INTERNATIONAL STANDARD

ISO 18557

First edition
2017-09

Characterisation principles for soils, buildings and infrastructures contaminated by radionuclides for remediation purposes

Principes de caractérisation des sols, bâtiments et infrastructures contaminés par des radionucléides, à des fins de réhabilitation

Reference number
ISO 18557:2017(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Sub-committee SC 5, *Nuclear fuel cycle*.

Introduction

The remit of WG 13 covers all aspects of the decommissioning phase, and thus it interfaces with other Sub-Committees and Working Groups whose work intersects with this phase.

Figure 1 below indicates some of the topics that could be included in SC 5 and/or WG 13. It provides a view of how the scope of this ISO Standard links with both generic and more detailed topics.

This document contains both guidance and references to documents which may be useful in relation to this work area. Read in conjunction with the supporting references, it gives a generic approach to the topic. It also may have connections with many other blocks across the whole diagram (e.g. Decommissioning strategy, Waste Management, Site remediation, Dismantling/Demolition, Cost issues, Safety).

Moreover, it was not intended to establish this document as a stand-alone document. When a member country already has national tools in this field (e.g. regulatory requirements, national standards), these requirements and national standards are applicable in conjunction with this document.

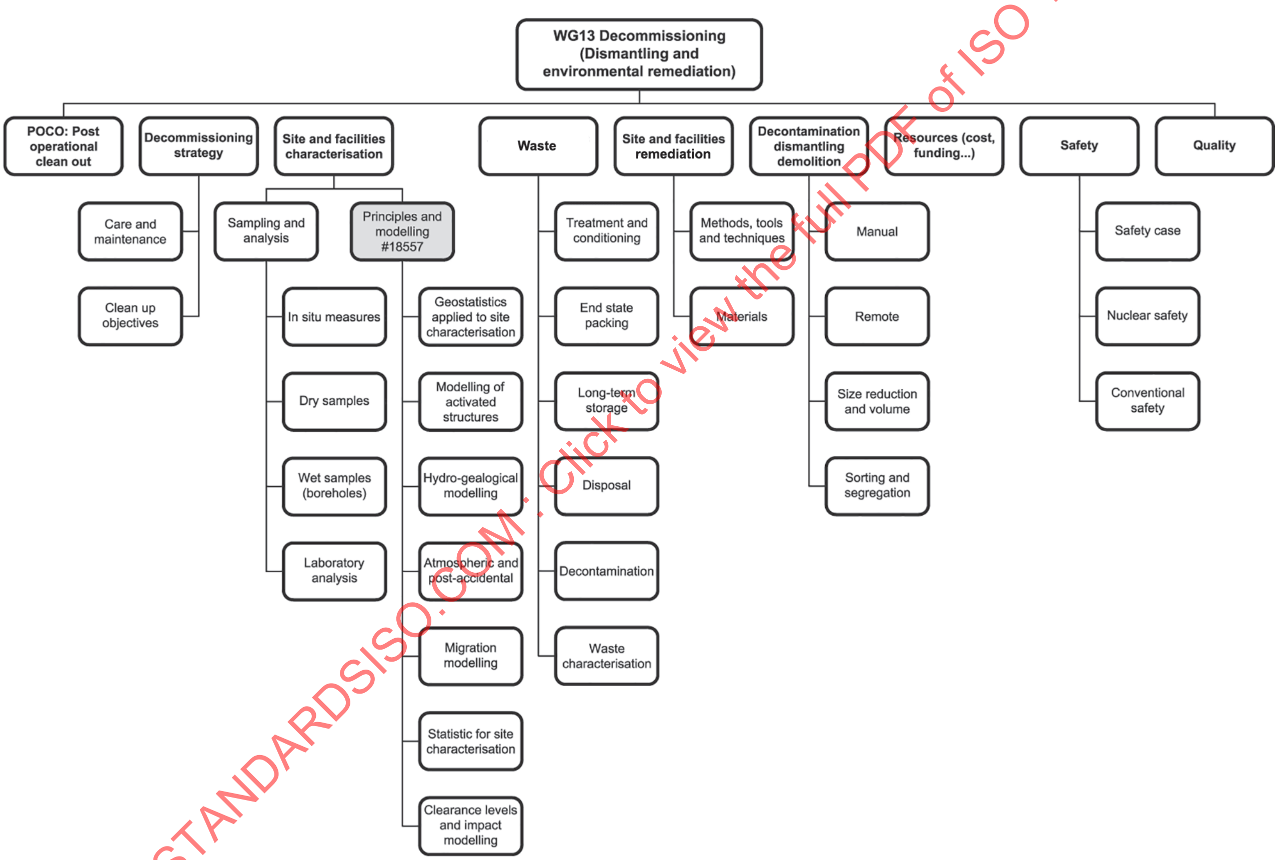


Figure 1 — Indicative chart of the topics included in WG 13, showing how this document is linked to other topics

This work stream structure can be used to clarify the scope of WG publications and to ensure that areas of joint interest between ISO teams and working groups are coordinated. The ISO shadow committee for a member body identifies proposals for further work and, if appropriate, submits them to the Working Group for international consideration as potential new work items. Figure 1 can be a useful prompt in this process. This document is part of an overall decommissioning and environmental remediation strategy including, for example, the monitoring and/or remediation of groundwater which might be addressed in a new work item.

Since the discovery of radioactivity at the end of the 19th century, numerous laboratories and facilities have dealt with radioactive substances (notably radium). In addition, the development and considerable expansion of the nuclear industry, both civilian and defence, has generated many nuclear facilities built since the 1940s, resulting today in legacy sites.

More recently, nuclear operators and state organisations have intensively undertaken the dismantling and remediation of shutdown nuclear facilities. Remediation projects also concern former mining sites, other legacy sites and industrial sites having produced NORM (Naturally Occurring Radioactive Material) and TENORM (Technologically Enhanced NORM) waste, where the main issue is the large volume of waste involved. The aim is primarily to demonstrate that the entire nuclear cycle is well managed. A large number of issues need to be considered:

— The nuclear regulatory framework did not exist at the beginning and it has evolved over time (release procedures, health and safety, environmental considerations…). In addition, there is more and more stakeholder involvement today, and this needs to be considered at the early stages of any project.

— The availability of waste management facilities and disposal sites varies between countries and through time. The classification based on activity levels: e.g. very low level waste (VLLW), low level waste (LLW), intermediate level waste (ILW), high level waste (HLW) and nuclide half-lives (short-lived or long-lived radionuclides) impacts remediation projects. These factors sometimes result in the partial clean-up of sites, due to the absence of a final solution for waste disposal. Waste may also have had to be temporarily stored on site for economic reasons.

— Remediation costs and schedules are optimized and rationalized using a graded approach, as these projects are generally expensive and time consuming. They also need to be securely funded and planned.

— In order to optimize waste categories, volumes and costs, characterization is a crucial issue enabling the best knowledge of the radiological state of the site (soils, buildings and infrastructures) to be obtained before making project decisions.

Lessons learned from the first sites to be remediated have demonstrated that poor characterization (based on incomplete historical information and too limited a number of data points or samples) strongly impacts the success of a remediation project, with inappropriate choices having been made (over-estimation of volumes and over-categorization of waste, unexpected contamination).

As a consequence, it is now recognized that accurate characterization is the key to successful dismantling and remediation projects. There are many characterization steps necessary throughout a project, each with specific objectives.

The main potential improvement concerns the sampling effort, sample representativeness and assessment of activity levels assessments. Combined with data analysis and processing, all the uncertainties involved are combined to deliver a result with a corresponding confidence interval. Therefore the characterization strategy and programme should be set well before the actual measurements, to ensure efficiency.

The preparation of any nuclear facility's remediation programme requires knowledge of its operational history. This covers the entire period from design, licensing and through to final shutdown, in order to establish the nature and location of potential or known radioactive contamination, together with possible associated chemical products, with the appropriate accuracy. The overall remediation strategy requires an estimation of the quantity and the volume of waste to be produced, and an assessment of its level of contamination. This enables appropriate optimized waste management.

In addition, a final characterization is compulsory for sites to be released and/or re-used in order to demonstrate compliance with remediation objectives (clearance levels, if any, or a release threshold set by, or agreed with, the regulatory body).

This document outlines the principles of characterization for remediation purposes of soils, buildings and infrastructures contaminated by radionuclides and possible associated chemical pollutants.

As the preparation of a sampling plan is an iterative process, decision-taking steps will be defined throughout this document taking into account constraints imposed by operations, budgets and regulations, while respecting the ALARA and ALARP principles.

The application of this methodology will aid the user to obtain the information necessary for compiling the files associated with remediation operations, as required by the regulatory authorities. It is applicable to each of the steps necessary for the remediation of sites, depending on the objectives (release into the public domain, re-use). It can enable an assessment to be established for contaminated soils, or in preparing to carry out post-remediation checks (even including the facility's civil engineering structures), in order to confirm that the remediation objectives have been met.

With regards to the recommendations of the International Atomic Energy Agency (IAEA), a graded approach should be considered for the characterization of soils, buildings and infrastructures for remediation purposes. The characterization strategy, programme and planning should be commensurate with the complexity of the remediation problem and with the established end state. A graded approach can limit occupational exposure for workers, as well as saving time and money [ref. IAEA = DeSa project (Evaluation and Demonstration of Safety for Decommissioning of Facilities Using Radioactive Material)].

