3D representation of radioisotopic dose rates within nuclear plants for improved radioprotection and plant safety

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Abstract: A better awareness of the origin and nature of gamma doses in nuclear environments is demonstrated by visualizing the dose maps created by individual radionucleides that are present in radioactive contaminations. This isotopic representation of doses is much more informative than showing a map of the measured total doses. Two practical examples are given : (a) the placing of protections, and (b) using radiation decay to help plan dismantling operations. The necessary radionucleide information can be easily obtained by the new EDF CZT gamma spectrometer that is now used by all its NPPs. Defining radioactive sources based on such information enables the reconstruction of the radiation situation in a virtual 3-D environment. In such a virtual environment, dose rates can be calculated in any position in space and information about how much each radionucleide contributes can be extracted. Such 3D visualisations increase the awareness and knowledge of the distribution of radiation in a nuclear facility and can be considered as an educational tool for training and improved ALARA procedures.

Keyword: VR, dose, ALARA, CZT

1 Introduction

In both nuclear maintenance and decommissioning projects knowledge of the radiation situation is essential for planning and radioprotection safety. A description showing the radionuclides present in nuclear power plant (NPP) areas is more informative than, and complementary to, mapping the total (measured) dose levels because it shows the origin of the doses. This gives a better basis for intervention planning and radioprotection since it allows for optimising the placement of shielding and taking into consideration the radioactive decay rates of the various sources. These are the basic tools of ALARA.

In most decommissioning projects, the majority of the participants are new and did not work on the construction or operation of the facility. Preserving plant knowledge is therefore difficult but of high importance. This challenge escalates when a plant is being kept in storage while radioactivity decays, political issues are being resolved or final waste storage is being decided.

Precise radionuclide characterization of a whole facility is an extensive operation and can require bulky and complicated tools and facilities. In most countries high and medium level waste disposal weigh heavy on the budgets and being able to down class or free-release larger volumes of material is an important goal.

If one is able to combine advanced 3D visualisation techniques with emerging technologies such as laser scanning, gamma photogrammetric investigations and gamma spectrometry then this is likely to be a huge advantage to a decommissioning project. Such a combination of technologies are in the process of being realized through a collaboration between EDF (the French electricity producer) and IFE (the Norwegian Institute for energy technology and coordinator of the OECD Halden Reactor Project).

In this communication we demonstrate the principle of such a combined methodology. Radionucleide information describing the nature of radioactive sources is incorporated into a 3D (virtual reality type) description of the scene so that operator dose rates can be visualised. In addition, the 3D display of both the total dose map and of the doses created by the individual radionucleides allows one to identify clearly areas of high doses and, more importantly, which radionucleides are responsible for these doses. Such ilustrations give a better radioprotection awareness and thereby improve the general safety of the NPP.

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EDF is the first nuclear energy producer in the world to equip all its NPP radioprotection personnel (58 operating reactors) with specially-designed, portable, CdZnTe (CZT) gamma spectrometers and associated spectral analysis software. The sensor is currently commercialised by Canberra.

The aim of this sensor is to identify the dominant radioactive isotopes (e.g. corrosion products) responsible for operator doses so that maintenance operations may be optimised. Getting spectrometric information easily is the starting point for the new EDF–IFE collaboration which is centred on using virtual reality to display the radiological characteristics of nuclear environments.

2 EDF CZT gamma spectrometer

In 2006, EDF equiped all its NPPs with a CZT gamma spectrometer so that an isotopic characterisation of radioactive contaminations may be performed in-situ by its NPP radioprotection personnel. The contaminations of interest result mainly from corrosion processes and are situated inside pipes and components (out-of-core contaminations).

Knowing the different radionucleides present within radioactive contaminations improves plant surveillance (e.g. water chemistry and unit operation) and can efficiently lead to both preventive measures and remedies for reducing operator doses. CZT gamma spectrometry is complementary to the analysis of the volume activity of water samples performed by the chemists.

EDF radioprotection services use the CZT spectrometer at each outage in order to identify the contaminations, follow their evolution, determine corrective actions (decontamination, shielding) and to detect new pollutions as quickly as possible.

