

# Chooz-A Steam Generators Characterization

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Keywords: decommissioning, characterization, waste management.

## ABSTRACT

*EDF nuclear waste management requires a deep understanding of characterization, classification and waste sorting operations. In fact, French nuclear waste management defines several classes with specific management, treatment and storage facilities. Based on particular criteria, the more the radiological risk of the nuclear waste is important, the more its management will be complex and expensive.*

*During the dismantling of the first French pressurized reactor Chooz-A, decontamination of the primary water circuits (not including the reactor vessel), the steam generators and the pressurizer have been carried out in order to reduce their activity levels. Thanks to these decontamination operations, and a specific characterization methodology, EDF was able to Re-classify the 4 steam generators and store them in one piece at the ANDRA Very Low Level Activity disposal facilities instead of the Low and Intermediate Level activity one. This re-classification allowed EDF to avoid important cutting and packaging processes.*

*To characterize and declare Chooz-A SG activity, EDF-CIDEN used a methodology defined by the French institute of atomic energy, CEA. The method is based on external gamma spectrometry measurements performed with NaI collimated detectors, associated with MERCURAD simulations providing the transfer functions for the detectors and activity sources. Internal measurements are carried out with a CZT (CdZnTe) probe inside the SG tubes to refine the 3D model. In fact, the primary side represents the main source of activity, and understanding its contamination distribution is important to reduce the model and calculation uncertainties. Measurements eventually provided SG  $^{60}\text{Co}$  global activity, from which the activities of other radionuclides of the spectrum were determined using scaling factors. The final activity declaration takes into account the standard deviation of the measurements in order to cover the uncertainties of the methodology. Thereby, the declaration is "slightly overestimative", enough to meet the waste storage facility acceptance criteria*

## I. INTRODUCTION

France's nuclear power consists of 58 Pressurized Water Reactors. EDF is the only operator of the French nuclear power plants. EDF also has a first generation decommissioning plan involving different types of reactors: Heavy Water Reactor, Natural Uranium and Gas Cooled Reactor and Fast Neutron Reactor. Chooz-A is the first Pressurized Water Reactor of the French decommissioning plan.

France has a specific nuclear waste management. A single public body is in charge of the long-term management of all radioactive waste, under the supervision of the Ministry of Ecology, Energy, Sustainable Development and the Sea, and the Ministry of Research: The National Radioactive Waste Management Agency or ANDRA.

ANDRA has defined different classes of nuclear waste in order to assess the radiological risk. The classification is based on two main parameters: the activity level, and the half-life of the radionuclides. The existing or expected treatments and disposal facilities are based on this classification. They are presented in the table below.

		Half-life	
		Short-lived	Long-lived
Activity	Very Low Level (VLL)	<u>Surface disposal facility</u> VLL waste disposal facility in Aube district: "CIRES"	
	Low Level (LL)	<u>Surface disposal facility</u> LL/IL waste disposal facility in Aube district: "CSA"	<u>Shallow disposal facility</u> Under study
	Intermediate Level (IL)		
	High level (HL)	<u>Reversible deep geological disposal facility</u> Under study	

*Table 1: French nuclear waste classification*

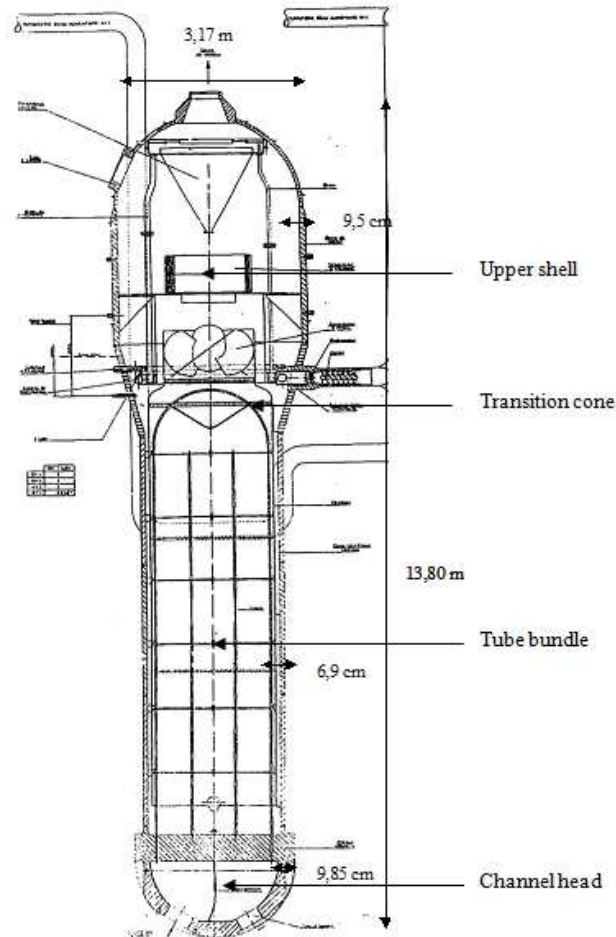
For the Chooz-A nuclear power plant dismantling, primary water circuits (except for the reactor vessel), steam generators and the pressurizer have been decontaminated in order to reduce their activity levels. Thanks to these important operations, the 4 steam generators (SG) were finally stored in one piece, avoiding important cutting operations and packaging processes, and reducing the dose for the operators.