Characterisation principles for soils, buildings and infrastructures contaminated by radionuclides for remediation purposes

1 Scope

This document presents guidelines for sampling strategies and characterization processes to assess the contamination of soils, buildings and infrastructures, prior to remediation and/or to check that the remediation objectives have been met (final release surveys). The principles presented need to be appropriately graded as regards the specific situations concerned (size, level of contamination…). *It can be used in conjunction with each country's key documentation.*

This document deals with characterization in relation to site remediation. It applies to sites contaminated after normal operation of older nuclear facilities. It could also apply to site remediation after a major accident, and in this case the input data will be linked to the accident involved.

The document complements existing standards, notably concerning sampling, sample preservation and their transport, treatment and laboratory measurements, but also those related to *in situ* chemical and radiological measurements. *References in the Bibliography contain links to appropriate documentation and techniques as required by individual member countries.*

The document does not apply to the following issues: execution of clean-up works, sampling and characterization of waste (conditioned or unconditioned) or to waste packages.

It does not apply to groundwater characterization (saturated zone).

Given the case-by-case nature of site remediation and decommissioning, the principles and guidance communicated in this document are intended as general guidance only, not prescriptive requirements.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
characterization
determination of the nature, concentration and spatial extent of radiological and chemical contents present in a specified place

Note 1 to entry: See also radiological and chemical survey.

3.2
clean-up work
actions taken to reduce the exposure to radiological and chemical substances from existing contamination through actions applied to the contamination itself (the source) or to the exposure pathways to humans and the environment

Note 1 to entry: See also *remediation* (3.22).

3.3
clearance level
release threshold
value, or a set of values, established by a regulatory body and expressed in terms of activity concentration and/or total activity, at or below which a source of radiation may be released from regulatory control

3.4
contaminant
radioactive or chemical substance or agent present in a medium which due to its properties, amount or concentration may have impacts on the environment and human health

3.5
contamination
presence of radioactive or chemical substance or agent in any medium where it is not desired, and which due to its properties, amount or concentration may have impacts on the environment and human health

3.6
cost-benefit analysis
decision aiding tool using a systematic evaluation of the positive effects (benefits) and negative effects (disbenefits) of undertaking an action, integrating technical, time-schedule, management, financial, societal, environmental issues.

3.7
data quality assessment
DQA
process performed once the collected data have been properly verified and validated

Note 1 to entry: In DQA, assessment means evaluation of quality of data that is meaningful only when it relates to the intended use of the data.

3.8
data quality objective
DQO
process used to establish performance or acceptance criteria, which serve as the basis for designing a plan for collecting data of sufficient quality and quantity to support the goals of a study

3.9
destructive analysis
DA
analysis of radioactive and chemical materials using methods which involve the destruction of a sample, e.g. chemical and radiochemical analysis, ICP-MS, alpha spectrometry

3.10
difficult to measure radionuclides DTM
nuclides that cannot be easily measured through their gamma radiation or beta emissions; usually comprise alpha-emitting nuclides without strong gamma lines or pure beta emitters

Note 1 to entry: Examples include ^{3}H, ^{14}C, ^{36}Cl, ^{90}Sr, ^{99}Tc, ^{129}I, ^{238}Pu.

3.11
easy to measure radionuclides
ETM
gamma emitting nuclides whose radioactivity can be readily measured directly by non-destructive analysis means

3.12
fingerprint
nuclide vector
used to infer and quantify the presence of other key nuclides

Note 1 to entry: Applying correlation factors enables estimations of *difficult to measure nuclides* (3.10).

Note 2 to entry: It is a method which involves measurements of *easy to measure radionuclides* (3.11) (usually gamma emitters, e.g. ^{137}Cs, ^{60}Co) to quantify *difficult to measure nuclides* (3.10).

3.13
geostatistics
statistical methodology based on the use of spatial correlations between couples of measured values, which produces interpolation maps by the kriging technique

Note 1 to entry: The added value of geostatistics lies in the quantification of the result uncertainty and its more advanced techniques (non linear, non stationary, multivariate…).

3.14
graded approach
application of safety requirements that is commensurate with the characteristics of the practice or source and with the magnitude and likelihood of the exposures

Note 1 to entry: The use of a *graded approach* is intended to ensure that the necessary levels of analysis, documentation and actions are commensurate with, for example, the magnitudes of any radiological hazards and non-radiological hazards, the nature and the particular characteristics of a *facility or site*, and the stage in its *lifetime*.

3.15
health impact assessment
combination of procedures, methods and tools by which a policy, programme or project may be judged as to its potential effects on the health of a population, and the distribution of those effects within the population

3.16
infrastructures
all ancillary equipment and facilities providing necessary support to the operation of a nuclear facility or site: e.g. sewage network, roads. but also heavy equipment which might be disposed of as waste or re-used after clean-up, such as bridge and portal cranes

3.17
in situ measurement
field measurement
measurement where the detection instrument is taken to the material: it is a non-destructive measurement

3.18
judgement assessment
measurements performed at locations selected using expert judgment based for instance on unusual appearance, location relative to known contaminated areas, high potential for residual radioactivity, general supplemental information.

3.19
mapping
representation of 2D or 3D objects

Note 1 to entry: Background layers consist of aerial or satellite images as well as vectorial maps. Measured data are represented in the form of a map (points, colourscale, size, symbol…). It also integrates 2D and 3D grid results (e.g. isocontours, slices, selection).

3.20
non-destructive analysis
NDA
number of analytical techniques that allow measurement of specific properties without physical destruction of the media/item

Note 1 to entry: Generally used for *in situ* measurements.

3.21
radionuclide
RN
nucleus (of an atom) that possesses properties of spontaneous disintegration (radioactivity)

Note 1 to entry: Nuclei are distinguished by their mass number and atomic number.

3.22
remediation
measures taken for contaminant removal, containment or monitored non-intervention at a contaminated site to reduce exposure to radiation, and for improvement in the environmental and/or economic value of the contaminated site

Note 1 to entry: to entry**:** Remediation of a site does not necessarily imply a restoration of the site to pristine condition.

3.23
remediation objectives
generic term for any objective, including those related to technical (for example residual contamination concentrations, engineering performance), administrative and legal requirements

Note 1 to entry: to entry**:** The future site end-use assumption forms the basis of remediation objectives and is used in developing the strategy for the decommissioning and remediation activities.

3.24
sample
set of individual physical portions or measurements drawn from a population whose properties are studied to gain information about the entire population

Note 1 to entry: to entry**:** The manner the sample is selected should be described in the *sampling plan* (3.27).

3.25
laboratory sample
sample intended for laboratory inspection or analysis

Note 1 to entry: When the laboratory sample is further prepared (reduced) by subdividing, mixing, grinding, or by combinations of these operations, the result is the test sample. When no preparation of the laboratory sample is required, the laboratory sample is the test sample. A test portion is removed from the test sample for the performance of the test or for analysis.

Note 2 to entry: The laboratory sample is the final sample from the point of view of sample collection but it is the Initial sample from the point of view of the laboratory.

Note 3 to entry: Several laboratory samples may be prepared and sent to different laboratories or to the same laboratory for different purposes.

3.26
sampling
act of taking or constituting (and preparing) a sample, in the aim of investigating a whole population

Note 1 to entry: For the purpose of soil investigation, "sampling" also relates to the selection of locations for in situ testing carried out in the field without removal of material.

3.27
sampling plan
detailed outline of which measurements will be taken, typically detailing at what times, on which material, in what manner, and by whom

Note 1 to entry: Sampling plans are designed in such a way that the resulting data will contain a representative sample of the parameters of interest and enable all questions, as stated in the goals, to be answered.

Note 2 to entry: The steps involved in developing a sampling plan are typically:

a) Identify the parameters to be measured, the range of possible values, and the required resolution.

b) Design a sampling scheme that details how and when samples will be taken.

c) Select sample sizes.

d) Design data storage formats.

e) Assign roles and responsibilities.

Note 3 to entry: This includes which surveys will be done, which samples will be taken, and how they will be collected, prepared and measured (e.g. sampling point, time of collection, depth of sampling, and other variables necessary to carry out a measurement of a specific sampling location in time and space).

Note 4 to entry: The plan may specify, for example, that the sampling is systematic and in two stages. In combination with the specification of the type of sampling, the sampling plan in this example also may specify the number of increments to be taken from a lot, the number of composite samples (or gross samples) per lot, the number of test samples per composite sample, and the number of measurements/tests per test sample.

3.28
probabilistic sampling
sampling conducted according to the statistical principles of sampling, to ensure that each particle or element in the population submitted to sampling has an equal chance of being part of the sample

Note 1 to entry: Probabilistic sampling results in boundary conditions for the type of sampling equipment used, the method of sampling (where, when, how) and the minimum size of increments and (composite) samples.

3.29
site
any installation, facility, or discrete physically separate parcel of land, or any building or infrastructure or portion thereof, that is being considered for survey and investigation and if necessary, remediation

Note 1 to entry: It includes soils, buildings and infrastructures (excluding surface and groundwater).

