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Radiological characterization and 3D Scanning of Hot Cell #3 of the LECA Facility

1. OUTLINE

The LECA Nuclear facility, located on CEA center of Cadarache in France, is currently undergoing a safety reassessment, following the '10 years-rules' set out by the French Nuclear Safety Authority. The inventory and the amounts of radioactive material (inside and outside concrete walls), defined by the term "contamination", is relevant information to reinforce the safety demonstration and consequently measure the potential hazard regarding existing regulation.

The accurate determination and validation of the radiological contamination of the LECA hot cells in operations is a major issue and a great challenge due to the high level of irradiation, as a consequence of the fuel presence. A nuclear measurement campaign, based on the combination of gamma spectrometry and imaging, has been carried by the LSTD Team of the CEA Marcoule [1] to provide a comprehensive radiological mapping of the LECA hot cell C3. The analysis of the experimental data enabled to build a robust radiological model which is valuable for the evaluation of the contamination of the hot cell.

In the meantime, geometric characterization of the inside of a hot cell remain a hot topic and can well be a real challenge in case of cells with old equipment for which data are incomplete or missing. The technology of 3D scanning gives an answer to this issue.

3D scanning and radiological contamination measurement were performed accordingly during fall 2015.

2. RADIOLOGICAL CHARACTERIZATION

MATERIALS AND METHODS

MATERIALS

Gamma Imaging

"CARTOGAM" is a gamma imager which is the CANBERRA industrial version [2] of the CEA prototype called "ALADIN". The imager (figure 1) is made of a shielding which attenuates the radiation incoming from outside of the field of view. Gamma photons are detected through a pinhole aperture and deposit their energy in a BGO scintillator. The spatial localization of each event is registered so that the 2D gamma radiological scene is reconstructed after image accumulation.

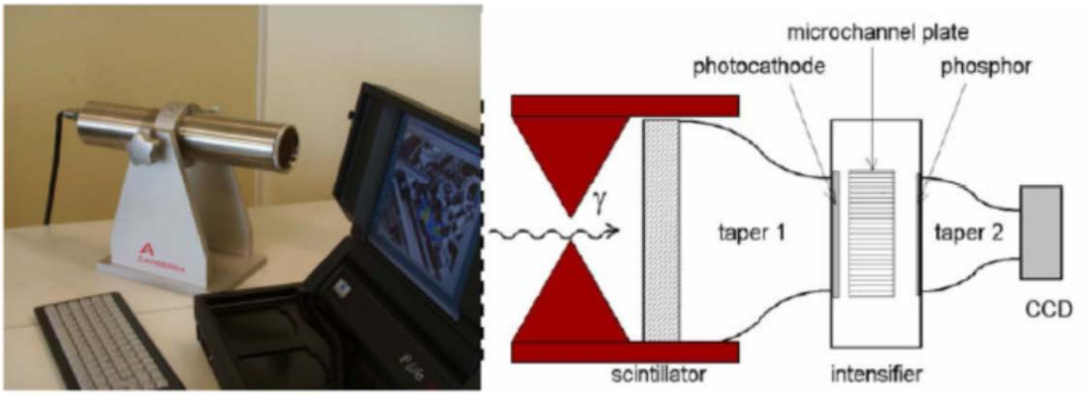

Figure 1 : Cartogam gamma imager

Gamma CZT spectrometry

The CdZnTe (also noted CZT) probe (figure 2) is a compact low energy resolution gamma detector. It provides energy distribution of gamma rays and can be used for a wide range of gamma dose rate (between tens of µG/h for 500 mm^3 CZT cristal probe to several Gy/h for the 0,5 mm^3 cristal probe).

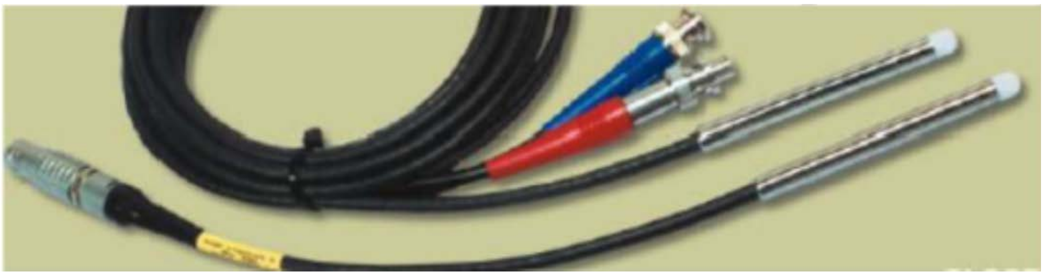

Figure 2 : Gamma spectrometry CdZnTe probe

Hot cell Radiological investigation system

The investigation system combines the following tools (figure 3) :