2.1 Acquisitions

The EDF spectrometer is comprised of an independent acquisition module to which interchangable CZT probes (from Ritec) can be attached via a 20 m cable (Fig. 1). Todate, the standard probes are 500, 60, 20 and 5 mm^3 detectors. The long cable allows remote acquisitions. The acquisition time depends on the source exposure, which probe is used and the method of deployment (collimated or uncollimated probe).

EDF usually uses an uncollimated probe that is placed on contact with the circuit component (Fig. 2). A typical acquisition time is 15 to 20 minutes.

The CZT spectrometer can measure gamma spectra over the energy range of 100 keV – 1.8 MeV. Dose rates are typically from a few µSv/h to several hundred mSv/h.

Fig. 1
EDF CZT spectrometer.

Fig. 2
Example of a CZT measurement
The probe is on contact.

2.2 Spectral analysis

Special analysis of the measured gamma spectrum, as defined by EDF, is performed using a PC WINDOWS-type computer. The main functions are :

a) An identification of the main corrosion and fission products : 60Co, 58Co, 110mAg, 137Cs, etc. . This library is programmable.
b) An estimation of the relative contribution of each radioisotope to the total dose at the point where the spectrum is measured.
c) An estimation of the relative activities of each radioisotope <u>inside</u> the component. In this case, the analysis compensates for the attenuation created by the component's wall (e.g. 5 mm of steel).

It is important to note that (b) and (c) above are expressed as *<u>percentages</u>*. Absolute doses and activities of the radioisotopes are not estimated because no information concerning the shape/form of the contamination is known.

An experienced operator can analyse a spectrum in about 5 minutes. Fig. 3 shows a measured CZT spectrum. Its analysis is immediately below.

In this example, 110mAg is very weak – it can be ignored because it creates little dose (~5 %). 60Co dominates by giving 54 % of the dose at the point of measurement (outside the pipe). It has 30 % of the source's activity inside the pipe. 58Co gives less dose (42 %) but is more active inside the pipe (67 %) which has a wall thickness of 26 mm of steel.

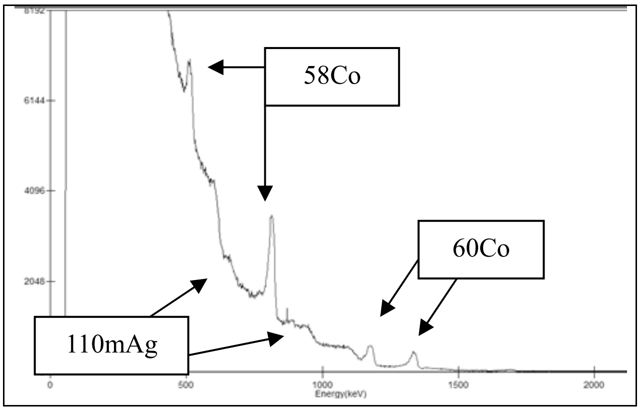


Fig. 3 CZT gamma spectrum.

Analysis results
60Co, 58Co & 110mAg are identified.

For the DOSE :

AG-110m	4.8 %	(2σ=3 %)
CO-60	53.6 %	(2σ=7 %)
CO-58	41.6 %	(2σ=7 %)

For the ACTIVITY (26 mm steel pipe thickness) :

AG-110m	2.9 %	(2σ=1 %)
CO-60	30.2 %	(2σ=4 %)
CO-58	66.9 %	(2σ=4 %)

3 Dose calculations

Spectrometric information (about the individual sources) and total dose rate measurements (of the scene) are fundamental parameters for creating a geometrical and radiological model of any nuclear environment. In addition, shielding can only be taken into account if the exact position, size, orientation geometry and type of material are known. When several sources are present calculations simply add up the contributions from different sources.

Such representations are then used by special radioprotection software to calculate dose rates at any point in 3D space (e.g. MicroShield, Visiplan, MCNP, etc.). Our approach is similar in this respect.

