Horizon 2020 Programme

INSIDER

Research and Innovation Action (RIA)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 755554.

Start date : 2017-06-01 Duration : 48 Months
http://insider-h2020.eu/

Recommended in situ measurement techniques for each constrained environment

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INSIDER - Contract Number: 755554

Project officer:

Document title	Recommended in situ measurement techniques for each constrained environment
Author(s)	Mrs. Margarita HERRANZ, Frederic Aspe, Khalil Amgarou
Number of pages	39
Document type	Deliverable
Work Package	WP05
Document number	D5.3
Issued by	UPV/EHU
Date of completion	2020-07-06 09:32:01
Dissemination level	Public

Summary

In line with the general objectives of the INSIDER project, the work package WP5 is devoted to the definition and implementation of the practical considerations surrounding in-situ radiological characterization of nuclear/radioactive facilities subject to a D&D (decommissioning and dismantling) programme. As a complement to the previous deliverables (D5.1 and D5.2) of the WP5, the present document 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. Such constrained environments are identified as radioactivity, materials, accessibility, and other hazards. In the Introduction section, the context, purpose and use of the present deliverable are stated. In the following sections of this document, from the definition of the investigation objectives, already provided in D5.2, and for each one of the measurement techniques analysed in D5.1, the environmental constraints that impact in these techniques and how to integrated them on the system definition, including the experimental design, the mechanical integration and the data management, to properly define the best radiological characterization method to comply with the objectives of the in-situ measurement activities, are described. Complementing this general view, this document takes into account the different phases of a D&D project ? from initial to final - to provide recommendations about the choice of the in-situ measurement technique. Strengths and weaknesses of the common detectors used for the different in-situ measurement techniques, as well as their recommended applications in nuclear/radioactive facilities subject to a D&D programme are also described.

Approval

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Improved Nuclear SIte characterization for waste minimization in DD operations under constrained EnviRonment

Research and Innovation action
NFRP-2016-2017-1

Recommended in-situ measurement techniques for each constraint

Deliverable D5.3

Version n° 1

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http://www.insider-h2020.eu

This project has received funding from the Euratom research and training programme 2014-2018 under the grant agreement n°755554

DRAFT

Document Information

Grant Agreement #:	755554
Project Title:	Improved Nuclear SIte characterization for waste minimization in DD operations under constrained EnviRonment
Project Acronym:	INSIDER
Project Start Date:	01 June 2017
Related work package:	WP 5: In-situ measurements
Related task(s):	Task 5.2: Suitability of existing methodologies for constrained environments
Lead Organisation:	ONET
Submission date:	2019-07-31
Dissemination Level:	Public

History

Date	Submitted by	Reviewed by	Version (Notes)

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Summary

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In the Introduction section, the context, purpose and use of the present deliverable are stated. In the following sections of this document, from the definition of the investigation objectives, already provided in D5.2, and for each one of the measurement techniques analysed in D5.1, the environmental constraints that impact in these techniques and how to integrated them on the system definition, including the experimental design, the mechanical integration and the data management, to properly define the best radiological characterization method to comply with the objectives of the in-situ measurement activities, are described.

Complementing this general view, this document takes into account the different phases of a D&D project – from initial to final - to provide recommendations about the choice of the in-situ measurement technique. Strengths and weaknesses of the common detectors used for the different in-situ measurement techniques, as well as their recommended applications in nuclear/radioactive facilities subject to a D&D programme are also described.

