# Recent Improvement of Measurement Instrumentation to Supervise Nuclear Operations and to Contribute Input Data to 3D Simulation Code – 13289

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## ABSTRACT

The CEA has developed many compact characterization tools to follow sensitive operations in a nuclear environment. Usually, these devices are made to carry out radiological inventories, to prepare nuclear interventions or to supervise some special operations. These *in situ* measurement techniques mainly take place at different stages of clean-up operations and decommissioning projects, but they are also in use to supervise sensitive operations when the nuclear plant is still operating. In addition to this, such tools are often associated with robots to access very highly radioactive areas, and thus can be used in accident situations. Last but not least, the radiological data collected can be entered in 3D calculation codes used to simulate the doses absorbed by workers in real time during operations in a nuclear environment. Faced with these ever-greater needs, nuclear measurement instrumentation always has to involve on-going improvement processes.

Firstly, this paper will describe the latest developments and results obtained in both gamma and alpha imaging techniques. The gamma camera has been used by the CEA since the 1990s and several changes have made this device more sensitive, more compact and more competitive for nuclear plant operations. It is used to quickly identify hot spots, locating irradiating sources from 50 keV to 1500 keV. Several examples from a wide field of applications will be presented, together with the very latest developments. The alpha camera is a new camera used to see invisible alpha contamination on several kinds of surfaces. The latest results obtained allow real time supervision of a glove box cleaning operation (for $^{241}$Am contamination). The detection principle as well as the main trials and results obtained will be presented.

Secondly, this paper will focus on *in situ* gamma spectrometry methods developed by the CEA with compact gamma spectrometry probes (CdZnTe, LaBr3, NaI, etc.). The radiological data collected is used to quantify the activity of hot spots and can also then be entered in 3D models of nuclear plants to simulate intervention scenarios. Recent developments and results will be presented regarding this.

Finally, thanks to a large amount of feedback, the interest of using complementary measurements will be discussed. In fact, the recent use of 3D simulation codes requires very accurate knowledge of nuclear plant radiological data. The use of coupled devices such as imaging devices, (gamma and alpha cameras), gamma spectrometry, dose rate mapping, collimated / uncollimated measurements and many other physical values gives an approach to the radiological knowledge of a process or plant with the lowest possible uncertainty. In line with

this, the paper will conclude with the future developments and trials that could be assessed in that field of application.

## INTRODUCTION

The knowledge of the radiological state of a process or a facility is of prime importance not only during the initial stages of a dismantling project's initial inventory, but also during the follow-up phases of clean-up and final checks. During a facility's operation, a clear view of the process radiological level is equally necessary, in order to plan maintenance scheduling and optimize interventions by personnel. Radiation protection teams generally ensure worker radiological safety, and also supply dose mappings for each of the areas associated with typical spectra. In most cases, this mapping does not give enough information to be used as input data when preparing maintenance or clean-up work.

With advances in activity modeling calculation codes, today 3D, CAD and simulation modeling tools can be coupled to particle transport codes previously used without a graphic interface. The power of these 3D tools is mainly due to major developments in video games over the last decade. So-called "classic" equipment, for example a dose rate detector, is now insufficient to supply input data which is both accurate and reliable enough for the possibilities offered by such modeling and simulation codes.

For *in situ* nuclear measurements, the way measurements are made on the site is a key factor (e.g. choice of the right detector(s), standardizing and carrying out the measurements), but the raw measurement data processing, usually cps, $Gy.h^{-1}$, $\gamma.cm^{-2}.s^{-1}$, etc., by a calculation code is also a decisive step in order the give the most accurate activity value (Bq) possible.

## *IN SITU* CHARACTERIZATION TOOLS

### Gamma Camera

#### Operating principle

Most of the current gamma imaging systems operate by the collection of gamma radiation on a scintillator, where it is converted into a visible light signal. Because of poor conversion efficiency, an image intensifier increases the signal applied to the CCD array. Signal shaping and 8-bit 572 × 752 pixel digital image acquisition is performed by dedicated circuitry in the control unit, usually located 30 to 100 meters from the gamma camera and which includes onboard electronics.

Two types of scintillators covering different ranges of irradiation levels have been used since gamma cameras were first deployed in dismantling projects. BGO (bismuth germanate) scintillators are generally used in highly irradiating environments; their low memory effects results in very high quality images with low residual electronic noise. CsI (thallium-doped cesium iodide) scintillators have much higher sensitivity and are used for lower irradiation levels, as their memory effects results in spurious signal measurements at high dose rates. Here, two scintillator thicknesses were tested: 2 mm and 4 mm (to obtain greater sensitivity). The unit was shielded by a Denal housing to protect the electronics and to obtain an acceptable signal/noise ratio for the final image.