The following equation is the classical way of calculating the air exposure rate from point sources with shielding and buildup (scatter) :

$$X_{air} = 5.26\times10^{6}\,\frac{A}{d^2}\sum_i y_i E_i (\mu_{en}/\rho)_i \times e^{(\mu/\rho)_i \rho\, r} \times B_s(E_i,\rho,r) \quad (1)$$

where

X_{air}	:	air exposure rate in roentgens/h,
A	:	source activity,
d	:	distance to the dose point,
y_i	:	yield of photons of energy E_i,
E_i	:	photon energy,
$(\mu_{en}/\rho)_i$	:	mass-energy absorption coefficient for air at energy E_i,
$(\mu/\rho)_i$	:	shield mass attenuation coefficient at energy E_i,
ρ	:	shield density,
r	:	distance travelled in the shield,
$B_s(E_i, \rho, r)$	:	Buildup factor at E_i for the shield.

This exposure rate can be used to give a very good estimation of the absorbed dose rate in soft tissue :

$$\mathbf{Dose}_{tissue} = \mathbf{X}_{air} \times 9.7 \quad (\mathbf{mSv/h}). \quad (2)$$

Even though the above equations are only valid for point sources they can be used repeatedly because 2D surface sources and 3D volume sources are merely collections of point sources.

Todate, the following radionucleides are supported by our 3D VR software : 58Co, 60Co, 137Cs and 110mAg. Shielding is supported for materials of iron, lead, water and concrete with geometry of a cylinder or a box.

The mass attenuation and mass-energy absorption coefficients are taken from [3] and the build-up factors are from[4].

Our VR software can also take into account a constant background radiation and it can calculate dose rates in the future since the radioactive decay of the given radionucleides is taken into account.

4 Combining radiological information and VR

The following two examples illustrate the usefulness of visualising radioisotopic dose distributions. The first deals with optimising the placing of protections. The second shows how spectrometric information and radiation decay can help plan dismantling operations and waste management.

4.1 Example 1 : Optimising shielding

Figure 4 shows a 3D visualisation of the total dose rate distribution for a scene that contains 3 point sources, 2 shields and 2 operators. The following information is given :

- The top left source contains 20 GBq 110mAg, 1 GBq 60Co and 10 GBq 58Co placed inside a pipe which has a wall thickness of 4 cm Fe.
- The bottom left source is composed of 10 GBq 137Cs and 10 GBq 60Co placed in a pipe of 0.5 cm Fe wall thickness. In addition, there is a 5 cm Pb shield between the pipe and the left operator.
- The right source is 80 GBq 58Co plus 80 GBq 60Co inside a 0.3 cm Fe pipe and behind a 40 cm concrete shield.
- The left operator has a dose rate of 0.11 mSv/h and the right operator receives 0.42 mSv/h. The doses are computed at a point which is 1.5 m above the floor (operator chest level).

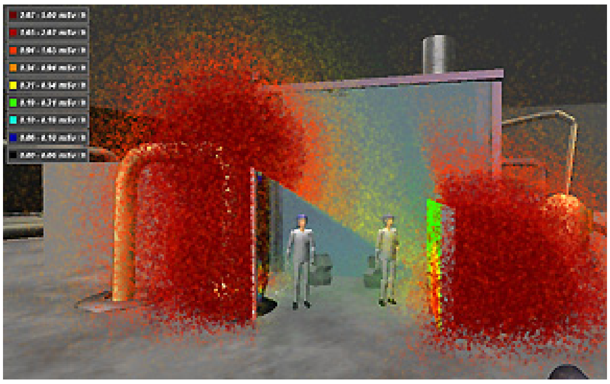


Fig. 4 VR representation of the total dose rate map.

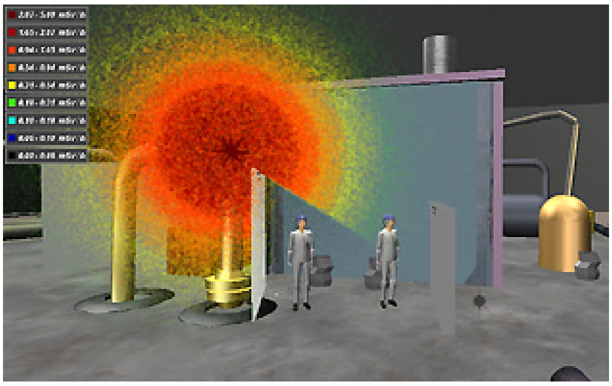
The following questions are now asked : Why is the right operator receiving approximately 4 times the dose of the left operator ? How can his dose rate de reduced ?

