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Classification and categorization of the constrained environments in nuclear/radiological installations under decommissioning and dismantling processes

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ABSTRACT

INSIDER is an EU Horizon 2020 research project, within the topic NFRP-7 of the EURATOM programme, that aims to develop and validate a new and improved integrated characterization methodology and strategy for the nuclear decommissioning and dismantling operations (D&D) of nuclear power plants, and post-accidental land remediation of nuclear facilities under constrained environments. In line with this general objective, the definition and implementation of the practical considerations surrounding the radiological characterization of nuclear/radioactive facilities subject to a D&D programme is under development. .

In-situ measurements are key for this radiological characterization. However, in some cases these measurements have to be carried out under constrained conditions, which poses some challenges to their realization. A constrained environment is a general term that includes all types of environment that hinder the choice of a non-destructive in-situ measurement method. In the context of this paper, it is applied to different situations: radioactive levels of the area to be characterised, difficult accessibility of this area, type and properties of the materials contained in it, as well as the possible presence of other environmental hazards, such as asbestos, chemical and/or organic/biological ones.

In this context, an analysis of the suitability of existing methodologies for in-situ measurements in constrained environment is being carried out. The first step to accomplish this task is to describe the constrained environments that could appear in the different nuclear/radioactive facilities and their respective challenges.

This paper includes a description of the different constrained environments, showing their corresponding challenges and a classification of the constraints, and it provides a series of tables linking the installations and areas inside them with the different constraints that appear. In the case of the radioactive constraints, a description of the expected level of their impact depending on the different D&D steps also appears.

1. Introduction

The INSIDER project (H2020-Euratom) aims at further improving the management of contaminated materials in nuclear facilities subject to a decommissioning and dismantling (D&D) programme, as well as during post-accidental site remediation and clearance, by proposing a methodology that allows the definition and selection of the most appropriate intervention scenarios,producing well-characterised radioactive waste for which storage and disposal routes are clearly identified. One of the different tasks defined to accomplish this is the optimisation of the radiological characterization process and thus, the analysis of the suitability of existing methodologies for in-situ measurements in constrained environments (INSIDER, 2017).

According to the Nuclear Energy Agency (NEA, 2013), the term “radiological characterization” represents the determination of the nature, location and concentration of radionuclides in a nuclear facility. It is a key element of the planning, controlling and optimising of decommissioning and dismantling (D&D) activities. It can be also considered as a continuous process, as adequate radiological characterization is of crucial importance in all stages of a decommissioning program or project, not least from a material and waste perspective. Radiological characterization plays a significant role in the decommissioning process of shut down nuclear facilities. An effective characterization allows the extent and nature of the contamination to be determined, thereby

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providing crucial information to support facility dismantling, the management of material and waste arising (IAEA, 2004; IAEA, 2007), the protection of workers, of the public and the environment, and associated cost estimations (IAEA, 1998a,b).

A conventional radiological characterization process may cover a wide range of evaluation objectives during a D&D project: doubt removal, identification of hot spots, spatial extent of contaminated materials, dose rate estimation for workers, monitoring of the decontamination work and final survey (IAEA, 1998a; NEA, 2017). In this context, it is a whole process that enables a different statistical process to ensure a suitable sampling strategy and plans, as well as the definition of in-situ measurement techniques that are adapted to each specific area and the selection of the best fit for purposes in lab analytical techniques. The statistical analysis, as well as the in-situ measurements, should be able to provide a radiological mapping of the area, whereas minimizing and properly defining the number and position of samples to be taken for remote control in the laboratory. This process contributes to the optimisation of the financial needs of the D&D process and helps to shorten it (Varley and Rush, 2011).

As the Organisation for Economic Co-operation and Development (OECD) and the NEA pointed out (NEA, 2014), one of the challenges in this radiological characterization process is the in-situ measurements and more specifically, the characterization in and around structures that are difficult to access. From a broader point of view, the challenge is the in-situ measurement techniques to be used in any constrained environment.

A constrained environment is a general term that includes all types of environment that hinder the choice of a non-destructive in-situ measurement method due to their ability to compromise the radiological characterization by disturbing to measurement equipment or affecting in-situ data due to interfering factors.

There is already a large number of publications devoted to D&D processes and to radiological characterization and in-situ measurements. Most of them are focused on a specific type of facility (Kalb et al., 2000; Danish Decomminsionning , 2012; Cruickshank, 2012; JRC, 2014; ASN, 2016 Matsumoto, 2016); or on how a constraint affects the operation of a particular piece of equipment (Moszynski et al., 2006; Baginova et al., 2018; Tsitsimpelis et al., 2019). There are also several studies establishing the different general factors or constraints that influence the overall project implementation of D&D strategies (Suh et al., 2018 and references therein; PerkoMonken-Fernandes et al., 2019). The main environmental constraints affecting in-situ measurement technique decisions, however, are not well identified and a systematic review of environmental constraints and the type of facilities and areas they appear in has not been addressed either. This is why it was included as an activity in the INSIDER project.

In this context, the present paper introduces, defines and analyses these constraints to highlight their influence on in-situ measurements during every part of the life cycle of the D&D project in each particular facility. Its aim is to synthesise the disturbing and affecting factors that could compromise the radiological characterization. This is the first challenge that must be dealt with before being able to recommend a specific in-situ measurement technique for each type of area inside a particular installation, which is one of the final objectives of this INSIDER project.

In this paper, the environmental constraints considered are contained in one of the following categories:

- radioactive levels of the area to be characterised
- difficult accessibility of this area
- type and properties of the materials contained in it
- possible presence of other environmental (chemical and/or biological) hazards

Each of these situations presents a different set of properties. Each one can affect the measurement process differently and also the interpretation of the data obtained.

All of the environmental constraints considered here can be considered to be technical constraints. However, there are other constraints which can be considered to be management constraints, which also affect the selection of in-situ measurements techniques. These are related to resources, staff and financial and security issues (IAEA, 2006; IAEA, 2008). Therefore, since they are not linked to the site itself, these management constraints are beyond the scope of this paper.

In this paper, the decision process used to define the best in-situ measurement technique, depending on the investigation objectives and on the different environmental and management constraints, is described in section 2. Section 2 also details environmental constraints, described as any type of constraint that hinders the choice of a non-destructive in situ measurement method during a D&D project. Management constraints are also briefly introduced in this section 2.

Finally, in sections 3 and 4, the constrained environments under consideration are classified according to their corresponding challenges. For this purpose, the considered installations, along with the different areas that are expected to be found in these, have been classified in different groups, with their different constrained environments also listed. Certainly, it should be taken into account that, for a specific area, the existing constraints could change along the different steps of the D&D process and then, the methodologies to be used for the in situ characterization would have to be adapted accordingly.

In summary, this paper provides a description of the constraints affecting the decision process of in situ measurements, showing their corresponding challenges and also listing in which areas of nuclear/radioactive installations they could appear along the different phases of any D&D programme.

It must be noted that in this paper, post-accidental site remediation and clearance are not taken into account, neither as a specific “installation” or “area” when defining constrained environments nor the challenges they provoke, as they are very particular for each situation. However, it is considered that some conclusions regarding the choice of in-situ measurement techniques could be drawn in light of the classification made in this paper.

This paper does not claim to be an exhaustive guide containing all the possible nuclear or radioactive installations, nor all the possible constrained environments. The main objective of this paper is to describe those situations that appear most often and those that are most challenging when they are under D&D process.

2. Decision process: defining the best in-situ measurement technique

2.1. Overview

Collecting radioactivity data for radiological characterization is essential in order to be able to evaluate the benefits and performance of the D&D process. Some data can be obtained by direct in-situ measurements or by obtaining a smear, scratching, or drilling a specific sample followed by in-lab analysis, with the in-lab analysis being more accurate and less prone to contamination or interference, although it is a more time-consuming and resource-intensive method.