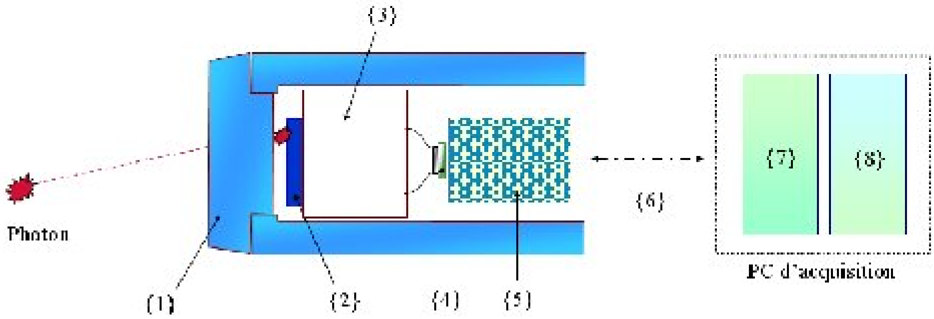


Fig. 1 : Gamma camera
{1} Collimator, {2} Scintillator, {3} Image intensifier tube
{4} CCD array, {5} Video circuitry / HT power supply
{6} 30 m cable, {7} Acquisition circuit board, {8} Software

## Configurations

Gamma camera sensitivity is related to the signal quantity accumulated by the scintillator within a given exposure time. The first prototype gamma cameras used a simple pinhole collimator 1.2 mm in diameter, which is still available today for the commercial Cartogam version. More recent work has shown that a coded aperture mask collimator with a large number of holes increases the scintillator illumination up to 50% of its total surface area.

One of the major advantages of the gamma camera is its compact size, allowing it to be managed by remote handling when in hostile environments. One of the reasons for the multiple configurations available is to conserve this advantage while enhancing its detection sensitivity.

*Pinhole collimator*

Historically, this was the first type of lens used on the Aladin prototype units. A 1.2 mm diameter aperture was used to collimate the incidental photons on the scintillator. As in photography, this technique generates an image that can be directly interpreted. Moreover, using the same optical axis with or without a shutter produces both gamma and visible-light images that are perfectly aligned and can therefore be superimposed.

The pinhole lens is still the most widely-used gamma camera operating mode, and gives a satisfactory performance in most applications. It is limited, however, for measurements at low dose rates or when the measurements are disturbed by uniform radiological noise.

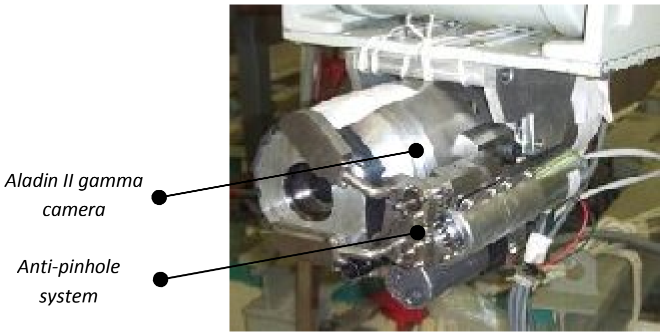



Fig. 2: Various configurations with coupled instruments

*Coded aperture mask collimator*

This technique, first used in the aerospace industry, was adapted for use with gamma imaging systems. It relies on a Hexagonal Uniformly Redundant Array (HURA) based on the mathematical theory developed by Fennimore and Cannon [5] [6].

A coded aperture mask consists of a repetitive hexagonal pattern positioned opposite the scintillator, modulating the incidental signal to create a coded image. The correlation kernel used to obtain the decoded image corresponding to the actual scene is constructed from the known position of the mask compared to the scintillator.

An interesting property of the HURA coded aperture mask is its 60° rotational anti-symmetry. Subtracting the image obtained from the second mask position appreciably diminishes the background noise in the decoded image. A gamma camera with a coded aperture collimator has several advantages in the case of low-level measurements, where very high sensitivity is required as described below. While this system is highly recommended for use in a fixed measurement station, it has several drawbacks for *in situ* measurements where the gamma camera is inaccessible due to the mask position in front of the scintillator, preventing the gamma camera from obtaining an on-axis visible light image.

*Pinhole/anti-pinhole collimator*

The use of two measurement positions on a coded aperture gamma camera (masks at 0° and 60°) substantially reduces spurious noise. The same principle has been applied to the pinhole collimator: a remotely actuated high-density shutter was developed to obtain a background image of the scene (Fig. 2).

This configuration is suitable for measuring hot spots with signals difficult to discriminate in a uniformly noisy environment. The measurement obtained with the shutter closed is subtracted from the raw image. This feature also extends the low-level sensitivity of the basic pinhole gamma camera, although it does not reach the levels possible using a coded aperture mask collimator.

