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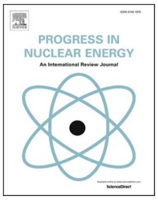

Recommendations for the selection of in situ measurement techniques for radiological characterization in nuclear/radiological installations under decommissioning and dismantling processes

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ABSTRACT

In this paper, in-situ radiological characterisation by means of non-destructive techniques is studied and analysed in the context of the different constrained environments (identified as radioactivity, materials, accessibility and other hazards) that may be encountered in the nuclear facilities undergoing decommissioning and dismantling. As a complement to a previous paper (Aspe et al., 2020), the present one gives a global guidance to assist with the decision making process regarding the selection of in-situ measurement techniques that could be applied in such constrained environments.

In addition, from the definition of the investigation objectives, and for each one of the most common in-situ measurement techniques, a brief description is given about the impact of the above constraints and how to integrate them onto the system definition, including the experimental design, the mechanical integration and the data management, to properly define the best radiological characterization methodology.

Moreover, complementing this general view, all the phases – from initial to final – of a D&D programme were taken into account to provide basic recommendations, together with some particular dispositions, for the appropriate implementation of the chosen instruments.

Strengths and weaknesses of the common detectors used for the different in-situ measurement techniques, as well as their recommended applications in nuclear facilities are also outlined.

1. Introduction

Decommissioning and dismantling (D&D) of nuclear facilities (power reactors, fuel cycle plants, research or medical accelerators, etc.), until their remediation and clearance, is a global international industrial challenge for the XXIth century. The strategy to be followed is specific to each country depending, amongst other considerations, upon the facility's characteristics, own regulatory policies, environmental protection and radioactive waste management (Laraia and Laraia, 2012). However, any D&D programme will result in a volume of waste materials that should be classified as radioactive or not.

Usually, after a first stage of historical collection and functional data, radiological inventory is established and consolidated with preliminary in-situ measurements, by means of non-destructive assay (NDA) techniques (Amgarou and Herranz, 2021). Undoubtedly, this constitutes a complex issue considering the wide variety of structures and equipment involved, so that their proper radiological characterization becomes a necessary prerequisite for a successful quantification of the different contaminated materials (IAEA, 1998). Such a radiological characterization is also needed during the dismantling activities to evaluate the efficacy of the applied decontamination procedures and to certify the final quality of the produced waste drums. Of course, in-situ NDA measurements do not always provide sufficiently complete radiological data and, in most cases, they should be complemented with laboratory analysis of representative samples.

However, the vast majority of nuclear facilities under D&D offer many constrained environments, due to their limited accessibility, the presence of high radiation levels, or even the extreme ambient conditions of the room where in-situ measurements are to be carried out. Classification and categorization of all these possible constrained

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environments has been already done in a previous paper (Aspe et al., 2020); whereas in this one, the ability of the existing equipment to be used in each one of them is analysed.

It is explained in Aspe et al. (2020) that for each facility subject to a D&D programme, the investigation objectives of the radiological characterization and, hence, of in-situ measurements, are given by project/authorities. Moreover, the description and historical information of the site are necessary for complementing the defined investigation objectives to accomplish the decision process (NEA, 2013).

Based on this preliminary information and the analysis of the prevailing environmental constraints, it is possible to determine the exact locations for the necessary in-situ measurements, 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. Such a process, which is known as "intervention definition", although it can condition the final decision about the in-situ measurement technologies, is outside the focus of this paper.

In this context, the present paper gives a global guidance to assist with the decision making process regarding the selection of the best in-situ measurement techniques that could be applied in constrained environments. For the sake of simplicity, these constrained environments are hereafter referred to as "constraints" and they are identified as radioactivity, materials, accessibility, and other hazards (Aspe et al., 2020). They may individually affect each in-situ measurement technique to be used and also the interpretation of the results obtained.

Some latest cutting-edge technologies, like laser induced breakdown spectroscopy or LIBS (Radziemski and Cremers, 2006) and muon tomography (Jonkmans et al., 2013) are not discussed here as, at least up till now, they have only been developed by a few research laboratories and they are not commonly used in the nuclear industry.

Fig. 1 shows a simplified flow diagram illustrating the key practices and arrangements that we have considered for the deployment of appropriate in-situ measurement techniques in constrained environments. All the recommendations given in the present document should not be interpreted as absolute or strict requirements. The reader needs to remember that these recommendations should not be taken literally when applied to their own specific case studies.

In what follows, basic recommendations are initially provided for the choice of in-situ measurement techniques for each phase during the whole D&D programme.

Afterwards, regarding the proposed in-situ measurement techniques, the incidence on their overall performance of the different constrained environments is highlighted together with an explanation of the three

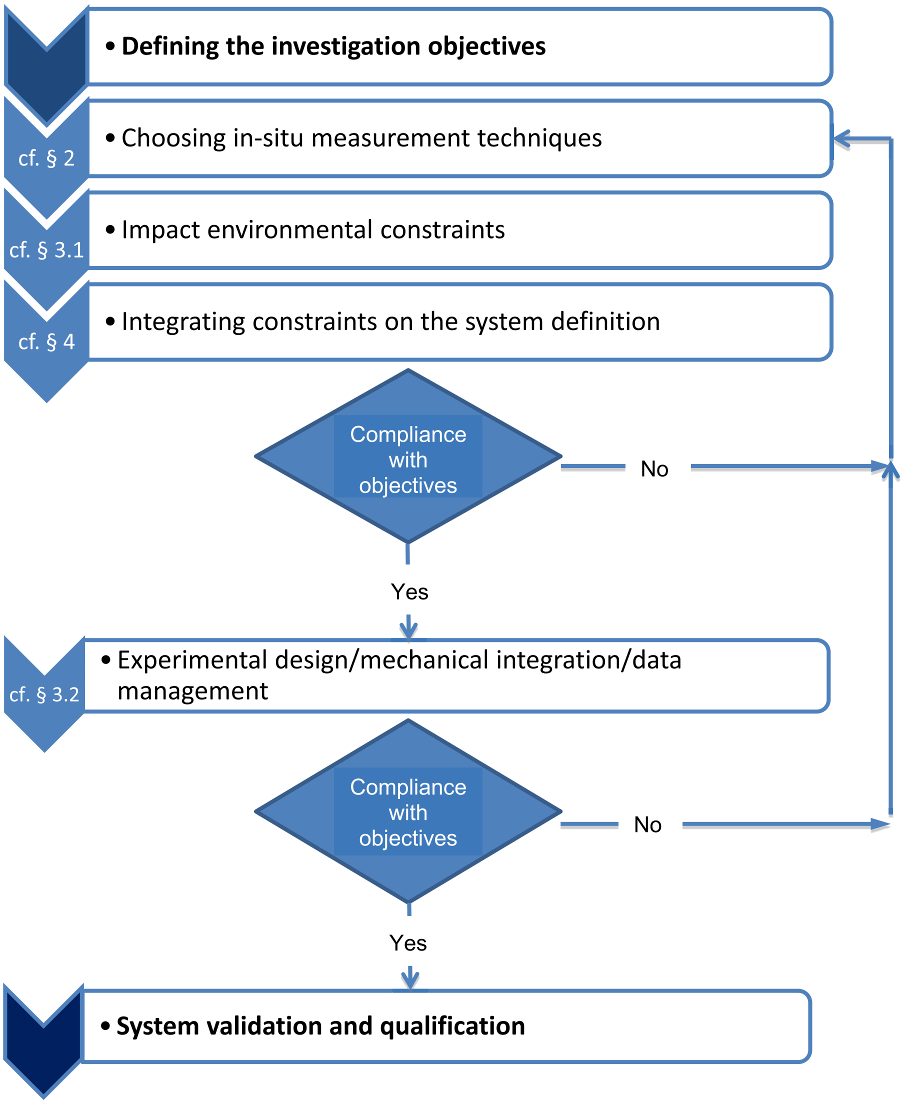

Fig. 1. Simplified flow diagram illustrating the minimum arrangements for the deployment of appropriate in-situ measurement techniques for each constrained environment.

design principles of system engineering that must be envisaged to integrate these constraints on the definition of the investigation methodology.

