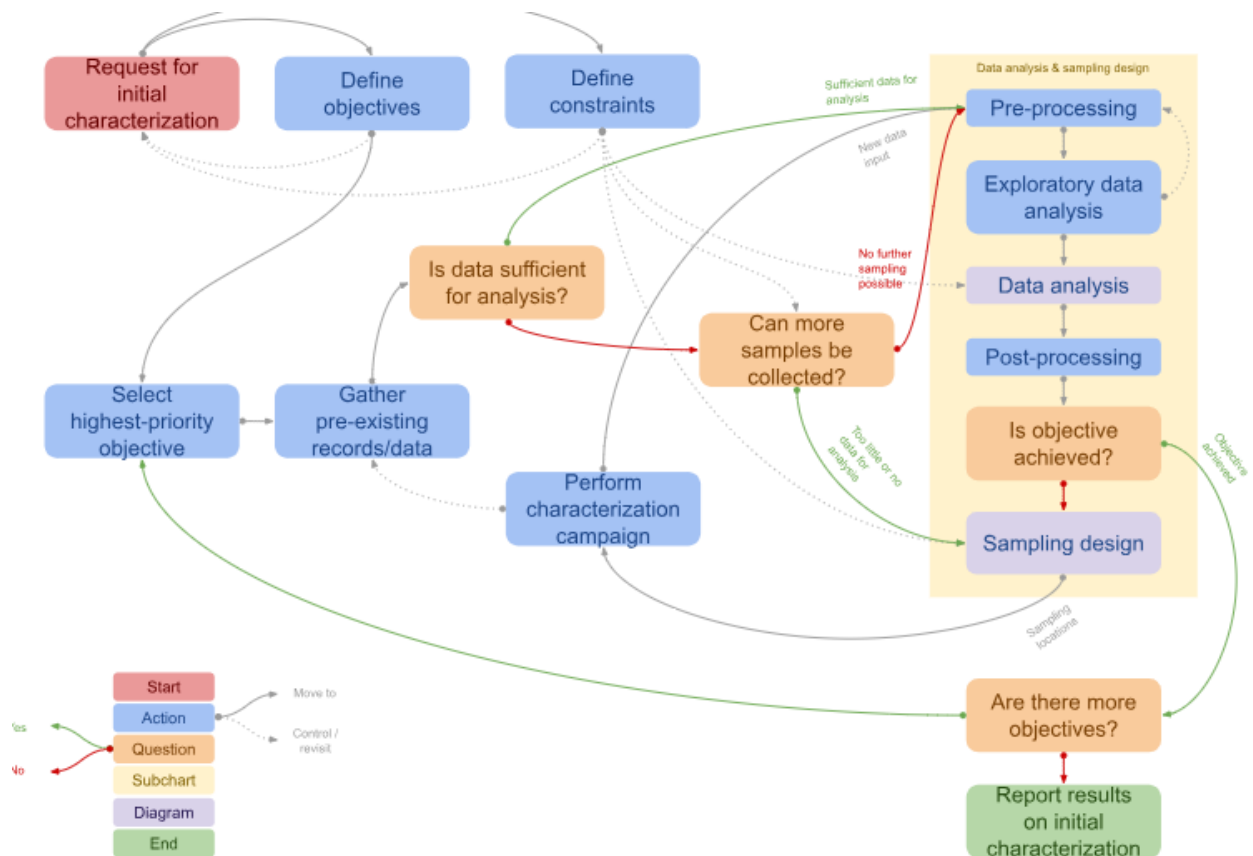




STRATEGIST – A tool for statistical analysis of plant characterisation data

CASE STUDY

KP-JRC-021

06/08/2026

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Foreword

In 2021, the European Commission (EC) adopted a new proposal for a Council Regulation establishing a dedicated financial programme for decommissioning nuclear facilities and managing radioactive waste. This instrument covers the co-funding of the decommissioning programmes of Bulgaria, Slovakia and the decommissioning of the Joint Research Centre (JRC). A separate Council Regulation was adopted for the decommissioning programme of Lithuania.

The EC JRC is mandated to foster the spread of decommissioning knowledge across all the European Union Member States and facilitate knowledge sharing arising from implementing the above-mentioned decommissioning programmes, funded by the Nuclear Decommissioning Assistance Programme (NDAP).

The decommissioning operators from the NDAP (NDAP Operators) implemented and tested a knowledge management methodology in 2021 through Project ENER/D2/2020-273. Using this methodology, the NDAP Operators can develop knowledge products that are currently available to share with other European stakeholders. In addition, this methodology is being implemented by the JRC Nuclear Decommissioning and Waste Management Directorate (NDWMD), which has become a knowledge generator extracting the knowledge from the ongoing decommissioning activities across the JRC's four different sites (Geel, Ispra, Karlsruhe and Petten).

The JRC's NDWMD aims to become a Centre of Excellence in nuclear decommissioning knowledge management and to develop a decommissioning knowledge platform which allows exchanging information building on EU best practices through executing the multi-annual financial framework (2021 – 2027) strategy. The operational phase of the project started in 2024 with the objectives to: develop ties and exchanges among EU stakeholders, document explicit knowledge and make it available through multi-lateral knowledge transfers on decommissioning and waste management governance issues, managerial best practices, technological challenges, and decommissioning processes at both operational and organisational level, as well as to develop potential EU synergies.

This is a Knowledge Product prepared by the [INSIDER Consortium](#) for the [JRC NDWMD](#).

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PRODUCT DESCRIPTION

The **INSIDER** project aims to develop and validate a new and improved integrated characterisation methodology and strategy during nuclear decommissioning and dismantling operations (D&D) of nuclear power plants, post accidental land remediation or nuclear facilities under constrained environments.