- Unshielded gamma CZT spectrometry measurement has been carried out. It provides radionuclide identification and quantification concerning the whole hot cell.
- Cartogam gamma imager which provides the spatial localization of the hot spots ;
- Shielded 60mm^3 shielded CZT gamma detector which measures the gamma spectrum of each hot spot. These data enable radionuclide identification and quantification for each detected hot spot.
- Dose rate SHI probe.

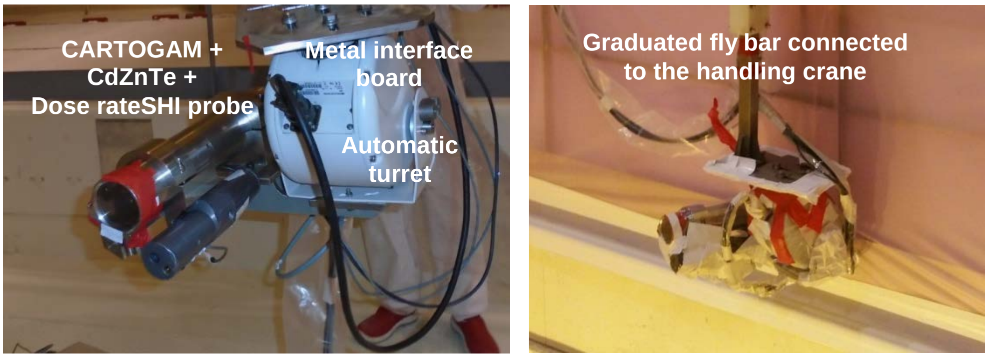

Figure 3 : System used for the radiological investigation of the LECA Hot Cell #3

The measurement system is mounted on a graduated fly bar which is handled by means of a handling crane. The measurement devices are protected against radioactive contamination by specific protective vinyl commonly used in the nuclear industry.

METHODS

The hot Cell #3 is open by removing the thick concrete floor slab. The measurement system is then introduced inside the hot cell (figure 4).

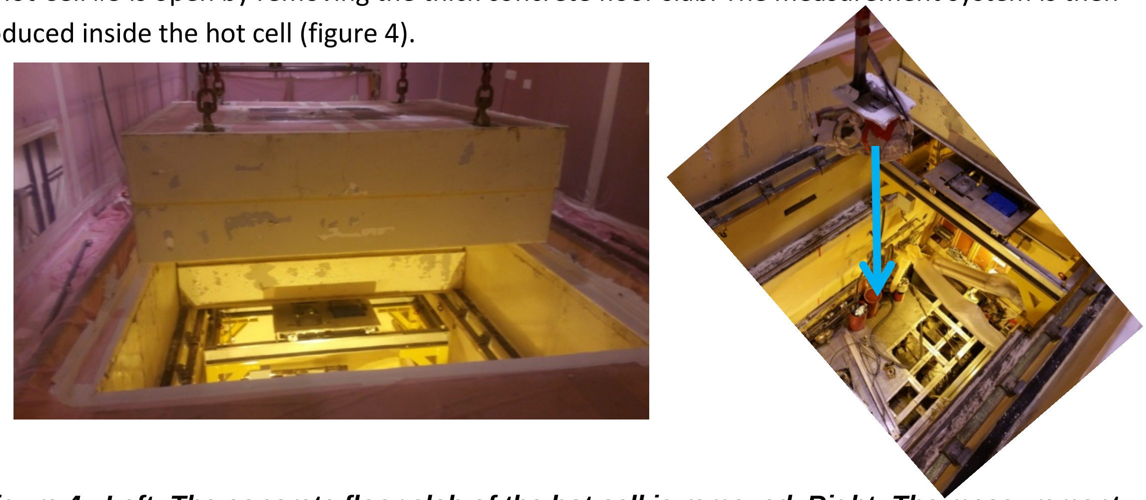

Figure 4 : Left: The concrete floor slab of the hot cell is removed. Right: The measurement system is introduced inside the hot cell.