For a specific area inside a certain installation, the choice of an in-situ measurement technique will depend on a set of information obtained through a complete decision process that starts by defining the investigation objectives of the characterization process, and hence of the in-situ measurement, and finishes by choosing not only the most suitable in-situ measurement technique but also the data interpretation methodologies and the response protocol for the in-situ activity. This decision process will depend on the environmental constraints or other constraints that the area may have, including those of management. Moreover, it should also be taken into account that the same area can have different environmental constraints throughout the whole decommissioning process (see section 3), which will condition the final

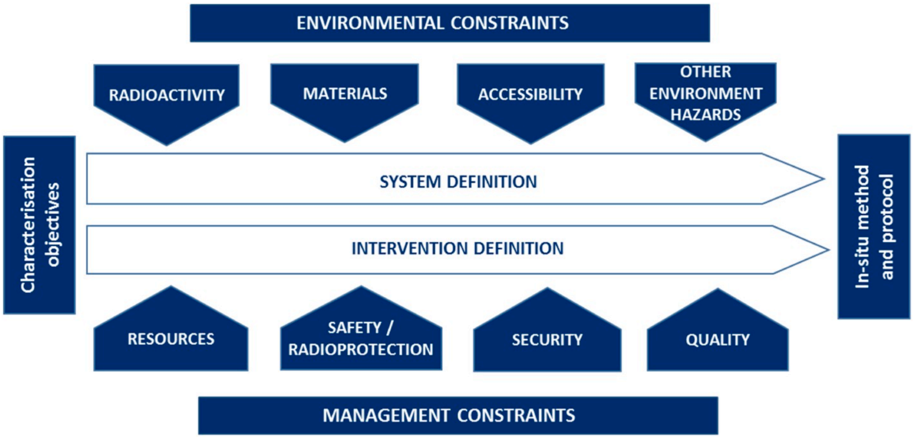


Fig. 1. From characterization objectives to in-situ methods and protocol.

choice of the in-situ measurement technique.

For each facility subject to a D&D program, the investigation objectives of the radiological characterization and, thus, of the in-situ measurements, are given by project/authorities and can be in terms of fissile materials, dose-rate levels, radioactive activities, radionuclides, etc. Moreover, the description and historical information of the site are necessary background information and complete the defined investigation objectives to accomplish the decision process (NEA, 2013).

Generally, before starting the first stage of the D&D project, a deep understanding of the facility can provide valuable preliminary data to start the process and, accordingly, documentation about the past history and events of the facility has to be reviewed (IAEA, 2002; Rossini et al., 2018). When information about the distribution of the source in the system or place is not available, characterization often aims to establish it. Thus, assumptions about the activity distribution have to be defined. According to radiation transport models, large uncertainties can result from lack of knowledge or from mistakes in the radioactive distribution assumption (Magnox Ltd, 2012). Therefore, at each phase of a D&D program, collecting relevant preliminary data is essential to consolidate the feasibility of the in-situ characterization.

Based on this preliminary information and the analysis of the environmental constraints present, it is possible to determine the exact locations for in-situ measurements needed, as well as the most suitable equipment and methodologies to be used. This process is named “system definition”. At the same time, it is essential to carry out an analysis of the resources, quality, safety and security issues, that is of the management constraints. This process, named “intervention definition”, is related to the response protocol of the in-situ activity and could condition the final decision about the in-situ measurement technologies beyond the environmental constraints. .

The whole decision process can be summarized as in Fig. 1.

The top blue arrows in Fig. 1 represent the environmental constraint categories that must be overcome to properly define the system, and the bottom arrows show the management constraints that condition the selection of the intervention definition. Both should be taken into account to define the in-situ measurement techniques and methodologies, starting with the characterization objectives.

All these constraints, both environmental and management ones, are described in the following subsections. However, only those regarding the system definition (environmental ones) are deeply analysed and considered in order to classify and categorize the areas and installations in this paper.

2.2. *Environmental constraints*

The in-situ measurements are mainly based on non-destructive assay methods to detect all types of ionizing radiation emitted by radionuclides α, β, photons (X- or γ-rays) and neutron emissions, in the item under investigation. The choice of the best in-situ measurement methodology is made with regard to the technical constraint categories (radioactivity, accessibility, materials and other environmental hazards), as previously stated.

Specific constraints that are included in each one of these constraint categories are presented in Fig. 2 and explained in more detail in the following paragraphs.

It should be taken into account that each constraint affects the in-situ measurement and, thus, the radiological characterization, in a different way. In some cases, the detector may turn out to be physically damaged

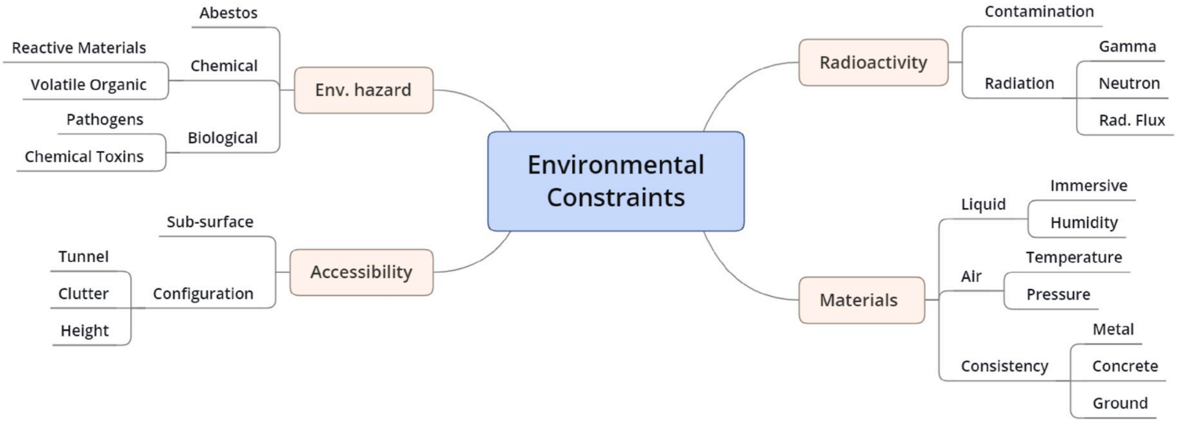


Fig. 2. Environmental constraint categories and specific constraints to be taken into account during the choice of in-situ measurement techniques.

or its characteristics compromised. However, in other cases it is the interpretation of the obtained data that could be compromised. For example, the radioactive source distribution assessment can be badly done because of the porosity of the source or the high background conditions. All these consequences can be minimised by selecting the appropriate in-situ measurement systems and methodologies. In this paper, both possibilities of interfering factors are considered.

This classification leads to the identification of different constrained environments in each facility. The way in which each of them affects the in-situ measurements is explained in more detail below.

2.2.1. *Radioactivity*

A high radioactive level is a major constraint of characterization in a nuclear/radioactive environment. Obviously, it causes difficulties for human intervention and requires special equipment (i.e. robotics, leak tight uniforms) in order to protect the people. It should be considered that different radioactive levels result in different in-situ measurement strategies.

Therefore, we can identify two ways in which radioactivity affects measurements: the ones coming from the high levels of radiation (mainly appearing as high gamma or neutron dose rates and high radiation fluxes in accelerator type installations) and others coming from contamination. Both are considered here.

It is assumed, for a same area, this radioactive level varies during the different phases of a decommissioning process, and the investigation method should be adapted at each phase. Irradiation constraints are present upstream during the decommissioning process and pre-dismantling phase, and should decrease in the remediation and final phase.

2.2.1.1. Radiation constraints. A measurement in high radiation level environment is very challenging and can affect measurements in several ways, such as, signal discrimination, detection performance, dead time issues and background corrections that must be considered when doing data interpretation and analysis after measurement. So, one needs to be very careful in the choice of detectors and their settings as well as its associated electronics.

Signal discrimination issues can happen in presence of different type of radiation fields producing interferences in the response of the detector. In the case of neutron detectors, particular attention needs to be given to Gamma Rejection Ratio (GRR) which is the intrinsic response of the neutron detector to the presence of a gamma ray field when no neutron source is present, or Gamma Absolute Rejection Ratio in the presence of neutrons (GARRn) regarding the absolute neutron detection efficiency in the presence of neutrons and gammas. Thus, if the gamma radiation level is sufficiently high the amplitude rejection efficacy can be reduced. At high rates, pulse pile-up effect can make peak amplitudes from gamma rays become considerably larger than any individual neutron pulse, therefore distorting the rejection system (Knoll, 2010; Kouzes et al., 2010).