Finally, some particular dispositions are formulated for the appropriate implementation of the chosen instruments, as well as further technical issues which the investigation methodology has to consider, in regard to every nuclear facility room or area where each of the major constraints have been identified.

2. Role of in-situ measurements in a D&D programme

In-situ measurements together with laboratory analysis of representative samples are of vital importance throughout the different phases of a D&D programme. It must be noted that, for a specific area, the existing constraints (Aspe et al., 2020) could change during the progress of these phases and then, the methodologies to be used for the corresponding in-situ characterization would have to be adapted accordingly. For example, most of the irradiation constraints are normally present at the beginning and should decrease during the remediation phase until they have almost disappeared by the end.

2.1. Initial – dismantling phase

One of the main objectives in the initial phase of any D&D programme is the estimation of the fissile mass quantity and/or the radioactive level of existing waste. For this purpose, in-situ radiation measurements, especially dose rate and total gamma strengthened with some gamma-ray spectrometry or neutron assay, are needed. Table 1 outlines the different studies carried out during this phase as well as their associated investigation objectives and recommended NDA techniques.

2.2. Intermediate - remediation phase

If consideration of the primary characterization leads to a decision to undertake remediation, the intermediate phase of the ongoing D&D programme must start immediately. During this phase, a more detailed characterization would be necessary to facilitate decisions to be made about the appropriate intervention means, and then on further details or steps of that action. At this stage, some in-situ measurements, like dose rate and total gamma, are needed to allow the full engineering design of the remediation phase. Table 2 resumes the recommended in-situ measurement techniques for each types of radioactivity during the intermediate or remediation phase of a D&D programme.

2.3. Final – release phase

The final D&D phase occurs only after the completion of all remediation activities and the justification for reaching the end state targeted by the operator. This means that both the considered site and its near environment are fully cleaned up to a predetermined endpoint (unrestricted release or further reuse), from any dangerous and radioactive substance. Therefore, the final objective regarding radiological characterization must be the evaluation of the possible presence of residual radioactivity in the remaining areas and ancillary buildings as well as underground contamination. The ultimate aim of this objective is to obtain the lifting of the regulatory controls to which a basic nuclear installation is subjected to. Often, at this stage, the number of in-situ measurements (as recommended in Table 2) strongly decreases and the major part of the characterization is focused on the in-lab analysis, which provide the lowest detection limits and the best efficiency.

Table 1
Different studies carried out during the initial phase of a D&D programme as well as their associated investigation objectives and recommended in-situ NDA techniques.

Needs	Objective of the investigation	Recommended in-situ NDA technique
Safety studies	Criticality control	Gamma-ray spectrometry Neutron measurements
Waste studies	Verification of radiological spectrum Radioactive level of existing waste	Surface contamination measurements Gamma-ray spectrometry Neutron measurements
Radioprotection studies	Site cartography	Environmental radiation measurements Surface contamination measurements
Dismantling scenario studies	Localization of nuclear material	Radiation cameras

Table 2
Recommended in-situ NDA techniques for each type of radioactivity during both the intermediate and final phases of a D&D programme.

Type of radioactivity	Recommended in-situ NDA technique
Non contaminated surface	None
Contaminated surface by “dry” contamination (dust, aerosol)	Surface contamination measurements
Contaminated surface by “liquid” contamination with no “deep penetration”	Surface contamination measurements Environmental radiation measurements Gamma-ray spectrometry
Contaminated surface by “liquid” contamination with deep structural penetration	
Activated inner walls	Gamma-ray spectrometry

3. Integrating constraints on the system definition

3.1. Impact of environmental constraints

Once the existing impacts are defined for a specific room, they should be integrated in the system definition process. Table 3 gives a broad indication on the incidence of the major environmental constraints on the existing measurement equipment based on experience gained and lessons learnt from past D&D activities. The different levels of all potential incidences are classified as follows:

- NA when it is just not applicable
- 3 for high incidence
- 2 for intermediate incidence
- 1 for low incidence
- 0 for no or unknown incidence

Section 4 formulates some recommendations that need to be taken into account for the appropriate choice of the instruments, as well as further technical issues the investigation methodology has to consider, in regard to every nuclear facility area where each of the major constraints have been identified. Although there might be the possible presence of other hazards, like chemical and/or biological ones which basically only affect the human intervention scenarios, some recommendations regarding this subject are also given in this section.

3.2. Conception methodology

Though independently organized, the three design principles of system engineering as illustrated in Fig. 2 are to be integrated into a global design process of in-situ measurements. Of all the existing possibilities, only those that meet the identified field needs and requirements should be chosen.

3.2.1. Experimental design

Experimental design is firstly based on the characterization

Table 3
Impact of the major environmental constraints on in-situ measurement techniques.

Environmental constraint NDA technique	*Radiation*				*Materials*							*Accessibility*			
					Air			Liquid		Others					
	Contamination	Gamma Dose rate	Neutron Dose rate	Radiation flux	Pressure	Temperature	Flow	Immersive	humidity	Metal	Concrete	Corridors/ Tunnel	Height	Clutter	Subsurface
Environmental radiation measurements	1	3	3	3	0[a]	0[a]	0	NA	0[a]	1	2	1	0	2	3
Surface contamination measurements	3	1	1	1	0	0	1	NA	2	1	2	0	0	2	NA
Gamma-ray spectrometry	1	3	1	2	0	1	0	1	2	1	1	2	2	2	3
Neutron measurements	0	3	3	2	0	1	0	3	2	0	2	1-3[b]	1-3[b]	1-3[b]	3
Radiation cameras	0-1[b]	2	1	2	0	1	0	NA	0	0	0	1-3[b]	1-3[b]	1-3[b]	3

[a] In the case of air-kerma measurements associated correction factors must be applied.

[b] Depending on the type and/or the size of the instrument used.