The activity of radionuclides in the Hot Cell #3 is divided into two components:

- Activity $\boldsymbol{A_{HOM}}$ of each radionuclide which **is assumed to be homogeneously distributed** on the walls and the floor of the Hot Cell. It is measured with unshielded CdZnTe gamma spectrometry.
- Activity $\boldsymbol{A_{HP}}$ of each radionuclide of the hot spot(s), which is (are) measured with combined gamma imaging and shielded CdZnTe spectrometry.

Dose rate measurements are used to validate the radiological model of Hot Cell #3.

UNSHIELDED CDZNTE GAMMA SPECTROMETRY

The unshielded CdZnTe probe measures the gamma spectrum of the whole Cell #3 (figure 5).

Generally speaking, the analysis of the gamma spectra provides information about the main gamma emitters. The geometrical transfert functions, which take into account the propagation of gamma photons in the Hot Cell, are calculated by using the 3D Monte Carlo code MCNP5. This is done by using the geometrical data obtained by 3D scan of Hot Cell #3 and other physical data likenature of material, their density, and so on.

For the unshielded gamma spectrometry measurement, the activity $\boldsymbol{A_{HOM}}$ of each radionuclide which **is assumed to be homogeneously distributed** on the wall and the floor of the Hot Cell and is determined as follows:

$$A_{HOM}(E_i) = \frac{N(E_i)/t}{K(E_i) * FT(E_i) * I(E_i)}$$

- $\boldsymbol{A_{HOM}(E_i)}$ is the activity (Bq) of the gamma emitter at energy E_i.
- $\boldsymbol{N(E_i)/t}$ is the count rate (s^{-1}) in the photoelectric pick at energy E_i.
- $\boldsymbol{K(E_i)}$ is the intrinsic efficiency of the CdZnTe detector at energy E_i.
- $\boldsymbol{FT(E_i)}$ is the geometrical transfert function ({$cm^{-2}.s^{-1}$}/Bq)
- $\boldsymbol{I(E_i)}$ is the emission intensity at energy E_i.

GAMMA IMAGING AND SHIELDED CDZNTE GAMMA SPECTROMETRY

Gamma imaging, shielded CdZnTe gamma spectrometry and dose rate measurements are carried out in the same time (figure 3).

The gamma imager acquires the raw signals of the hot spot, which are post processed (removal of background noise, thresholding, false colors and finally superimposition on the visible image of the investigated scene). The hot spot is identified and its position is determined. Its gamma spectrum is measured with the shielded CdZnTe probe. The analysis of these data enables the estimation of the activity $\boldsymbol{A_{HP}}$ (HP for "Hot Spot") of each radionuclide present in the hot spot.

RESULTS AND DISCUSSIONS

UNSHIELDED CDZNTE GAMMA SPECTROMETRY

The activity $\boldsymbol{A_{HOM}}$ of ^{137}Cs is estimated as follows:

Radionuclide (energy)	**Count rate (s^{-1})**	**K(E_γ=662keV)**	**Direct gamma fluence rate ($\gamma.cm^{-2}.s^{-1}$)**	**Transfert function ($\gamma.cm^{-2}.s^{-1}$).Bq^{-1}**	**A_{HOM} ^{137}Cs**
^{137}Cs (662 keV)	103	1,94x 10^{-3} (±21 %)	5,31x 10^{4} (±12 %)	1,82x10^{-6} (± 33%)	**2,9 x 10^{10} Bq (± 40 %)**

Table 1 : Determination of A_{HOM} of ^{137}Cs

Theoretical dose rates are calculated and are compared to the dose rates. Mean relative deviation between theoretical and experimental is below 30 % which is uncertainty of the gamma dose rate measurement.

Measurement point (depth)	**Measured dose rate (mGy/h)**	**Calculated dose rate (mGy/h)**	**Relative deviation measured/calculated**
-2 m	0,45	0,8	+43 %
-3 m	0,70	0,84	+14%
-4 m	1,00	0,89	-11%

Table 2 : Comparison between measured and calculated dose rates in Hot Cell #3

Results concerning the activities of ^{134}Cs and ^{154}Eu were also obtained. The experimental ^{134}Cs/^{137}Cs and ^{154}Eu/^{137}Cs ratios are in good agreement with the theoretical ones which were derived from the waste spectrum of the LECA Nuclear Facility.