Methodology for radioactive waste characterization is an important issue for EDF radioactive waste management since it defines waste classification and final disposal facility. This paper presents the specific radiological characterization of the Chooz-A SG.

The radiological characterization of the Chooz-A steam generators is based on external gamma spectrometry measurements associated with MERCURAD simulations providing the transfer functions for the detectors and activity sources. Internal measurements are carried out with a CZT (CdZnTe) probe inside the SG tubes to refine the 3D model.

## II. DESCRIPTION

Chooz-A Steam Generators are steel vertical heat exchangers. The primary water flow through 1662 vertical inverted U-tubes, which vaporizes the water coming from the secondary loop. A SG weighs about 110t and is almost 14m long. The shell steel is 5 to 10cm thick and the diameter is 2.36m in the primary side, and 3.17m in the upper shell. Each SG represents a total volume of about 70m<sup>3</sup>.



*Figure 1: CHOOZ-A SG dimensions*

The channel head and the inside part of the tubes were in contact with contaminated primary water. Even if they were decontaminated, they are still the main sources of activity in the SG.

It is important to notice that for the Chooz-A SGs, there were significantly different levels of activity in the tube bundle. The main differences were initially due to tube deterioration during the reactor operation. When they are identified, these tubes are capped, in order to prevent a tube rupture accident. For the decontamination, these tubes were unblocked and specific treatments were applied. The decontamination factor was less important for these tubes, which partially explained differences in activity levels in the tubes. Moreover, during the decontamination, the process was less efficient in localized zones, which contributes to the heterogeneity of the tube bundle activity distribution.

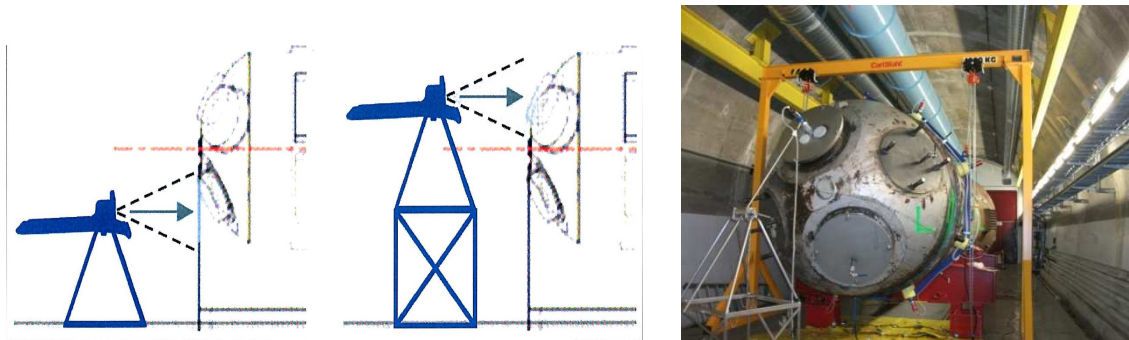
The main radionuclides of the Chooz-A SG inventory, twenty years after the shutdown, are activated corrosion products such as  $^{60}\text{Co}$  gamma rays emitter,  $^{63}\text{Ni}$  with beta decay, and also alpha emitters coming from fuel cladding cracks such as  $^{241}\text{Am}$ . The radiological spectrum of the Chooz-A primary water circuits is well known and the characterization consisted in searching for only one key radionuclide. Here it was the  $^{60}\text{Co}$ , easy to measure gamma emitter. The appropriate scaling factors were then applied to determine the other radionuclide activities. After the decontamination, radiochemical analyses on samples from tubes were carried out to check on the scaling factors and the global spectrum.