For some other systems based on the peak amplitude to discriminate signals (e.g., those from alpha and beta emissions in proportional counters), the same pulse pile-up effect due to high levels of radiation can alter peak amplitudes and reduce the effectiveness of the crosstalk or spill over corrections that account for the discrimination of signals and their correct assignment. All these signal discrimination problems may lead to problems related to the efficiency calibration (Knoll, 2010).

High radiation levels also lead to deterioration of detection performance and to a high decrease lifetime of detectors themselves and also of their associated electronics. Exposure over long periods to high levels of radiation can produce damaging chemical reactions in gas detectors, or cause crystal defects in the structure of the detectors (Tsoulfanidis and Landsberger, 2015). For example, in the case of BF3 (Boron Trifluoride Neutron) detectors, at very high gamma rates, chemical changes can occur in the sensitive gas volume due to molecular disassociation, altering the pulse height spectra coming from neutron-induced events. In some extreme cases, these chemical changes can result in permanent damage to the detector. (Knoll, 2010).

In semiconductor detectors and particularly in High Purity Germanium (HPGe) detectors, high levels of neutrons can produce damage on the crystal lattice by displacing atoms. Effects on HPGe are more pronounced compared to thinnest silicon detectors, as they usually have large volume and long charge collection paths (Ahmed, 2007). It must be mentioned that some of the new developed detectors have high resistance to radiation damage (Knoll, 2010).

Scintillators performance can also be affected by high radiation level environments. Radiation damage causes degradation in the scintillation output of plastics and some inorganic scintillators also worsen after exposure to severe radiation fluxes (Knoll, 2010). In the case of the avalanche photodiode, the damage mechanism is the same as in semiconductor detectors.

High radiation levels may also affect the performance of electronic components of the detectors. Changes start taking place inside the device well before it reaches the point of failure. X/gamma rays generally interact with matter by ejecting electrons mainly via photoelectric or scattering (Compton) effects – at least in the energy range below one MeV. They do not affect the crystal structure or atomic order of the detector material, but they produce a large number of free electrons, and of course positively charged ions (or holes). If the material is conductive, the electrons quickly recombine, and the equilibrium in the material is restored. However, if the material is an insulator, the most energetic electrons often get ejected leaving behind a permanent positive charge. Integrated circuits rely on one or more insulating or dielectric layers to separate conductors and help control electric fields inside the device. Charge build-up in these layers directly modifies the underlying electric fields, and therefore the charge transport properties of the silicon. In a CCD this means that the charge transfer becomes inefficient and the device quickly stops working. In a CMOS transistor it means that the threshold voltage of the transistor slowly shifts, until the device is either always on or completely closed off. Digital devices, as well as carefully designed analog devices, are able to tolerate moderate amounts of threshold voltage shifts, enabling them to continue to function normally until the transistors stop working and the device definitively fails (Hopkinson and Mohammadzadeh, 2004).

Dead-time losses are well-recognized drawbacks in counting and spectrometry systems, in-situations where there are high radiation levels with their associated high counting rates. Losses up to several per cent may occur due to the electronic dead time of the system. Some detectors have very low associated dead time, like organic scintillators but Geiger-Müller has the largest one (Knoll, 2010; Tsoulfanidis and Landsberger, 2015). Several hardware and software methods are available to reduce or to correct for electronic dead-time in certain circumstances, but they shall be considered in advance when undertaking the suitable selection of detection systems.

Background correction issue is also altered in high radiation level environments. In the case of gamma rays, the fact is that high radiation levels may imply high levels of counts in some energy channels of spectrometry systems under the peaks corresponding to the analysed source. Interfering radiation can be observed as a result of the interaction of primary gamma rays with the structural and shielding materials around the detector, through processes like Compton scattering, secondary annihilation photons through pair production and characteristic X-rays from photoelectric effect. This provokes a high level of background along the whole spectrum that can prevent the detection of some peaks from the analysed source with lower count rates, depending on the resolution of the spectrometry system. This effect can be expected to increase with the active volume of the detector. In some cases, high levels of radiation from neutrons can create some activation reactions in the detector, generating peaks from their gamma rays in the spectra (Baginova et al., 2018) that may cause interference and increase the background.

Background from high radiation levels usually needs development of specific characterization gears to reduce it, such as high efficiency collimators or background signal compensation. The use of collimators, due to their volume and weight, may limit the way of accessing the measurement point, creating accessibility constraints, which are considered later. In some situations of high radiation levels, if possible, alternative access to the point under investigation may be considered as a way to minimize its influence. After measurement, post data treatment may also be necessary to ensure the correct source distribution assessment of a local area in a high dose rate background.

If high dose rates cause problems for human intervention, alternative and special means of measurement techniques must be selected to account for radiation protection concerns for technicians. Among this special equipment, telescopic radiation meters, use of robots, special lift gears or unmanned aerial vehicles can be found available (NEA, 2013).

2.2.1.2. Contamination constraints. Radioactively contaminated materials arise from the decommissioning of all nuclear facilities and are due to the deposition of some radioactive materials transported during the operation of the facilities. Contamination constraints have led to the development of particular intervention means (robots, leak tight uniform, etc. (NEA, 2013)) which can complicate in-situ measurements, not only because of contamination background, but also as a consequence of the material confinement of the electronics.

Special care needs to be taken when there is a minimal possibility of contamination of the detector. The solution is achieved through confinement of the detector and its electronics with a sufficient guarantee.

However, this way of protecting from contamination can complicate in-situ measurements as it can cause heat damage to electronics and/or produce detection variation of energy spectrum due to the modification of the temperature of the electronics. This is the case for scintillation detectors, leading to problems related to an adequate energy and FWHM calibration (Ahmed, 2007).

This protection can also produce radiation attenuation, important in the case of alpha and beta radiation, leading to problems related to an adequate efficiency calibration (Knoll, 2010).

Sometimes, if contamination has penetrated into the matrix of the materials investigated, like contamination of porous materials that are not protected by any coating, surface contamination monitors are no longer valid and gamma ray spectrometry must be made and some core samples will also be required for analysis in laboratory to establish the depth profile and the penetration depth.

2.2.2. Materials

Material constraints represent all constraints linked to the physical ones for both human interventions and also those that could lead to dysfunction of detectors and to data misinterpretation. In order to achieve a successful performance of the detector system in different possible scenarios, the detector response should be investigated as a function of different environmental parameters like temperature and humidity. Moreover, the radiological characterization experience with Magnox (Magnox Ltd, 2012), especially on Ion Exchange resin, points out that the radiation transport model which relates measured dose rate to 137Cs activity, lays on distribution assumption (e.g. activity and resin heterogeneity), where large uncertainties can result. Uncertainty also arises in the empirical or mathematical detector calibration, including differences between the assumed and the true source distribution (i.e. differences in geometry, density and chemical composition).

2.2.2.1. Liquid constraint. Immersive or high humidity measurement is very challenging and needs particular technologies and means of intervention. Most often, technologies when this constraint is of particular relevance, consists of developing special mechanical equipment to protect a standard detector, with particular attention to the interface and electrical connection.

The presence of liquids can alter some detector performances in different ways.

Some inorganic crystal detectors (particularly scintillators like NaI (Tl) or CsI(Na)) are hygroscopic, which means they are easily damaged when exposed to moisture in air at normal humidity levels. Therefore, the hermetic seals used in these types of detectors must be protected at all times. Similarly, it is advisable to never expose them to mechanical shock that may crack or chip the seals. Because hydration adopts some colour, it is an excellent absorber of photons in the visible domain and will significantly degrade the scintillation light output and thereby the detection efficiency, so that the detector performance deteriorates. Other scintillators (e.g. Pure CsI, CsI(Tl) and BaF2) that are not hygroscopic can be also damaged by drops of moisture or excessive condensation (Saint-Gobain, 2016).

Spurious pulses of about the same size as those from the real signal can sometimes appear and are due to fluctuations in leakage currents through insulators, particularly under high humidity environments (Knoll, 2010). In DC ion chambers operated with ambient air as the fill gas, the volume recombination rate increases in case of high humidity, altering the ionization current measured (Knoll, 2010).

Because most fluids attenuate particles, interpretation of immersive measurement is also challenging and requires more precision in the measurement position. As stated in the contamination subsection, particle attenuation leads to problems related to an adequate efficiency calibration that must be considered.