One of the important outcomes of this strategy development is a statistical approach guideline coupled with a web tool, which serves as a user-friendly interactive interface.

ABSTRACT

This knowledge product (KP) aims to develop and make available to potential users a tool for statistical analysis of plant characterisation data: it is a statistical approach guideline that is transformed into a web tool, which serves as a user-friendly interactive interface. The web tool, named **STRATEGIST (Sampling Toolbox for Radiological Assessment To Enable Geostatistical and statistical Implementation with a Smart Tactic)**, intends to guide experts in defining the problem and applying a strategy based on proper data analysis and sampling design.

OBJECTIVE

To develop a sampling guide for initial nuclear site characterisation in constrained environments, before decommissioning, based on a statistical approach.

APPROACH

The report collects the experience gathered in developing and validating an improved **plant characterisation methodology** by the partners of the **INSIDER Consortium** (BS, CEA, CMI, EdF, Energorisk, Geovariance, HZDR, JRC, FZJ, KIT, LGI, LNE, MTA, NPL, ONET, PSI, SCK/CEN, UPV/EHU) and was endorsed by the project End-User Group members.

RESULTS, FINDINGS AND INSIGHTS

The first task consisted in providing an overview of available sampling design methods described in standards and guides followed by a brief presentation of the statistical methods that can be used to demonstrate meeting the objectives in the context of initial nuclear site characterisation in constraint environments.

The second task aims at developing a strategy for sampling in the field of initial nuclear site characterisation in view of decommissioning, with the most important goal to guide the end user to appropriate statistical methods (including but not limited to those identified during the first task) to use for data analysis and sampling design. To aid the end user in applying this strategy, a user-friendly web-based tool for guiding the end user through the contents of the strategy and the initial characterisation process is the aim of this deliverable. The tool is available via the following link:

<https://strategist.sckcen.be/#introduction>

TARGET USERS

This KP is intended for the following users:

- Operators that are going to engage in a decommissioning project and need to start an initial facility/plant/site characterisation.
- Experts of teams performing plant characterisation activities.

APPLICATION, VALUE AND USE

This KP supports operators of decommissioning projects to prepare a request of initial characterisation of a nuclear facility/plant/site.

It can be referred to in order to help teams of experts, who are responsible for plant characterisation, in designing an effective data gathering and sampling strategy and helping them evaluate the data with a sound statistical background. The guideline is complemented by a tool which guides the team through a process that includes:

- definition of plant characterisation objectives,
- definition of constraints,
- prioritisation of objectives,
- gathering and analysis of pre-existing data,
- identification of needs for further data collection,
- optimisation of sampling plan,
- analysis of new data,
- report the plant characterisation.

The developed methodology has a wide range of applicability. It covers the classical preliminary plant characterisation for decommissioning of nuclear plants, but it can be also used for post-accidental analysis in nuclear plants and environmental remediation after accidental radioactive material releases.

A clear added value provided by **STRATEGIST** is the reduction in the number of additional measurements required and how utilising the tool can lead to increased confidence in the characterisation results. Furthermore, following or otherwise leveraging aspects of the methodology could, for example, result in cost savings as well as a reduction in worker doses.

KEYWORDS

Plant characterisation, contamination mapping, sampling strategy, statistical data analysis.

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LIST OF ACRONYMS AND DEFINITIONS

ALARA	As Low As Reasonably Achievable
D&D	Decommissioning and Dismantling Operations
INSIDER	Improved Nuclear Site characterisation for waste minimization in DD operations under constrained Environment
KP	Knowledge Product
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
NDA	Non-Destructive Analysis
STRATEGIST	Sampling Toolbox for Radiological Assessment To Enable Geostatistical and statistical Implementation with a Smart Tactic
UC1 - 3a/b	First to third a/b case studies, respectively

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1. BACKGROUND. WHY THIS PRODUCT

1.1. Description of the Challenges or Problem



The decommissioning of nuclear facilities refers to the final step, after shutdown, in their life cycle and covers the whole process whereby the considered site is properly dismantled and its near environment is cleaned up to a predetermined endpoint (unrestricted release or further reuse), from any dangerous and radioactive substance.

It is a long, expensive, complex and non-revenue generating activity (in general) with a **multidisciplinary nature**, thus representing a global challenge. In addition to this, the followed strategy is specific to each country depending, amongst other considerations, upon the facility's characteristics, own regulatory policies, environmental protection requirements and availability of waste disposal routes.

For this purpose, it is undoubtedly essential to act on the upstream stage of a given decommissioning programme for the optimum definition of viable and cost-effective dismantling scenarios as well as for the safe classification and segregation of all radioactive wastes. This constitutes a complex issue considering the **wide variety of involved structures and equipment**, so that a proper characterisation of these later becomes a necessary precondition for a successful quantification of the different contaminated materials.



According to the latest ISO standard that has been recently published in this domain [1], knowledge of the physical and radiological condition of a nuclear facility subject to a decommissioning programme is the major characterisation goal.

Nevertheless, although contributing to meet the corresponding remediation and/or decontamination objectives, characterisation must also consider other specific targets such as:

- complying with health and safety requirements during cleanup and dismantling activities,
- mastering the estimation of radioactive contaminated volumes to be sent to a temporal storage or a final disposal facility,
- obtaining relevant information to carry out a radiation protection or environmental impact study,
- and/or evaluating intervention costs, etc.

Overall, the characterisation of nuclear facilities may thus need to address some or all of the following objectives:

The determination of the: (a) **radionuclide vectors** and **chemical compositions** for each expected type of **radioactive wastes** and (b) **radiological** and **chemical background** around the site.