### II.A. Measurement devices

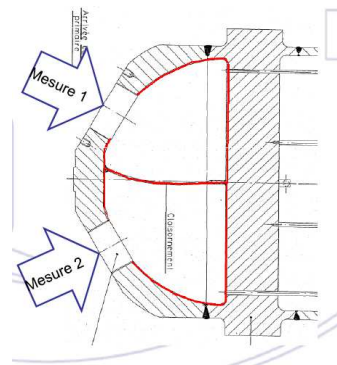
To characterize and declare Chooz-A SG activity twenty years after the shutdown, EDF-CIDEN used a methodology defined by the French institute of atomic energy, CEA. The method is based on external gamma spectrometry measurements along the SG, performed with scintillation NaI 3\*3 inch collimated detectors. Internal measurements were also carried out with a semiconductor CZT (Cadmium Zinc Telluride) probe inside the SG tubes.

As shown on the figures below, external measurement devices were set on stands.

A variable height support could provide measurements on the channel head. Two measurements were carried out in front of the primary inlet and outlet cover plates.

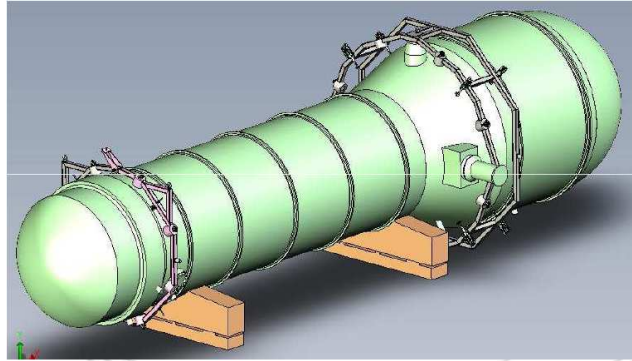


*Figure 2: Measurements device for the channel head*



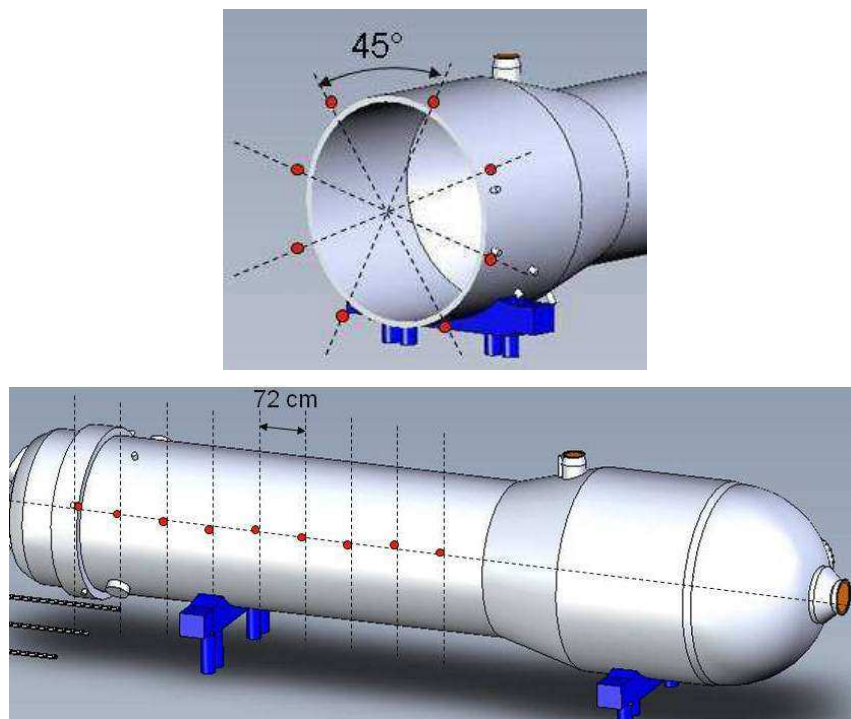
*Figure 3: Measurements on the channel head*

Two mobile chains of 8 angular detectors enabled measurements around the lower and upper shells. Each had a unique diameter in order to measure the shell surrounding the tube bundle and the upper shell (or secondary side). The detectors were moved lengthwise along the SG. They were positioned 10cm from the shell.