2.2.2.2. Air constraint. Air also affects the performance of detectors, especially in the case of soft radiation detection which only lightly penetrates the materials and in the case of temperature sensitive detectors.

Alpha and beta detection is very sensitive to the density of air between the radiation source and the detector. The ionizing radiation becomes more absorbed and scattered when the density of air grows, which depends on pressure and temperature. Readings from ionization cameras and air-kerma monitors, for example, have to be corrected for air density, for any difference between the conditions met during their calibration and those found during measurements (Knoll, 2010). Contamination counter readings are also affected by the properties of the air that the radiation has to travel before entering into them.

As regards temperature, detectors should not be left near heating elements, sun-warmed surfaces, radiator or air conditioners, as they are intended for use in a normal laboratory environment.

Moreover, some detectors for gamma ray spectrometry (particularly scintillators like NaI(Tl) and LaBr3) are highly sensitive to temperature changes (IAEA, 2017). The photomultiplier is sensitive to temperature changes, as well as to stray magnetic fields. Silicon and avalanche photodiodes are also prevented in operations at elevated temperatures (Knoll, 2010). HPGe detectors are unaffected by changes in ambient temperature or magnetic field. However, temperature also affects electronics associated to these detectors, and can cause deviation of measurement on the energy range of interest. This can lead to large uncertainties or misinterpretation of in-situ measurements. When it is possible, one of the solutions consists in performing measurements in a constant temperature environment (for example, if the temperature varies along the day, measurements can be done only every morning), or pay special attention to in-situ calibration. In a last resort, a temperature compensation system, based on stabilization schemes, can also be implemented on detectors, for energy calibrations compensating gain adjustments by other electronic means.

2.2.2.3. Consistency constraint. Good knowledge of the materials to be characterised is essential for the success of the in-situ investigation. In most cases, this constraint significantly affects the data interpretation after measurement more than the in-situ equipment. Additionally, the type of materials being analysed during radiological characterization sometimes hinders a good performance of this characterization.

Regarding material data, in the case of gamma spectrometry, in most cases, some modelling of source distribution and the scene around it, as a way to calculate transfer functions, using mathematical and geometrical analysis, is needed. When structures or systems are complex, the production of accurate models is hard. Beyond the physical properties, involved in the interactions between radiation and materials, and affecting the measurements, some other factors could be noticed, highlighting the necessity of good material knowledge (IAEA, 2003).

While radiological characterization is performed through gamma spectrometry and the use of Monte Carlo techniques for modelling, certain assumptions about the distribution of the radioactivity source in the material analysed must be made that might be based on previous information about the site. Very often, it is assumed that the activity concentration in the material is uniformly distributed across a surface, or that it is homogenous throughout the material from which radiations reach the detector. Some sampling is also required (in particular, core samples) to determine the depth profile and the maximum penetration depth. The source distribution may be approximated by uniform distribution as a first approach in some cases when an approximate estimation of the specific activity concentration (in terms of Bq/g or Bq/m^3) of an extended source is required. In other cases the assumption of a surface source (limited only by the shielding afforded by passage of radiation through air) it is more advisable and very often an exponentially decreasing function that relates the activity concentration to depth is assumed. It must be considered that the mixing of the source with the materials or small undulations in the surface will greatly reduce the radiation flux arriving at the detector in comparison with a theoretical estimate (IAEA, 1998b).

In other cases, for example, direct measurements of alpha-emitting and beta-emitting radionuclides from porous (e.g. wood) and volumetric (e.g., soil, water) materials are hardly possible as they are generally performed by placing the detector on or near the surface to be measured and only particles from the surface are recorded. Thus, these measurements are generally restricted to relativity smooth, impermeable surfaces such as concrete, metal, or drywall where the activity is present as surface contamination. However, special instrument such as the long range alpha detector, large area gas-flow proportional counter or arrays of beta scintillators have been developed to measure the concentration in soil under certain conditions.

NEA (2013) points out that radiological protection coating can represent an obstacle for radiological characterization. The use of protective coating on metallic and building surfaces against contamination is effective for easy decontamination during the operational phase for radiation protection purposes. However, it is often found to be an obstacle for radiological characterization: in many cases this coating has been refurbished by applying a new layer on top of existing ones without full decontamination of the lower layer, which is acceptable from the point of view of radiation protection for the personnel. Multiple layers shall, however, render measurements that have been carried out on the topmost layer with contamination measurement devices useless, as such measurements do not detect activity in greater depths. In cases where multiple layers are discovered only afterwards, extensive re-investigation or reliance on samples shall be needed. Similar considerations apply to building surfaces where the penetration depth has been incorrectly determined.

According to the NEA (2013), the use of certain decontamination techniques may lead to changes in nuclide vector, which may affect the planning of the radiological characterization process. In particular, chemical decontamination methods have the potential to selectively reduce the amount of certain elements (e.g. metals) while not or slightly affecting radionuclides (e.g. actinides), thus altering the composition of residual contamination in percentage terms (for example, the percentage of alpha emitters would increase). This would render any characterization aiming at derivation of nuclide vectors prior to the application of the decontamination process useless.

2.2.3. *Accessibility*

The accessibility not only to the site but also to the room or specific place is not always easy when in-situ measurements should be carried out. Thus, during the planning process it is necessary to consider access logistics, including the ability to physically enter the site for any equipment brought. It should also be considered whether there are any overhead or underground utilities, which may impact the investigation. Different aspects related to the accessibility constraint are the shape and size of the area (presence of clutter environment, presence of corridors or tunnels and height) and the case of subsurface investigations.

The constraints of working, such as access configuration in a challenging operational environment, require the use of approaches and experimentation with innovative techniques.

Another aspect to consider is that, depending on the nearby environment around the point where measurements are to be carried out and as the walls surrounding the detector increase the radiation background of the detector through radiation scattering on them, high efficiency collimators and background signal compensation shall be considered. But, the use of collimators increases the accessibility constraint due to their weight and size. (IAEA, 1998b).

2.2.3.1. Configuration constraint. In corridor/tunnels or clutter environments, the lack of distance which impacts on solid angle can modify measurement strategies. To keep the optimum solid angle, it could be necessary to reduce measurement distance. Thus, to measure a same object, it could be necessary to multiply characterization zones.

In the case of using gamma cameras, even though much progress has been made in their technologies, poor angular resolution is still a limitation that makes it impossible to precisely and quickly localize radioactive hotspots that are placed far from a robot by use of a single image (Ardiny et al., 2019).

Regarding accessibility of detectors for some narrow spaces, the telescoping handle of radiation detector allows for greater versatility. Smaller detector heads mounted on flexible tubes for easy head angle adjustment may be selected instead of large volume detectors. Some teleoperated pipe crawler systems were developed to perform visual and radiological investigations of the interior of pipelines (IAEA, 1998a).

Where HPGe detectors are needed, as they operate at cryogenic temperatures, dewar flasks with a certain volume, filled with liquid nitrogen are routinely used. However, newer HPGe with portable electrically-cooled systems can now operate in portable mode with easy access to difficult areas.

Regarding accessibility of equipment for high spaces, logistically special lift gears are needed. In that case, heavy collimators are hardly implementable on lift systems. Moreover, measurements at height require the signal from detector to be recovered to the treatment electronic or computer as well as wireless technologies.

2.2.3.2. Subsurface. The majority of subsurface investigations concern nuclear geophysics, which is an important part of investigations in the decommissioning process. The instruments used for nuclear geophysical measurements commonly occur in basic configurations of sample, source and radiation detector. In all these configurations, the radiation detected for monitoring the geophysical process may be X rays, neutrons, alpha particles or gamma rays. If radionuclide identification is needed, gamma ray spectrometry is usually carried out with either scintillation detectors or high resolution germanium detectors. However, both types of detector are somewhat fragile for in-situ measurement in subsurface. For this reason, more rugged scintillation spectrometers using photodiodes instead of photomultipliers are advisable, although some limitation currently exist to the small sizes of detectors. CdTe or CZT semiconductor spectrometers are available in small sizes and can be used in in-situ down-hole logging operation, but they have significantly poorer resolution than HPGe detectors (Knoll, 2010). In addition, probes cannot be used where the soil is laden with rocks and boulders due to possible probe or pipe breakage.