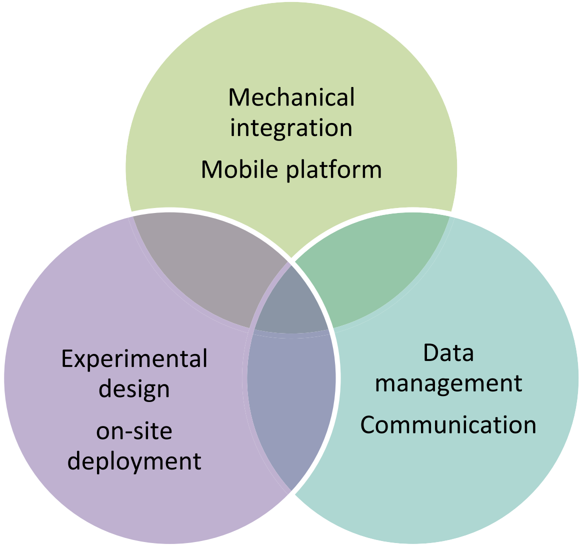

Fig. 2. Design principles of system engineering applied for in-situ measurements.

objectives. Such an important step must be formalized as follows (in order of priority):

- The choice of the detector with the best characteristics depending mainly on the properties of the measured object, such as its shape, volume, weight or mass density, material composition, as well as the inner spatial distributions of the radioactive source.
- The choice of the measurement configuration that takes into account the characterization objectives, the desired statistical precision, the available space, etc.
- Potential installation of radiation attenuation screens. This kind of set-up is being reserved for cases where the application of the above choices do not offer satisfactory results.

All these technical choices essentially depend on the different constrained environments, without forgetting the required particular dispositions that have to be integrated on a case-by-case basis (see Section 4).

3.2.2. Mechanical integration

Mechanical integration in the case of in-situ measurements consists of:

- The choice of the carrier platform (robot, drone, articulated arm, special machine, etc.) according to the previously established needs and requirements: entire autonomous system, remotely controlled (either wired or wireless), measurement by the operator in the field.
- The definition of the mechanical integration of the whole system according to the design constraints related to the choice of the radiation detector, its associated electronics and any other component or device, if necessary, as well as their handling, packing, transportation and on-site deployment of the whole system.

Some of these technical choices also depend on the different constrained environments. Several other factors related to the system reliability, availability, maintainability and safety must also be taken into account. In practice, reliability depends on both the system complexity and the working environment, so that attempts should be made to have proper combination of components, avoiding or reinforcing the critical ones, in order to reduce, to the strictest minimum, the overall frequency of unwanted failures during the operational phase.

3.2.3. *Data management*

The term “data management” includes secure communication with all the deployed devices and sensors together with data gathering, transfer, processing and storage.

In no case should data management neglect the correct choice of the interpretation method and the quality of the measurements. This means that it has to constantly contemplate the following aspects:

- The definition of the interpretation methodology, which is intrinsically linked to the system design of the device and it must be considered as a key step in the success of in-situ measurements. Such an interpretation is most often based on assumptions and good practices taken by considering the history of the item to be characterized.
- The strategic approach to reduce and evaluate uncertainties. Above all, their identification at the initial stage makes it possible to formalize all the assumptions regarding the system design and to integrate them numerically into the final results.

On-site deployment in the majority of nuclear facilities requires fast and reliable indoor wireless bidirectional networks. Advantages of a Li-Fi connection (Dimitrov and Haas, 2015) in enclosed spaces with respect to the Wi-Fi one are: a wide bandwidth (from infrared to ultraviolet); it can operate in electromagnetic sensitive areas (not even the cause of such interferences); it is almost hundred times faster; and in principle with no limits of capacity.

4. Particular dispositions

4.1. *Environmental radiation measurements*

This section is mainly focused on environmental measurements of the X/γ radiation. Such measurements may include gross counting, air-kerma or $H^*(10)$ monitoring. Although $H^*(10)$ measurements may also be performed for neutrons in some circumstances, all the constraints influencing this kind of measurement are discussed separately in Section 4.4 together with those associated to the neutron coincidence counting mode.

Table 4 summarizes the strengths and weaknesses of the common detectors used for environmental radiation measurements as well as their recommended applications in nuclear facilities subject to a D&D programme.

4.1.1. *Radioactivity constraints*

4.1.1.1. *Radiation*

4.1.1.1.1. Identification of constraints. A measurement in high dose rate environments is very challenging when using gas-filled detectors and can be affected in several ways, such as signal discrimination, detection performance, dead (or resolving) time issues and background correction.

In situations of elevated count rates, problems of the loss of linearity followed by a complete saturation or paralysis (i.e., the filling gas remains permanently ionized) of the detector used could occur, requiring very careful choice of its intrinsic or setting parameters (i.e., operating voltage, temperature and gas pressure) and its associated electronics (Usman and Patil, 2018).

In addition, exposure to extremely high flux of neutrons, charged particles and very energetic photons (i.e. above 10 MeV) may seriously damage electronic components or compromise their characteristics, thus leading to a drastic decrease in the detector lifetime. In such irradiation circumstances, organic insulators may also break down.

4.1.1.1.2. Integration of constraints on the instrument design. In principle, very compact gas-filled detectors can be used to challenge high radiation dose rates, but those based on silicon PIN diodes also constitute a good alternative. This is particularly important for background level studies and real-time reporting of any abrupt elevation in this level to the first responders. Fast response, low operating voltage, low power consumption, portability, compactness and practically unlimited operating life make them better adapted in such circumstances. For example, the employment of energy-compensated Si-based detectors provides a more or less flat response over a wide photon energy range (60–1250 keV) and can tolerate radiation dose rates going beyond 20 Gy/h (Mitra et al., 2016).

4.1.1.1.3. Integration of constraints on the final mechanical design. It may be necessary to implement shielding and collimation mechanisms with small opening angles in order to restrict the field-of-view of the chosen instruments, preferably of very reduced-size, to only specific areas or portions of the item to be measured. The acquisition can therefore be performed at different positions around the object providing a high degree of precision. The extra possibility, in the case of ionization chambers and proportional counters, of only considering low inner gas pressure must also be envisaged.

Furthermore, the complementary deployment of a remotely mobile platform, such as a robot or drone, with increased radiation tolerance of both its mechanical and electronic components, is also a good alternative (Tsitsimpelis et al., 2019).

4.1.1.2. Contamination. Most of the available detectors for environmental radiation measurements, except perhaps those having a thin end-window, are adequately protected against the potential presence of airborne radionuclides and their outer surfaces effectively facilitate their proper cleaning after each use. Sometimes their additional protection within plastic bags can be counterproductive as it may either block their internal heat exhaust or produce more attenuation phenomenon, especially for β-particles and low-energy X/γ radiation.

4.1.2. *Materials constraints*

4.1.2.1. Air. Air-kerma measurements are not trivial and several correction factors must always be considered, namely the ones associated to the possible variations with respect to the air pressure and temperature under which the detector calibration was carried out.

In addition, big changes regarding the air density has a non-negligible impact on the overall performance of the other detectors thus leading to large uncertainties and data misinterpretation, mainly when measuring weakly penetrating radiation.

It should also be borne in mind that insulation of conventional cables and BNC connectors as well as most of the electronic components tend to fail at critical temperatures. For example, when they are left near heating elements, sun-warmed surfaces, radiators and large cooling machines. Alternatively, a temperature compensation system can also be implemented on detectors and their associated electronics.

4.1.2.2. Liquid. According to Radiation Protection rules, there is no need or interest to perform environmental measurements under liquid immersion conditions as both $H^*(10)$ and air-kerma operational quantities for external exposures to ionizing radiation are defined and calibrated considering only a free-in-air geometry configuration.

In addition, considering what has been said in the previous Section, another correction factor must be applied when measuring air-kerma in very humid atmospheres.

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).

4.1.2.3. Consistency. In general, in-situ measurements of bulky radioactive materials are seriously affected by uncertainties on the characteristics of the detector used, on the properties of the measured object, as

Table 4
Strengths and weaknesses of the common detectors used for environmental radiation measurements as well as their recommended applications in nuclear facilities subject to a D&D programme.