List of abbreviations

ASN	Autorité de Sûreté Nucléaire (French Nuclear Safety Authority)
BF_3	Boron trifluoride
BGO	Bismuth germanium oxide or bismuth germinate
CFC	Chlorofluorocarbons
CZT	Cadmium zinc telluride
CdTe	Cadmium telluride
D&D	Decommissioning and Dismantling
GM	Geiger-Muller
IAEA	International Atomic Energy Agency
INSIDER	Improved Nuclear SIte characterization for waste minimization in DD operations under constrained EnviRonment
$LaBr_3$(Ce)	Cerium-doped lanthanum bromide
Li-Fi	Light fidelity
LiI(Eu)	Europium-activated lithium iodide
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
NaI(Tl)	Thallium-activated sodium iodide
NEA	Nuclear Energy Agency/
OECD	Organization for Economic Co-operation and Development
Wi-FI	Wireless fidelity
WP	Work Package
ZnS	Zinc sulphide

1 Introduction

1.1 Structure of the document

Following the Introduction section, which establishes the context and the purpose of the present deliverable, Chapter 2 provides general recommendations for the choice of in-situ measurement techniques for each phase of investigations operations. At this stage, it is important to notice that despite INSIDER project is mainly focused to initial on-site radiological characterization, we consider that this deliverable should also take into account investigations during other D&D phases. Therefore, while synthetizing information of the first WP5 deliverables (D5.1 and D5.2), the chapter suggests a number of useful and practical recommendations for the different investigation steps during the whole D&D programme.

Regarding the proposed in-situ measurement techniques, Chapter 3 indicates the incidence on their overall performance of the different constrained environments, and explains a global methodology to integrate these constraints on the conception of the investigation methodology.

In turn, Chapter 4 formulates some recommendations that need to be followed for the appropriate choice of the instruments and the technical issues the investigation methodology has to stand for in regard to every nuclear facility room or area at where each of the major identified constrained must be overcome.

Finally, Chapter 5 concludes the document by stating the general interest of this study and highlighting its main outcomes.

1.2 Context and purpose of the document

In line with the general objectives of the INSIDER project, the work package WP5 is devoted to the definition and implementation of the practical considerations surrounding in-situ radiological characterization of nuclear/radioactive facilities subject to a D&D programme, taking into account specific outputs from work packages WP2, WP3 and WP4.

As a complement to the previous deliverables (D5.1 and D5.2) of the work package WP5, the present document 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.

These latter include the radioactivity level of the area to be characterized, the difficult accessibility of this area, the type and properties of the materials contained in it, as well as the possible presence of chemical and/or biological hazards.

For the sake of simplicity, such constrained environments are hereafter referred to “constraints” and, in coherence with the deliverable D5.2, they are identified as radioactivity, materials, accessibility, and other hazards. They may individually affect the in-situ measurement techniques to be used as also the interpretation of the results obtained.

Some latest cutting-edge technologies, like laser induced breakdown spectroscopy or LIBS, are not discussed here as, at least up till now, they were only developed by few research laboratories are not in common use in the nuclear industry.

1.3 Use of the document

Figure 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 to be interpreted as absolute or strict requirements. The reader need not expect that every of these recommendations have to be taken literally and to be applied to their own case studies.