3.30
radiological survey
chemical survey
type of survey that includes facility or site sampling, monitoring, and analysis activities to determine the extent and nature of *contamination* (3.5)

Note 1 to entry: Characterization surveys provide the basis for acquiring necessary technical information to develop, analyse, and select appropriate cleanup techniques.

Note 2 to entry: See also *characterization* (3.1).

3.31
variogram
semi-variogram
measure of spatial variation of a variable

3.32
zone of interest
area of interest
area where *contamination* (3.5) is suspected after historical analysis, functional analysis or preliminary *characterization* (3.1)

4 Strategy applied to the remediation of contaminated sites

4.1 Principle

This clause focuses on the needs of project managers dealing with the remediation of contaminated sites. Its objective is to give a global overview of the different characterization steps. The main goal remains sound assessment of activity levels from the selection step for a remediation strategy and through to the final release of the site.

For the different characterization steps, data quality objectives (DQO) and data quality assessment (DQA) or similar should be defined and used to ensure efficient characterization.

Figure 2 shows the characterization strategy logic diagram for soils, buildings and infrastructures contaminated by radioactive substances and associated chemicals.

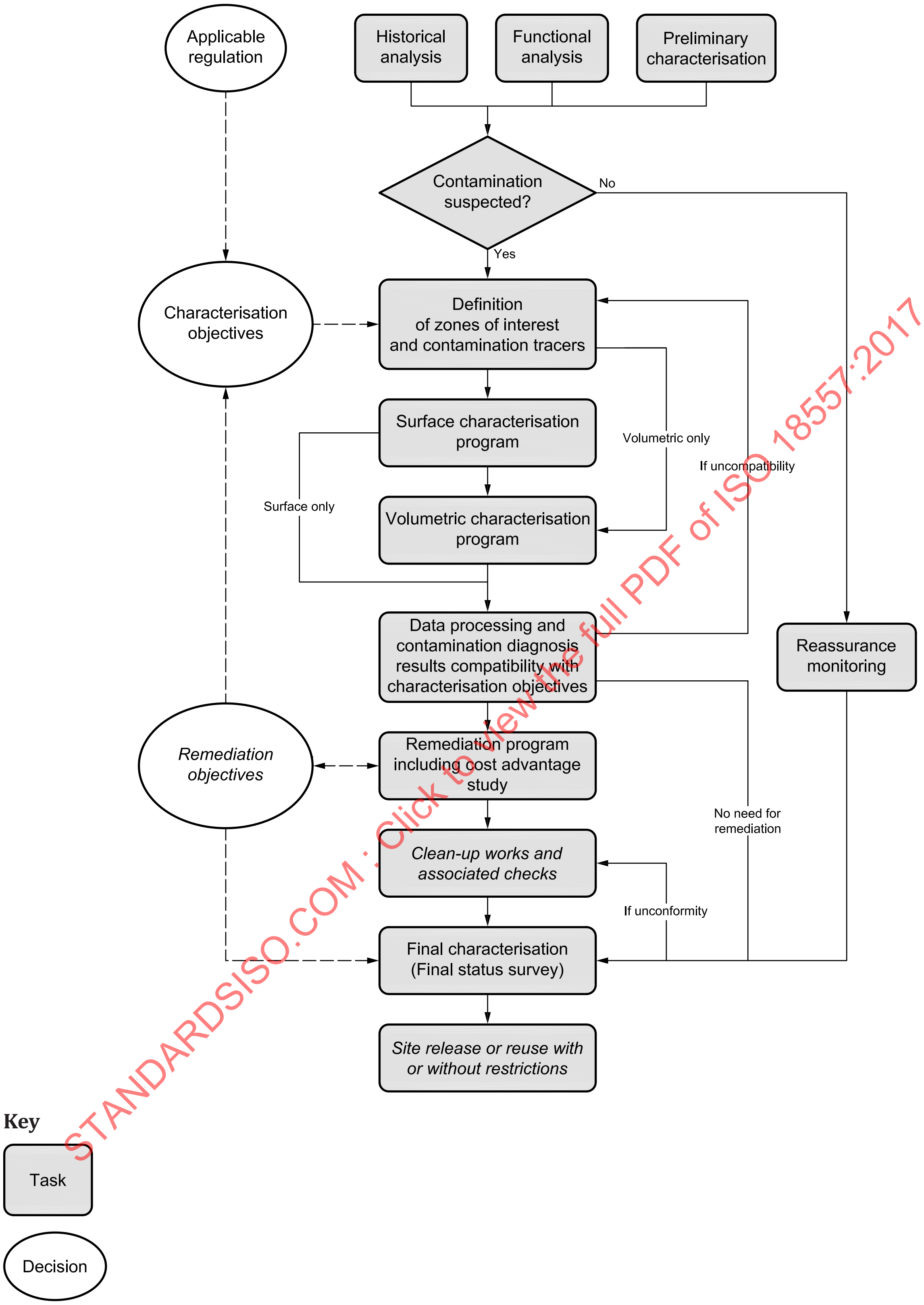


Figure 2 — Characterization strategy workflow applied to the remediation of sites contaminated by radioactive substances (and possible associated chemical substances)

4.2 Characterization and remediation objectives

Knowledge of the physical and radiological condition of sites and facilities is the most challenging characterization objective for operators, contributing to plans for appropriate graded actions to be carried out when the time comes for remediation and dismantling. This objective may concern a whole site or only part of it.

Remediation or decontamination objectives should be defined or determined in accordance with the different national regulations. These objectives can be the final criteria for site release or building decommissioning. They are generally derived from dose risk assessment, taking expected reuse into account. They may be set by regulations (clearance levels) or negotiated case by case.

As well as contributing to meeting remediation objectives, characterization may also be necessary for other specific objectives, for example Health and Safety requirements and their impact on clean-up and dismantling work areas, the estimation of contaminated volumes in order to determine the amount of radioactive waste to be sent to a storage or a disposal facility, obtaining input data to carry out a radiation protection or environmental impact study, or, to help estimate remediation costs. At the end of the remediation process, the goal of the characterization carried out during a final release survey is to demonstrate that the remediation objectives of the clean-up of all or part of a site have been reached.

Thus, characterization may need to address some or all of the following objectives:

- determination of the radiological fingerprint and chemical composition,
- identification of areas as regards their radiological/chemical characteristics and impacted media,
- determination of the spatial extent of contamination in all the facility structures, systems and components, as well as the soils around the facility itself and possibly outside the nuclear site,
- determination of the radiological and chemical background around the site,
- verifying results of the numerical model calculations (e.g. activation, migration or diffusion),
- identification and quantification of radionuclides which are difficult to measure,
- helping in modelling the dose calculations, in order to determine the remediation criteria for buildings and soils,
- helping in selecting decontamination or remediation techniques,
- determination of doses likely to be received by personnel during clean-up and dismantling,
- quantifying the radiation protection actions needed for the dismantling and clean-up work,
- waste categorization in order to decide on its treatment/conditioning, packaging, shipment options and management route (clearance, recycling, reuse, storage, disposal),
- estimation of the dismantling and remediation costs,
- determination of the dismantling and remediation actions to be undertaken,
- determination of any possible easements needed depending on the final facility or site condition,
- demonstration that the remediation objectives have been met,
- giving formal input to the documentation to be used for final approval/decisions

A characterization should always meet well-defined objectives. This ensures that a robust decision can be taken as regards the final facility or site condition. Unclear objectives may result in useless data or over-characterization.

4.3 Historical analysis

The historical analysis should consider:

— the site context (e.g. geology, hydrogeology, occupations in the surroundings),

— the different industrial activities or operation processes implemented over the years,

— any incidents that occurred during operation (on site and off site) and their consequences.

Knowledge of these aspects is critical in order to be able to identify zones of particular interest for the characterization process.

Gathering historical data with information gained through functional analyses, process knowledge and preliminary characterization results forms the basis of the workflow input data.

The historical analysis report will describe (list, maps...) all possible radiological hazards and potential contamination.

It gives priority to documentary archives, particularly the regulatory and administrative texts available as well as process and operational records. It should cover a period which is sufficiently long to give an overall understanding of the contaminating substances on the site. It may also be based on the testimony of employees who were connected with the site operations.

In the absence of comprehensive historical information, more substantial characterization may be considered.

4.4 Documents

Document sources for historical analysis include namely the safety reports, process design and process evolution, the operation and effluent release authorization permits or licence, the radioactive source holder permit(s). Research on these documents is guided by the modifications which will have taken place at each major period during a facility lifetime.

Other documents will be consulted to constitute a file of the plans and topographical documents, showing the borders of the blocks of land and mentioning for instance the existence of any possible easements, incident reports. They may be completed by industrial property titles. Historical aerial photographs are a very useful source of information, as they help to confirm or to identify the location or purpose of past buildings, storage areas, digging works or underground structure locations to help compensate for what has never been written or has been forgotten.

A thorough review of these documents provides useful data to assess the knowledge of past events including possible contamination, and the consequences for the facility functioning.

Research may also focus on climatic events and natural catastrophes, which could have impacted the site permanently or temporarily concerning operations, environmental factors and possible transfers to the environment.