DETECTOR TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
Ionization chambers	•can be made to have a very good X/γ energy and polar response as also acceptable β characteristics •no problems with pulsed fields •good dynamic range of dose rates, typically 2 μSv h^{-1} up to 10 Sv/h •can use small polarising batteries	•very low signal level at normal radiation protection dose rates leading to statistical fluctuations or slow response times •generally unusable below 2 μSv h^{-1} •susceptible to temperature and humidity corrections •requires careful use and good maintenance, particularly regular drying of desiccant •expensive	•almost all nuclear facility areas and equipment except the ones under liquid immersion conditions
Proportional counters	•good X/γ energy response down to 30 keV •useful beta response at higher energies •generally satisfactory with pulsed fields •high detection efficiency •wide dynamic range of useable dose rates by varying the gas amplification or the polarizing voltage	•relatively vulnerable detector, for the β versions •uses a very high polarising voltage •expensive •susceptible to high voltage variation •pulse pile-up effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones under liquid immersion conditions and at high radiation gamma dose rates and radiation fluxes
Energy-compensated GM detectors	•very easy to process signal •with a more or less (±30%) flat energy response in terms of H*(10) •much more sensitive than an ionization chamber, a volume of 10 cm^3 has the same detection efficiency as an ionization chamber of 300 cm^3 •stable and long operating life, if physically undamaged •low cost •rugged	•no useful β response •X/γ response that falls rapidly below ~50 keV •seriously affected by pulsed fields, untrustworthy when the count rates exceed about 35% of the pulse rate from a machine producing narrow (μs) pulses •dead time effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with pulsed fields or under liquid immersion conditions
Thin end-window, energy-compensated GM detectors	•very good X/γ energy response from 10 or 15 keV upwards to 1.25 MeV •good polar response	•instruments where the filter can be removed so that the detector can be used as a conventional end-window detector are susceptible to physical damages •dead time effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates or under liquid immersion conditions. Pay special attention to corrosive chemical compounds that can easily affect detector windows.
Thin end-window GM detectors	•respond to X/γ radiations from 5 keV upwards and to all β radiation which contributes to ambient or directional dose equivalent rate •good polar response ("pancake" types)	•very vulnerable when used with the end-window unprotected, i.e. to measure β-particles and/or very low energy X/γ radiation, subsequent physical damage is generally fatal and cannot be repaired •must be protected with a fine etched metal or plastic grill •poor energy-response •dead time effect at intense radiation fields •very thin detector windows can easily be affected by corrosive chemical compounds	•almost all nuclear facility areas and equipment except the ones with high dose rates or under liquid immersion conditions
Plastic scintillation detectors	•good X/γ energy and polar response down to 20 keV for instruments with smaller scintillators and thin cans •high detection efficiency •background rejection •good dynamic range by varying the polarizing voltage •easy to produce a logarithmic dose rate response	•large detector (scintillator and photomultiplier tube) •expensive •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones under liquid immersion conditions

already stated in Section 3.2.1, and on the considered geometric configuration of the whole scene under study. Therefore, they need a series of theoretical simulations in a way to calculate *ad hoc* transfer functions and to correctly evaluate all the uncertainties that have a wider influence on the final results.

However, as nuclear facilities contain huge structures and complex equipment, producing accurate models becomes extremely difficult because in most circumstances such detailed information is missing. In that case, several hypothesis, as realistic as possible, must be considered, taking into account the available historical knowledge (even when incomplete) and their plausibility has to be checked by comparing the associated results obtained from at least two different in-situ measurement techniques each time.

4.1.3. Accessibility constraints

4.1.3.1. Narrow or clutter spaces. The possible deployment of a remotely mobile platform, based on reduced-size detectors and equipped with the necessary sensors (position, motion, inclination, proximity), would allow access to those spaces with very limited accessibility (Tsitsimpelis et al., 2019).

As an example of best practice in this domain, given the need to ensure a frequent battery recharging of such a mobile platform operating in difficult access areas, Ishida and Furukawa (2015) developed a method for transmitting electrical power through thick concrete walls, based on magnetic resonance coupling, without the need neither for laboriously drilling holes in them nor for eventual routing of cables (often over long distance corridors) from one side to another.

In line with this, a self-powered wireless system for ultrasonic data transmission has recently been designed (Wu et al., 2019) to be applied under very harsh environments in almost all the enclosed structures of nuclear facilities. To successfully address these kind of problematic aspects, it may be helpful to consult the review carried out by Yang et al. (2015) about the current viable technologies to power and communicate with hidden sensors behind metallic barriers.

4.1.3.2. Height. Access to great heights may need the use of drones, lift gears, telescopic tubes or extension arms. One important aspect to highlight is that the additional use of the shields and collimators, if needed, will add too many complications due to their weight and size.

4.1.3.3. Subsurface. Environmental measurements throughout deeply contaminated areas or soils may be very suitable initially to have an idea about the potential presence of radioactive singularities or hotspots, and can be roughly correlated with the activities of the major gamma-ray emitting radionuclides.

4.1.4. Other hazards

The deployment of an unmanned mobile platform can also be of great utility to correctly control the air quality as well as to detect the presence of toxic, flammable or combustible atmospheres and other dangerous agents in remote areas, thus avoiding any unnecessary risk of human exposure.

The presence of corrosive chemicals may also affect the performance of the radiation detectors and extreme attention must be paid to the ones hermetically sealed with plastic materials or using a thin end-window, in order to measure weakly penetrating radiation.

4.2. Surface contamination measurements

The following tables (Tables 5 - 7) summarize the strengths and weaknesses of the common detectors used for surface contamination measurements as well as their recommended applications in nuclear facilities subject to a D&D programme.

4.2.1. Radioactivity constraints

4.2.1.1. Radiation. Proportional counters, which can be used to control the radioactive contamination on surfaces, offer the possibility to distinguish the alpha-induced pulses from the beta ones by simply adjusting the bias voltage. In fact, 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).

In those areas with extreme levels of radiation, surface contamination can hardly be evaluated by direct methods. The only way in this case would be by taking smear samples from each suspected contaminated area, by means of a remotely robot preferably under wireless mode, and measuring, once recovered back in a safe room, its associated removable contamination with the appropriate instruments as listed in the above tables. Nevertheless, the use of drones in such circumstances has to be strictly forbidden since their propellers are able to re-suspend contaminating particles in the air and the extent of surface contamination to other areas or objects, which were originally clean enough to be

Table 5

Strengths and weaknesses of the common detectors used for surface contamination measurements, in the case of α-particles, as well as their recommended applications in nuclear facilities subject to a D&D programme.