The identification and quantification of: (a) different areas as regards their radiological/chemical characteristics and impacted environments as well as (b) hard-to-measure radionuclides.

The **estimation** of: (a) the spatial extent of radioactive contamination in all the facility structures, systems and components, as well as the soils around the facility itself and possibly outside the nuclear site and (b) occupational doses during clean-up and dismantling.

The **validation** of the results of the numerical simulations (e.g. activation, migration or diffusion).

Helping with: (a) modelling the radiation levels, in order to determine the remediation criteria for buildings and soils; (b) selecting decontamination or remediation techniques, (c) defining the radiation protection actions to be implemented during the dismantling and clean-up activities, (d) defining the dismantling and remediation optimal scenarios to be undertaken and (e) designing any possible easements needed depending on the characteristics of the nuclear facility or site.

Facilitating the waste categorization in order to decide on its treatment/conditioning, packaging, shipment options and management route (clearance, recycling, reuse, storage, disposal).

The **evaluation** of the dismantling and remediation costs.

Demonstrating that the remediation objectives of the clean-up of all or part of a site have been reached and providing **formal inputs** to the documentation to be used for final approval/decisions.

It is important to note that:

! Incomplete characterisation often leads to reliance on overly conservative assumptions and with considerable uncertainties, which at end are costly and time consuming.

1.2. Constraints



This KP is not aimed at providing an overview of all the existing statistical methods or guidelines to the end user. It rather tries to point the end user to methods that can be applied in specific situations and for specific goals, while highlighting the different assumptions and limitations.

As the **list of possible situations and goals is extensive**, an effort has been made to provide a structured way for the end user to determine what type of situation is at hand, and which corresponding methods can be applied. By no means has it been attempted to provide an exhaustive list here, it is simply an effort to cover **most potential practical applications** in the field of initial nuclear site characterisation with at least a few options. Other methods and/or approaches might be of equal use and reliability, when handled with sufficient expertise. The latter is of course also required when applying the methods discussed here.

1.3. Relevance



An efficient and effective plant characterisation process allows operators to better estimate the radiological conditions of the plant and of all subsystems and components. This can lead to an optimisation of the dismantling operations in order to minimise the doses to the workers.

Moreover, it enables the operator to:

- select the most suitable decontamination and dismantling procedures,
- evaluate the amount and classification of radioactive waste and clearable material,
- optimise the waste treatment processes.



This can bring significant benefits during the decommissioning in terms of savings in human and financial resources and execution time.

2. SCOPE



This KP could support decommissioning operators to prepare a request of initial characterisation for a nuclear facility/plant/site. It could help teams of experts responsible for plant characterisation to design an effective data gathering and sampling strategy, as well as help them in the evaluation of the data with a sound statistical background.

The KP is complemented by a tool which can be referred to guide end users through a process that includes:

- definition of plant characterisation objectives,
- definition of constraints,
- prioritisation of objectives,
- gathering and analysis of pre-existing data,
- identification of needs for further data collection,
- optimisation of sampling plan,
- analysis of new data,
- reporting on plant characterisation.



The developed methodology has a wide range of applicability. While it covers the classic preliminary plant characterisation for the decommissioning of nuclear plants; it could also be used for post-accidental analysis in nuclear plants and environmental remediation after accidental radioactive material releases.

3. DESCRIPTION OF THE CASE STUDIES

3.1. Source of information

This KP has been fully derived from several reports issued by the partners of the **INSIDER** project, who are fully credited for the present KP:

- Deliverable 3.1: “Sampling strategy: state-of-the-art report” [2].
- Deliverable 3.2: “Report on statistical approach” [3].
- Deliverable 3.3: “Software of statistical approach” [4].
- Deliverable 3.4: “Sampling plan for use case 1” [5].
- Deliverable 3.5: “Sampling plan for use case 2” [6].
- Deliverable 3.6: “Sampling plan for use case 3” [7].
- Deliverable 4.3: “Statistical approach guideline” [8].

This KP summarises the main outcomes from the above referenced reports, some of which can be freely downloaded via the following link: <https://insider-h2020.eu/results/>.

Whereas the **STRATEGIST** web-tool can be accessed at: <https://strategist.sckcen.be/#/introduction>.

3.2. Potential users

This KP is intended for the following users:

- Operators that are going to engage in a decommissioning project and need to start an initial characterisation of a facility/plant/site.
- Experts of teams performing plant characterisation activities.

3.3. Background

[Figure 1](#) summarises the different steps that must be followed during the characterisation of a nuclear facility subject to a decommissioning programme [3].

