz-A reactor allows to calculate DPA values in a stainless steel element irradiated in the core of this reactor. Due to a lack of information concerning the analysed samples (initial ^{59}Co quantity), an iterative process was developed and applied successfully. Some verifications were carried out to check the robustness of this process, in particular to ensure the uniqueness of calculated DPA results.

Activation of ^{59}Co is not the best reaction to adjust DPA since this reaction is sensitive to thermal neutrons but DPA function is sensitive to fast neutron. But this is the only available experimental result. It should be remembered that the goal of this study is not to determine the best-estimate values of DPA but to correct the modelling data to improve the calculation of DPA.

New DPA results are lower than oldest ones computed years ago. They are now more consistent with experimental observations.

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