The situation is complex and difficult to understand mentally because it involves multiple sources each containing several radioisotopes of different activities and which are placed at various distances in 3D space. In addition, the three sources have different shielding.

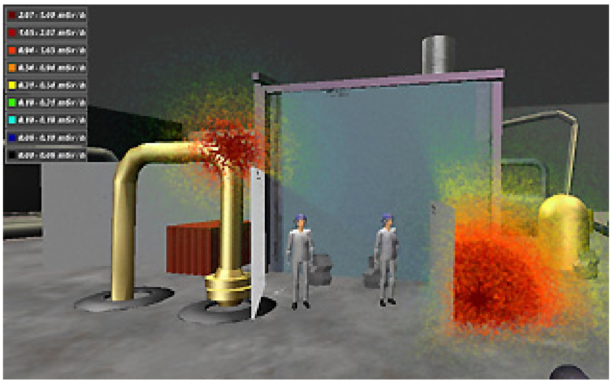
Visualising the total dose rate in 3D, as in Fig. 4, is useful but not sufficient for understanding the origin of the operators' doses. One can clearly see that the lead and concrete shields create a "shadow volume" that has less exposure. One also sees that the top left source is located higher than the height of the (left) lead shield and thus exposes the right operator. Another feature is that radiation penetrates the protections, especially on the right shield. The problem is that one is simply unable to appreciate the relative dose contributions of each source and therefore is unable to decide how to optimise the protections.

4.1.1 Visualising radioisotopic dose maps

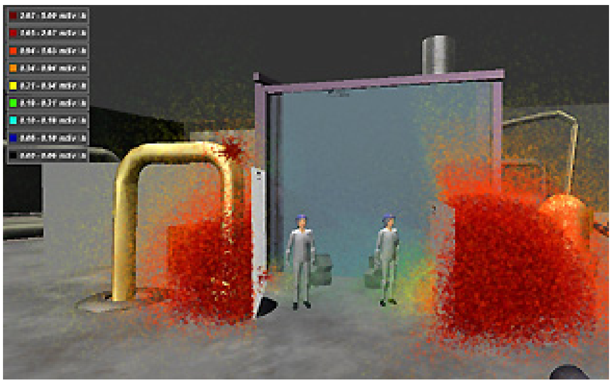
If one examines the individual dose rate maps created by each radioisotope one appreciates better the origin of the operators' doses (Figs. 5(a)-(d)).



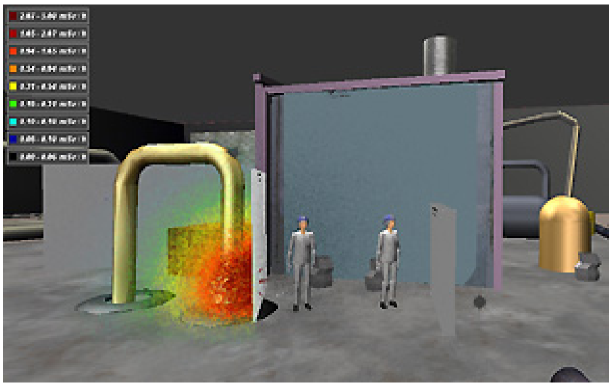
(a) 110mAg dose map



(b) 58Co dose map



(c) 60Co dose map



(d) 137Cs dose map

Fig. 5 Visualisation of the dose rates created by each radioisotope.

These independent radioisotopic visualisations immediately draw attention to certain radiological properties of the scene :

(i) The left shield greatly reduces the radiation from 137Cs but seems to be insufficient as far as 60Co is concerned. Thus the left operator is probably receiving most of his dose from 60Co in the bottom left source.