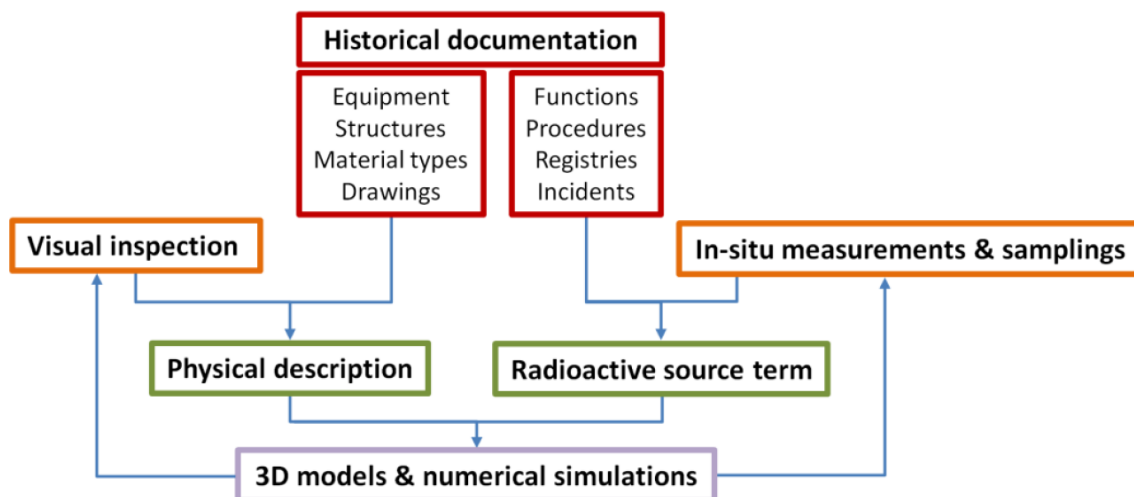


Figure 1. Process for characterisation of a nuclear facility

First of all, in order to establish its physical description together with an inventory of the associated radioactive source term, it is necessary to carry out a huge effort of analysing all of the facility's historical documentation.



In most cases, the above physical description is complemented with visual inspection (using video imaging, laser scanning and/or photogrammetry), whereas the radioactive source term is usually validated by means of in-situ measurements (gamma spectrometry, alpha/beta contamination, dose cartography, etc.) and laboratory analysis of representative samples.

The whole process can be improved, updated and consolidated with the help of **3D modelling** and **numerical simulations**. For instance, by performing more visual inspections to refine the 3D models on one side and on the other by comparing the calculation results with the measured dose cartography.

It has already been stated that the **main objective of this KP** is to provide a draft strategy for data analysis and sampling design for initial nuclear site characterisation in constraint environments before decommissioning, based on a statistical approach.



This is done by selecting state-of-the-art techniques concerning data analysis and sampling design, using prior information and multiple iterations, testing the approach through different case studies and reviewing the feedback from overall uncertainty calculations.

The process followed to meet the main objective consists of four steps:

1. Status

Provide an overview of the available sampling design methods and state-of-the-art statistical techniques [2].

2. Development

Develop a strategy for data analysis and sampling design, referring to state-of-the-art techniques, and provide guidance to the end user through a web-based tool in which the strategy contents can be explored in a user-friendly way [3,4].

3. Implementation

Follow the strategy when working out the methodology for the different test cases, in order to test its adequacy and identify potential flaws [5, 6, 7].

4. Guidance

Summarise all the findings in a comprehensive data analysis and sampling design strategy guide [8].

The pre-decommissioning radiological plant characterisation process should:

- **Quantify** the **radiological status** of the facility and the nature and extent of **potential problem areas** in order to decide on:
 - **dismantling procedures**: direct, semi-remote or remote working and tools required, shielding,
 - **safety assessment** and **As Low As Reasonably Achievable (ALARA) planning** (e.g. radiological protection of workers, the general public and the environment).
- **Quantify** the **material inventory** and **couple it with** the radiological status:
 - **waste classification**: waste management and transportation during and after dismantling (recycling, reuse, temporary storage, final disposal),
 - **economic optimisation**: decontamination processes in order to declassify certain waste streams.

3.4. Overview of data analysis and sampling design strategy



The first step was tackled and resulted in a first document (reference [2]), that provides an overview on sampling design methods and state-of-the-art statistical techniques for preliminary analyses and data processing. It starts by setting the scene on the main objectives of plant/site characterisation, the physical quantities and statistical indicators to be estimated and data collection.

One **major question** is often posed with respect to sampling strategy: **how many samples are needed and where should they be taken**? In general, there is not enough time, energy, money, manpower, equipment, and access to suitable sites to measure every single item or site within the parent population or the whole sampling frame.

For example, in most cases, it is not feasible to characterise every single item of waste before dismantling operations. The **main purpose of statistical sampling is to collect representative data sets** on which statistical analysis will provide responses with regard to the characterisation objectives of surface, objects, etc.



Therefore, it is important to obtain a small, informative and above all sufficient subset of the population under study. Given the radiological constraint of measurements and costs, the sampling strategy (which consists in defining the number and the location of the measurements) needs to be optimised in order to provide the most realistic and reliable information with a reasonable size of measurement data.

It describes the three major typologies of statistical approaches and the relative methodologies:

- analysis of data with spatial structure and enough data,
- data with no spatial structure,
- small data sets.

The full report [2] is publicly available and freely downloadable via the link provided above.

As a second step, report [3] provides an overview of the developed data analysis and sampling design strategy. All key steps are described in sufficient detail to enable end users to make well-founded decisions.

The starting point is the **request for initial nuclear site characterisation** to a radiological characterisation team. Following this request, a clear list of all **objectives** and the identification of the **constraints** is absolutely necessary. This stage might need to be iterated with the applicant to agree on the goals and priorities.

All **prior information** that is available and relevant for the investigated case should be gathered as a first step. If any data can already be made available, a first analysis to check if the objective has been achieved would be very useful, even if the results present many uncertainties.

The **data analysis** following the data collection **consists**, in general, of the **following steps**:

- pre-processing,
- exploratory data analysis,
- the actual data analysis,
- and potentially a post-processing step.



If the objective is not achieved, a sampling design should be proposed using the most appropriate method(s) given all prior information and the data analysis result.

Following the design, the corresponding characterisation campaign should be performed. Additional characterisation can reveal unexpected issues, and often revisiting the gathering of prior information is then useful. After the additional characterisation, the updated dataset is again analysed, and the iterative procedure is continued until the objective is finally reached.