Radionuclide (RN)	^{137}Cs	^{134}Cs	^{154}Eu
Activity (Bq)	2,9 x 10^{10}	2,2 x 10^{9}	5,6 x 10^{8}
Experimental Ratio (RN/^{137}Cs)	---------------------	7.6 %	1,9 %
Theoritical ratio (RN/^{137}Cs) according to LECA waste spectrum		12,1 %	1,7 %

Table 3 : Results for ^{134}Cs and ^{154}Eu

GAMMA IMAGING AND SHIELDED CDZNTE GAMMA SPECTROMETRY

Only one hot spot was detected by the gamma imaging measurements. It is situated at a depth of 3.7 m near the South-West bottom corner of the hot Cell.- Figure 5 show two examples of combined {visible/post processed gamma} images of the same hot spot.

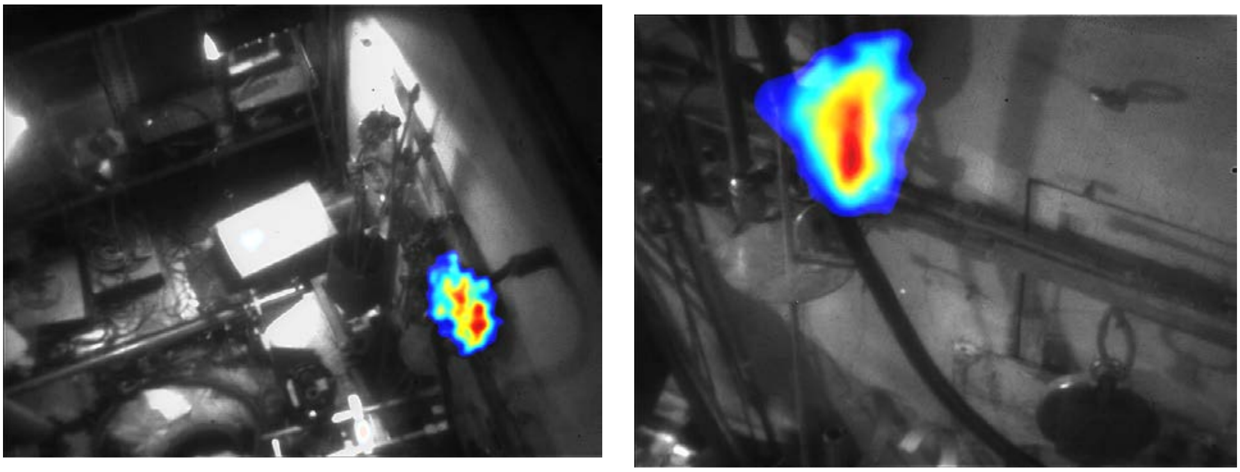

Figure 5 Combined visible/gamma images of the hot spot detected in Hot Cell #3

Table 4 summarizes the main results. It shows that the 6.6 % of the ^{137}Cs is due to the hot spot and the other 93.4 % is distributed homogeneously on the walls and floor of the Hot Cell #3. The good agreement between calculated and measured ambient gamma dose rates (table 4) validates the radiological model established by this measurement campaign.

Term source Component	Hot Spot	Terme source gamma homogène (répartition homogène du terme source des parois et du plan de travail)
^{137}Cs activity @ 661,66 keV (Bq)	A_{HP}=1,9 x 10^{9}	A_{HOM}= 2,71 x 10^{10}
Ratio of the total ^{137}Cs activity	6,6 %	93,4 %

Table 4 : ^{137}Cs activities in the Hot Cell #3

3. 3D SCANNING

TOPIC ISSUE

The introduction of new equipment in hot cells using remote handling require to know precisely the geometrical interfaces for equipment in order to reduce the risk of mistakes as it is very difficult or impossible to remove an equipment for repair once it has entered the cell. The design of new equipment must therefore be made on a consolidated geometric environment.

Given the difficulty of access of a hot cell, the precise knowledge of the geometric environment of the inner of cells or equipment can well be a real challenge in the case of cells with old equipment for which data are incomplete or missing.

The means used to perform only dimensional measures may then lead to the development of specific tools adapted to master-slave manipulators and even physical access needs. It can result in several months of downtime for decontamination of the cell and result in doses for intervention staff.

TECHNOLOGY

Advances in rapid characterization environment, developed especially for buildings needs have identified the possibility of using 3D scanning technology to meet the needs of remote characterization of a hot cell.