(ii) The right operator's dose appears to come from both 60Co in the right source and from 110mAg in the top left source.

These visual suspicions are confirmed by the statistics that can be extracted interactively from the VR representation (Table 1).

Table 1. Dose rate information obtained by interactively exploring the VR representation

Source	Radionucleides	Dose rate (mSv/h) Left operator	Right operator
Top left	Total	0.01	0.30
	(110mAg)	0.004	0.24
	(60Co)	0.001	0.01
	(58Co)	~0	0.05
Bottom left	Total	0.04	0.02
	(137Cs)	~0	~0
	(60Co)	0.04	0.02
Right	Total	0.06	0.10
	(58Co)	0.01	0.01
	(60Co)	0.05	0.09
ALL	TOTAL	0.11	0.42

These statistics show the total dose rate, the dose rate from a specified source and the dose rates from each radionucleide present in a specified source.

Table 1 not only clarifies what we suspected from the radionucleide visualisations, but also it indicates precisely from where the operators' doses are coming : the left operator's dose comes from the 60Co which is present in both the nearby bottom left and far away right sources and both sources give roughly the same dose rate.

As for the right operator, he receives most of his dose from 110mAg (very dominant). Only 30 % of his dose comes from the 60Co behind the concrete shield (right source).

It is important to remember that real nuclear environments are often geometrically and radiologically complex and that it is not practical to always present the detailed information of Table 1 for all combinations of sources, radionucleides and shielding. The radioprotection operator would quickly be saturated with so much information and would probably miss the key (radiological) features(As an example, some EDF maintenance operations have been known to require the creation of a geometrical – radiological model involving over 200 radioactive (point) sources which are distributed over components and circuits of different sizes).

It is much more efficient to first use VR visualisations with interactive capabilities and then let the operator explore the scene as he prefers. This is precisely our approach.

4.2 Example 2 : Radiation decay

Nuclear dismantling is a good example of where an initial radiological survey, with spectrometric information, can influence the planning of operations. It is also important for waste management. In both cases it is important to know the radioisotopes.

This second example shows how the dose rate maps change after 1 year (Fig. 6) and after 4 years (Fig. 7). The scene and the colour scale are the same as in Fig. 5.

Tables 2 and 3 quantify the various source and radionucleide dose rates for the two operators. Again, these estimates can be extracted interactively from the VR visualisations which merely guide the user's interrogation of the scene.

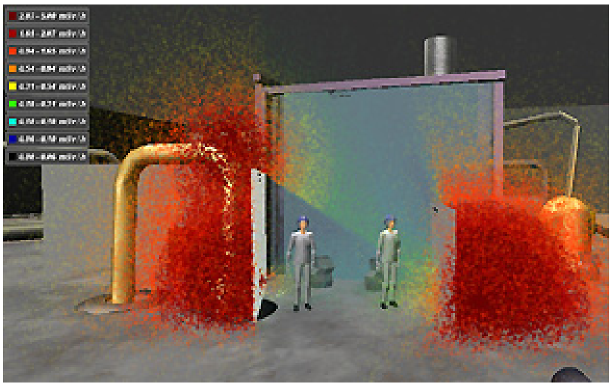


Fig. 6. Visualization of the total dose rate map after 1 year of radiation decay.

Table 2 Dose rate information after 1 year of radiation decay

Source	Radionucleides	Dose rate (mSv/h) Left operator	Right operator
Top left	Total	~0	0.10
	(110mAg)	~0	0.09
	(60Co)	~0	0.01
	(58Co)	~0	~0
Bottom left	Total	0.037	0.02
	(137Cs)	~0	~0
	(60Co)	0.037	0.02
Right	Total	0.045	0.08
	(58Co)	~0	~0
	(60Co)	0.045	0.08
ALL	TOTAL	0.08	0.20

After 1 year the 58Co has reduced considerably (half-life of 71 days). 110mAg has also decayed but to a lesser extent (250 day half-life). The conclusion is that the right operator's dose rate has been halved after 1 year with equal doses now coming from 110mAg (top left source) and 60Co (right source). 60Co is now the dominant dose source in the scene for both operators (half-life of 5.3 years).