**Location of hot spots in 3D: Application to the characterization of FP tanks**

The location of hot spots on a site usually depends on the measurement configuration. Some "simple" interventions enable the use of a laser telemeter in order to know the exact distance between the gamma camera and the element observed. However, only rarely is the element directly observed in the gamma camera field at the actual origin of the gamma signal measured. Triangular measurement is therefore necessary to find the exact position of the hot spot in space.

In the following case, a gamma camera was used to carry out the initial characterization as well as the follow-up phases for the rinsing of tanks which had contained fission products (AVM facility, Marcoule). During the initial characterization phases, as the dose rates generated in the storage zone could be up to several Gy.h$^{-1}$, the characterization equipment was set up in the tank peripheries and required the use of special mechanical carriers. An X and Y axis location feedback sent to the control post enabled a complete mapping to be made of the tanks during the two phases.

The exact position of the hot spots in space, their shape and their contributions to the doses generated as measured at the gamma camera contributed to the building of a robust radiological model.

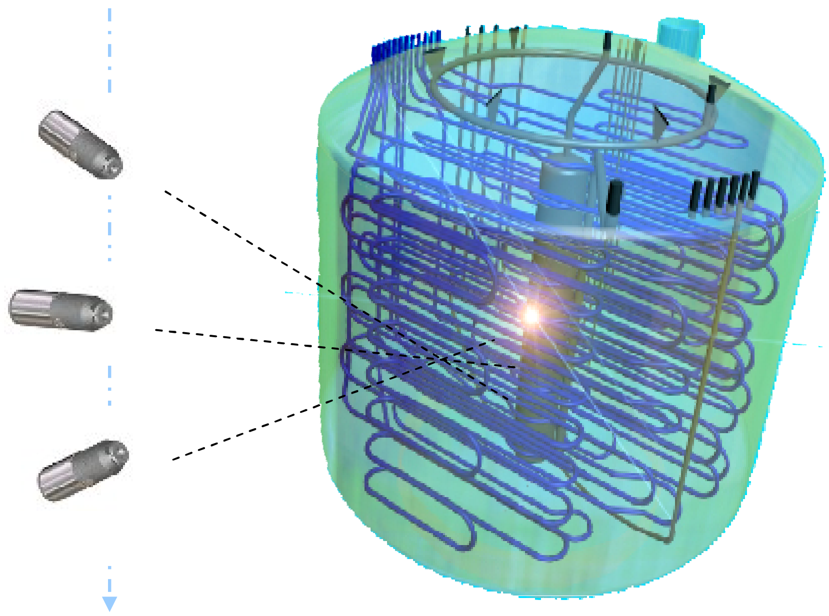

Fig. 3: Use of a gamma camera for the internal characterization of fission product tanks

The use of visible cameras, which are generally associated with gamma cameras to create the final images, was not possible, but the use of a complete 3D modeling of the tanks (including all the tank internals) enabled the validation of the hot spot positioning inside them. With the integration of the gamma camera's field of vision parameters in the 3D visualization software, it was possible to generate the exact views for the camera's different positions. These were aligned with the optic axis of the device, and the gamma and 3D images were thus perfectly super-imposable, precisely identifying the tank internal giving off the gamma signal measured.

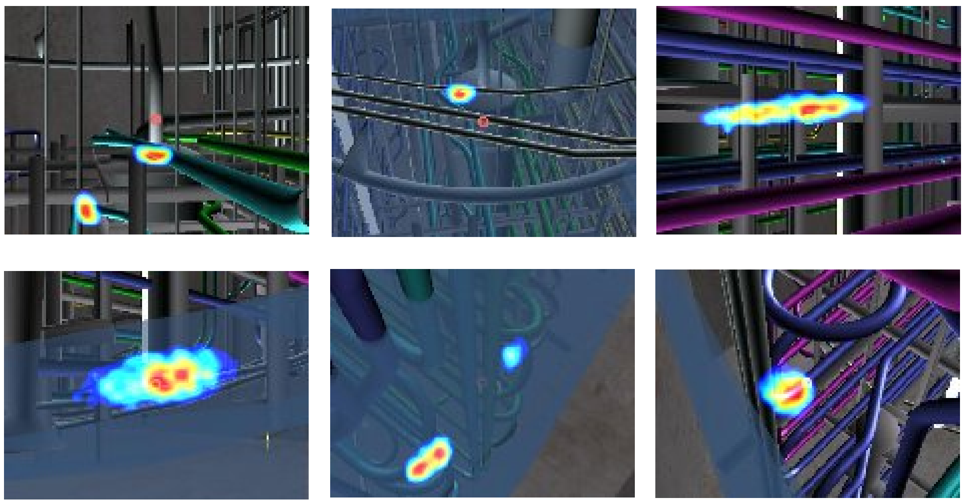

Fig. 4: Location and super-imposition of hot spots in the 3D model

The final radiological model was also completed with collimated gamma spectrometry measurements for the full height of the tank (gamma scanning) as well as ambient dose measurements (without collimator) in order to consolidate the model after assessment of the residual activity remaining inside the tank.