*Figure 4: Mobile chains of detectors*

Characterization of the tube bundle relied on 10 positions' measurements as shown on the figure below. The 10<sup>th</sup> position surrounded the bundle bend. The measurements were taken every 72cm, except between position 1 and 2 which were 55cm spaced (because of the tube plate).



*Figure 5: Measurements on the tube bundle*

Characterization of the tube bundle was completed with inner tube measurements. They were carried out with a semiconductor CZT (Cadmium Zinc Telluride) probe used as a gamma counter. The whole signal was assigned to  $^{60}\text{Co}$  which is reasonably overestimative and acceptable to study surface contamination levels. Measurements were taken between 1.5m to 3m (distance from the tube plate) with an increment of 20cm, on both sides of the U-tubes, resulting in 22 readings for one tube. 41 to

141 tubes were probed per SG. For SG4, measurements on 141 tubes were necessary to understand the different activity levels in the tube bundle.

The secondary side shell was also measured by the 8 angular detector chain on five positions along the SG. However, the contamination of the secondary part represents less than 1% of the global activity, and these measurements were rather a non-contamination check.

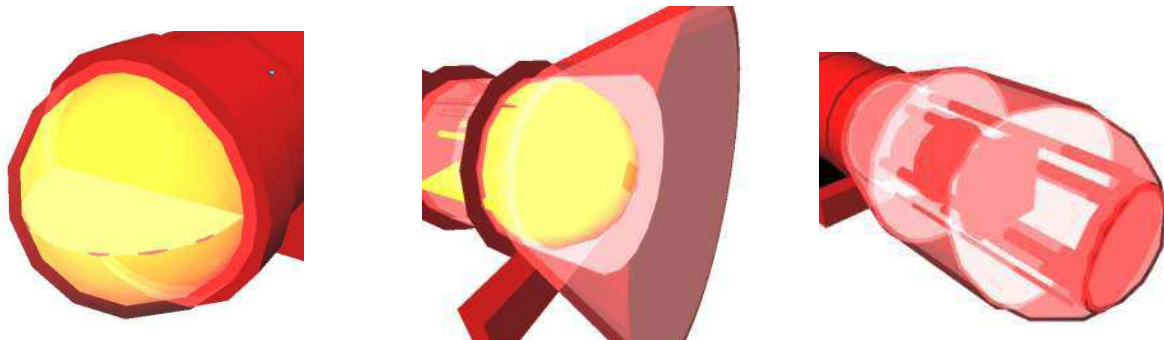
The external measurements (including installation of the measurement devices and detectors calibration) represented a week of work. For the inner measurements, an average of 2 weeks was necessary for SG1, SG2 and SG3 but for SG4 more than 3 months were needed.

### *II.B. Principal Hypothesis of the MERCURAD Simulation*

A MERCURAD simulation enabled the calculation of transfer functions and thereby the activities. MERCURAD is a Canberra 3D simulation software for dose calculation.