DETECTOR TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
Solid state detectors	•very good detection efficiency •ultra lightweight and compact	•extremely susceptible to electromagnetic interference •tend to be microphonic •expensive •fragile •can be sensitive to β, γ and neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with electromagnetic interference or under liquid immersion conditions •considering only smooth and impermeable surfaces
ZnS scintillation detectors	•good detection efficiency, the majority of α-particles that penetrate the window with significant energy will be counted •available in a wide range of sizes •reasonable β, X and γ rejection although ultimately either false counts will be recorded at high dose rates or the detector will fail to danger •lightweight, most of them use separate probes •low intrinsic background •easy setting up procedure	•extremely vulnerable, unlike the scintillator and photomultiplier combination, the delicate and expensive part is just behind the window •can be sensitive to β, γ and neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones under liquid immersion conditions •considering only smooth and impermeable surfaces
Dual phosphor scintillation probes (ZnS on plastic scintillator)	•good detection efficiency, as for standard α pulses •useful for mixed α and high to intermediate energy β contamination •lightweight •easy window repair	•may not tolerate high magnetic fields, unless using a proper Mu-metal shielding •can be sensitive to β, γ and neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high magnetic fields or under liquid immersion conditions •considering only smooth and impermeable surfaces
Thin end-window GM detectors	•large, easily processed pulse •very simple setting up procedure •consistent operating voltage and radiation characteristics •lowest cost overall option in most circumstances •light and compact •small "pancake" GMs are reasonably cheap	•extremely fragile •background count-rates generally too high •no discrimination against other radiations •dead time effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high rates or under liquid immersion conditions •considering only smooth and impermeable surfaces without corrosive chemical compounds
Thin end-window gas-filled proportional counters	•very good detection efficiency. •virtually any α particle passing through the window with an energy in excess of 0.5 MeV will be counted •available in very large sizes, if required •possible discrimination against β-particles •easy window repair •consistent operating potential •not influenced by magnetic fields	•extremely fragile •the uniformity of the larger detectors can be poor, with a low response to activity in the detector corners •can be sensitive to γ and neutrons •pulse pile-up effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates or under liquid immersion conditions •considering only smooth and impermeable surfaces without corrosive chemical compounds

Table 6

Strengths and weaknesses of the common detectors used for surface contamination measurements, in the case of β-particles, as well as their recommended applications in nuclear facilities subject to a D&D programme.

DETECTOR TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
Scintillation detectors	•available in a wide range of sizes •good sensitivity •can cover a wide range of energies •window easily replaced •lightweight •easy setting up procedure	•susceptible to magnetic interference, unless using a proper Mu-metal shielding •fragile •can be sensitive to γ and neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with magnetic interference or under liquid immersion conditions •considering only smooth and impermeable surfaces
Thin end-window gas-filled proportional counters	•a very good detection efficiency down to ^{14}C (i.e., β-particles with $E_{max} \geq 156$ keV) •available in very large sizes, if required •easy window repair •consistent operating potential •not influenced by magnetic fields •good α rejection	•very variable operating potential within any one type •fragile •can be sensitive to γ and neutrons •pulse pile-up effect at intense radiation fields	•almost nuclear facility areas and equipment except the ones with high dose rates or under liquid immersion conditions •considering only smooth and impermeable surfaces without corrosive chemical compounds
Thin titanium window xenon-filled sealed proportional counters	•useful for β and low energy X/γ radiation •relatively tough window •lightweight •no gas filling required •consistent operating potential and radiation characteristics	•require high voltage •uniformity of larger detectors can be poor •can be sensitive to γ and neutrons •pulse pile-up effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates or under liquid immersion conditions •considering only smooth and impermeable surfaces without corrosive chemical compounds
Thin end-window GM detectors	•large, easily processed pulse •very simple setting up procedure •consistent operating voltage and radiation characteristics •lowest cost overall option in most circumstances •light and compact •small "pancake" GMs are reasonably cheap	•no alpha discrimination unless in 'dual phosphor probe' form •fragile •can be sensitive to γ and neutrons •dead time effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates or under liquid immersion conditions •considering only smooth and impermeable surfaces without corrosive chemical compounds
Thin walled GM detectors	•more robust than the thin window variety •larger useful area than the thin window variety •very simple setting up procedure •consistent operating voltage and radiation characteristics •low cost •light	•expensive •not appropriate for low-energy β-particles ($E_{max} < 0.5$ MeV) •require regular refreshing with counting gas •can be sensitive to γ and neutrons •dead time effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates or under liquid immersion conditions •considering only smooth and impermeable surfaces without corrosive chemical compounds

Table 7

Strengths and weaknesses of the common detectors used for surface contamination measurements, in the case of X/γ radiation, as well as their recommended applications in nuclear facilities subject to a D&D programme.

DETECTOR TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
Thin end-window compact sodium iodide scintillation detectors	•small crystal size is a very efficient X/γ radiation, for the 3 mm thickness the detection probability is greater than 0.5 for normal incident radiation up to 120 keV •a typical aluminium window of 14 mg cm-2 thick has a transmission of at least 0.8 for normal incident X/γ radiation down to 10 keV •for a beryllium window of 46 mg cm-2 thick, the transmission at normal incidence is at least 0.8 down to 5 keV •the combination of the proper scintillator and window thus offers a very efficient detector over a wide energy range	•the scintillator is very brittle and easily crazes with mechanical shock •can be sensitive to neutrons •pulse pile-up effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates, excessive room temperature variations or under liquid immersion conditions •considering only smooth and impermeable surfaces
Titanium end-window xenon-filled proportional counters	•useful for β and low energy X/γ radiation •relatively tough window •lightweight •no gas filling required •consistent operating potential and radiation characteristics	•end-window can be physically damaged, which if not carefully repaired will lead to a gradual deterioration of the scintillator, resulting in an increase in the energy threshold •can be sensitive to neutrons •pulse pile-up effect at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates or under liquid immersion conditions •considering only smooth and impermeable surfaces without corrosive chemical compounds

classified as conventional waste.

4.2.1.2. Contamination. Surface contamination measurements need to be as close as possible (no more than a few mm) to the object under examination and special care must be taken to not contaminate the detector itself. In addition, because of the extremely low penetration of alpha particles, an ultra-thin barrier must be considered to allow the particles to enter the active region of the detector, while simultaneously protecting this latter. Most times, a detector with an end-window, made of an aluminized Mylar or mica film (~0.8 mg/cm^2), is used and thus any eventual contact with hard objects may puncture it.

4.2.2. Materials

4.2.2.1. Air. Almost the same as for environmental radiation measurements (see Section 4.1.2.1).

4.2.2.2. Liquid. Such a constraint is not applicable for surface contamination measurements.

4.2.2.3. Consistency. When a radioactive substance has been able to fully infiltrate, somehow or other, inside porous materials or the ones with structural cracks, like in a concrete wall, its surface contamination measurements are no longer valid. They should in consequence be restricted, especially in the case of α-particles, to only smooth and impermeable surfaces.

4.2.3. Accessibility

4.2.3.1. Narrow and/or clutter spaces. The possible deployment of a remotely and well-equipped robot (a drone cannot be used for the same reasons explained in Section 4.2.1.1), preferably under wireless mode, could be envisaged to control the extent of surface contamination in difficult access rooms.

4.2.3.2. Height. Same recommendation as in Section 4.1.3.2 but not considering the drone option (see explanation in Section 4.2.1.1).

4.2.3.3. Subsurface. Such a constraint is not applicable for surface contamination measurements.

4.2.4. Other hazards. Same recommendation as in Section 4.1.4 but not considering the drone option (see explanation in Section 4.2.1.1).

4.3. Gamma-ray spectrometry

Table 8 summarizes the strengths and weaknesses of the common γ-spectrometry detectors as well as their recommended applications in nuclear facilities subject to a D&D programme. There are obviously many other detectors of the same families (i.e., inorganic scintillators and semiconductors) but their behaviour does not differ a lot from those already mentioned in this table.