Consultation of industrial facility operation and maintenance documents will also give relevant input data. For example, information about changes made to surface coating/paint will have an impact on the possibility of local subsurface contamination.

Other elements can be obtained by consulting the register of monitoring environmental information or dose rates compilations.

4.5 Interviews

The two main goals of interviews are first, to confirm and improve the documentation analyses and second, to obtain additional information about non written practices or incidents.

Any accident or incident should be considered carefully, based on archive studies or if necessary by interviewing witnesses who may be able to provide relevant information.

The interviews may also provide further information identifying additional zones of interest.

4.6 Functional analysis

A functional analysis is the necessary complement to a historical analysis.

Its objective is to review the different industrial processes implemented on the site, in order to know the radionuclides and the chemical substances that have been used and their estimated quantities and locations. This gives rise to a qualitative and quantitative inventory of the radioactive substances and chemical products or reagents likely to be present in significant quantities.

Most of the information will be contained in the description of the facility, the process record books or in any synthesis document containing facility functioning and quantitative data, as well as the detailed equipment specifications. For example, it is important to know if pipes had single or double casings, in order to determine their leak risk.

This analysis will also examine changes or modifications to the process or the spatial organization, as well as possible operating incidents likely to have induced contamination.

Among the important aspects to cover are the locations of storage zones for raw materials, finished products, and for waste and operation residues, as well as the transfer pipe systems and drainage networks.

4.7 Preliminary characterization

A preliminary characterization associated with a site visit is fundamental in order to check the conformity of the data gathered from the historical documentation and functional analysis. The preliminary characterization should also consider surrounding areas that are linked with past site configuration.

Several visits may be necessary. During this step, a preliminary characterization should be carried out based on a few *in situ* measurements (including at least dose rate, gross beta and alpha counting) and on some surface samples to be analysed in laboratory. On-site laboratories or mobile laboratories are becoming more widely used, making it possible to perform preliminary characterization (as well as final characterization) by non-destructive assays (dose rate measurements, gamma spectrometry), as well as radiochemical measurements. These reinforce the preliminary characterization and facilitate further characterization steps.

The decisive criteria for the choice of measurement methods (e.g. activity level, dose rate, concentration) in qualitative and quantitative terms should be defined taking into account the historical and functional analyses.

The preliminary characterization is intended to confirm the potential presence of any radionuclides or contaminants and to give a basic estimation of their activity or concentration. This gives a first indication of the nuclide fingerprint.

The points where samples should be taken or dose rates measured are defined on the basis of an expert judgment depending on site characteristics, available data and the targeted objectives. They are generally localized in the areas where contamination is most expected (incident, accumulation points…). There is guidance available on sampling, see 5.2, Annex A and Bibliography.

4.8 Definition of the zones of interest and contamination tracers

The goal here is to make an inventory of areas where potential contamination may exist.

It should be based on the results of the historical and functional analyses and include data from the preliminary characterization, indicating the location and the nuclide activity levels of each zone.

Attention should be paid to nuclide fingerprint evolution with time (radioactive decay) notably when choosing the tracer to measure (generally a gamma emitter). Chemical tracers may also be considered if relevant.

The perimeter should address both horizontal and vertical extension, even if it can sometimes be limited to a surface area. As site fences or storage areas may have changed, it is necessary to delineate the area to be investigated based on prior knowledge from historical and functional analyses.

Analysis of input data enables the definition of one or more "suspected contamination zones" which may contain surface and/or in-depth contamination.

Depending on the number of zones identified, a hierarchy can be established on the basis of a multi-criteria analysis (reliability and/or absence of data, nuclear safety, radiation protection and personnel safety, transfer to the environment, etc.).

The study may also identify a lack of information (insufficient quantity or quality) that will impact further characterization steps, and thus require extra efforts.

4.9 Surface and/or volumetric characterization program

Based on the characterization objectives, the characterization programme integrates all information coming from the historical and functional analyses, the preliminary characterization and the definition of the zones of interest and contamination tracers. Poor historical and functional analyses (due to a very limited amount of documents and data for a very old site, for example) usually mean a more significant characterization campaign is needed. However, due to various constraints (budget, planning, worker protection…) a defined optimum (reasonable) amount of quantitative data should be obtained to avoid having useless data or over-characterization.

The specifications should define the surface and/or volumetric characterization programme and the data processing method. The implementation of a characterization programme associated with a sampling plan means it is possible to create a model to determine the qualitative and quantitative distribution of contaminants by zones. This enables a project manager to take the required decisions with a reasonable confidence level.

Usually, the characterization programme starts with surface characterization of the site, as these measurements are cheaper and quicker to carry out than volumetric investigations.

This will enable a first assessment of the surface contamination inventory, and may also reveal new zones of interest. If necessary, this step can be completed by a volumetric characterization. Should buried contamination be suspected from information gathered during the historical and functional analyses, volumetric characterization will be essential. The initial surface step may confirm the absence of surface contamination in that particular case.

Different sampling strategies (screening, random sampling, regular grid sampling, judgmental expertise) should be combined to provide relevant and representative results. The sampling should generally take place in different campaigns, as an iterative process has been shown to be the best available practice. It permits optimization of the sampling effort based on prior information and the results already collected.

The characterization and sampling programme should specify the methods to be used, and define the numbers and locations of *in situ* measurements (non-destructive analysis) and of samples intended for laboratory analysis (destructive analysis). This programme should ensure that the characterization data available (e.g. analysis results, dose rates, gross alpha and beta counting) will guarantee a sound characterization. Data Quality Objectives and Data Quality Assessment (DQO/DQA) are relevant tools to meet this challenge as they can be applied to the entire process, from collecting and analysing samples to data processing and reporting. They are statements that provide crucial definitions of the confidence levels required in drawing conclusions from the entire set of project data. These objectives will determine the degree of total variability (uncertainty or error) that can be tolerated in the data. Limits of variability should be incorporated into the sampling and analysis plan, and are achieved by using detailed sampling and analysis protocols. In addition, a complete, perennial and comprehensive database enables records to be kept for results (dose rate, activity level, concentration) as well as context information (coordinates, campaign name, date...). The results obtained are critical elements in decision-making regarding future remediation actions and strategy definition.

The intended future use of the site may strongly impact the characterization program. There is a wide range of potential uses: nuclear or non-nuclear industrial activities, offices, housing, etc.

Other constraints such as time, budget and accessibility may have a significant impact on the surface/volumetric characterization programme.

4.10 Data processing and contamination assessment

The characterization data should enable a sound estimation of the contamination present, and be based on appropriate data processing and interpretation. It should enable the characterization objectives to be met.

The data collected should be organized in a consolidated and validated database.

The main physical quantities measured concern:

a) dose rate and gross counting;

b) surface and specific activities (e.g. Bq/cm^2, Bq/g, Bq/m^3);

c) contaminant concentration (e.g. mg/kg).

Any other quantitative values related to the measurement (weight, chemical composition, date...) or qualitative information (visual observations, matrix) should be reported, as they are highly valuable for subsequent interpretation.

Measurement results need to be reported with their uncertainties, including those coming from sampling. To make the data set consistent and minimize bias (e.g. differences of model, of configuration, detector, matrix, method); the same protocol should be used for the same type of data.

Attention should be paid to processing results on the basis of consistent data sets, e.g. unit, dry weight, wet weight.

These parameters may also extend to the physical (e.g. grinding, sieving) or chemical (e.g. dissolution, acidification) treatment of the sample.

The data processing may consist of:

— statistical analysis and interpretation (histogram, background level...);

— establishment of fingerprint (or nuclide vectors) based on correlations. This can also come from prior knowledge (e.g. similar pathways, chemical affinities);

— diffusion coefficient and migration profile analyses;

— calibration of numerical models (e.g. activation, atmospheric dispersion, migration, hydrogeology);

— geostatistical surface/volumetric processing;

— statistical hypothesis tests;

— health impact assessment.

To meet the different characterization objectives, it is often necessary to use or combine several types of processing.

The characterization report should permit comparison of the results (radionuclides present, surface or in-depth contamination mapping, chemical contaminant level) with the remediation objectives. It is based on data acquisition as described in previous sections and on data processing and interpretation.

The file should contain all the elements necessary to characterize the radiological and chemical contaminants (contamination levels, spatial extent…). It should contribute to a technical and financial assessment of the remediation programme.

4.11 Conformity of the results to the characterization objectives

The characterization program may result in an updating of the remediation objectives and the final characterization file (with or without reservations) without calling into question the methodology.

The data processing results can be compared with the characterization objectives.

If the results are compatible with the initial objectives as described in 4.2, the remediation programme phase, as described in 4.9, can begin.

Similarly, if the results do not permit a definitive conclusion meeting the initial characterization objectives, the characterization programme should be revised. For instance, new investigations may be required. The objective is to improve the characterization and consolidate the decision-making process, taking into account the newly identified constraints (e.g. activity levels, volumes, budget, time).

4.12 Remediation programme

The preparation of a remediation programme depends on the remediation objectives proposed in the context of the intended future site use. The definition of these objectives is bound by acceptable health risks, as defined by national or international authorities and regulations.