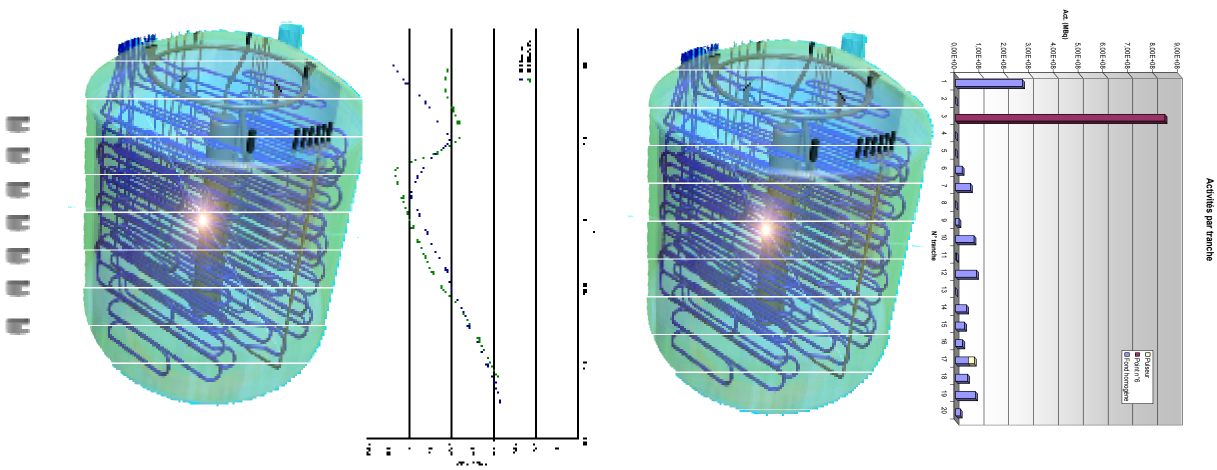

Fig. 5: {1} Complementary measurements using a γ CdZnTe spectrometry detector, {2} residual activity assessment, and {3} checks for the final radiological model

The collimated gamma spectrometry measurements were carried out along the generators around the tank. This scanning enabled the tank to be visually cut into 20 cm sections, with the gamma spectra confirming and quantifying the measurements. Non-collimated dose rate measurements were also carried out along the same lines, and were used to validate the final radiological model by comparing them to the dose values generated by simulation.

This methodology, coupling gamma imaging, 3D modeling, collimated CdZnTe spectrometry measurements and ambient dose rate measurements as illustrated here for the fission product tanks, is also widely used on other components or processes.

## Alpha Camera

### Operating principle

The objective of the alpha camera development project was to know how to remotely locate an alpha contamination spot. The phenomenon measured in order to achieve this comes from the radio-luminescence of nitrogen in air during the passage of alpha particles, which is accompanied by the emission of photons in the near-visible UV: λ of the preponderant lines between 280 nm and 390 nm (discrete spectrum). The main UV emissions associated with the passage of the alphas are concentrated near the radioactive source, given the short travel distances of alpha particles in the air. However, the detection and integration of a UV signal was made possible at a distance and through translucent materials (e.g. plexiglass).

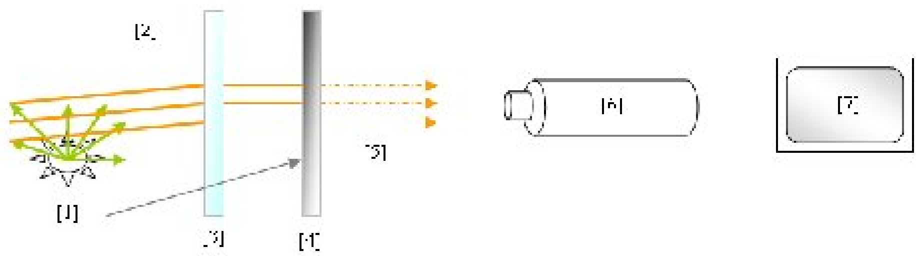

Fig. 6 Diagram of remote alpha particle detection

[1] Emission of alpha particles [2] radio luminescence with the $N_2$ in the air [3] translucent medium [4] filtering system (optional) [5] attenuated UV beam [6] detection system [7] acquisition and processing stations

Due to the proximity with the visible spectra, UV images can only be produced in darkness or using specific filters. The patent for this detection principle, associated with a camera prototype, was filed by the CEA in 1998 and is still currently maintained [3]. The alpha imaging device being studied at present consists of a high performance intensified CCD sensor using a dual micro channel plate intensifying unit, making luminous gains and high dynamic sensitivity possible in order to observe low photonic signal phenomena. In order to obtain the maximum quantum efficiency at the phenomenon's predominant wavelengths, no "solar blind" technology was added to the measuring device. The CCD sensor is combined with a multi-alkali photocathode, optimized for UV radiation. Its response spectrum expands from 180 to 800 nm. The assembly has a quantum efficiency which is greater than 20% for $\lambda \rightarrow$ 200 nm to 440 nm. The digitalization of the image is carried out in 16 bits. Given its high sensitivity, the image can be used as for a luminous environment of $10^{-6}$ lux. Finally, a standard (C mount) UV objective associated with a UV lens enables UV photons to be collected with greater than 60% transmission as from 230nm.