During in-situ operation, detectors are submitted to all environmental constraints (humidity, temperature, consistency and also natural radioactivity). The difficulty of collimation also requires a particular approach of background irradiation level, for instance led by geostatistical approach. Measurements made where high natural radiation levels are present need significant post-measurement corrections, depending on the energy resolution of the detector chosen.

2.2.4. Other environment hazards

When performing investigations there is a need to consider other environmental hazards that can affect worker safety and so they complicate the characterizations operations and the measurement planning, either by reducing available time of operations or special cleaning operation before intervention, but they can also affect some measurement techniques.

2.2.4.1. Asbestos. As in other parts of industry, nuclear plants were built with asbestos insulation to protect the machinery (such as boilers, pipes and turbines) producing intense amounts of heat. Therefore, asbestos risk still exists and has to be managed from a personal protection point of view. For instance, cutting into asbestos insulation would make fibers airborne, where they could be easily inhaled. Over time, lodged fibers could develop into cancerous tumours or dangerous tissue scarring. If not removed, intervention in asbestos environment requires special tight gear. Thus considering the presence and location of asbestos is particularly important to ensure worker safety and to develop the appropriate work methods. Presence of asbestos does not affect the measurement itself but determines the measurement planning and ways to develop it, like using automated or remotely controlled power tools as asbestos presence can limit the accessibility (Larsson et al., 2013).

2.2.4.2. Chemical hazards. Chemical hazards arise from the composition of the original construction materials, chemicals used in operational processes and chemical spills and incident associated with the facility. According to the NEA (NEA, 2017), important chemical hazards can be reactive metals, volatile organic compounds and other reactive chemical compounds.

Taking this kind of risk into account, it is particularly important for worker safety and can restrict the radioactive characterization possibilities in terms of the measurement planning and ways to develop it, as with asbestos.

The analysis of the measurements done also has to consider the possible presence of chemicals affecting materials under characterization. Understanding the presence and the chemical form of reactive metals such as sodium, magnesium and aluminium can be very important with respect to configuration for which the characterization is planned to be performed. In addition, data interpretation of neutronics measurements is substantially impacted by plutonium/uranium chemical form (UO_2, PuO_2, UF_6, PuF_4, etc.).

Furthermore, the presence of some chemicals also affects the performance of the detectors. Consideration must be given to the fact that very thin detector windows used for alpha and beta surface contamination or for X-ray detection can easily be affected by corrosive chemical compounds. As pointed out before, some scintillation inorganic crystals, like NaI(Tl) or CsI(Na), are hygroscopic. For this reason, contact with strong organic solvents must be avoided, which may dissolve or soften epoxy hermetic seals used in these assemblies to protect the crystal (Saint-Gobain, 2016).

2.2.4.3. Biological hazards. Biological pathogens and chemical toxins properties may also be important in some places, producing inaccessible and hazardous environments, particularly where decommissioning has been deferred. For example, algal growth in ponds or tanks can create organic rich sludge; bird or bat guano leading to the generation of the organic rich and biologically hazardous waste streams (World Nuclear Association, 2019).

Moreover, the presence of gas generating from microbes within packaged waste has the potential to lead to package deformation and/or early loss of package as well as additional risks to workers to be exposed.

Once again, this type of constraint that restricts the accessibility of people determines the measurement planning and the ways to carry it out. Automated or remotely controlled power tools may be helpful as they pose as ideal solutions to overcome these difficulties (Tsitsimpelis et al., 2019).

2.3. Management constraints

Once the technical means of characterization have been defined, these have to be implemented in a global scenario intervention (IAEA, 1998, IAEA, 2007). This scenario is impacted by external constraints associated with resources (human/financial), safety and security rules, as well as the aspects regarding quality control and normative prescriptions (IAEA, 2016). Note that the global scenario can thus influence the technical prescription. For instance, time devoted to measurement can be limited by aspects related to radiation protection, like the exposure dose rate in the environment being measured.

These management constraints, which are very specific for each individual facility, are briefly described in this section.

2.3.1. Resources

Three different types of resources should be considered in the context of radiological characterization for the decommissioning of nuclear installations: staff requirements, financial resources and time.

The NEA (NEA, 2013) describes the selection of strategies for performing in-situ measurements. One of those that influence such operations is staff requirements. Team capabilities are of key importance when carrying out in-situ measurements. People in charge of these measurements must be properly trained, not only with regards to the equipment to be used and its technical specifications, but also in the radiological protection risks and challenges that exist in the area under measurement.

Furthermore, financial resources and, indeed, technical resources have to be well established before attempting any activity of D&D. The D&D plans and associated cost estimates need to be prepared in advance, to ensure that sufficient financial resources are available, although they will evolve during the lifetime of the facility, becoming more detailed towards the end of the nuclear facility's lifetime. They are really important because they undeniably limit the in-situ measurement plans.

Another very limiting resource is linked with the needed time to perform the whole characterization strategy. Nevertheless, appropriate and careful planning of the characterization work may help to avoid all the above mentioned limitations, reducing costs, decreasing the time required to perform jobs and preventing possible delays. As what frequently happens with most projects, cost escalation often arises from very poor planning.

2.3.2. Safety and radiation protection

Safety and radiation protection are typically the most challenging constraints to be overcome. Not only dose limits defined by ICRP (ICRP, 2007) or by international/national (NRC, 2007) regulations should be undertaken; but also other national regulations applying to protection of workers, general public and environment (IAEA, 2001).

The investigation of contaminated sites shall involve site workers to close, and possible prolonged, contact with potentially hazardous materials. Therefore, health and safety should be a fundamental consideration in the design and the selection of in-situ measurement methods. In-situ measurements personnel should be not only suitably trained but also equipped (IAEA, 2006; IAEA, 2008). Planning should prescribe detailed working procedures, including monitoring and dosimetry equipment, protection clothing, identification of access, etc.

A good understanding about the type of radioactive material, on which the radioactive measurement is made, is essential. It allows adaptation of the device used but also the performance of the risk analysis according to the radiological properties. For example, the quantification of fissile mass in equipment by gamma spectrometry has to trigger a criticality risk analysis, because shields used to reduce the background radiation measured, could constitute a reflector for neutrons.

In-situ measurements techniques should be designed in such a way as not to contribute to the further spread of contamination on site, or off site. This is of particular concern when dealing with radioactive contamination. In the case of contaminated areas, it may be necessary to limit their access to only specially trained site workers, and also allowing for a decontamination zone for both the equipment and the personnel.

The safety analysis of the in-situ operation, includes an impact assessment due to the different operations planned and hypothetical accidental situations. In addition, it should underline the types of safety and radiological protection required for the protection of workers, the general public and, of course, the environment.

This analysis may lead to the use of alternative ways to assess the radiological status, like automated and remotely controlled power tools, for example, using robots in the case of hot cells or in highly contaminated areas (Tsitsimpelis et al., 2019).

2.3.3. Security

Regarding security issue, there should be an awareness of safety considerations of installations, the workforce, the local public and the environment during in-situ measurements operations in D&D projects. Setting up adequate security is an important and mandatory issue, as unauthorised invasions or malicious acts such as sabotage, damage, theft, loss or unauthorised use of equipment or installations may happen. Technical security measures include fencing protected areas, access control, security illumination, security management systems and monitoring systems in order to ensure contaminated material is not spread from the site and the public does not have access to the site, thereby ensuring their protection (IAEA, 2016). Thus, to ensure all these security measures more personnel in D&D tasks may be required than during the routine operation of the installation.

Security management systems include information security, workers training and access control. Workers must be suitably trained and qualified to complete the activities assigned to them in the specific area they have to carry out measurements. A training programme should be developed so as to ensure that the workers involved are provided with the necessary level of knowledge and skills to fulfil each task specified in the measurement plan that guarantees overall security. (IAEA, 2006; IAEA, 2008).

Throughout the different phases of any D&D programme the security level changes. Once the fuel, process fluids and operational waste are removed from the site the main radiological and security hazards have disappear and less equipment is needed and areas protected.

2.3.4. Quality assurance and quality control

Any planning of collecting and evaluating in-situ measurement data must be concerned with ensuring the right characterization information that has to be gathered as well as the results and their evaluation are of an appropriate quality. This is a guarantee of meeting the characterization objectives.

This, of course, requires proper equipment selection and its adequate control. Tools, gauges, instruments, together with other measuring and test equipment (including software) used in determining item status, shall be of the proper range, type, accuracy and precision. Almost all of them should be protected from damage or deterioration during handling, maintenance and storage.