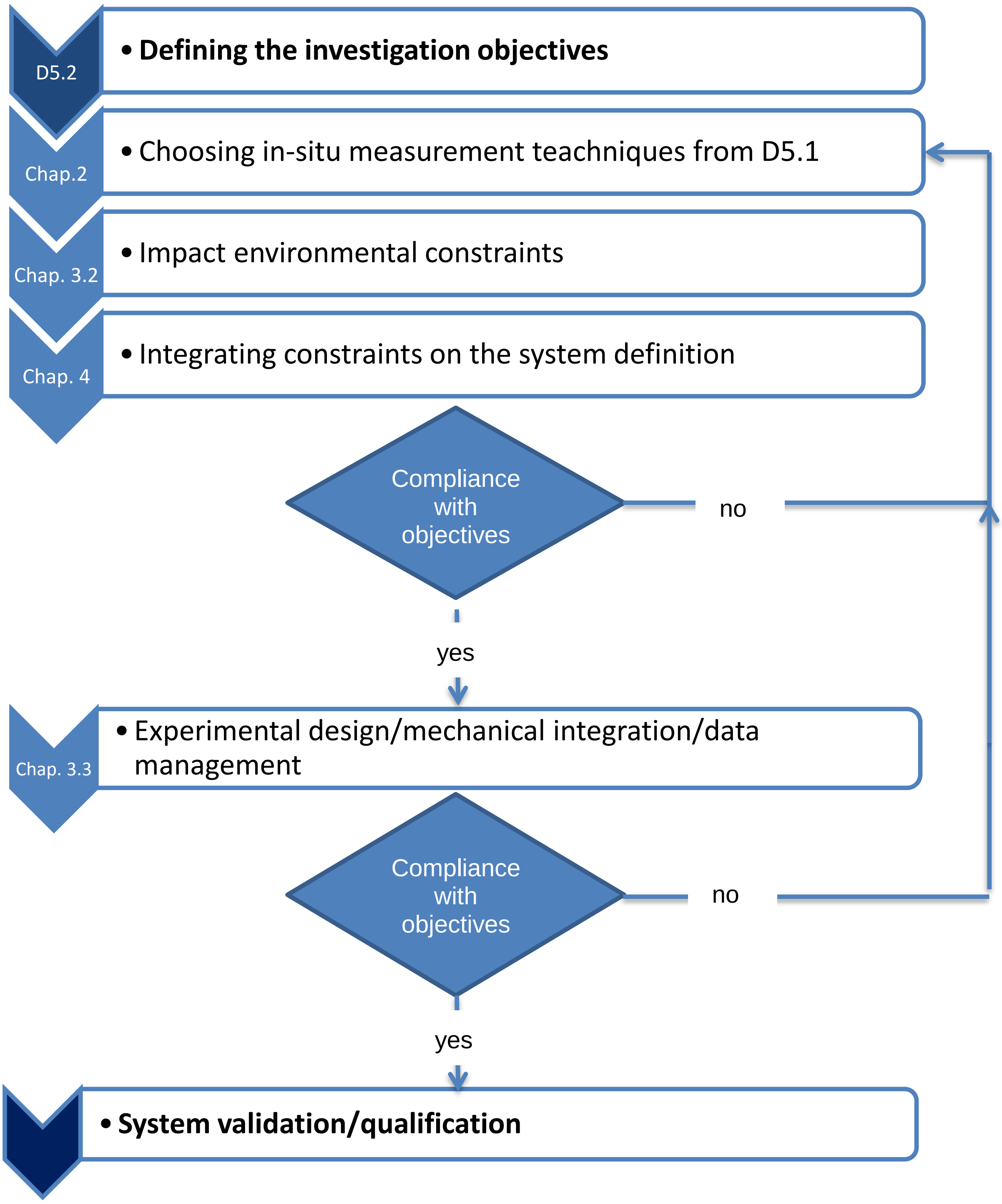

Figure 1: Simplified flow diagram illustrating the minimum arrangements for the deployment of appropriate in-situ measurement techniques for each constrained environment.

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

As stated in deliverable D2.2 of the INSIDER Work Package WP2, in-situ measurements together with laboratory analysis of representative samples are of vital importance all along the different phases of a D&D programme. It must be noted that, for a specific area, the existing constraints (see deliverable D5.2) 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 in the beginning and should decrease during the remediation phase until almost disappearing at 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 fissile mass quantity and/or radioactive level of existing waste. Radioactive in-situ measurements, especially dose rate and total gamma strengthened with some in-situ gamma spectrometry or neutron assay, are needed. Gamma-spectrometry helps modelling the whole scene under measurement in a way to improve theoretical predictions, using mathematical and geometrical analysis, while structures or systems are complex, producing accurate models is a hard process. Table 1 outlines the different studies carried out during this phase as well as their associated investigation objectives and recommended instrumentation tools.

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

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 measurement techniques.

2.2 Intermediate - Remediation phase

If consideration on the primary characterization led 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.