4.3.1. Radioactivity constraints

4.3.1.1. Radiation

4.3.1.1.1. Identification of constraints. When a given gamma-ray spectrometer is exposed to intense radiation fields dead time and pulse pile-up effects may occur (Usman and Patil, 2018). Several hardware and software methods are available to reduce or to correct these effects in certain circumstances, but they shall be considered in advance when undertaking the suitable selection of detection systems. Some detectors have very low associated dead time, like organic scintillators (Knoll, 2010; Tsoulfanidis and Landsberger, 2015).

In addition, exposure to extremely high flux of neutrons charged particles and very energetic photons (i.e. above 10 MeV) may cause several intrinsic defects and/or failures (lattice displacements, deep-level traps, glitches, parasitic structures, single events, etc.) in both inorganic scintillators and semiconductors and associated electronics therefore affecting their detection properties.

Another key issue already highlighted by Aspe et al. (2020), refers to the background correction problem liable to be altered at high dose rates, thus implying an increase in counts under the total absorption peaks corresponding to the radionuclides of interest. More interference phenomena can also arise as a result of the interaction of primary X- or γ-rays with the structural and shielding materials around the detector, through processes like Compton back-scattering, Bremsstrahlung radiation, secondary annihilation 511 keV photons after electron-positron pair production and characteristic X-rays issued from the photoelectric effect. They are expected to increase with the active volume of the detector and, depending on the energy resolution of this latter, they can prevent the appearance of some less intense peaks of the analysed radionuclide source. In some cases, the presence of high flux neutrons may activate the detector material, eventually emitting new X- or γ-rays that can once again interfere with the measured spectrum (Baginova et al., 2018).

4.3.1.1.2. Integration of constraints on the instrument design. Dedicated digital signal processing equipment and algorithms can be used to automatically correct, even partially in some extreme situations, both the dead time and pulse pile-up effects (Stranneby and Walker, 2004).

Whereas most of the above intrinsic failures can be prevented by using radiation-tolerant and redundant integrated circuits (Calligaro and Gatti, 2018), some of the crystal defects like lattice displacements can be repaired after the measurement through the so-called annealing process (Peplowski et al., 2019). That is a kind of “reset” during which the detector needs to be heated at a temperature around 100 °C for some time (normally several days) and left afterwards as long as necessary for correction of such defects.

4.3.1.1.3. Integration of constraints on the final mechanical design. The possibility of using low-noise charge preamplifier (Pullia et al., 2005) allowing the remote control from large distances of the detector with adequate shielding and collimation cannot be excluded.

Furthermore, as already stated before for other measuring equipment, the complementary deployment of a remotely mobile platform, with increased radiation tolerance of both its mechanical and electronic components, is also a good alternative.

4.3.1.2. Contamination. All preventive actions need to be taken when there is a minimal possibility of radioactive contamination of the detector. For this reason, only those measurement instruments not using an internal fan mechanism to cool down their unit head have to be favoured. For practical considerations, even the use of liquid nitrogen, CFC, or any other refrigerant (flammable or not) must be strictly forbidden. For example, an HPGe detector coupled to a pulse-tube cryocooler can be considered as the only choice among the refrigeration possibilities. Additional protection solution is achieved through confinement of both the detector and its electronics within plastic bags. However, as already stated in Section 4.1.1.2, this way of protecting from contamination can be counterproductive as it may either block their internal heat exhaust or produce more attenuation phenomenon of low-energy X- and γ-rays. This is the case for scintillation detectors, leading to problems related to an adequate energy and FWHM calibration (Ahmed, 2007).

4.3.2. Materials

4.3.2.1. Air. Inorganic crystal detectors may show a gain drift due to temperature variations. In fact, they are usually coupled to a photomultiplier tube, which is highly sensitive to temperature changes, as well as to stray magnetic fields. Although, when using rather a silicon avalanche photodiode, this latter is also prevented in operations at elevated temperatures (Knoll, 2010).

Table 8
Strengths and weaknesses of the common γ-spectrometry detectors as well as their recommended applications in nuclear facilities subject to a D&D programme.

DETECTOR TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
NaI(Tl) detectors	•widely used •the detection efficiency of a 3" × 3″ NaI(Tl) crystal was historically taken as the reference to compare that of the other γ-spectrometers •available in many sizes •do not require reinforced cooling	•poor energy resolution (~7% @ 662 keV) •possible gain drift due to temperature variations •hygroscopic material (must be fully sealed) •sensitive to neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates, excessive room temperature variations, or under liquid immersion conditions
BGO ($Bi_4Ge_3O_{12}$) detectors	•better detection efficiency than NaI(Tl) •non-hygroscopic material •hard and rugged	•poor energy resolution (~10% @ 662 keV) •possible gain drift due to temperature variations •unsuitable at elevated temperatures (>50 °C) •sensitive to neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates or room temperature variations
$LaBr_3$(Ce) detectors	•slightly better detection efficiency than NaI(Tl) •moderate energy resolution (~3% @ 662 keV) •do not require reinforced cooling	•possible gain drift due to temperature variations •hygroscopic material (must be fully sealed) •sensitive to neutrons •intrinsic background due to the presence of ^{138}La and ^{227}Ac •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates, excessive room temperature variations, or under liquid immersion conditions
$CeBr_3$ detectors	•slightly better detection efficiency than NaI(Tl) •moderate energy resolution (~4% @ 662 keV) •very low intrinsic background •do not require reinforced cooling	•possible gain drift due to temperature variations •hygroscopic material (must be fully sealed) •sensitive to neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates, excessive room temperature variations, or under liquid immersion conditions
CZT detectors	•moderate energy resolution(~2.5% @ 662 keV) •do not require reinforced cooling •tolerate temperature variations •low cost	•low detection efficiency •sensitive to neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment, especially, when small sizes are required.
CdTe detectors	•good energy resolution (~0.6% @ 662 keV) •allow ultra-thin designs •do not require reinforced cooling •tolerate temperature variations •can use polarising batteries	•low detection efficiency •sensitive to neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment, especially, when small sizes are required.
HPGe detectors	•excellent energy resolution (~0.15% @ 662 keV) •adapted to multiple γ-ray emitting radionuclides	•low detection efficiency •need a vacuum enclosure and cooling to cryogenic temperature (<80 K) •very expensive •sensitive to neutrons •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with narrow spaces, high dose rates, excessive room temperature variations, or under liquid immersion conditions

Conversely, HPGe semiconductors are in essence unaffected by changes in ambient temperature or magnetic field but not their associated electronics. This can lead to large uncertainties or misinterpretation of the measured gamma-ray spectrum. When it is possible, one of the solutions consists in performing measurements in a constant temperature environment (for example, if the temperature varies throughout the day, measurements can be done only every morning), or pay special attention to in-situ calibration. As a last resort, a temperature compensation system, based on stabilization schemes, can also be implemented.

See the commentary of Section 4.1.2.1 related to conventional cables and BNC connectors.

4.3.2.2. Liquid. 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, consist 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 (see Table 8) are hygroscopic, which means they can be easily damaged when directly 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 strongly advisable to handle them with care and avoid mechanical shocks that may crack or chip the seals. Because hydration adopts some colour, it is an excellent absorber of photons in the visible domain and can significantly degrade the scintillation light output and thereby the detection performance.