The remediation programme examines various hypotheses and remediation scenarios, giving information regarding the spatial limits of the investigation zones and including the risks of contamination dispersion in surrounding media.

The creation of these scenarios requires knowledge not only of the physical-chemical nature and activity of the radionuclides and the characteristics of chemical contaminants present, but also of the remediation programme cost and resource estimation. Costs may change depending on the integration of partial results, which may influence or raise questions concerning the initial approach, for instance identification of new toxic products, wider extension of the zone, transfer of contamination, excessive cost.

Depending on the results and the remediation objectives, a financial assessment can be required based on a cost-advantage study (or cost-benefit analysis). This study will indicate if the remediation objective is reasonable for the project. If not, the initial remediation objectives will need to be revised.

This cost/advantage study is intended to help choose the best remediation scenario, taking into account qualitative and quantitative aspects, e.g.:

— site constraints (e.g. decommissioning schedule, accessibility);

— type of remedial techniques to remove the source of contamination;

— type of remedial techniques to cut the different pathways if the source is difficult to remove;

— worker protection;

— waste types and volumes generated;

— harm to the environment generated by the remediation (species destruction, tree felling, truck transport, noise, vibration, etc.);

— dose or risk objective that the remediation scenario would achieve;

— technical feasibility of implementing the remedial techniques;

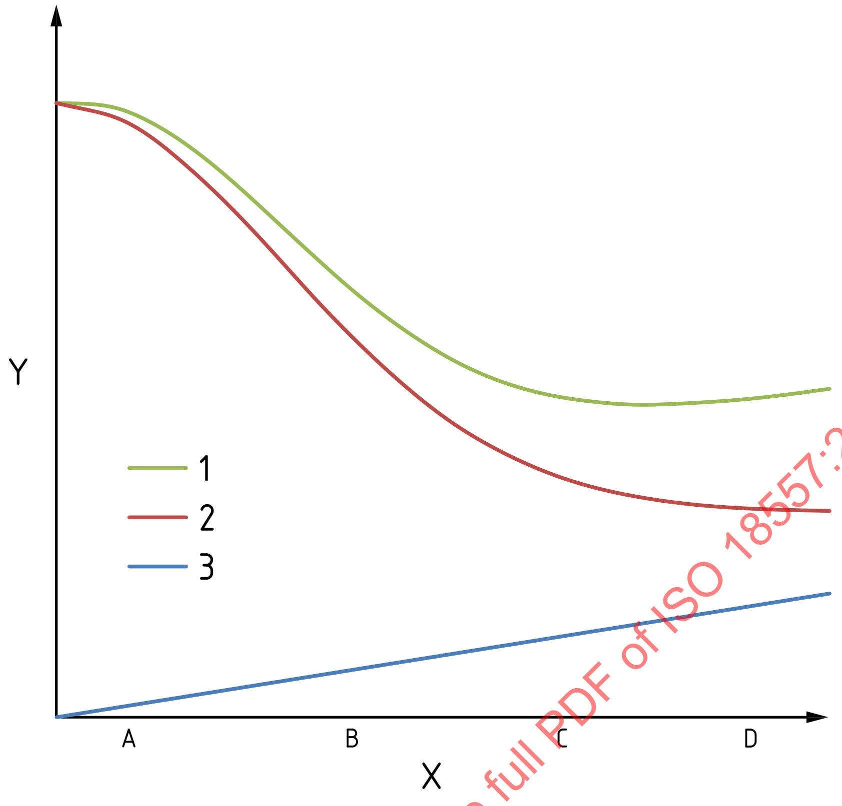
— restrictions to be applied or not;

— authority and/or legislation framework;

— financial cost.

It should be noted that a poor characterization effort can often lead to overly conservative assumptions or, on the contrary, to the discovery of unexpected contamination during the remediation work. Both cases mean expenses unforeseen by the remediation project, and usually higher than the cost of an appropriate characterization.

A general review of past remediation projects for contaminated soils, buildings and infrastructures demonstrates the relevance of the characterization effort. These observations are valid for radionuclide contamination as well as chemical pollution. To summarize Figure 3, the sampling and characterization effort should be optimized as regards remediation project issues (total impacted volumes, contamination levels) in order to reduce the decontamination /remediation costs (works and waste costs) and therefore the total cost of the project. With a very limited characterization effort, attention should be paid to an over-categorization of the contaminated volumes or to the risk of facing unexpected contamination that would drastically increase remediation costs. On the contrary, once contaminated volumes are correctly estimated and cannot be reduced any further, there is no need to over-characterize (unnecessary samples) given that this would result in wasting time and money. The latter case is not common, as the characterization process is generally undersized.



Key

X characterization effort
Y relative cost
1 total cost
2 remediation
3 characterization cost
A insufficient
B intermediate
C optimised
D excessive

Figure 3 — Relevance of the characterization effort as regards the total cost of the remediation project

4.13 Final characterization

The final characterization goal is to demonstrate the compliance of the site remediation results with the remediation objectives. This means demonstrating to the regulatory body and other stakeholders that the potential dose or risk from residual contamination is within the remediation objectives (release criteria / clearance level) and that the site is suitable for its future planned use.

For this kind of characterization, a probabilistic approach to sampling should be applied in order to give a representative image of the final site status. This approach will enable the production of data to which statistics may be applied. Therefore the compliance demonstration will rely on scientific methods, taking into account the fact that measurement uncertainties are associated with characterization techniques and that 100 % confidence in a decision cannot be achieved. A level of risk should be discussed by the project team and the regulatory body. Depending on the history of the different areas of a site, the design of this final characterization may differ, ranging from random sampling or non-destructive measurements to a sampling design based on statistical tests defining how many samples are sufficient to be representative of the area or site.

Based on the final characterization file and usually also on its own measurements, the regulator will decide whether the site has been remediated to a satisfactory level and if it can be released with or without restrictions.

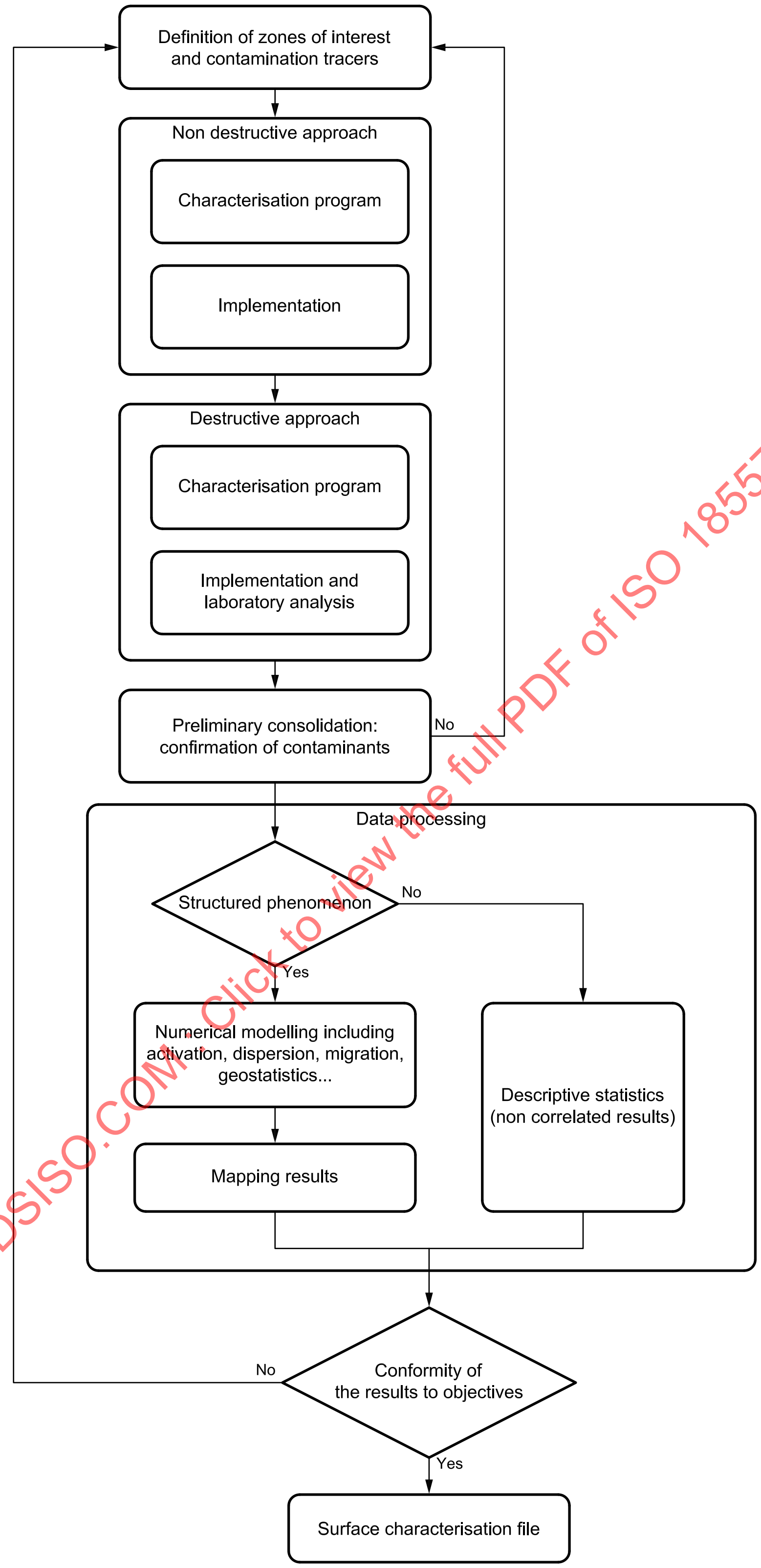
5 Surface characterization programme

5.1 Principle

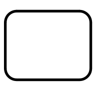
As mentioned above, the characterization programme generally starts with a surface characterization of the site to identify potential contaminated areas. From the previous historical and functional analyses and the definition of zones of interest, this surface characterization combines non-destructive and destructive analyses. Depending on the operation or site constraints and the results aimed for, it is necessary to choose the suitable measurement method and means among those available (e.g. simple checks, non-destructive or destructive analyses, in situ measurement). A structured phenomenon in space appears when the observations or measurements present correlations between them (for example area contamination).