<table>
<tr><th>Type of radioactivity</th><th>Recommended
in-situ measurement technique</th></tr>
<tr><td>Non contaminated surface</td><td>None</td></tr>
<tr><td>Contaminated surface by “dry” contamination (dust, aerosol)</td><td>Surface contamination measurements</td></tr>
<tr><td>Contaminated surface by “liquid” contamination with no “deep penetration”</td><td>Surface contamination measurements
Environmental radiation measurements
Gamma spectrometry</td></tr>
<tr><td>Contaminated surface by “liquid” contamination with deep structural penetration</td><td rowspan="2">Gamma spectrometry</td></tr>
<tr><td>Activated inner walls</td></tr>
</table>

Table 2 : Recommended in-situ measurements techniques for each types of radioactivity during both the intermediate and final phases 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. That is both the considered site and its near environment is fully cleaned up to a predetermined endpoint (unrestricted release or further reuse), from any dangerous and radioactive substance. Therefore, the latest objective regarding radiological characterization must be the evaluation of the eventual presence of residual radioactivity in the remaining areas and ancillary buildings as well as underground contamination. Such an objective ultimately enables 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, providing the lowest detection limits and best efficiency.

3 Integrating constraints on the system definition

3.1 Decision process

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 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 (Westall and Tawton, 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, all of them can be referred to as “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.

Figure 2 summarizes the whole decision process that must necessarily be taken into account to properly define in-situ measurement techniques and methodologies, starting with the characterization objectives. All these identified constraints, as well as the followed principles in such decision process, are explained in more detail in deliverable D5.2, from which only the most relevant aspects may be reproduced in this document.

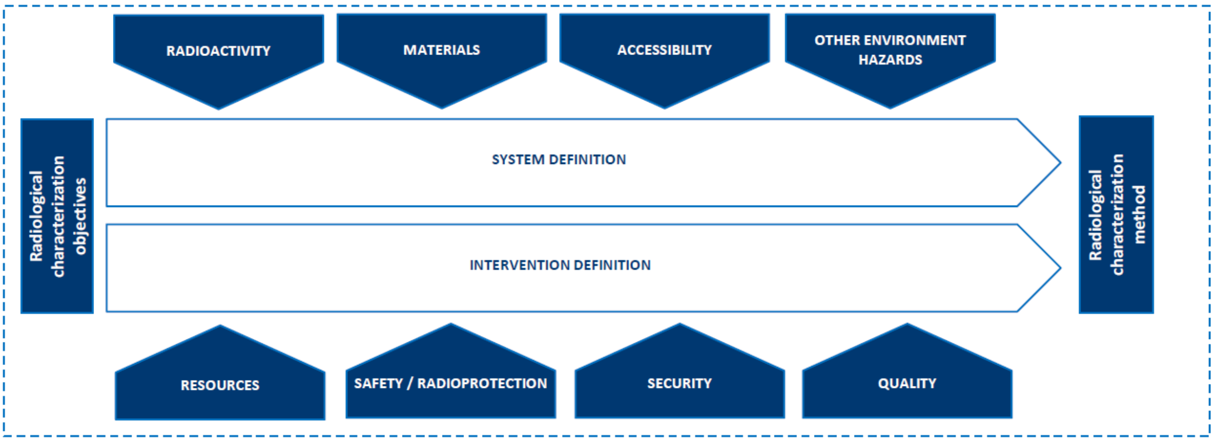

Figure 2: From investigations objectives to investigation methods

3.2 Impact of environmental constraints

Table 3 gives a broad indication on the incidence of the major environmental constraints over the existing measurement equipment based on insights 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

Environmental constraint / Equipment	***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*	0*	0	NA	0*	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 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**	1-3**	1-3**	3
Radiation cameras	0-1**	2	1	2	0	1	0	NA	0	0	0	1-3**	1-3**	1-3**	3

*: in the case of air-kerma measurements associated correction factors must be applied (see deliverable D5.1)
**: depending on the type and/or the size of the instruments used

Table 3 : Impact of environmental constraint on in-situ measurement techniques

Chapter 4 formulates some recommendations that need to be considered for the appropriate choice of the instruments and the technical issues the investigation methodology has to stand for in regard to every nuclear facility area at where each of the major identified constrained must be overcome. Although the possible presence of others hazards, like chemical and/or biological ones, basically only affects the human intervention scenarios, some recommendations regarding such a subject are also given in this chapter.