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

4.3.2.3. Consistency. Same recommendations as for environmental radiation measurements (see Section 4.1.2.3).

4.3.3. Accessibility constraints

4.3.3.1. Narrow and/or clutter spaces. Same recommendations as for environmental radiation measurements (see Section 4.1.3.1), without excluding the possibility of also considering CdTe or CZT semiconductors as they are available in very small sizes.

4.3.3.2. Height. Same recommendations as for environmental radiation measurements (see Section 4.1.3.2) and the only limitation would be the heavy shielding that must be implemented with the detector.

4.3.3.3. Subsurface. Section 4.1.3.3 explains the benefits of carrying out preliminary environmental measurements throughout deeply contaminated areas or soils from a qualitative point of view. Hence, they must always be complemented by means of γ-spectrometry in order to be able to identify the potential presence of the major gamma-ray emitting radionuclides and to quantify their activity by assuming, as a first approximation, uniform depth distribution up to a certain limit. For more details on this aspect, it will be necessary to plan many representative core samples and to send them for further analysis in the laboratory.

Although widely used, both scintillation detectors and HPGe detectors are somewhat fragile for in-situ measurement in subsurface. For this reason, as CdTe or CZT semiconductors are available in very small sizes, they can be very useful for down-hole logging operations despite their lower energy resolution compared to HPGe detectors (see Table 8). More rugged scintillation detectors using silicon avalanche photodiode instead of conventional photomultiplier tubes are also advisable, albeit with some limitations that are currently encountered with the small sizes of detectors. Notwithstanding, this kind of measurements cannot be carried out when the soil is laden with rocks and boulders that may cause serious damages to the detector used.

4.3.4. Other hazards

Same recommendations as for environmental radiation measurements (see Section 4.1.4).

4.4. Neutron measurements

At the risk of being repetitive and as any of the available radiation detectors can be easily adapted on a practical level, with the addition of an appropriate converter material, to measure neutrons, almost all the particular dispositions discussed above (namely those in Section 4.1) are also valid here.

Table 9 summarizes the strengths and weaknesses of the common neutron detectors as well as their recommended applications in nuclear facilities subject to a D&D programme.

4.4.1. Radioactivity constraints

4.4.1.1. Radiation

4.4.1.1.1. Identification of constraints. As stated in Aspe et al. (2020), particular attention is given to the intrinsic response of the neutron detectors to X/γ radiation. Such response is typified as Gamma Rejection Ratio (GRR) when no neutron source is present and or Gamma Absolute Rejection Ratio in the presence of neutrons (GARRn). Both of them can be corrected on the basis of pulse shape discrimination or PSD. Indeed at high dose-rates, peak amplitudes from gamma rays become considerably larger than any individual neutron pulse, due to pulse pile-up effect, distorting in this manner the above rejection ratios (Knoll, 2010; Kouzes et al., 2010).

Molecular disassociation could also be caused when using $^{10}BF_3$ detectors at very elevated radiation levels. This can alter the pulse height spectra coming from neutron-induced events. In some extreme cases, inner chemical changes can cause permanent damage to most detectors (Knoll, 2010).

4.4.1.1.2. Integration of constraints on the instrument design. Practically all the challenges that can be encountered in very intense radiation fields can be easily addressed by means of fairly thin metallic activation foils (Son and Nguyen, 2018). Their associated neutron-induced radioactivity can be measured with a conventional instrument, once recovered back in a safer room.

Another possible solution is the one based on self-powered neutron detectors or SPNDs, which are usually used for in-core monitoring. They have a highly compact coaxial structure consisting of a central metallic electrode (leading mostly to short-lived β-emissions after neutron activation) surrounded by a mineral insulator and enclosed in a metallic sheath. Such a configuration provides a net current that is proportional to the incident neutron flux and can be measured externally (Giot et al., 2017).

4.4.1.1.3. Integration of constraints on the final mechanical design. Same recommendations as for environmental radiation measurements (see Section 4.1.1.1.3).

4.4.1.2. Contamination. Much of the recommendations given in sections 4.1.1.2 and 4.3.1.2 are also valid here.

4.4.2. Materials

4.4.2.1. Air. Neutron measurements based on activation metallic foils or on SPNDs offer a good stability under variable air temperature and pressure conditions.

See the commentary of Section 4.1.2.1 related to conventional cables and BNC connectors.

4.4.2.2. Liquid. See Section 4.1.2.2 regarding the appearance of spurious pulses under high humidity environments.

4.4.2.3. Consistency. Same recommendations as for environmental radiation measurements (see Section 4.1.2.3).

4.4.3. Accessibility

4.4.3.1. Narrow and/or clutter spaces. Same recommendations as for environmental radiation measurements (see Section 4.1.3.1), except in the coincidence neutron counting mode since the associated instrument is a bit bulky and heavy.

4.4.3.2. Height. Same recommendations as for environmental radiation measurements (see Section 4.1.3.2) except in the coincidence neutron counting mode since the associated instrument is a bit bulky and heavy.

4.4.3.3. Subsurface. Coincidence neutron courting could be foreseen as often as possible to improve the knowledge gained about the subsurface source term from environmental radiation measurements (see Section 4.1.3.3), γ-spectrometry and laboratory analysis of representative core samples (see Section 4.3.3.3). Otherwise, total neutron counting may also be of great utility.

Table 9

Strengths and weaknesses of the common neutrons detectors as well as their recommended applications in nuclear facilities subject to a D&D programme.

DETECTOR TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
^{3}He gas-filled proportional counters	•reasonably light •good neutron cross-section •varied filling pressure •inert and non-toxic gas •resistant to intense radiation fields	•^{3}He shortage •highly expensive •reduced γ rejection •sensitive to vibrations •pulse pile-up effect at intense radiation fields	•almost all nuclear facility areas and equipment
$^{10}BF_3$ gas-filled proportional counters	•reasonably light •good γ rejection •readily available than ^{3}He	•low neutron cross-section •toxic and corrosive •sensitive to vibrations •limited filling pressure •pulse pile-up effect and gas degradation at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates
^{10}B-lined proportional counters	•reasonably light •good γ rejection •readily available than ^{3}He •can be filled with non-toxic gas (90% Ar + 10% CO_2) •resistant to intense radiation fields	•low neutron cross-section •limited^{10}B coating thickness (only a few μm) •sensitive to vibrations •pulse pile-up effect at intense radiation fields	•almost all nuclear facility areas and equipment
^{6}LiI(Eu) scintillation detectors	•compact design •good detection efficiency* •insensitive to vibrations	•poor γ rejection •availability and cost of enriched ^{6}Li •hygroscopic material (must be fully sealed) •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates or under liquid immersion conditions
ZnS(Ag):^{6}LiF scintillation detectors	•ultra-compact design •good detection efficiency* •can discriminate γ signals •insensitive to vibrations	•poor light transmittance •availability and cost of enriched ^{6}Li •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates
CLYC ($Cs_2^6LiYCl_6$:Ce) scintillation detectors	•compact design •good detection efficiency* •can discriminate γ signals •spectroscopic capability •insensitive to vibrations	•availability and cost of enriched ^{6}Li •hygroscopic material (must be fully sealed) •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates
CLLBC ($Cs_2^6LiLa(Br,Cl)_6$:Ce) scintillation detectors	•compact design •good detection efficiency* •can discriminate γ signals •spectroscopic capability •insensitive to vibrations	•availability and cost of enriched ^{6}Li •hygroscopic material (must be fully sealed) •intrinsic background due to the presence of ^{138}La and ^{227}Ac •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with high dose rates
GSO (Gd_2SiO_5:Ce) scintillation detectors	•ultra-compact design •huge neutron cross-section •no need for isotope enriching •non-hygroscopic material •high radiation hardness (up to 10^7 Gy)	•poor γ rejection but less pronounced for thin detectors •very fragile (cleaving and cracking issues)	•almost all nuclear facility areas and equipment
^{6}Li glass fibers doped with Ce	•flexible design •good detection efficiency* •chemical inert material •tolerate high temperatures •high count rates •insensitive to vibrations	•poor γ rejection •availability and cost of enriched ^{6}Li •may contain naturally occurring radionuclides (at best $< 3.33 \times 10^{-3}$ Bq/g)	•almost all nuclear facility areas and equipment