The entire process can then be repeated to tackle the eventual other objectives. Once all objectives have been achieved, the initial characterisation study should be reported in a transparent way, making clear what has been measured, which results were obtained from the data analysis, and how large the corresponding uncertainty is.

While the overall strategy often takes the form of the generic workflow (shown in [Figure 2](#)), the data analysis and sampling design (shown in [Figure 3](#)) depend strongly on the situation, the available data and the specific goals and constraints.

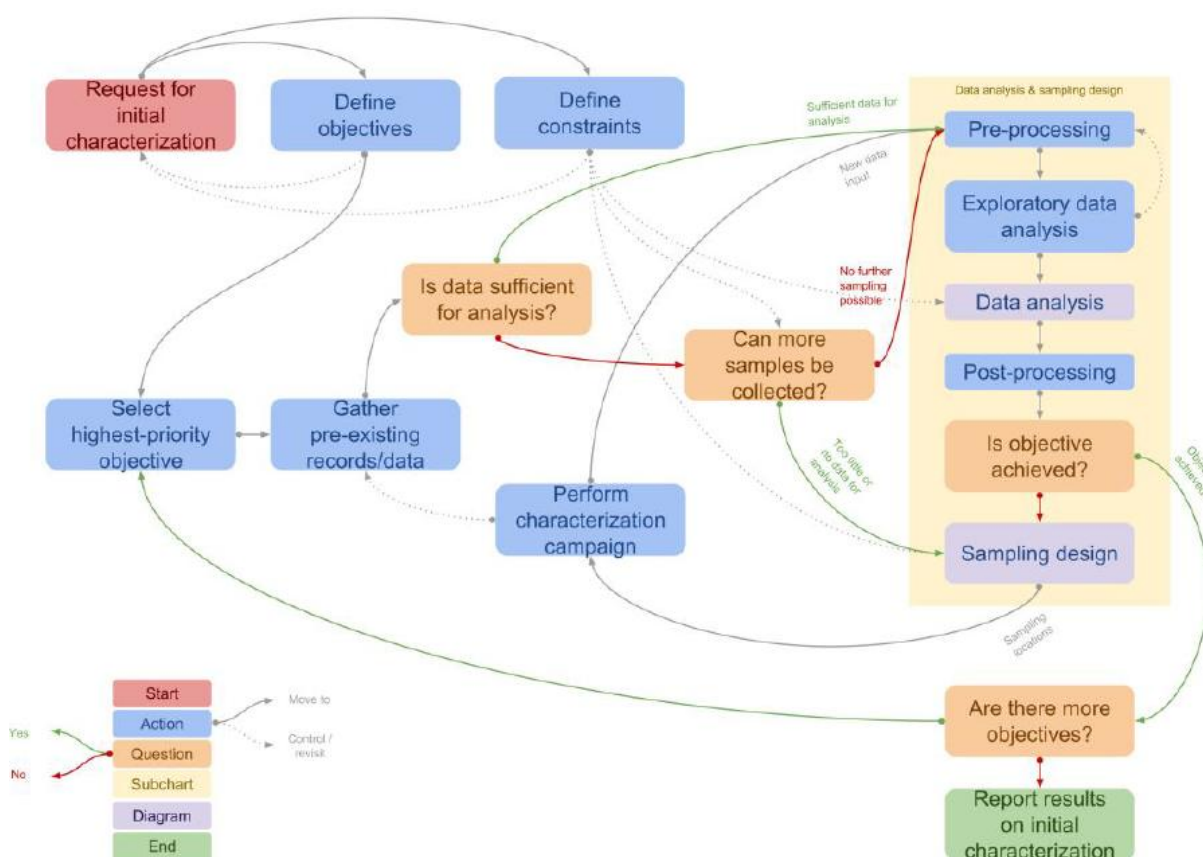


Figure 2. Overall strategy flow chart

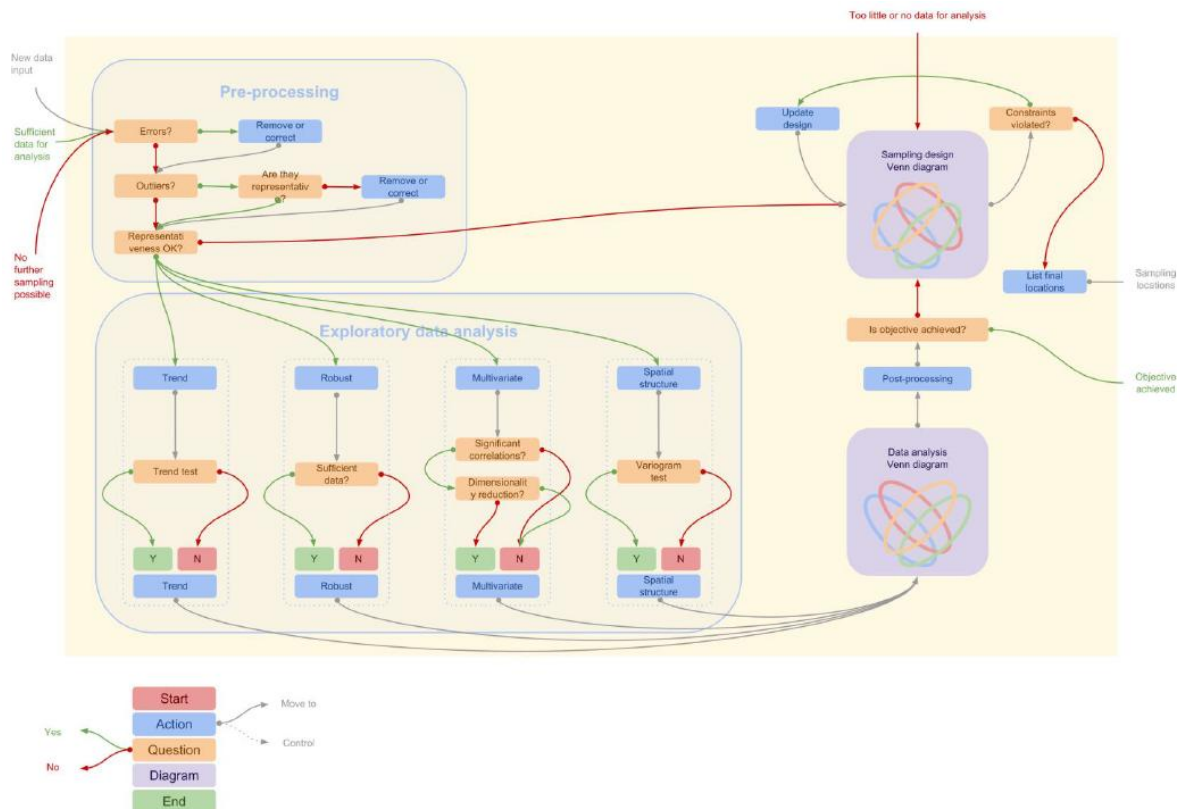


Figure 3. Data analysis and sampling design flow chart

The pre-processing step is relatively straightforward, and encompasses checking for errors, outliers, making possible corrections and removing parts of the data irrelevant to the problem at hand. The exploratory data analysis can also still be structured in a way that it is applicable to most problems in D&D for constrained environments, by looking into four aspects of the data:

1. Is this a **univariate or multivariate** problem?
2. Is this a problem involving **spatial trends**?
3. Is this a problem involving **spatial structure**?
4. Is this data requiring **robust methods**?



The outcome of the exploratory data analysis, i.e. the answers to the above questions, is used to bring some structure to the range of methods which can be employed to carry out the actual data analysis.

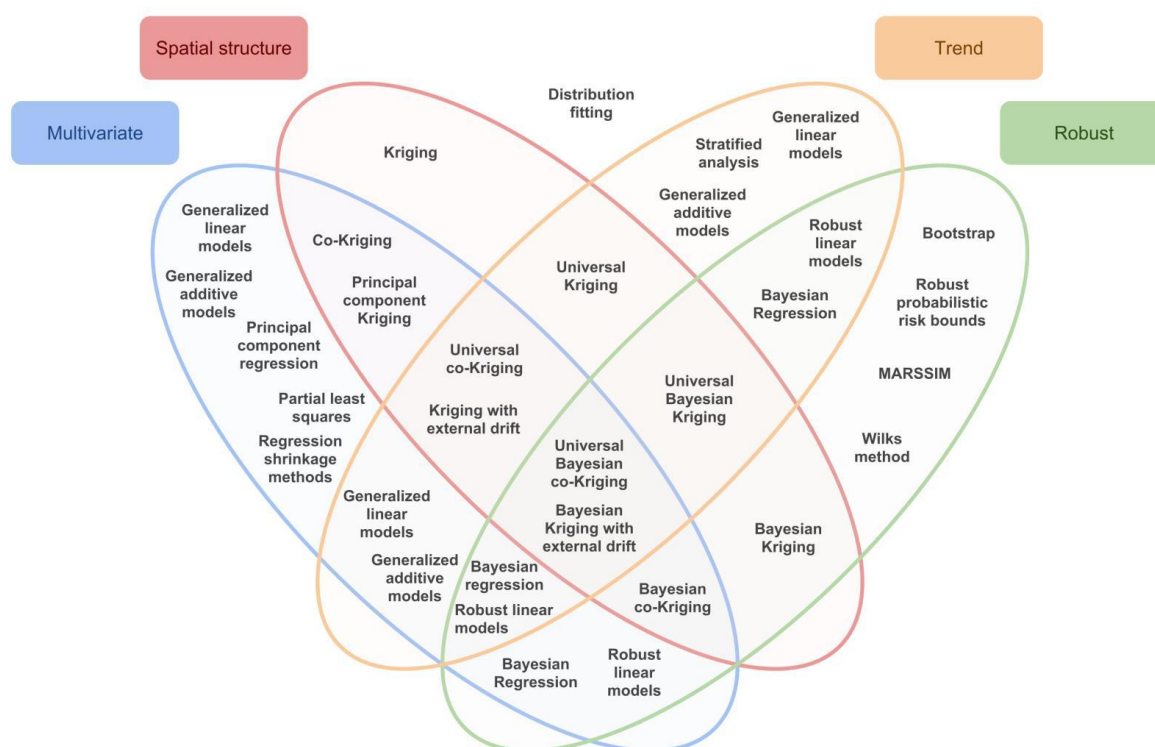


Figure 4. Venn diagram for data analysis

The list of methods for data analysis are organized in a Venn diagram (show in [Figure 4](#)) according to the four aspects of the data mentioned above. A post-processing step can be required to translate the obtained results into the required information to check if the objective has been achieved. If it has not, a sampling design approach (shown below in [Figure 5](#)) must be selected.