3.3 Conception methodology

Albeit being independently organized, the three design principles of system engineering as illustrated in Figure 3 are to be integrated into a global design process of in-situ measurements. Of all existing possibilities, only those that meet the identified field needs and requirements should be chosen.

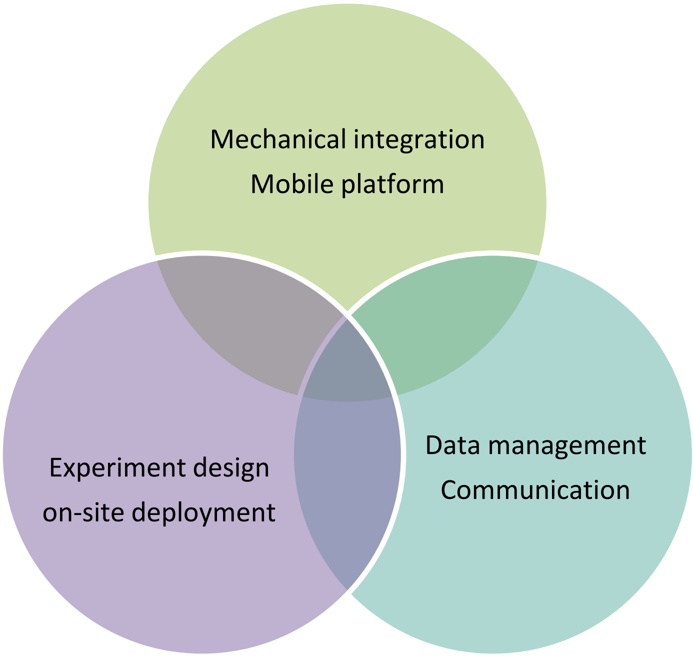

Figure 3: Design principles of system engineering applied for in-situ measurements.

3.3.1 Experimental design

Experimental design is firstly based first on the characterization 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 own 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 term.
- The choice of the measurement configuration that take 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, already identified in deliverable D5.2, without forgetting the required particular dispositions that have to be integrated on a case-by-case basis (see Chapter 4 for more detail).

3.3.2 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, 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.

Several other factors related the system reliability, availability, maintainability and safety must also be taken into account. In practice, reliability depends on both the system complexity as well as on 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 at the strict minimum the overall frequency of unwanted failures during the operational phase.

3.3.3 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 data management should 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. After 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),
- can operate in electromagnetic sensitive areas (not even the cause of such interferences),
- 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 to environmental measurements of the X/γ radiation. As explained in the deliverable D5.1 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/radioactive facilities subject to a D&D programme.

DETECTOR TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
Ionisation 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 • generally good dynamic range of dose rates, typically 2 µSv/h 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/radioactive facility areas and equipment except the ones under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)
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 usable 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/radioactive facility areas and equipment except the ones under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)

Energy-compensated GM detectors	• very easy to process signal • with more or less (± 30%) a 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/radioactive facility areas and equipment except the ones with pulsed fields or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)
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/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)
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	• almost all nuclear/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)
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/radioactive facility areas and equipment except the ones under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)

Table 4 : Strengths and weaknesses of the common detectors used for environmental radiation measurements as well as their recommended applications in nuclear/radioactive 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 environment is very challenging when using gas-filled detectors and can affect measurements in several ways, such as for instance 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 to be very careful in the choice of its intrinsic or setting parameters (i.e., operating voltage, temperature and gas pressure) as well as 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 their characteristics compromised thus leading to a drastic decrease of 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 radiation 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 provide 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 hence 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.