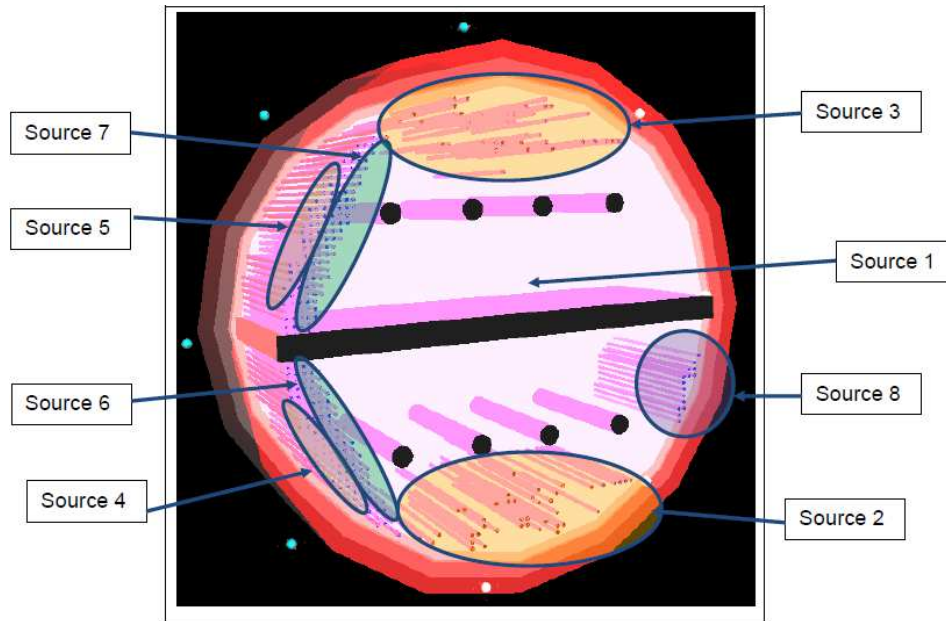
The SG was modeled in 4 subsections: the bottom or channel head (primary inlet and outlet), the tube bundle, the transition cone (with the bend of inverted U-tubes) and the secondary side (upper shell). The channel head and the inside part of the tubes were the main sources of activity.

For the channel head, the transition cone, and the upper shell models, contamination was uniformly spread. The models were very simple, consisting of homogeneous half spheres and cylinders as shown in the figures below.



*Figure 6: MERCURAD model of channel head, transition cone and upper shell (from left to right)*

For the tube bundle, the contamination was first uniformly spread (see “source 1” on figure 7). With the inner measurements and a complex resolution of an influence matrix, tubes with significant level of activity were identified and their level of activity was determined. These tubes were then described as specific sources in the MERCURAD model (see source 2 to 8 on figure 7). On the basis of the CZT activity calculations, the flux of the different sources was weighed in the simulation.



*Figure 7: Chooz-A SG4 tube bundle MERCURAD model*

As shown in figure 7, inner tubes measurements on the 4th SG allowed the description of 8 different activity levels for the tube bundle (modeled as 8 different sources).

A transfer function was determined for each of the sources in the model, for each detector, in each position. It took into account theory gamma flux simulated by MERCURAD for the two  $^{60}\text{Co}$  gamma ray energies (1.17MeV and 1.33MeV) and the calibration rate of the detectors.

### *II.C. Global Activity calculation*

For the channel head and the tube bundle, the final  $^{60}\text{Co}$  activity is the average of the activities calculated with the measurements and the transfer functions from each detector. For the tube bundle, the activity of each position was calculated, from which the global activity was calculated as the sum of the 10 positions.

If the upper shell is also measured by the mobile detectors chains, it is mainly to check that secondary contamination represents a very low level of activity. The final activity calculation was done by inner activity surface measurement applied to the entire inside shell surface.

The activity of the other radionuclides was determined by appropriate scaling factors. Chooz-A primary water contamination is well known. The scaling factors for the primary loop rely on several measurements on Chooz-A but also benefit from many measurements and analysis on French PWR park. The scaling factors applied for the SG characterization rely on specific measurements on the SG before decontamination. Radiochemical analysis on metal samples from tubes after decontamination showed that the global beta/gamma and alpha spectrum was conserved.

The SGs decontamination factor was greater than 100 and their total activity after decontamination was 2GBq(each) on average.

### III. DISCUSSION

The main issues of the detectors data exploitation lie in the understanding of the method uncertainties and in their appropriate consideration in the final activity declaration.

#### *III.A. Uncertainties*

The uncertainties of the characterization methodology are due to:

- The measurements
- The calibration
- The simulation (hypothesis of the 3D model, of activity distribution...)

The uncertainty due to the hypothesis of the simulation is the most important one, and the most delicate part for the SG characterization is the tube bundle. In fact, the CEA study demonstrated that the characterization of the tube bundle could be done by 8 external angular detectors and that more detectors would not give a more precise measurement, however these conclusions relied on the main hypothesis of a homogeneous activity distribution in the tube bundle. As presented in the description paragraph, they are different levels of activity in Chooz-A SG tubes and that is why inner tube CZT measurements were added. Differences in activity levels not taken into account in the sources theoretical gamma flux increase the average standard deviation.