*The high atomic density of ^{6}Li in the sensitive material fully compensates for its very low cross-section.

4.4.4. *Other hazards*

Same recommendations as for environmental radiation measurements (see Section 4.1.4).

4.5. *Radiation cameras*

This section only deals with the gamma camera as the alpha and neutron ones are neither mature nor widely industrialized technologies. In addition, to the best of our knowledge, there is not enough information to get the necessary recommendations regarding their application in nuclear facilities subject to a D&D programme.

Accordingly, Table 10 summarizes the known strengths and weaknesses of the different γ-camera types as well as their recommended applications under such circumstances.

4.5.1. *Radioactivity constraints*

4.5.1.1. Radiation. High radiation levels may also affect the performance of electronic components of the cameras. Such an effect has largely been discussed in Aspe et al. (2020), so there is no need to reproduce all the content of this publication here. However, some other features could be explained like those aspects related to the accumulation of charge carriers (i.e., free electrons and holes) within integrated circuits, with a direct influence on the underlying electric fields and then on the electrical properties of silicon sensors. For example, the CCD charge transfer becomes inefficient and the device quickly stops working, whereas the threshold voltage of a CMOS transistor shifts slowly, until the device is always on or fully closed. Digital circuits, similar to some analog ones, can tolerate moderate amounts of threshold voltage changes, allowing them to continue operating normally until the device definitely breaks down (Hopkinson and Mohammadzadeh, 2004).

Table 10

Strengths and weaknesses of the different γ-camera types as well as their recommended applications in nuclear facilities subject to a D&D programme.

CAMERA TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
Pinhole	•optimal angular resolution (1.9°–6.7°) •wide γ-energy range, from ^{241}Am to ^{60}Co •good dose-rate linearity •enhanced signal-to-noise ratio	•heavy (≥15 kg) •low sensitivity •small field-of-view (30° or 50°) •moderate energy resolution •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment except the ones with narrow spaces
Coded aperture	•can be ultra-compact (<300 g) •high sensitivity •optimal angular resolution (2.5°–6°) •wide γ-energy range, from 30 keV to ^{60}Co •good dose-rate linearity •possibility of background subtraction under mask/anti-mask mode	•small field-of-view (45°–50°) •moderate energy resolution •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment
Compton	•can be compact (3–5 kg) •field-of-view up to 360° •high energy resolution	•low sensitivity •moderate angular resolution (10°–30°) •hardly applicable below 250 keV •pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	•almost all nuclear facility areas and equipment

4.5.1.2. Contamination. Almost the same as for γ-spectrometry (see Section 4.3.1.2).

4.5.2. Materials constraints

4.5.2.1. Air. See the commentary of Section 4.1.2.1 related to conventional cables and BNC connectors.

4.5.2.2. Liquid. Almost the same as for γ-spectrometry (see Section 4.3.2.2).

4.5.2.3. Consistency. Same recommendations as for environmental radiation measurements (see Section 4.1.2.3).

4.5.3. Accessibility constraints

4.5.3.1. Narrow and/or clutter spaces. Same recommendations as for environmental radiation measurements (see Section 4.1.3.1).

4.5.3.2. Height. Same recommendation as for environmental radiation measurements (see Section 4.1.3.2).

4.5.3.3. Subsurface. Same recommendations as for environmental radiation measurements (see Section 4.1.3.3).

4.5.4. Other hazards

Same recommendations as for environmental radiation measurements (see Section 4.1.4).

5. Conclusion

This paper analyses the appropriate in-situ measurement techniques to be used when different kind of constrained environments are present at sites under D&D processes and serves as a global guidance to assist with the decision making process. It also provides some particular dispositions, for the appropriate implementation of the chosen instruments.

As a first step in this guidance, the recommended in-situ measurement technique in each of the three phases of a D&D programme is established as a function of the needs, objective of the investigation and type of radioactivity present at the phase of a D&D programme. The second and most important analysis done is the level of impact of the different environmental constraints on each in-situ measurement technique.

The analysis performed in this paper shows that most of the existing constraints impacting the in-situ measurements carried out under the D&D programmes for nuclear facilities have a solution or have been already considered for the product/system developers, and thus there is a way to deal with them.

The most conventional and classical determinations, such as environmental radiation measurements and surface contamination ones, are those for which constraints are more integrated in the system definition. Different solutions for the instrument design, as also in the field of its mechanical integration, have been developed over the years in which D&D activities have become increasingly common. Several types of gas-filled detectors and the newly developed plastic scintillators, with different configurations, are normally used for environmental measurements. From gas-filled detectors to scintillators or solid state detectors, also with multiple configurations, can all be applied, depending on constraints and contamination types, for surface contamination measurements.

In the case of gamma-ray spectrometry, a wide range of detectors and technical solutions already exists to allow the integration of the different constrains in the system definition. However, there is a great limitation for the HPGe detector, although being the reference one due to its high energy resolution, as it needs to be cooled to cryogenic temperatures. One must not forget the drawback, associated with its restricted application to limited accessibility areas. In addition, due to the current big gap between the HPGe energy resolution and those of the other γ-ray spectrometers that can properly work in environmental conditions, there is still a real challenge for on-going R&D activities, not only in detector development domain, but also in those related to the mechanical integration, latest generation electronics and advanced spectral analysis. Dedicated digital signal processing equipment and algorithms can be provided to automatically correct signal distortion produced by intense radiation fields, alongside the use of low-noise charge preamplifier with adequate shielding and collimation.

Neutron measurements are not as common in the D&D programme activities. Actually, they are limited to certain zones and situations. However, most of the constraints are well integrated in the system definition and solutions for the instrument design, as well as for its mechanical integration, are available for users. The well-known gas-filled proportional counters (^{3}He or $^{10}BF_3$) are usually used but alternative scintillation materials with neutron converters can also be applied.

Regarding the radiation camera, only the gamma ones have been taken into account in this document, as those able to locate alpha and neutron sources are neither mature nor widely industrialized technologies. In this case, we are talking about compact systems, commercially available, designed to provide a specific solution; the selection of one or other depends on the application itself and on the room where the measurement must be performed. The most important constraint, the radiation one, has almost the same impact on all types of the existing γ-cameras and has not been solved yet, neither in the design nor in its mechanical integration.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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