The complementary deployment of a remotely (either wired or wireless) deployed 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 must always consider several correction factors, 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.

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 (see the deliverable D5.1, Appendix A) are defined and calibrated considering only a free-in-air geometry configuration.

On the other hand, in coherence of what has been said in the previous Section, another correction factor must be applied when measuring air-kerma in 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 own properties of the measured object as already stated in Section 3.3.1, and on the considered geometric configuration of the whole scene under study. They hence need a series of theoretical simulations in a way to calculate *ad hoc* transfer functions and to well 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 become 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 although it is not complete enough, and their plausibility has to be checked by comparing each time the associated results obtained from at least two different in-situ measurement techniques.

4.1.3 Accessibility constraints

4.1.3.1 Narrow or clutter spaces

The possible deployment of a remotely (either wired or wireless) mobile platform, such as a robot or drone, based on reduced-size detectors and equipped with the necessary sensors (position, motion, inclination, proximity), may confer to the whole system extra capacity to go through narrow spaces, to claim stairs or steep slopes and to cross between obstacles (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 well address these kind of problematic aspects, it may be helpful to consult the review endeavoured 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 used 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 along deeply contaminated areas or soils may be very suitable in the first instance 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 emitting radionuclides.

4.1.4 Other hazards

The deployment a unmanned mobile platform, such as a robot or drone, can also be of great utility to well 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 an extreme attention must be paid to the ones hermetically sealed with plastic materials or using a thin end-window, in order to measure measuring weakly penetrating radiation.

4.2 Surface contamination measurements

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

DETECTOR TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
Solid state detectors	• very good detection efficiency • very 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/radioactive facility areas and equipment except the ones with electromagnetic interference or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • 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/radioactive facility areas and equipment except the ones under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • 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	• sensitive to high magnetic fields, unless filled with a mu metal screen • 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/radioactive facility areas and equipment except the ones with high magnetic fields or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • 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/radioactive facility areas and equipment except the ones with high rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • considering only smooth and impermeable surfaces
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/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • considering only smooth and impermeable surfaces

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/radioactive 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 • inefficient response to low-energy X/γ radiation, helping to minimise background • window easily replaced • lightweight • easy setting up procedure	• susceptible to magnetic interference, this may be a big issue • 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/radioactive facility areas and equipment except the ones with magnetic interference or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • 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/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • considering only smooth and impermeable surfaces
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/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • 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	• 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/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • considering only smooth and impermeable surfaces
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/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • considering only smooth and impermeable surfaces

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/radioactive 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/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • 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/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2) • considering only smooth and impermeable surfaces

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/radioactive facilities subject to a D&D programme.

4.2.1 Radioactivity constraints

4.2.1.1 Radiation

Proportional counters, which are commonly 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, radioactive contamination on surfaces can hardly be evaluated by direct methods. The only way in this case would be by taking a smear sample from each suspected contaminated surface, with 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 classified as conventional waste.

4.2.1.2 Contamination

Surface contamination measurements need to be as close as possible (~1 cm) 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, a soft barrier must be considered to allow the particles to enter the active region of a detector, while simultaneously protecting this active region. Most times, a detector with an ultra-thin end-window, made of an aluminized Mylar or mica film (~2 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 a concrete walls, 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 (in no way a drone for the same raisons 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 Spectrometry

Table 8 summarizes the strengths and weaknesses of the common γ-spectrometry detectors as well as their recommended applications in nuclear/radioactive 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.