Suitable calibration procedures are essential to provide confidence in the measurements. In the time between calibrations, the equipment should also receive a performance check prior to use and periodically during use. When using portable equipment a daily check is recommended when in use. The selection, identification, use, checking and calibration requirements, in addition to checking and calibration frequency of all measuring and test equipment, should be specified. During in-situ measurements, it is advisable to carry out a certain number of repeated measurements as part of the quality control.

The responsibility for measuring and test equipment controls should be defined and included in the process of characterization as well as maintaining the records of calibration and checking results. Some information could be obtained mainly from MARSSIM (MARSSIM, 2000) but also from ISO standard 17025 (ISO, 2017) and from MARLAP (MARLAP, 2004) procedures.

Establishing and implementing a quality plan is the safest mean to ensure all these aspects are met or, at least, a specific procedure that defines how measuring equipment is calibrated, the frequency of calibration, a suitable identification of calibration status, its detailed maintenance operations (including scheduled services and checks) and, finally, how to protect equipment from damage.

3. Methodology for constrained environments classification

This section describes the methodology followed to obtain a classification and a categorization of the constrained environment present in the different areas existing in nuclear/radioactive installations. This methodology includes the previous identification and classification of the installations that could be involved in in-situ radiological characterization and also of the different areas, which may be contained in these facilities.

In this paper the word “area” is used to describe not only a certain room in the installations but also a specific place (i.e. equipment, building or ducts) inside the facility with similar radiological characteristics and constraints. In this context, it should be considered that an area can be included in different rooms (i.e. a duct) or to be a room (i.e. equipment room); can be small (i.e. office) or high (i.e. reactor cavity) also depending on the facility.

After that, for each constraint category previously identified, a specific table is produced. In these tables, areas are linked to the different installations, and the impact level of the constraint is categorized.

It should be also considered that, depending on the constraint considered, its impact level in a specific area can be variable depending on the different phases of any D&D programme. These phases should be summarized as follows:

- *Initial – Dismantling phase:* The main objectives are estimations of fissile mass quantity or radioactive level of existing waste.
- *Intermediate - Remediation phase:* If consideration on the primary characterization led to a decision to undertake remediation, then the intermediate stage starts and a more detailed characterization would be necessary to facilitate decisions to be made about the appropriate remediation method.
- *Final – Release phase:* It occurs only after the completion of the dismantling work and the justification for reaching the end state targeted by the operator. During this final characterization stage, the objectives are often to determine residual contamination or underground contamination. It enables obtaining the lifting of the regulatory controls to which a basic nuclear installation is subjected to. Often, in this phase, the number of in-situ measurements strongly decreases and the major part of the characterization is focused on the in-lab analysis.

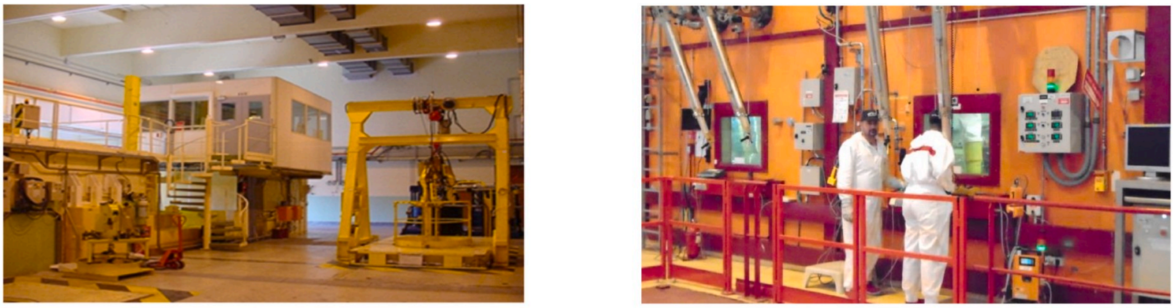
Table 1
Type of areas considered.

Outdoor	Office	Personal airlock	Grid hot cells	Secondary cooling system
Foundations-Structural Materials and apron	Service room	Truck bay	Waste hot cells	Tanks
Traffic Corridor	Equipment room	Hot cells	Process hot cells	Spent fuel pit
Technical galleries	Peripheral galleries	Hot cells front area	Process ducts	Refueling cavity
Waste storage	Process control room	Hot cells back area	Ventilation ducts	Reactor cavity
Technical area	Decontamination room	Cleaning hot cells	Chimney	
Changing room	Equipment airlock	Storage hot cells	Reactor coolant system	

3.1. *Type of installation*

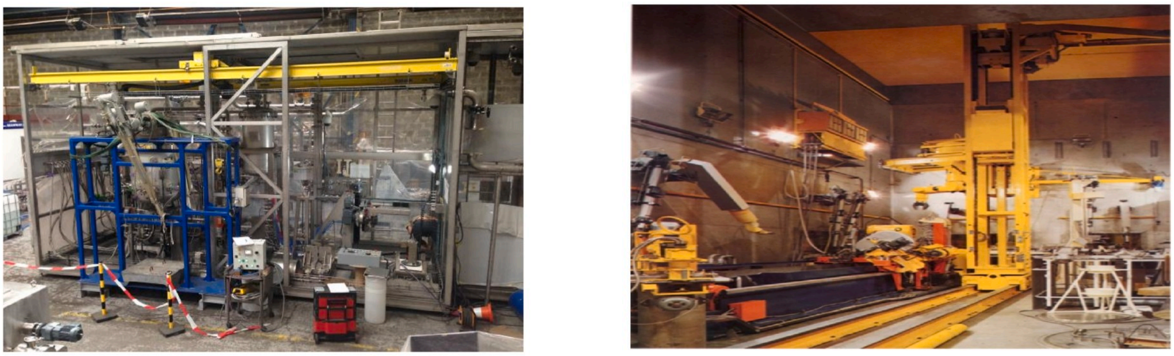
There are a great number of installations with different possibilities of use (exploitation, storage, maintenance) than can be involved in D&D scenarios requiring radiological characterization by in-situ measurements that they can be classified in four big groups, as follows:

- Reactors:
  - power generating reactors,
  - research reactors,
  - training reactors,
- Plants:
  - uranium mining and milling plants,
  - uranium enrichment plants,
  - uranium converting plants,
  - fuel fabricating plants,
  - spent fuel reprocessing plants,
  - other fuel facilities,
  - radioisotope production plants,



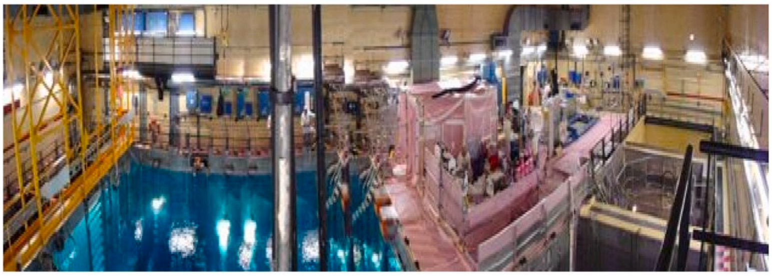
Example of equipment room : waste compaction process for ILW-LL waste

Example of hot cells front area : hot cells for research and development activities on fuel.



Example of decontamination room: contaminated waste treatment plant

Example of decontamination room: waste treatment hot cell



Example of refueling cavity

Fig. 3. Pictures of some areas according to Table 1.

Table 2
Classification of areas according to the radioactivity constraint category.