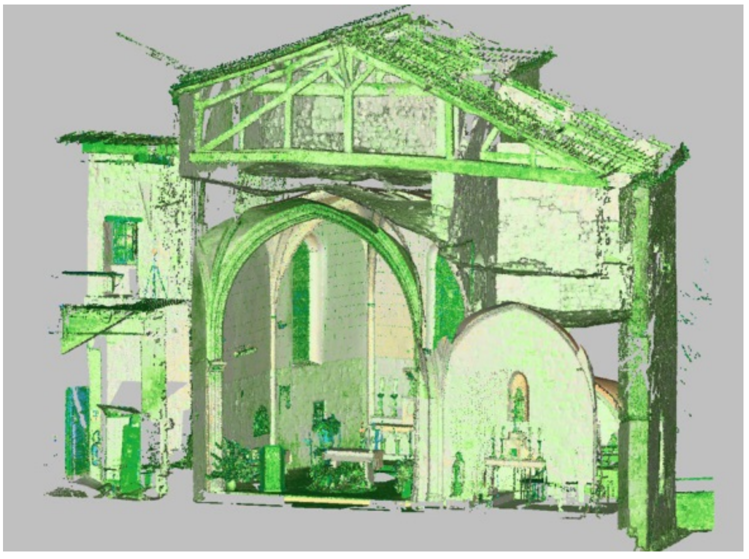

***Figure 6** : Sample scan of the inside of a church*

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Equipment has been acquired by the LECA / STAR for testing in a hot cell. This is an industrial 3D scan used for the rapid characterization of building areas (inside-out). Its principle of operation and performance are as follows:

Operating principles

A laser beam is emitted from the scanner and is send to a rotating mirror. The rotation of the scanner on its base combined of rotation of the mirror allows scanning the entire environment around the scanner (except the shadow area under its base). The distance to the scanner is measured via the laser beam. Combined with the position of the scanner and the mirror, the scanner calculates the coordinates of each measured point (x, y, z). The software recovers all data to build a point cloud conform to the reality of the environment. The number of generated point depends on the acquisition time. it generally consists of millions of points..

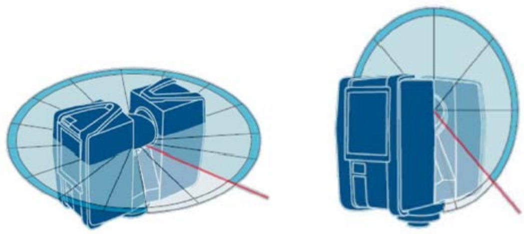

Figure 7 : Rotating laser beam

Several scans in the same area are generally required to display the shadow areas related to recoveries of equipment. The scanner should then be moved in the area. The registration of the various acquisitions and the reconstruction of the whole points cloud is made through the post-processing software, using common fixed points in the environment.

Performances

Figure 8 : Picture of the 3D scanner.

- The sampling frequency is 120 000 points per second.
- The range of the scanner varies from 0.5 m to 50 m.
- Measurement accuracy is + - 2 mm to 50 m.
- The device is stand-alone once launched (by wi-fi or by RJ45 cable). The acquisition is carried out locally on an SD card.

IMPLEMENTATION OF THE OPERATION

The operation took place in the LECA-STAR facility in September 2015, on a cell under renovation. The fuel had previously been removed from the cell and the cell had been cleaned, but not be a thorough clean-up. The dose rate at the work surface was 0,5 mSv/h.

The cell roof has been fully open to perform the operation. A specific equipment was developed to let movement of the 3D scanner in the XYZ three dimensions of the cell. The scanner was fixed upside down on a sliding rod which is movable horizontally by means of a mechanical support.

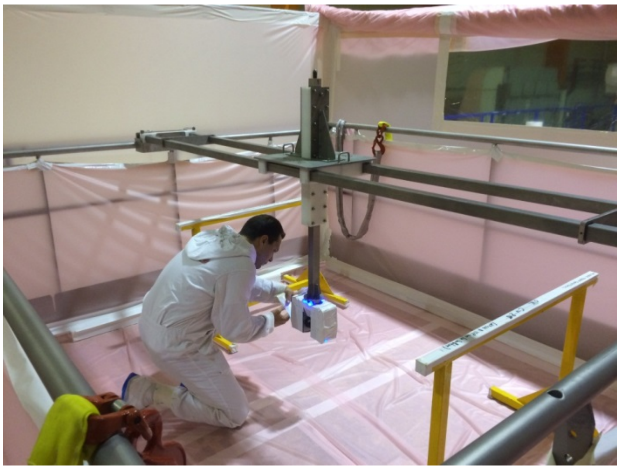

Figure 9 : Scanner preparation

The scanner was protected against contamination. The principle of the 3D scanner does not allow a full head protection (need to allow free passage of the laser beam).

The cell was then opened and the scanner down. Two measurements were made at the cell center; at two levels.