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 • sensitive to neutrons • pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	• almost all nuclear/radioactive facility areas and equipment except the ones with high dose rates, excessive room temperature variations, or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)
BGO detectors	• better detection efficiency than NaI(Tl) • non-hygroscopic material • hard and rugged	• poor energy resolution (~10% @ 662 keV) • do not tolerate temperature variations • sensitive to neutrons • pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	• almost all nuclear/radioactive facility areas and equipment except the ones with high dose rates or room temperature variations (see tables 3 - 6 in deliverable D5.2)
$LaBr_3$(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 • sensitive to neutrons • pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	• almost all nuclear/radioactive facility areas and equipment except the ones with high dose rates, excessive room temperature variations, or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)

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/radioactive facility areas and equipment (see tables 3 - 6 in deliverable D5.2)
CdTe detectors	• good energy resolution (~0.6% @ 662 keV) • allow ultra-compact 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/radioactive facility areas and equipment (see tables 3 - 6 in deliverable D5.2)
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/radioactive facility areas and equipment except the ones with narrow spaces, high dose rates, excessive room temperature variations, or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)

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

4.3.1 Radioactivity constraints

4.3.1.1 Radiation

4.3.1.1.1 Identification of constraints

When a given gamma spectrometer is exposed to intense radiation fields dead time and pulse pile-up effects may occur (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 cause several intrinsic defects and/or failures (lattice displacements, deep-level traps, glitches, parasitic structures, single events, etc.) in semiconductors and associated electronics affecting in this manner their detection properties.

Dead-time and pulse pile-up effects are well-recognized drawbacks and 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 (Knoll, 2010; Tsoulfanidis and Landsberger, 2015). Furthermore, 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 at high dose rates, implying high levels of counts under the total absorption peaks corresponding to the radionuclides of interest. Interference phenomena can also be observed 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 therefore can prevent the emergence of some peaks, from the analysed radionuclide 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.

4.3.1.1.2 Integration of constraints on the instrument design

Dedicated digital signal processing equipment and algorithms can be used to automatic 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 king 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 to correct for such defects.

4.3.1.1.3 Integration of constraints on the final mechanical design

In any case, it cannot be excluded 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.

Furthermore, as already stated before for other measuring equipment, the complementary deployment of a remotely (either wired or wireless) deployed mobile platform, such as a robot or drone, 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 has 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 on real necessity among the rest of its refrigeration options.

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

Several inorganic crystal detectors, like NaI(Tl) and $LaBr_3$(Ce), may show a gain drift due to temperature variations (see Table 8). In fact, they are usually couple 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 last is also prevented in operations at elevated temperatures (Knoll, 2010).

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 spectrum. 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.

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, 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 (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 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 can significantly degrade the scintillation light output and thereby the detection performance.

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.

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).

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 implement with the detector.

4.3.3.3 Subsurface

Section 4.1.3.3 explains the benefits of carrying out preliminary environmental measurements along 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 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.

Even though either scintillation detectors or high resolution germanium detectors are widely used, are somewhat fragile for in-situ measurement in subsurface. For this reason, as CdTe or CZT semiconductors are available in small sizes, they can be very useful for down-hole logging operations, but they have significantly poorer resolution than HPGe detectors (see Table 8). In addition, probes cannot be used where the soil is laden with rocks and boulders due to possible probe or pipe breakage. More rugged scintillation detectors using silicon avalanche photodiode instead of conventional photomultiplier tubes are advisable, albeit with some limitations that currently exist to the small sizes of detectors.

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 practically any of the available radiation detectors can be easily adapted, with the addition of an appropriate converter material, to measure neutrons so that almost all the particular dispositions discussed above (namely those in Section 4.1) are also valid here4.1.1.1.3.