Areas	Type of installation	Phase	Contamination	Gamma Dose rate	Neutron Dose rate	Radiation flux
Outdoor	All	Final	very low	no	no	no
Foundations-Structural Materials and apron	All	Final	very low	no	no	no
Traffic Corridor	All	Intermediate Final	very low	no	no	no
Technical galleries	All	Intermediate Final	very low	no	no	no
Waste storage	All	Initial	very low	high	high	no
Technical area	All	Final	very low	no	no	no
Changing room	All	Final	very low	no	no	no
Office	All	Final	very low	no	no	no
Service room	All	Final	very low	no	no	no
Equipment room	Reactors Plants Accelerators	Intermediate Final	low	low	low	low
Peripheral galleries	Reactors Plants Accelerators	Intermediate Final	low	low	low	low
Process control room	Reactors Plants Accelerators	Final	no	no	no	no
Decontamination room	Reactors Plants Accelerators	Initial Intermediate Final	high	low	low	no
Equipment airlock	Reactors Plants	Intermediate Final	low	no	no	no
Personal airlock	Reactors Plants	Intermediate Final	low	no	no	no
Truck bay	Reactors Plants Accelerators	Final	low	no	no	no
Hot Cells	Reactors Plants Accelerators	Initial Intermediate	very high	very high	very high	no
Hot Cells	Reactors Plants Accelerators	Final	high	high	nigh	no
Hot Cells front area	Reactors Plants Accelerators	Intermediate Final	low	no	no	no
Hot Cells back area	Reactors Plants Accelerators	Initial Intermediate Final	high	high	high	no
Cleaning Hot Cells	Reactors Plants	Initial Intermediate Final	high	low	low	no
Storage Hot cells	Reactors Plants	Intermediate	low	very high	very high	no
Storage Hot cells	Reactors Plants	Final	low	high	high	no
Grid Hot cells	Reactors Plants	Initial Intermediate Final	high	low	low	no
Waste Hot cells	Plants Accelerators	Initial Intermediate	low	very high	very high	no
Waste Hot cells	Plants Accelerators	Final	low	high	high	no
Process Hot cells	Reactors Plants	Initial Intermediate	very high	very high	very high	no
Process Hot cells	Reactors Plants	Final	high	high	high	no
Process ducts	Reactors Plants	Initial Intermediate	very high	very high	very high	no
Process ducts	Reactors Plants	Final	high	high	high	no
Ventilation ducts	All	Intermediate	low	no	No	no
Chimney	All	Final	low	no	No	no
Reactor coolant system	Reactors	Initial Intermediate	very high	very high	very high	no
Reactor coolant system	Reactors	Final	high	high	high	no
Secondary cooling system	Reactors	Intermediate	low	no	no	no
Tanks	All	Initial	very high	very high	very high	no
Tanks	All	Intermediate	high	high	high	no
Spent fuel pit	Reactors Plant	Initial Intermediate	very high	very high	very high	no

(*continued on next page*)

Table 2 (*continued*)

Areas	Type of installation	Phase	Contamination	Gamma Dose rate	Neutron Dose rate	Radiation flux
Spent fuel pit	Reactors Plant	Final	high	high	high	no
Refueling cavity	Reactors Plant	Initial Intermediate	very high	very high	very high	no
Refueling cavity	Reactors Plant	Final	high	high	high	no
Reactor cavity	Reactors	Initial Intermediate	very high	very high	very high	high
Reactor cavity	Reactors	Final	high	high	high	high

  - nuclear maintenance workshop,
  - storage facilities,
  - waste management facilities,
- Accelerators,
- Other installations for industrial or medical applications:
  - irradiation facilities,
  - testing laboratories,
  - research laboratories.

3.2. *Type of areas*

Each one of the above mentioned installations have different areas where the various constraints can affect the choice of the equipment to be used to carry out in-situ measurements. These areas can be included under the general terms shown in Table 1.

Of course, not all these areas exist in all facilities and neither this relation claims to be exhaustive, but the most common ones are included.

Fig. 3 shows some different examples of the definition of “area” in this paper, having different size and structure.

The classification of the constrained environments has been done linking the installations and areas inside them with the different constraints mentioned before and can be found in different tables shown in the following section.

4. Classification

Several tables (Table 2–5) have been generated one for each constraint category previously identified (Radioactivity, Materials, Accessibility, Environment). Each table includes for each area listed in Table 1, the installation(s) concerned, the decommissioning phase(s) when the constraint category has to be considered and the impact expected for each one of the specific constraints considered included in this category. When for an area in all the installations the impact of the entire specific constrains do not exist, the line (register) is deleted from the Table to only provide in the Tables relevant data for the constraint category considered. In fact, the whole set of installations and areas do not appear in every table but only those relevant for the constraint category considered.

The presence of a particular constraint is quoted in a conservative approach and is pointed out with an x. However, in the case of radioactivity constraints, they are quoted different level of constraint mainly considered in decommissioning process (from very low to very high). Of course, for a given area, radioactivity constraint level decreases during the decommissioning process, from initial to intermediate and final phases.

Not only theoretical knowledge, but also practical experience have been used to develop these Tables.

As expected, radioactivity is the constraint category that is mostly present in all areas at all time. There are many areas in which access is constrained primarily due to the risks and measurement problems caused by high levels of radiation exposure. However, the radioactive dose rates and contamination levels change along the decommissioning process; irradiation constraints are mainly present during the decommissioning process and pre-dismantling phase and they should decrease in the remediation and final phase. Their levels are higher in reactors and plants, mainly in areas related to fuels and radioactive sources. In these same areas and depending on the form of the radioactive sources, the contamination constraint is also present in a large extent. In the final phase of the D&D process the radioactive constraint decreases its relevance but contamination can be found even in offices or service areas.

These high levels affect the choice of the in-situ equipment, from sealed equipment, to prevent its contamination, to the use of telescopic devices or robots to prevent the radiation exposure to the workers and the appropriate selection of the gamma or neutron detector device depending on the particle field present in the area under measurement, as explained in section 2.2.1.

Regarding materials constraints, attention should be paid to the fact that different and complicated ranges of ambient conditions of temperature, humidity and pressure or aqueous conditions can be found in different locations from almost every installation, as well as constraints related to fact of having radioactivity distributed in concrete or metal. However, the occurrence of ground material is only observed in outdoor situations. The impact of these constraints in the selection of the in-situ equipment is completely different; the consistency constraints mainly affect workers safety and measurement data interpretation. However, liquid and air constraints only have a strong effect on the equipment to be used, from strongly sealed detectors and electronics to the careful selection of detectors depending to their response to temperature and air density changes and also their resistance to the humidity conditions. Attention should be also paid to the response of the electronics and interfaces to these changes. See section 2.2.2. for more details.

Other environmental hazards due to the presence of toxic atmospheres is a constraint that is not frequently found. Asbestos is restricted to some technical and peripheral galleries or some ducts and do not directly affect the equipment to be used for in-situ measurements. The presence of chemical and biological hazards is found in all D&D phases practically around hot cells, waste storage facilities and in some ducts; biological hazards do not directly affect the equipment to be used for in-situ measurements but the chemicals ones do and the hygroscopic characteristics of some devices and the endurance of the detector window before choosing the equipment should be considered. See section 2.2.4. Of course, to prevent the impact of these hazards in the workers, telescopic or robot devices could be used.

Accessibility constraints also appear in almost all the areas at all time and D&D phases. Configuration constraint can be found in different areas in almost all installations and they strongly affect the selection of the equipment needed to carry out the in–situ measurements, see section 2.2.3. for more details. In the case of subsurface constraints it should be considered that the access to subsurface distributions is usually made not in the initial phase, when detailed characterization is necessary, as subsurface contaminants are commonly present in structural materials that adsorb radionuclides or are activated. So this accessibility constraint related to subsurface is easily found in substructures, foundations and structural materials, in some galleries and in different outdoor characterization, mainly in the final phase. They also strongly affect the selection of the in-situ equipment; in the case of gamma

Table 3
Classification of areas according to the materials constraint category.