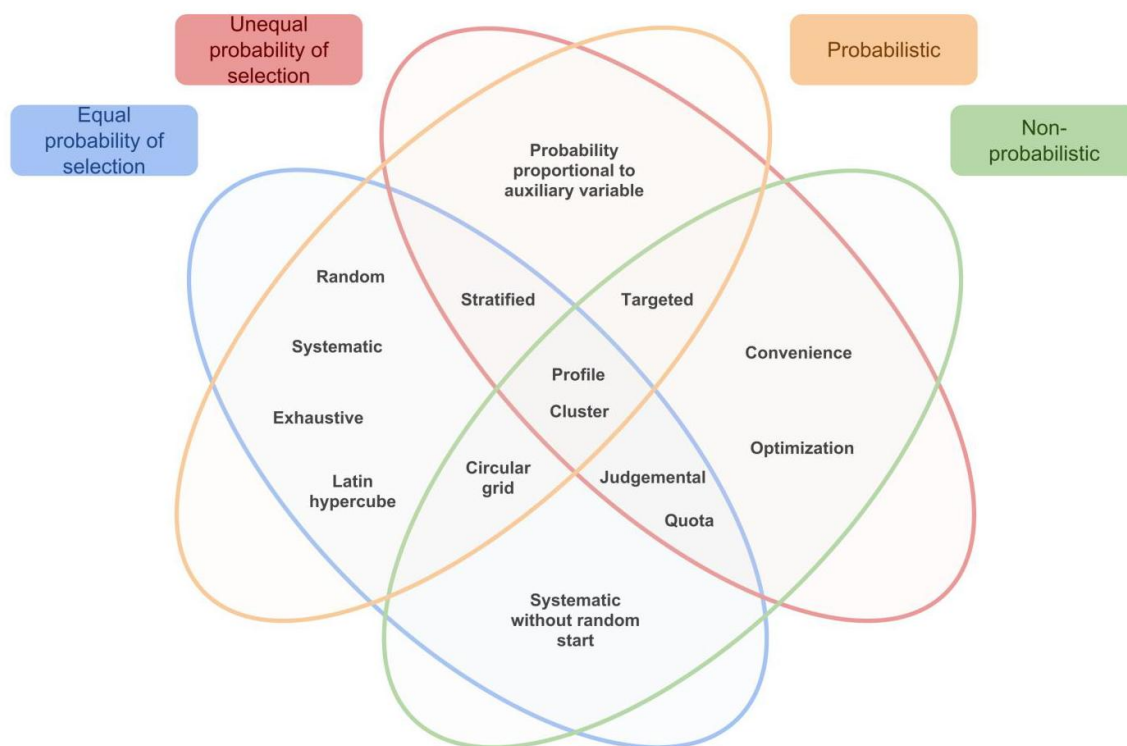


Figure 5. Venn diagram for sampling design

A detailed discussion of all these steps and applicable methods has already been given in reference [3], which is publicly available and freely downloadable via the link provided above.

The report, in addition to the overall strategy and data analysis and sampling design described above, explicitly describes **methods for data analysis** (such as: probabilistic risk bound, bootstrap, geo-statistics, multi-agency radiation survey and site investigation manual (MARSSIM), Wilks method, regression and distribution fitting) and **for sampling design** (such as: random, systematic, stratified, cluster, judgemental, targeted, convenience, circular grid, Latin hypercube, profile, quota, probability proportional to auxiliary variable, exhaustive sampling and optimisation).

3.5. Web-tool for data analysis and sampling design strategy



To aid the end user in applying the proposed strategy, a web-based tool presenting it in a user-friendly way has been developed [4]. The **STRATEGIST** web-tool is available at the link: <https://strategist.sckcen.be/#introduction>

STRATEGIST is intended to:

- Guide experts in defining the problem and applying a strategy based on proper data analysis and sampling design.
- Promote the application of an integrated characterisation methodology and strategy during nuclear D&D operations of nuclear power plants, post-accidental land remediation or nuclear facilities under constrained environments.
- Rely on state-of-the art statistical techniques for preliminary analysis and data processing.



STRATEGIST is complemented by a report [8] that details a blueprint for the web-tool and is publicly available and freely downloadable. Moreover, in the frame of the **INSIDER** project, the above-described developed strategy has been tested and validated in a few selected use cases described in the next sections.

The **INSIDER** use cases are described in reference [9] and the complete results of the benchmark, including not only sampling strategy, but also non-destructive analysis (NDA) and laboratory measurements, are fully reported in reference [10]. The specific activities for sampling strategy and data analysis applying the methodology described above are reported in the three documents which have been referenced [5, 6, 7].

Concise descriptions of the use cases follow in the next sections, accompanied by summaries of the sampling strategies as well as data analysis processes and results.

3.6. Case study #1

1

The first case study (UC1) was intended to cover the case of the **decommissioning of a back/end fuel cycle and/or research facility**. The selected facility for UC1 is the liquid waste storage facility at the JRC site of Ispra (Italy), generally denominated "Tank farm".

This is a building (shown in [Figure 6](#)), commissioned in 2010, designed to collect all remaining liquid waste present on site, mostly stored in tanks in the old liquid effluent treatment station, to be routed for cementation or other solidification treatment. Most of the liquid waste is contained in two double walled tanks.