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

DETECTOR TYPE	STRENGTHS	WEAKNESSES	WHERE TO APPLY
BF_3 gas-filled proportional counter, spherical moderator	• reasonably light • near isotropic response • good γ rejection • more readily available than ^3He	• toxic and corrosive • sensitive to movement vibration • limited filling pressure • pulse pile-up effect and gas degradation at intense radiation fields	• almost all nuclear/radioactive facility areas and equipment except the ones with high dose rates (see tables 3 - 6 in deliverable D5.2)
^3He gas-filled proportional counter, spherical moderator	• reasonably light • good detection efficiency • near isotropic response • high filling pressure • resistant to intense radiation fields	• ^3He shortage • expensive • reduced γ rejection • sensitive to movement vibration • pulse pile-up effect at intense radiation fields	• almost all nuclear/radioactive facility areas and equipment (see tables 3 - 6 in deliverable D5.2)
BF_3 gas-filled proportional counter, cylindrical moderator	• reasonably light • good γ rejection • more readily available than ^3He	• non isotropic response • toxic and corrosive • sensitive to movement vibration • limited filling pressure • pulse pile-up effect and gas degradation at intense radiation fields	• almost all nuclear/radioactive facility areas and equipment except the ones with high dose rates (see tables 3 - 6 in deliverable D5.2)
LiI(Eu) scintillator, spherical moderator	• compact design • good detection efficiency • insensitive to motion vibration	• poor sensitivity (~0.2 s^{-1} $\mu Sv^{-1}h$) • an energy response inferior to the cylindrical form • poor γ rejection • variable operating voltage • hygroscopic material • pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	• almost all nuclear/radioactive facility areas and equipment except the ones with high dose rates or under liquid immersion conditions (see tables 3 - 6 in deliverable D5.2)

Table 9 : Strengths and weaknesses of the common neutron detectors as well as their recommended applications in nuclear/radioactive 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

In the case of neutrons detectors, particular attention is 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. Both GRR and GARRn are carried out on the basis of pulse shape discrimination or PSD. This means that if the gamma-ray flux is sufficiently high the PSD efficacy can be reduced. At high dose-rates, pulse pile-up effect can make peak amplitudes from gamma rays becoming considerably larger than any individual neutron pulse, distorting in this manner the above rejection ratios (Knoll, 2010; Kouzes et al., 2010).

In addition, when using BF_3 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).

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) and measuring, once recovered back in a safe room, their associated neutron-induced radioactivity with a conventional instrument.

Another possible solution is the one based on self-powered neutron detectors or SPNDs, which are usually used for in-core monitoring, with 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 varied 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.

4.4.4 Other hazards

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

4.5 Radiation cameras

This section deals only 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/radioactive 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.

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 (≥ 15kg) • 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/radioactive facility areas and equipment except the ones with narrow spaces (see tables 3 - 6 in deliverable D5.2)

Coded aperture	• can be ultra-compact (< 270 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/radioactive facility areas and equipment (see tables 3 - 6 in deliverable D5.2)
Compton	• can be compact (3 - 5 kg) • field-of-view up to 360° • high energy resolution	• low sensitivity • moderate angular resolution (10° - 30°) • cannot be applied below 250 keV • pulse pile-up effect as well as intrinsic defects and/or failures at intense radiation fields	• almost all nuclear/radioactive facility areas and equipment (see tables 3 - 6 in deliverable D5.2)

Table 10 : Strengths and weaknesses of the different γ-camera types as well as their recommended applications in nuclear/radioactive facilities subject to a D&D programme.

4.5.1 Radioactivity constraints

4.5.1.1 Radiation

High radiation levels may also affect the performance of electronic components of the cameras. Changes start taking place inside the device well before it reaches the point of failure. X/γ 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).

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 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

The analysis performed in this document shows that most of the existing constraints impacting the in-situ measurements activities carrying under the D&D programmes for nuclear/radioactive facilities have a solution or have been already considered for the product/system developers and thus, have 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 multiples configurations, all can be applied, depending on constraints and contamination types, for surface contamination measurements.

In the case of in-situ gamma spectrometry measurements, 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. Without forgetting among other of its minor limitations the ones associated with limited accessibility areas. On the other hand, because of the current big gap between the HPGe resolution and that of the others scintillation and solid-state detectors 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 those related to the mechanical integration, latest generation electronics and advanced spectral analysis.

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 are usually used but alternative compact scintillators can also be applied.

Regarding the radiation camera, only the gamma ones have been taken into account in this document, as those able to localize 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 is not already solved either in the design or in its mechanical integration.

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