These zones, significant for SG3 and SG4, have been identified as particular radioactive sources and weighted in the MERCURAD simulation thanks to the inner measurements. That is why the number of tubes measurements presented in the description part increased considerably for the last two SGs treated.

#### *III.B. External Detection of Singular Zones*

If identified before the external measurements, particular activity concentration areas can be studied through the internal measurements. It is more difficult to understand what is at stake when unreasonably high signals are detected from the outside (with regard to the average of the other position measurements).

Therefore, higher counting levels on SG1 positions 7, 8, 9 led to a further examination with additional contact dose measurements and a specific simulation of the area. It was then difficult to conclude on the type of radioactive source generating the signal: it could be either a tube improperly decontaminated or a contamination re-deposition in the lowest point of the decontamination drain system. However, the contamination level estimation of this zone was sufficient, and taken into account in the activity calculation.

For SG2, it was decided not to consider the inconsistent results given by one of the 8 angular detectors. In fact, the correlation between inner measurements and a further study as in the SG1 case have led to the conclusion of the presence of a non-decontaminated tube. Its surface activity has been calculated specifically and added to the global activity. The detector most influenced by the radiation of this tube was not considered in the global activity calculations.

Feedbacks on the first two SG characterized show that it is difficult, but possible, to understand tube bundle activity heterogeneities with external measurements. However, in order to improve the understanding of the tube bundle contamination distribution, the number of inside tubes measured was increased, and the global inner measurement plan was optimized.



### *III.C. Final Activity Declaration*

As discussed above, the main issues of the activity calculation resides in the tube bundle characterization. In fact, and especially after decontamination operations, the model of the particular contamination distribution in the tubes is the major source of uncertainty.

In order to take into account these imprecision and uncertainties of the methodology, it was decided to declare the activity of the tube bundle including the equivalent of two average measurement standard deviations.

For SG1 and SG2, it enabled us to cover the uncertainties of the method while remaining reasonably overestimative. For SG3 and SG4, using first two SGs operational experience, the important number of inner measurements, the better understanding of the contamination levels in the tube bundle, and the model adaptations, a well managed approached was used. Therefore, the addition of two standard deviations seemed very penalizing. Indeed, by being too overestimative, the waste type of classification could change and thereby its storage destination (and management costs). Thus, after discussion and demonstration of the reasoning to ANDRA, it was decided that only one standard deviation would be added to the SG3 and SG4 declaration.

### *III.D. Feedback*

The takeaway of this study highlights the importance of the understanding and the appropriate modeling of the contamination distribution in the tube bundle. In the case of Chooz-A SGs, the characterization was understood by the internal measurements and by specific studies of localized zones after detection of a particular activity concentration by the external detectors. Although significant progress in the methodology has been made through the study of these four SG, the fact remains that some of the difficulties encountered were unique to each SG.

#### IV. CONCLUSIONS

EDF nuclear waste management requires a deep understanding of characterization, classification and waste sorting operations. For the dismantling of the first French pressurized reactor CHOOZ-A, decontamination of the primary circuits (not including the reactor vessel), the steam generators and the pressurizer have been carried out in order to reduce their activity levels. Thanks to the decontamination operations and the specific characterization methodology presented in this paper, EDF was able to re-classify the 4 steam generators and store them at the ANDRA Very Low Level Activity disposal facilities, instead of the Low and Intermediate Level activity one. This re-classification allowed EDF to avoid important cutting and packaging processes.

The external gamma characterization associated to inner tube measurements enabled EDF-CIDEN to know and declare SG global activity. The big issue of this characterization is the measurement and the simulation of the tube bundle, main activity source of the SG. In fact, the SG working history and decontamination treatments created a particular activity distribution in the tube bundle. It is important to understand and take into account this activity level distribution in the simulations in order to reduce the model and the calculation uncertainties. Thereby, the activity declaration can be more accurate. By adding measurement standard deviation to the global activity, the uncertainties of the methodology are covered and the final activity declaration is “slightly overestimative”, enough so to meet the waste storage facility acceptance criteria.

#### ACKNOWLEDGMENTS

The author would like to thank EDF-CIDEN Aurélien Colas, Lionel Thevenet, Julia Mazzilli, Pierre Audouze, and the Chooz-A teams.

The author would also like to thank Saad Soufi for editing the text.