			Air			Liquid		Consistency		
Areas	Type of installation	Phase	Pressure	Temperature	Flow	Immersive	Humidity	Metal	Concrete	Ground
Outdoor	All	Final		x	x					x
Foundations-Structural Materials and apron	All	Final							x	
Traffic Corridor	All	Intermediate Final							x	
Technical galleries	All	Intermediate Final							x	
Waste storage	All	Initial		x				x		
Technical area	All	Final							x	
Changing room	All	Final							x	
Office	All	Final							x	
Service room	All	Final							x	
Equipment room	Reactors Plants Accelerators	Intermediate Final		x				x	x	
Peripheral galleries	Reactors Plants Accelerators	Intermediate Final		x			x		x	
Process control room	Reactors Plants Accelerators	Final							x	
Decontamination room	Reactors Plants Accelerators	Initial Intermediate Final	x	x				x	x	
Equipment airlock	Reactors Plants	Intermediate Final						x	x	
Personal airlock	Reactors Plants	Intermediate Final						x	x	
Truck bay	Reactors Plants Accelerators	Final							x	
Hot Cells	Reactors Plants Accelerators	Initial Intermediate Final	x	x				x	x	
Hot Cells front area	Reactors Plants Accelerators	Intermediate Final						x	x	
Hot Cells back area	Reactors Plants Accelerators	Initial Intermediate Final		x				x	x	
Cleaning Hot Cells	Reactors Plants	Initial Intermediate Final		x			x	x		
Storage Hot cells	Reactors Plants	Intermediate Final		x					x	
Grid Hot cells	Reactors Plants	Initial Intermediate Final					x	x		
Waste Hot cells	Plants Accelerators	Initial Intermediate Final						x		
Process Hot cells	Reactors Plants	Initial Intermediate Final	x	x		x	x	x		
Process ducts	Reactors Plants	Initial	x	x	x	x	x			
Ventilation ducts	All	Intermediate			x		x			
Chimney	All	Final			x			x		
Reactor coolant system	Reactors	Initial	x	x		x		x		
Secondary cooling system	Reactors	Intermediate	x	x		x		x		
Tanks	All	Initial Intermediate	x			x		x		
Spent fuel pit	Reactors Plant	Initial Intermediate Final		x		x		x	x	
Refueling cavity	Reactors Plant	Initial Intermediate Final		x		x		x	x	
Reactor cavity	Reactors	Initial Intermediate Final	x	x		x		x	x	

Table 4
Classification of areas according to the environment constraint category.

			Abestos	Chemical		Organic/biological	
Areas	Type of installation	Phase	Abestos	Reactive metals	Volatile organic compounds	Pathogens	Chemical toxins
Technical galleries	All	Intermediate Final	x				
Waste storage	All	Initial		x		x	x
Technical area	All	Final	x	x	x	x	x
Equipment room	Reactors Plants Accelerators	Intermediate Final		x	x	x	x
Peripheral galleries	Reactors Plants Accelerators	Intermediate Final	x				
Decontamination room	Reactors Plants Accelerators	Initial Intermediate Final		x			
Truck bay	Reactors Plants Accelerators	Final	x				
Hot Cells	Reactors Plants Accelerators	Initial Intermediate Final		x	x	x	x
Hot Cells front area	Reactors Plants Accelerators	Intermediate Final				x	x
Hot Cells back area	Reactors Plants Accelerators	Initial Intermediate Final		x	x	x	x
Cleaning Hot Cells	Reactors Plants	Initial Intermediate Final		x	x	x	x
Storage Hot cells	Reactors Plants	Intermediate Final		x	x	x	x
Grid Hot cells	Reactors Plants	Initial Intermediate Final		x	x	x	x
Waste Hot cells	Plants Accelerators	Initial Intermediate Final		x	x	x	x
Process Hot cells	Reactors Plants	Initial Intermediate Final		x	x	x	x
Process ducts	Reactors Plants	Initial	x	x	x	x	x
Ventilation ducts	All	Intermediate	x				
Tanks	All	Initial Intermediate				x	x

spectrometers the most rugged have poor energy resolution and those with better resolutions are more fragile; in any case a strict sealing of the equipment is required.

Analysing these Tables from the point of view of the areas, it can be concluded that the most challenging areas for in-situ measurement are hot process ones (Hot cells, Ducts, Pit, Tanks), and reactors primary environment (Coolant system, fuel pit, refueling cavity and of course reactor cavity). Realizations of in-situ-measurements in these areas are not only subjected to high irradiation and contamination constraints but also to other constraints such as temperature or immersive measurement. In addition, the lack of familiarity of interventions in these areas, the complex phenomenon that can occur (i.e. presence of alpha emitters, criticality constraints, phenomenon of activation), make the intervention process very challenging.

On the contrary, all peripheral areas (i.e. technical galleries, process control room, service room) are not considered as areas of high level constraint for in-situ measurement. However, constraint of accessibility of these areas must be particularly considered while preparing the intervention, because they are not usually designed for facilitating heavy materials access.

A particular approach needs to be deployed concerning outdoor or foundations characterization, because of the major risk of contamination dissemination during investigations operations.

5. Conclusions

Once defined the investigation objectives for radiological characterization of either one particular nuclear site/installation or a specific area inside it, the most suitable investigation methodology, for in-situ measurements, should be defined as well as the proper equipment and protocols to be used. The selection of that in situ investigation methodology depends on various challenges to be overcome or constraints to be taken into account.

In this paper, the decision process that goes from the definition of the characterization objectives to the definition of the in situ investigation method (in-situ equipment, methods and protocol) has been analysed considering different challenges belonging to the system definition and to the intervention definition.

The main focus of this paper is the system definition that is related to technical problems or environmental constraints that challenge the choice of the equipment; inside it different categories of constraints are defined: radioactivity, materials, accessibility and other non-radiation environmental hazards. The various characteristics that can be included in each one of these categories are defined and described and their impact in the detection systems is briefly summarized.

Once the different environmental constraints and their challenges are analysed, a classification and categorization of different constrained

Table 5
Classification of areas according to the accessibility constraint category.

Areas	Type of installation	Phase	Tunnel	Height	Clutter	Subsurface
Outdoor	All	Final				x
Foundations-Structural Materials and apron	All	Final	x		x	x
Traffic Corridor	All	Intermediate Final				x
Technical galleries	All	Intermediate Final	x	x	x	x
Technical area	All	Final		x		
Equipment room	Reactors Plants Accelerators	Intermediate Final		x		
Peripheral galleries	Reactors Plants Accelerators	Intermediate Final	x	x	x	
Truck bay	Reactors Plants Accelerators	Final		x		
Hot Cells	Reactors Plants Accelerators	Initial Intermediate Final			x	
Hot Cells front area	Reactors Plants Accelerators	Intermediate Final		x	x	
Hot Cells back area	Reactors Plants Accelerators	Initial Intermediate Final		x	x	
Cleaning Hot Cells	Reactors Plants	Initial Intermediate Final		x		
Waste Hot cells	Plants Accelerators	Initial Intermediate Final		x		
Process Hot cells	Reactors Plants	Initial Intermediate Final	x	x	x	
Process ducts	Reactors Plants	Initial	x	x	x	
Ventilation ducts	All	Intermediate		x	x	
Chimney	All	Final		x		
Tanks	All	Initial Intermediate	x		x	
Refueling cavity	Reactors Plant	Initial Intermediate Final	x		x	

environments in the D&D process activities has been accomplished by listing the most important installations where in-situ measurements could be accomplished. Reactors, (power generating and research), plants (uranium enrichment, fuel converting, fabricating, spent fuel processing, other fuel facilities, radioelement production, nuclear maintenance workshop, storage facilities, low-level rad-waste facilities); accelerators and other installations (irradiation facilities, testing and research laboratories) have been considered for this classification.

Although only three different possibilities of use of the above mentioned installations exist (exploitation, storage, maintenance), we have considered that each installation is constituted by different areas where the four identified environmental constraints can affect them in different ways. Specifically, we consider that these areas can be grouped into 33 different types shown in Table 1.

Last but not least, the classification has been accomplished producing several tables, one for each constraint, where areas are linked to installations and to the specific properties of the constraints. For each one of these constraints also differences among the various phases of a given D&D programme (Initial –, Dismantling phase; Intermediate - Remediation phase, if needed, and Final – Release phase) have been outlined. In the case of radiological constraint, the impact of it in the different areas has been categorized from very low to very high.

As a general conclusion and as expected, it is in the nuclear power plants where the number of constraints and its categorization are the highest and where the need of well-defined methodologies and in-situ equipment is more challenging.

This study serves to establish the different constrained environments that arise in radiological characterization, through in situ measurements, during nuclear decommissioning and dismantling operations and the way they are affected and challenged by the constraints, so the next step would be an analysis of suitability of existing methodologies for in-situ measurements in all the constrained environment described here.

CRediT authorship contribution statement

Frederic Aspe: Conceptualization, Methodology, Writing - review & editing. **Raquel Idoeta:** Conceptualization, Methodology, Writing - review & editing. **Gregoire Auge:** Conceptualization, Methodology, Writing - review & editing. **Margarita Herranz:** Conceptualization, Methodology, Writing - review & editing.

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Appendix A. Supplementary data

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