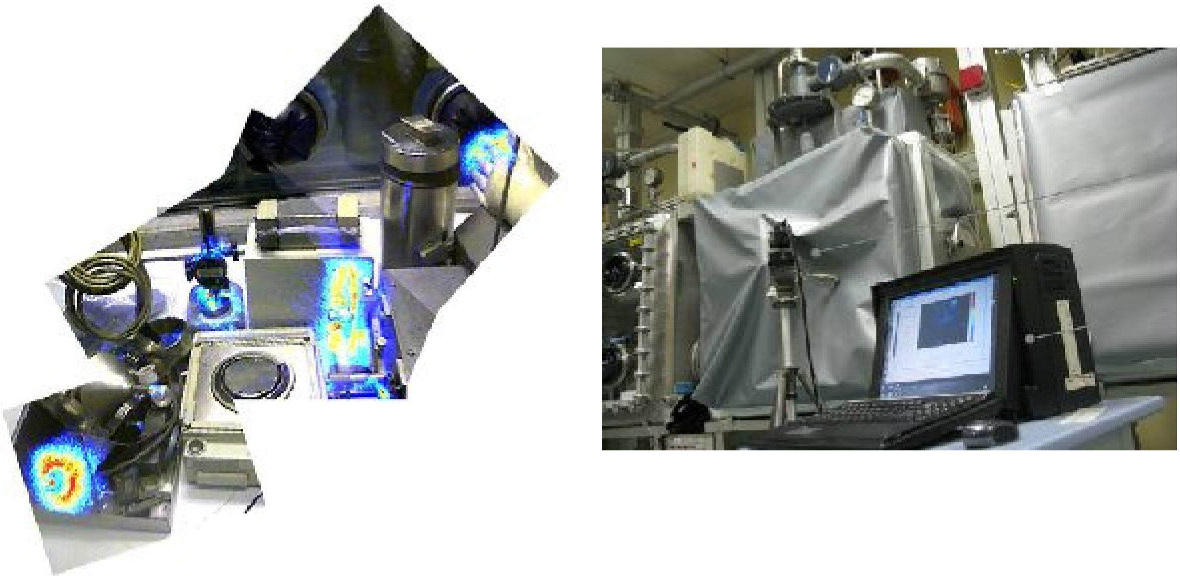

Fig. 7 {1} Alpha camera mapping result {2} System during measurement

**Location of contaminated surfaces: application to the characterization and clean-up of glove boxes**

The characterization of glove boxes for initial mapping, cleaning monitoring or radiological characterization is a delicate operation, in particular in the presence of minor actinides. In this context, the alpha camera is a device which can provide additional data on the spatial distribution of contamination within the box. In addition, setting the system up in glove boxes is quite simple and allows the darkness conditions required for quality measurements to be easily obtained. The positioning data for contaminated surface zones mean:

- During operation: warning of possible radioactive matter accumulations and guiding regular cleaning operations in order to optimize worker doses,
- During clean-up/dismantling: carrying out complete radiological surveys of the glove boxes, specifying the location of source terms during activity and mass assessments.

A first example of its implementation is the initial study of an operational glove box.

Next, the clean-up was piloted by the creation of several images during the cleaning steps carried out by workers. Based on the previously-made report, the main contaminated zones were treated first, in order to optimize the doses involved.