The data processing then leads to the surface mapping of the area and the determination of the nuclide fingerprint, including difficult to measure nuclides, and the composition of chemical contamination if relevant.

Figure 4 presents the logical progress of a surface characterization programme.


Definition of zones of interest
and contamination tracers
Non destructive approach
Characterisation program
Implementation
Destructive approach
Characterisation program
Implementation and
laboratory analysis
Preliminary consolidation:
confirmation of contaminants
No
Data processing
Structured phenomenon
No
Yes
Numerical modelling including
activation, dispersion, migration,
geostatistics...
Mapping results
Descriptive statistics
(non correlated results)
No
Conformity of
the results to objectives
Yes
Surface characterisation file

Key



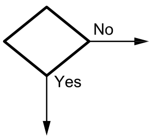


Figure 4 — Global logic diagram for surface characterization

5.2 Non-destructive analysis

5.2.1 Characterization programme: Determination of the sampling design and the number of data points

The objective in collecting samples for analysis is to obtain a small and informative portion of the population under investigation. Usually, representative samples are sought, i.e. samples that can be expected to adequately reflect the properties of interest in the population being sampled. However, targeted samples are sometimes needed, e.g. a particular spot at a contaminated site that appears to be discoloured. Samples taken at that spot, however, should be representative of it at the time the samples were taken. Planning for informative sampling should be an integral part of any study.

Based on the information previously gathered, i.e. zones of interest, incident records, lists of contaminants and means of measurement (see 4.3, 4.4, 4.5 and 4.6), it is possible to determine the adequate number of field measurements and samples, and their locations. The aim is to obtain the data necessary to carry out the characterization (e.g. determination of dose rates, activity levels, concentrations) for a given level of confidence.

Several sampling strategies can be considered, closely linked to the planned data processing technique:

— **Appropriate judgement by qualified expert** should be considered when using numerical models (activation, migration, atmospheric dispersion...) to calibrate and validate the input parameters. The numbers and locations of data points are closely linked to the numerical model, its accuracy and its sensitivity.

— The initial mesh size can be determined based on **geometric considerations**, depending on the characteristic size of the expected contaminated areas. Data points are collected along a regular grid. The mesh is determined by the probability of hitting a contaminated area of a given size (which is equivalent to the proportion of identified areas with the same given size).

— This initial mesh on a regular grid can also be estimated taking similar contaminations into account as regards a priori spatial continuity (characteristic spatial structure of the contaminated areas). Good practices are presented in Annex A. The latter is closely linked to the **geostatistical approach** that is planned to be used on the collected values.

— **Statistical design**: data processing is based on statistical tests. Considering statistical risk levels and (possibly) prior estimates or hypotheses for the phenomenon characteristics (e.g. variance, symmetric distribution, homogeneity), the number of data points is determined by the test hypothesis itself. Data points are generally randomly located.

By default, the sampling strategy should be based on a limited number of judgmental assessments enabling a preliminary localization of contaminated zones. A more precise characterization is then performed by sampling iterations and data processing updates, depending on the nature of the contamination and the characterization objectives. Systematic designs (regular grid) make additional point collection easier, and reduce uncertainty in identified areas.

Another way to proceed is the use of exhaustive scanning (mainly for dose rate and gross gamma emitters) with real-time measurements (around one second, while driving or walking or even flying). This approach gives very interesting semi-quantitative data identifying hot spots and matrix changes. It also can give very useful information regarding surface contamination spatial structure.

5.2.2 Implementation

There are many ways to obtain non-destructive results. Robots, humans and vehicles can be equipped with measuring apparatus and positioning devices. GPS is very convenient for outdoor applications, whereas laser and up-to-date volumetric reconstitutions are more and more frequently used for interiors. Correct, reliable plans and maps are a necessity.

Measurements of gross gamma counting and of dose rates, as well as the use of specific alpha, beta, X, or neutron detectors, should be adapted to the nuclides of interest. The detection limit is a major issue, as is the estimation of the activity of difficult-to-measure nuclides, notably for alpha and beta emitters. Collimators and distances from the area measured should be selected carefully, bearing the representativeness of the results and the sampling design in mind.

In addition, some non-destructive determinations of the penetration depth of contamination are sometimes possible. This can be a first assessment of the vertical extent of the contamination during the surface characterization step.

Some chemical compounds can be estimated with *in situ* techniques, for example volatiles, light chemical elements and metals.

These *in situ* results are expected to be relative rather than in absolute values. Scaling factors with activity levels will result from the comparison with destructive analyses. Qualitative information, e.g. matrix appearance and nature, weather conditions, needs to be taken into account in the interpretation of the complete data set.

5.3 Destructive analysis

5.3.1 Characterization programme

Given the previous non-destructive results and preliminary mapping, surface samples taken for destructive analyses are generally positioned based on judgment. They are collected from specific sampling locations, for example expected accumulation areas. They may be linked to the topography or to the building structure (culvert, sump, etc.). In this case, a prioritization of the analyses can be used to rationalize the amount of information (with the objective of limiting redundant data) and consequently to save time and money.

Destructive analyses are of crucial importance in the case of non-conclusive non-destructive measurements (alpha emitters, for example). In this case, all considerations from 5.2.1 directly apply for destructive samples.

The selection of the nuclides to be analysed and of associated chemical compounds depends on the preliminary historical and functional analyses.

5.3.2 Implementation and laboratory analyses

Surface samples can be collected easily, using basic tools for soils and with hammering or drilling techniques for concrete or hard rock. Sample constitution and representativeness are important issues for the later data processing and for the confidence given to the results. Composite samples may be appropriate in tackling these issues. The detection limits of measurement methods are important criteria in deciding on the number of samples and the quantity of materials to be collected for laboratory analyses. The choice of methods should be optimized to fit the characterization objectives. This decision should namely consider the relevance and importance of the contaminant in the safety or environmental assessment, technical performances, the cost of the measurement.

More and more mobile laboratory units have been developed to reduce logistics, time and cost aspects. On-site lab measurements have considerable value for responsiveness purposes.

Chemical measuring kits are also available (e.g. Laser Induced Breakdown Spectroscopy (LIBS), Photoionization detection (PID), heavy metals X-fluorescence) for situations where chemical pollutants need to be characterized.

5.4 Preliminary consolidation

If the contaminants found are different from those expected or if there are several contaminant compositions (several fingerprints), it can be necessary to review/reinforce the historical assessment and/or collect additional data.

Consistency checks may be necessary between the location of values (base-map) and the expected contamination areas.

5.5 Data processing

5.5.1 Spatial structure of the phenomenon

In order to use the appropriate data processing technique, it is first necessary to check if the phenomenon presents a spatial continuity or spatial randomness. Statistical tests and estimations are well adapted to the latter, whereas other techniques are required for the spatially structured cases.

5.5.2 Data processing in the case of spatially structured contaminations

When dealing with spatially correlated phenomena, numerical models are widely used to represent the radioactive material distribution (e.g. atmospheric dispersion, activation, migration, rate of species migration). They are based on the mathematical modelling of the physical phenomena (e.g. Gaussian plumes, cross sections, distribution of impurities in the activated material, integrated neutron flux distribution). Values from measurements and samples are mainly used first to calibrate and then to validate the numerical model (data assimilation).

However, the phenomenon may be spatially structured but is often too complex to be represented by deterministic models. In this case, geostatistical methods can be used advantageously, as this type of data processing takes spatial correlations between variables into account. The approach underlines the spatial gradient from the measured values themselves. Therefore, it generally requires a significant amount of data.

A multivariate approach is often necessary to integrate additional information coming from historical analyses, numerical models (described previously) or other measurements or parameters. The set of correlated data may improve the estimation and reduce uncertainties.

An example of good practice is presented in Annex A.

5.5.3 Result mapping in the case of spatially structured contaminations

Based on results from numerical models, surface mapping displays represent the contamination spread and contaminated surfaces which can be delineated.

The difficult issue is quantifying the uncertainty of the result. This can be addressed by sensitivity tests on input parameters and the hypotheses of numerical models. It can also be addressed within the geostatistical framework (nonlinear estimations, e.g. risk of exceeding a threshold) as the spatial variability is modelled.