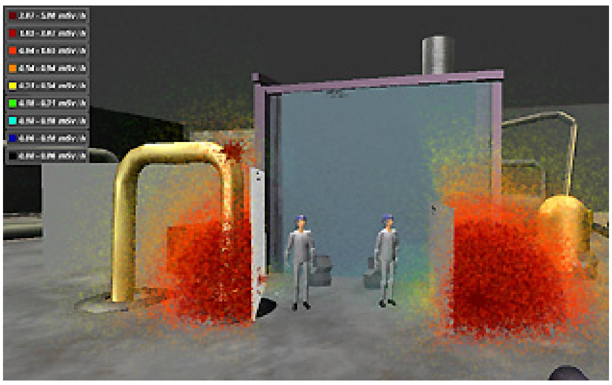


Fig. 7 Visualization of the total dose rate map after 4 years of radiation decay

After 4 years both operators receive approximately the same dose rates. 58Co has virtually disappeared and 110mAg has been greatly reduced. 60Co still dominates the doses for both operators. 137Cs will be active for longer (30 year half-life) but it is not a problem because the left shield is efficient.

Table 3 Dose rate information after 4 years of radiation decay

Source	Radionucleides	Dose rate (mSv/h) Left operator	Right operator
Top left	Total	~0	0.012
	(110mAg)	~0	0.004
	(60Co)	~0	0.008
	(58Co)	~0	~0
Bottom left	Total	0.025	0.015
	(137Cs)	~0	~0
	(60Co)	0.025	0.015
Right	Total	0.03	0.05
	(58Co)	~0	~0
	(60Co)	0.03	0.05
ALL	TOTAL	0.055	0.077

This particular example again illustrates the advantages of examining dose rates at the radionucleide level.

5 Discussion and conclusions

When one wishes to visualise radiation conditions several challenges exist and one of these is selecting what to visualise. Our examples have shown that it can be useful to know how the different radionucleides in the different sources contribute to operator dose rates.

The all important spectrometric information describing the radioactive sources is now easy to obtain with in-situ CZT gamma spectrometry.

Our examples have shown that being able to interact with the 3D virtual-reality representation of the scene gives a visually easy-to-understand description of the radiological aspects of the environment. These visualisations can be used to illustrate the effects of various actions such as placing, moving or removing shielding, decontaminating circuits, changing operator positions, postponing activities etc. .

Both nuclear dismantling and maintenance are good examples of where an initial radiological survey, with spectrometric information, can influence the planning of operations. It is also important for waste management. In all cases it is important to know what radionucleides are present in the sources and what doses they generate.

CAD simulations are often performed by engineering divisions who prepare large operations. Visualizing dose maps in different ways means that one can examine both the geometrical and dosimetric feasibilities of a planned intervention. This is important for complex situations.

Knowing which radioisotopes are present in a source and their corresponding contributions to doses significantly enhances the decision base for NPP radioprotection staff. Being able to communicate these findings to work teams through a 3D model of the work environment improves the overall radiation awareness of the staff and cross-disciplinary understanding.

The pedagogical element should not be ignored. The above examples illustrate how dose is dependent on the type of radionucleide, its activity, the shielding placed in front of it and the operator-source distance. These fundamental aspects of radioprotection can be used in training and/or awareness programmes (ALARA).

Our conclusions are as follows :

1) Displaying the dose rate distribution created by individual radionucleides present in a radioactive source is much more informative, and creates a better radiation awareness, than showing the total (measured) dose rate distribution.

2) 3D (virtual reality type) techniques are a powerful and easy-to-understand means of visualizing total and radioisotopic dose rate distributions, especially in complex nuclear environments. This is the aim of the EDF-IFE collaboration.

2) An awareness of dose rate distributions from radionucleides has applications in nuclear maintenance and dismantling. It is important for radioprotection services and engineering divisions who plan complex interventions. It can also be used as an educational tool for teaching/training to convey better ALARA practices.

Further developments include visualising work scenarios and minimising worker doses based on movements through the workspace.

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