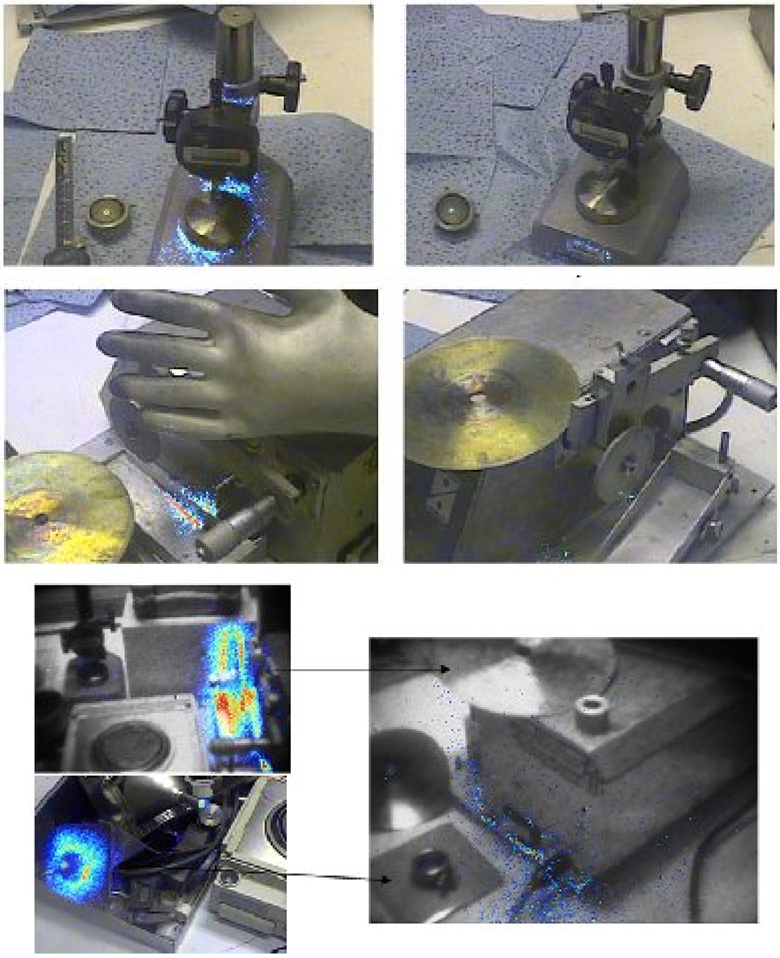

Fig. 8 Real-time clean-up as followed by alpha imaging

The alpha imaging measurements, like the data obtained from gamma imaging, thus complete the input data to be used for radiological modeling. These measurements are particularly well-adapted to surface activity estimations. The results add to those obtained from a gamma camera, and enable accurate mapping of alpha contaminated processes where gamma imaging is inefficient (weak dose rate, as the alpha emitters also emit low-energy gamma).

## CALCULATION CODE DEVELOPMENTS

NARVEOS is a new generation software tool for the simulation of interventions in a gamma environment. It has the major advantage of taking the input of the 3D mockup of a facility and integrating a dose rate estimator, taking into account the radiological *in situ* measurements. From this, it is possible to estimate the likely dose rate, integrating the sources and the shields in the

3D environment. Unlike competitor programs [17] [18], this software enables the computation of effective dose rate on a CAD geometry used to represent the intervention area very precisely.

### Narveos Features

The core system is a digital mockup that enables such functionalities within a single framework. The objective was to merge virtual reality (VR) technologies with a dose calculation code [19]. Within the VR framework, NARVEOS includes additional description functions, such as physical composition for a 'shield' or activity description for a 'source'. These data structures allow more interactivity for less computational power than in a CAD environment.

The dose rate assessment is based on the straight line attenuation method with build-up factors, a well-known approach implemented in many computation codes. More specifically, it integrates the NARMER code developed by the CEA, which is a MERCURE new release. In NARVEOS, major improvements were made in order to manage complex scenes, including models imported from CAD software tools, while computing the dose response very quickly. Interactivity is a key feature of NARVEOS [21], allowing the user to quickly and intuitively test different configurations and modeling options.

### NARVEOS Step By Step

In order to implement a realistic simulation in NARVEOS, some basic steps have to be respected to obtain precise, reliable results. This section describes the overall approach.

#### *1. Build The 3D Model*

Building the 3D model can be carried out several ways. If the 2D facility plans available are up to date, a 3D mockup is made by a simple 3D reconstruction. Unfortunately, for instance for the oldest facilities to be dismantled, drawings are often not sufficiently updated and modern reconstruction technologies have to be used to obtain a reliable mockup.

One of the techniques used is photogrammetic reconstruction [20]. It enables a 3D model to be built up, using the parallax obtained between the images acquired depending on the different points of view. It implements the correlation calculation between the digital images to give a 3D reconstruction of the model. After an *in situ* photo campaign, processing consists of identifying and digitalizing the points with common physical details on the photos, as well as the apparent contours of lines and cylinders. This reconstruction is semi-automatic, and is carried out from basic construction elements (tube valve, nut, screw, elbow…). The model obtained is compatible with standard CAD software (Microstation, SolidWorks), and is accurate to about 5 cm. The technique was used for this application case, and the result is shown below (Fig. 11).

Fig. 9: A tank (left) and its 3D model (right), rebuilt by photogrammetry

Another technique used to “rebuild” is based on laser scanning. It uses a 3D laser scanner, which scans the space vertically and measures millions of points. The cloud of points is then processed by CAD software to rebuild shapes. Laser scanning is very fast, and can take up to 1 000 000 points per second.