In addition, geostatistics enables sampling optimization in order to reduce estimation uncertainties. The criterion may focus on under-sampled areas (kriging error variance), high variability areas (confidence interval), and classification improvement or misclassification risk reduction (probability of exceeding a threshold).

5.5.4 Statistical processing in the case of non-structured contaminations

When variables are independent and non-correlated with each other, use is made of descriptive statistics for global trends (mean, median, mode) and for dispersion (spread, inter-quartile interval, variance, standard deviation, coefficient of variation, minimum, maximum, percentiles), as well as shape indicators (asymmetry coefficient, flattening coefficient).

Classical statistics are also used as an initial assessment with data coming from the characterization of spatially structured contaminations.

In this non-spatially structured situation, neither the sampling effort nor the characterization estimations can be optimized, as contamination is randomly distributed. However exhaustive characterization or specific sorting techniques can be used to reduce the production of waste, e.g. conveyor belts with measurement devices, waste categorization by non-destructive analysis of the sorted units (objects, packages).

In addition, the categorization of a contamination as non-structured may be the consequence of an insufficient number of samples to identify a structured phenomenon.

5.6 Conformity of the results with the characterization objective

At the end of the data processing, it is necessary to check result conformity with the initial objective. If deviations can be observed, it is necessary to go back to the initial stages of the workflow to update the different input parameters (perimeter, radionuclides…).

As already mentioned, intermediate checks and internal loops occur at several stages (e.g. preliminary consolidation, uncertainty reduction).

In addition, in order to reduce these prediction uncertainties (confidence interval, risk of exceeding a threshold), additional measurements can be decided on (iterative sampling) within the geostatistical framework on a judgmental basis or by using automatic algorithms.

5.7 Surface characterization file

For surface contaminations, a classical surface characterization file may include the content that has been described in the above sections. In particular:

— context and objective of the surface characterization,

— conclusions of the historical and functional analyses, and of the preliminary characterization,

— identification of the zones of interest and contamination tracers,

— sampling strategy and measuring devices or techniques which are implemented,

— presentation of the values collected and their preliminary analysis,

— results of estimations (impacted areas, activity levels, maps, etc.),

— achievement of initial characterization objectives,

— planned remediation/decontamination works in the case of surface contamination,

— input data for the volumetric characterization program if volumetric contamination is to be dealt with (see Figure 2).

6 Volumetric characterization programme

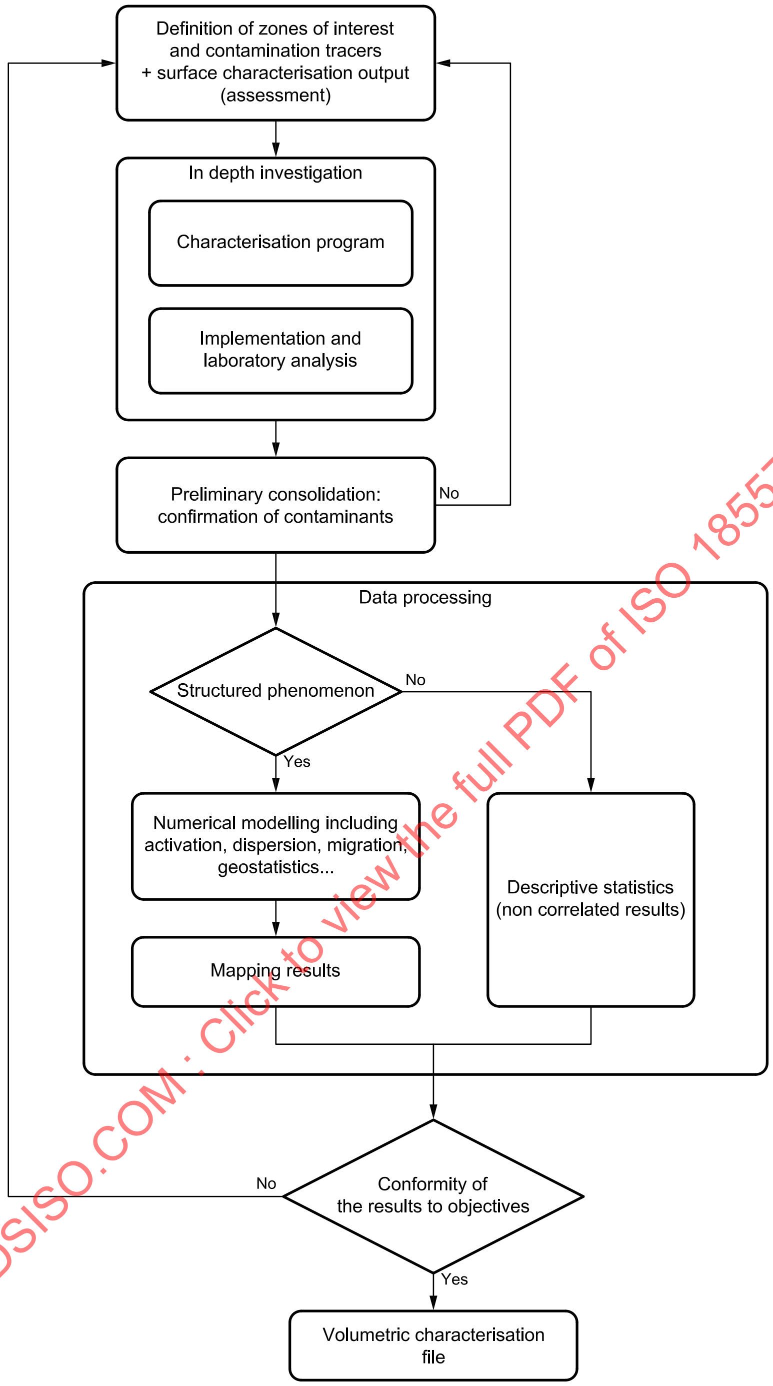
6.1 Principle

The structure of the volumetric characterization programme is similar to the surface characterization programme.

From the previous historical and functional analyses and the definition of zones of interest, and from the surface assessment if relevant, volumetric characterization is strongly based on in-depth destructive samples.

Like surface characterization, volumetric characterization aims at fulfilling the characterization objectives by aggregating and processing all available input data.

Figure 5 presents the logical progress of a volumetric (in depth) characterization program and related sampling plans.



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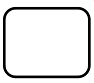


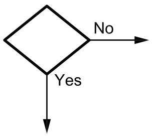


Figure 5 — Global logic diagram of volumetric characterization

6.2 Volumetric investigations

6.2.1 Characterization programme

Estimations of the surface and the depth to be characterized constitute the first step in defining the volumetric perimeter, based on the historical data (see 4.3) combined with the functional analysis (see 4.6), the results of the preliminary characterization (see 4.7) and the surface characterization outputs if relevant (see 5.7). For an open site, attention should be paid to natural soil depth (intended to be reached and sampled) and/or water table level or perched water. For indoor characterization, wall or slab thicknesses are among the main parameters to consider.

Firstly, the characterization programme focuses on drillings (including the number, location, sequencing, and depth) in order to obtain cores. The global volumetric investigation programme is frequently limited by cost and time constraints. Hence an appropriate sampling strategy is of great importance. Iterative investigations enable an optimized characterization by reducing uncertainties and by improving volumetric extents for different activity (or concentration) criteria. All existing pieces of information (historical analyses, surface assessments) are first level aids.

Then a further step defines the samples to be taken along the drill cores (number, location, and mass) for laboratory analyses. This second step can be driven by a regular pattern or, more optimally, by taking non-destructive measurements (dose rate or gross gamma counting, gamma spectrometry scanning, X-scanning) into account. Correlations between raw data (count rate, dose rate, etc.) and laboratory analyses, or among laboratory results themselves (correlations between easy-to-measure and difficult-to-measure nuclides) are relevant tools for the optimization and limitation of lab analyses. Frequent updates of the database and its assessment are a very effective way to adapt and reduce the number and types of laboratory measurements.

Geological media is also a relevant input parameter, and should be carefully assessed and recorded.

In addition the vertical resolution along cores should be adapted to the characterization objectives, which include the preparation for the remediation/decontamination works. It should also take the contamination profile and decontamination techniques envisaged into account. For instance, if a block of contaminated land is expected to be remediated by units of 50 cm horizontal layers, a 1 cm vertical pattern for samples and analyses is definitively disproportionate (too many redundant values at the 50 cm scale). However for a 50 cm concrete slab, the activity can be expected to vary significantly in the first centimetres and sampling should reflect this (not using a 50 cm core average sample).

6.2.2 Implementation and laboratory analyses

Depending on the choice of the characterization method, it will be necessary either to organize *in situ* measurements by successive observations or to carry out samplings and the transfer of samples to the measurement laboratory for destructive measurements. In the latter case, it is useful to define the actions needed prior to the measurement, be these physical (e.g. grinding, sieving) or chemical (e.g. dissolving, leaching). The considerations described in 5.2.2 and 5.3.2 naturally apply for in-depth samples.

Obtaining the raw results consists in gathering all or part of the measurement results and putting them in a suitable form in order to be able to apply the appropriate statistical processing. The group of results will make up the characterization database.