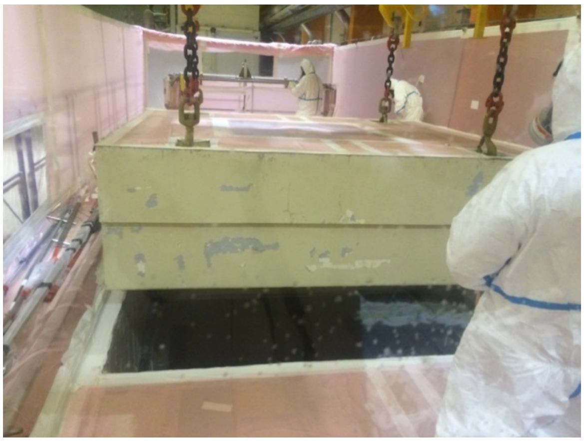

Figure 10 : Cell roof opening

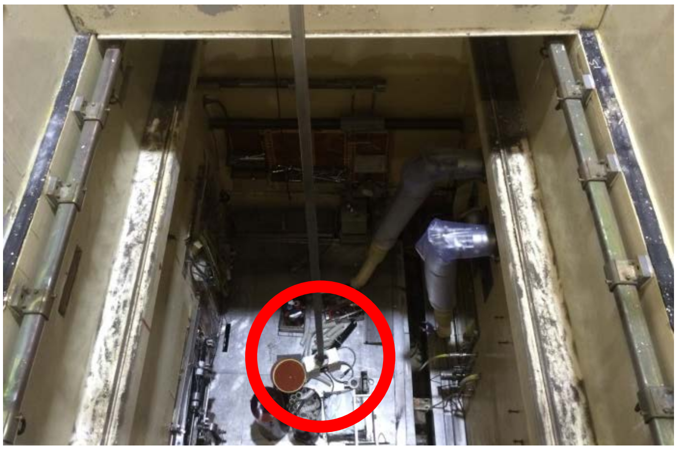

Figure 11 : measurement acquisition

Figure 12 : Control of scanner

RESULTS

The operation was successful. The scanner has performed the operation, controlled by Wi-Fi without any difficulty. The dose rate in this cell did not affect the measurements or the operation of the scanner.

The image shown below is the point cloud in 3D. Several operations are then possible from the cloud:

- Move, zoom in the cloud,
- Production of cutting section,
- Taking measurement (all points are clickable)
- Addition of information on the equipment (labels)
- ...

From this cloud, it is possible to recreate the as-built environment of the cell as its equipement.

Figure 13 : Display of the cloud point

4. CONCLUSION

Two radiological characterization methodologies were implemented during the measurement campaign:

- CdZnTe unshielded gamma spectrometry measurement to estimate the overall radiological activity of the shielded cell ;
- Cartogam Gamma imaging measurements for detecting and locating gamma radiation concentrations (more commonly known as "hot spots") coupled to the shielded (collimated) gamma spectra measurements emitted by said hot spots.

The gamma spectrometry experimental data were analyzed and interpreted by both standard analysis method of gamma spectra and radiological modelling with MCNP5 particle transport. The gamma imaging data obtained were analyzed using the post-processing tools developed by the Nuclear Measurement Team of The Simulation and Dismantling Tools Team of CEA Marcoule and by operating data of the 3D model of the cell provided by the DEC / SLS LECA Team.

To summarize, the combination of gamma imaging with gamma spectrometry CZT collimated has highlighted, one hot spot whose ^{137}Cs activity has been determined. This method allowed to evaluate the two components of the ^{137}Cs contamination : , first component corresponding to the activity $\boldsymbol{A_{HOM}} \approx$ ***27 GBq*** of each radionuclide which is assumed to be homogeneously distributed on the wall and the floor of the Hot Cell and the second component corresponding to the activity $\boldsymbol{A_{HP}} \approx$ 1,9 GBq due to the contribution of the Hot Spot.

Taking into account these results and the LECA waste, one can estimate the Hot Cell #3 overall activity **83 ± 33 GBq.**

For 3D scanning, the results were particularly successfully. The precision and reliability of the scan has allowed many uses. Several equipment has been developed to enter the cell with a reliable environment interface. This technology is now used as often as possible. Next step is to test it in a more irradiated cell.

REFERENCES

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[2] O. Gal, C. Izac, F. Laine and A. Nguyen, ´ CARTOGAM: a portable gamma camera, Nucl. Instrum. Meth. A 387 (1997) 297