Whatever the method chosen, NARVEOS offers a function enabling the check of the polyhedrons conformity imported from CAD tools for dose rate assessment.

### *2. Add radiological data*

In order to merge the *in situ* measurement data with the rebuilt 3D model and calculate the response function, some information has to be added to the 3D model imported by NARVEOS, e.g. the sources found, the shields involved in the simulation and the points where the calculation is done. Based on the straight line attenuation and build-up method, NARVEOS is able to create different kinds of source activity: radio-elements, energy rays or groups (195 groups in the range of 15kEv – 10 MEv). It is possible to combine several activities in one volume source. Next, shields have to be defined, using a material library available. It is also possible to create a new material by customizing the composition definition. Every object in the 3D mockup can be used as a shield. The last pieces of information to be added are the calculation points. The figure below (Fig. 12) illustrates an application case in NARVEOS, where the 3D model, rebuilt by photogrammetry, is imported and the radiological data obtained from the *in situ* measurement is added.

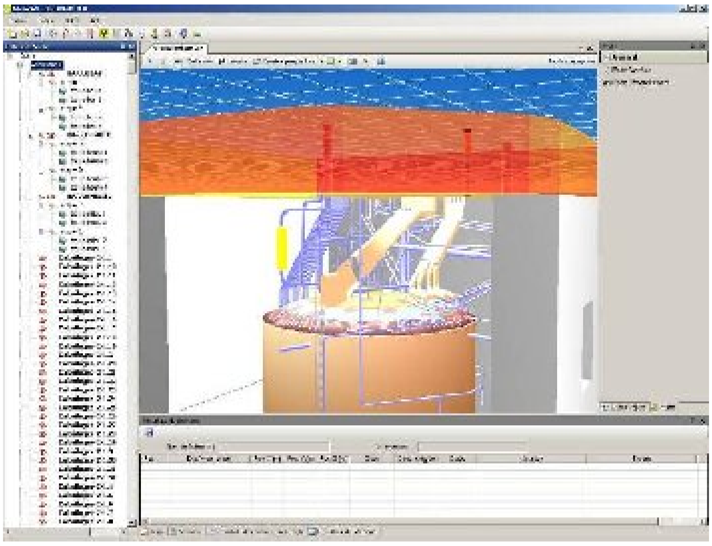

Fig. 10: Model of a tank in NARVEOS

### *3. Simulate*

Once the radiological data is added to the 3D model, NARVEOS is also able to calculate several response functions, such as ambient dose rate, particle flow rate, energy and kerma. The calculation is done in real-time and shows the evolution of the response function calculated on the calculation points defined, taking into account the modification of the modeling, such as the position change of a source, a shield or a calculation point.

NARVEOS offers a user-friendly GUI, in which it is very easy to quickly change the properties of radiological data, to navigate within the 3D model and to have a global view of all objects, and their roles in the scene. The signal answer of the code can be dose rate ($Gy.h^{-1}$) or particle flow rate ($\gamma.cm^{-2}.s^{-1}$).

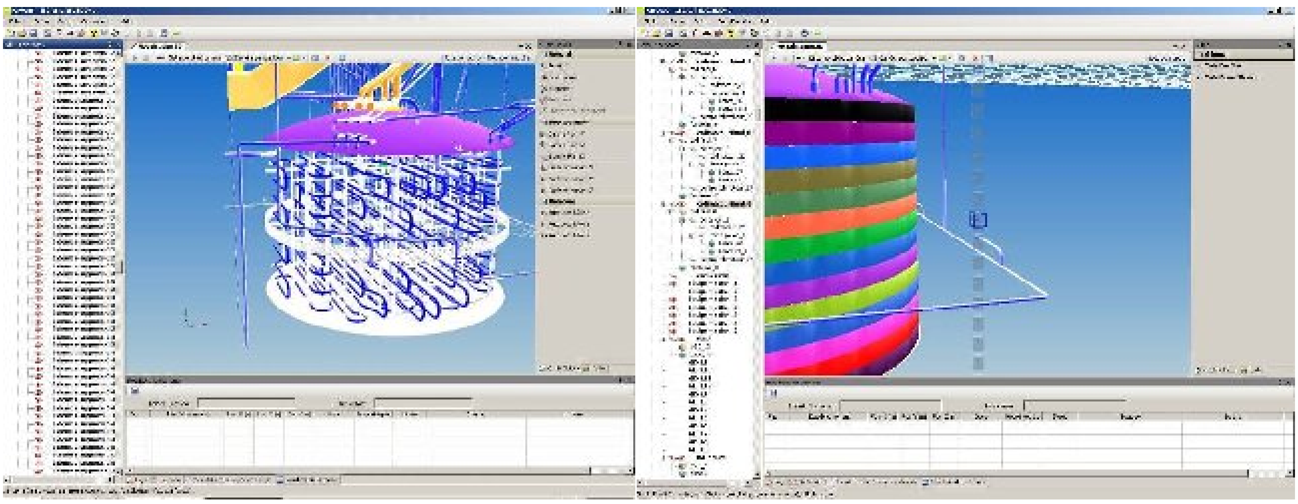

Fig. 11: Example of NARVEOS use to simulate the dose rate or particle flow rate

It is also possible to add the presence of a worker to the mockup and calculate the dose rate received. Advanced functions include the worker's motion in a model and the definition of a simple intervention scenario (Fig. 14).