6.3 Preliminary consolidation

Similarly to the surface preliminary consolidation, if contaminants are different from those expected or if they differ between identified contaminant compositions (several fingerprints), it is necessary to review/reinforce the historical assessment and/or collect additional data.

Consistency checks are necessary between the locations of values (base-map) and expected contamination areas.

The same applies to material matrices and structural thicknesses for building structures, for instance. A good radiological characterization starts with a good physical characterization. This is even more crucial when facing volumetric characterization.

6.4 Volumetric Data processing

6.4.1 Case of structured contaminations

Similarly to surface characterization, data processing should consider the possible spatial continuity of the phenomenon. If the surface analysis points to this spatial correlation, it is naturally extended to the third dimension.

However, spatial continuity is generally less in the vertical direction than on the horizontal plane. This anisotropy can be mathematically modelled if it is relatively simple (migration profile in soils or concrete structures according to an exponential decrease, for instance), or directly analysed with directional variograms within the geostatistical framework.

6.4.2 Case of non-structured contaminations

When values are spatially independent and non-correlated with each other, use is made of descriptive statistics for position (mean, median, mode, minimum, maximum, percentiles) and for dispersion (spread, inter-quartile interval, variance, standard deviation, coefficient of variation), as well as shape indicators (asymmetry coefficient, flattening coefficient).

The mean and the variance measured on a sample are pinpoint estimations of the mean and the variance of the variable on the whole population.

In the case of non-structured contaminations, alternative sorting techniques for the contaminated materials may need to be used in order to correctly segregate the waste produced.

6.5 Compatibility of the results with the objectives

The compatibility of the output data with the characterization objectives is assessed. If this compatibility is established a volumetric assessment file, possibly including a surface characterization section, can be prepared.

If the compatibility has not been established, it is necessary to re-examine the input data as well as the characterization objectives.

6.6 Volumetric characterization file

For in depth contaminations, a classical volumetric characterization file may include the content that has been described in the above sections. In particular

— context and objective of the volumetric characterization,

— conclusions of the historical and functional analyses and of the preliminary characterization,

— identification of the zones of interest and contamination tracers,

— outputs from the surface characterization if relevant,

— sampling strategy and measuring devices or techniques that are implemented,

— presentation of the values collected and preliminary analyses,

— results of estimations (impacted areas, activity levels, maps, etc.),

— comparisons with initial characterization objectives,

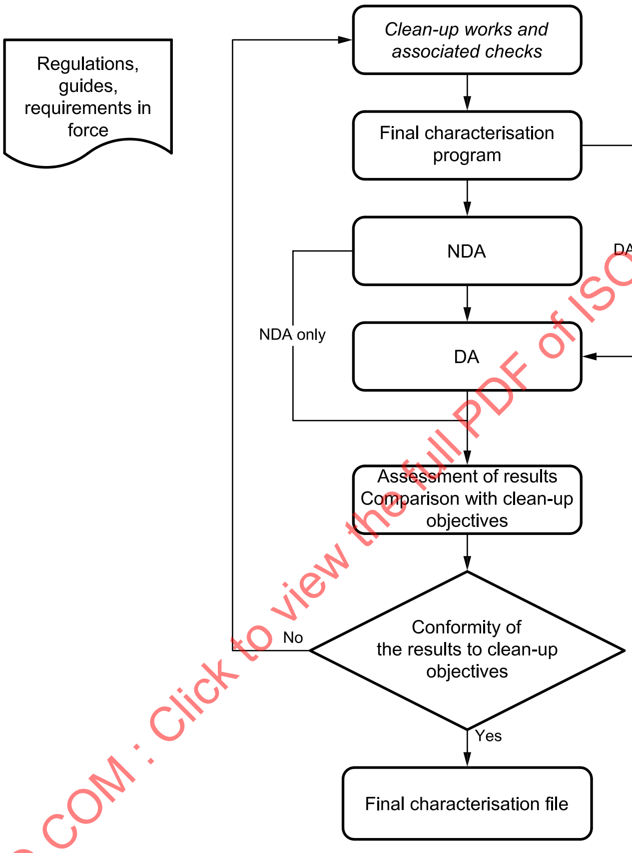
— planned remediation/decontamination works.

7 Final characterization programme

7.1 Principle

As mentioned in 4.13, the principal goal of this characterization is to ensure that the site has been adequately remediated and can be released for unrestricted or restricted use, depending on what has been agreed with the regulator and stakeholders.

Figure 6 presents the logical process for a final release characterization.



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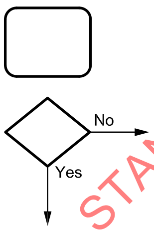

Figure 6 — Logic diagram for carrying out final release characterization

7.2 Final characterization programme

The main objective of a final characterization programme is to assess the residual activity and concentration levels on the site (soils, buildings and infrastructures).

At this specific stage there are two challenges to deal with: the first is that accurate measurements of low levels of radioactivity or small concentrations of chemical substances are required, and the second is that the programme needs to demonstrate sufficient representativeness and robustness in order to convince the regulator and stakeholders prior to their decision making and final approval.

This programme takes into account several important factors:

— if there will be restrictions on the site, this will have an influence on the levels of the remediation objectives and therefore on the detection limits needed for the equipment and methods used for the final characterization;

— knowledge of the natural background levels is necessary to optimize the characterization strategy and thus the equipment (feasibility of *in situ* measurement, surface and/or in-depth sampling and on- or off-site laboratory measurement, or a combination of the three) and the interpretation of the results;

— the initial input data will enable a classification between different types of areas (for example, those that were contaminated and remediated, those that were slightly contaminated but under the remediation objectives, those that are not contaminated) and this will condition the sampling strategy in that it will be more extensive on remediated areas than on non-remediated and non-contaminated areas;

— reassurance monitoring to confirm the absence of contamination spread;

— the difficulty of proving that the sampling is representative for the site or facility; hence the benefit of using a statistical approach in order to evaluate the uncertainties associated with the decision for compliance;

— the point above implies that the project manager or operator needs to choose the percentage of risk taken in the decision (or confidence level), and to reach an agreement with the regulator;

— the financial resources.

Therefore, the programme should define

a) the number and location of measurements,

b) the radionuclides and/or chemical substances to measure and their detection limits (MDA: Minimum Detectable Activity),

c) the type of measurements, i.e. *in situ* measurements and area coverage, in-depth boreholes and sampling,

d) use of on-site laboratory and/or off-site laboratory,

e) the way the measurement results will be processed (usually statistically), and

f) the way to deal with any possible high levels of radioactivity or concentrations of chemicals.

7.3 Processing the final characterization results

The first step consists of data verification in order to see if the results collected are usable, and to define the means to evaluate the precision, bias, representativeness and completeness of the data. In particular, global homogeneity should be checked and/or homogeneous sub-areas should be defined to ensure the validity of this assumption or to provide the basis for data stratification.

The second step is to process the results. Depending on what has been defined in the programme, different interpretations can exist: for example, to process with averaging or to process every single measurement. A generally sound manner to proceed is the use of statistical tests to determine whether compliance has been achieved.

The easy situation is when all the single measurements comply with the remediation objectives. If an averaging assessment is used, the mean obtained for data may comply with the remediation objectives and can therefore be taken to conclude that the remediation is fulfilled. However if the mean value of the data is close to the remediation criteria and the standard deviation is large, a more comprehensive statistical study should be conducted. If the mean of the data exceeds the remediation objectives, the remediation has failed and further actions are needed.

Statistical processing is key in demonstrating the representativeness of the sampling for the cleaned-up zone or site, as well as the level of confidence attached to the results presented, is adequate to demonstrate the remediation objective has been reached.

In the case of isolated high level areas, it may be necessary to perform a new characterization around each area identified. This could lead to simple, easy remediation actions if the remaining contamination is localized, or a complete new characterization programme (surface and possibly volumetric) may need to be carried out in parallel with a reassessment of the input data.

7.4 Final characterization file

If the statistical processing leads to the conclusion that the remediation objective has been reached with a level of confidence acceptable to all stakeholders, the operator will be able to prepare the final characterization file. This will then support the declassification of the facility, or the release / reuse of the zone or site for nuclear or non-nuclear purposes. This file should include

— the remediation objective chosen,

— the final surveys, and

— any possible restriction(s) proposed for post-dismantling and remediation reuse or release.

8 Final report

This report *typically* includes relevant data for the declassification of the facility or for site release, to be validated by the authorities. A typical table of contents would include:

- site/facility context:
  - geology;
  - hydrogeology;
  - historical study;
  - functional analysis;
  - future use of the site or facility;
  - remediation objectives;
- assessment: surface or volumetric characterization file for contaminated zones:
  - characterization measurement results;
  - data processing of the results and the location of the contamination;
  - conclusion of the assessment, with local and global confidence levels;
- remediation programme:
  - cost/advantage or cost/benefit study;
  - clean-up works undertaken and associated checks;
  - possible issues noted following the remediation, and actions undertaken;
- final characterization:
  - characterization measurement results;
  - processing of the results;

- conclusion on the demonstration of compliance with remediation objectives and future use;
- conclusion on restrictions and any need for further long-term monitoring.

The final decision (free release, easement for reuse) is taken by the regulatory body.