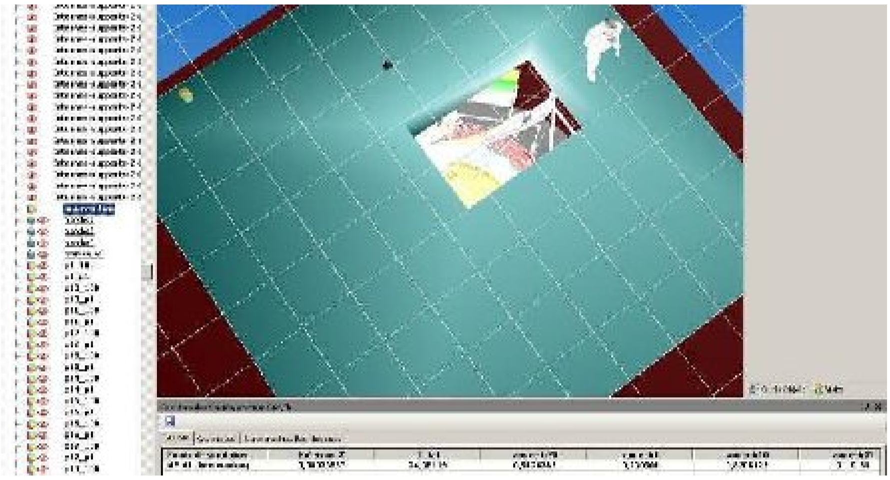

Fig. 12: While the worker is moving in the cell, NARVEOS calculates his dose rate.

## CONCLUSION

The NARVEOS software is a well-adapted tool which aids the teams in charge of designing optimal scenarios to prepare for interventions under radiological environment constraints. Furthermore, the software supports various technical fields managed during decommissioning projects: radiation protection, decontamination, engineering support, dismantling and demolition, safety and risk assessment and public information. The roadmap of the product will include Robotics and Remote Handling, while current performances will be further improved (more realistic manikin simulation, flexible cables, user-defined arbitrary cutting surface for demolition, etc.). In the near future, NARVEOS will be compatible with some immersive technologies (Cave).

Nuclear instrumentation is still in progress and the evolution of technology and software allow us to get imaging information in real time. The gamma camera is going to evolve and to become more compact and more sensitive. The alpha camera will be commercially available through 2013. This tool is well adapted to carry out decontamination operation on glove-boxes as well as feeding 3D calculation codes data to give the best estimate of the internal activity.

What feedback shows is that all these techniques should be associated to give the best dataset to the new 3D calculation codes.

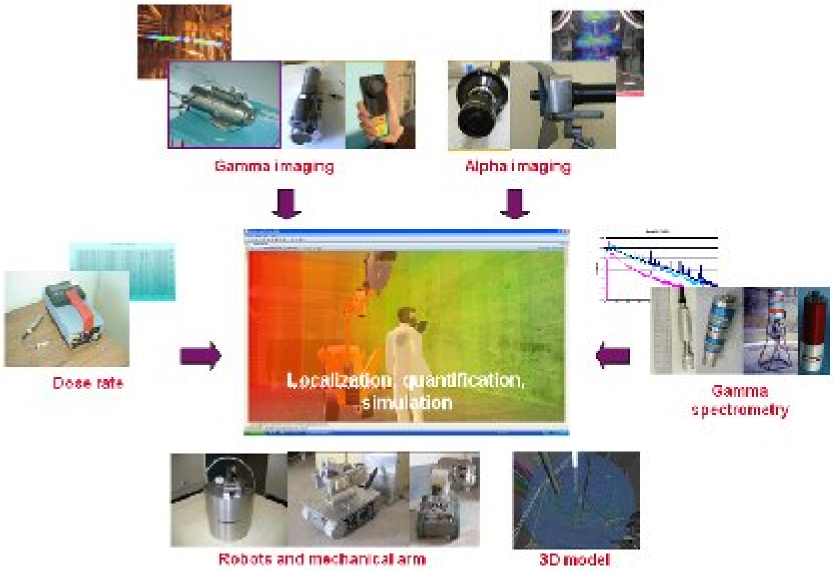


Fig. 13: Summary of techniques to be used to feed 3D calculation codes

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