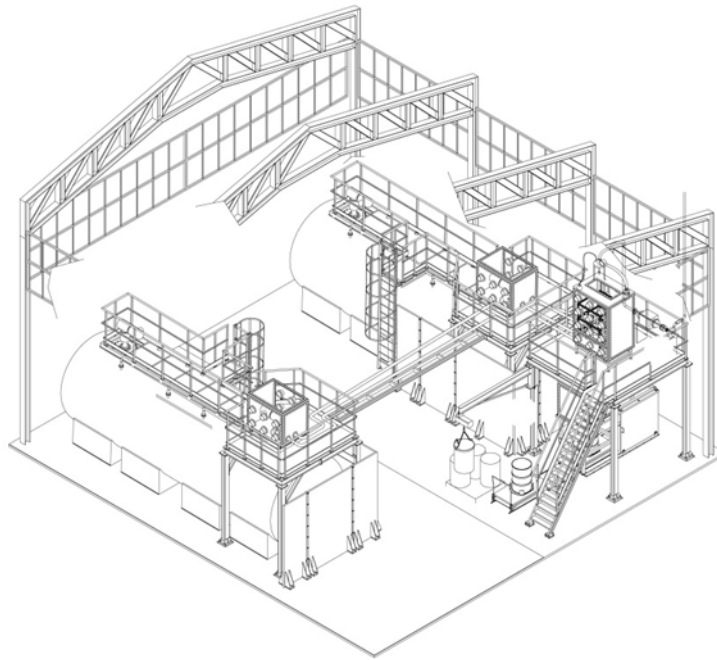


Figure 6. Schematic view of the tank farm facility

The objective of the experimental benchmark was to reproduce the complete radiological characterisation of at least one tank, through both in-situ measurements and samples shipped to analytical laboratories. Reference [5] refers to the sampling strategy and data analysis process and results for UC1, in detail. From **preliminary data** provided, some information was available to support the preparation of the sampling plan:

- The **historical origin** of the waste is the operation of a nuclear research facility including a nuclear research reactor.
- The **sampling plan's stated objective** was to classify and characterise the waste in view of conditioning and management of the waste for storage and/or disposal, and to obtain a better understanding of the radiological safety implications of storing and processing the waste.
- **Apart from one sampling campaign** during which the chemical and radiological properties of the tank contents were measured **in 2013, no additional data** from environmental or radiological surveillance relating to the waste **was available**.
- A stated uncertainty relates to the relative inhomogeneity of distribution of radionuclides in the waste.
- Scaling factors were available but were not provided together with the sampling reports because it is a stated intent of the benchmark exercise to come up with **scaling factors** (if any) which are not prejudiced by way of information supplied in advance.
- The **maximum dose rate** on contact of the tanks was recorded as **30 μ Sv/h**.
- **Accessibility of the waste** in the tanks for laboratory sampling was limited to in-stream sampling while pumping contents from the tanks or through a sampling loop.

- **External access to the tanks for dose rate measurements** was possible in general but was restricted because of the location of the tanks against the building walls, and by a shielding wall covering part of one tank.
- **Surface contamination** was not expected to be an issue as the waste was contained within the tanks. The absence of surface contamination was stated in the information provided.

The **objective** for the campaign was to fulfil the necessary requirements for conditioning and removing the waste according to the relevant waste acceptance and possibly disposal criteria. This can be summarised as:

- **Determine physical and chemical properties** of the waste, and
- **Determine radiological properties** of the waste, including:
 - dose rate in the working area,
 - degree of homogeneity/spatial distribution,
 - nuclide inventory and quantification, and
 - waste classification.

Given the pre-existing knowledge about the waste, including the pre-existing laboratory data with comprehensive analysis of physico-chemical parameters, the radiological characterisation of the waste here was the **highest priority objective**, i.e. determination of:

- type, isotopic composition and volumetric distribution of radioactive waste in waste containers (tanks) and
- difficult-to-measure nuclides and their correlations or scaling factors to easy-to-measure nuclides.



If a uniform distribution of data is expected, an unbiased survey is the preferred sampling method, and vice versa, if the distribution is expected to be non-uniform, a biased survey is the better option.

Major **constraints** for sampling were:

- **Accessibility:** limited access for NDA measurements and destructive sampling of the sludge in the tanks is restricted to sampling in-stream while pumping the tank contents through a loop, via a bag-in bag-out glove box arrangement.
- **Homogeneity:** tanks are equipped with stirrers to ensure homogeneity of the contents. Therefore, it can be expected that measurements before and after stirring events will yield different outcomes. Notwithstanding the option of stirring tank contents, deposition of solids at the tank bottom may have occurred that is not possible to mobilise through stirring, leading to a layered structure of the radioactive waste in the tanks.
- **Unavailability of suitable reference samples** with adequate solid fraction.

The analysis of **pre-existing data** provides comprehensive information about physico-chemical properties of the waste. Only a limited number of additional samples (e.g. 6 per tank) should suffice to confirm the characteristics determined via the pre-existing data.



The first step in the sampling campaign was the establishment of the approximate distribution of the activity in the tanks by external gamma spectrometry or by collimated dose rate measurements. It was expected that one of the tanks would be quite inhomogeneous, while the second should have better homogeneity.

Following **non-destructive gamma dose rate measurements**, there will be an indication of whether the contents are fairly **homogeneous** with respect to **specific activity**, or whether there is a **significant elevation profile**.



In the case of an elevation profile, biased sampling should be performed on that portion of the waste with the highest activity contained, prior to performing any mixing.

The number of samples to take may be limited by access of the different levels within the tank, but a minimum number of samples of about 6 may be sufficient for confirming the usefulness and applicability of previously identified scaling factors.



In the case of no elevation profile, sampling can skip the previous step (biased sampling) and can proceed to unbiased sampling, which should be performed after mixing tank contents. Therefore, only the probabilistic sampling method can now be used for sampling the sludge.

The minimum number of samples is determined by the requirements of an approach for univariate statistics on non-spatially distributed data. As preparatory homogenisation measures will be used for homogenisation, the expected variance of activity concentration should be low. Therefore, the number of samples can be low (10 to 20).



If a uniform distribution of data is expected, an unbiased survey is the preferred sampling method, and vice versa, if the distribution is expected to be non-uniform, a biased survey is the better option.



If the biased sampling step was skipped, the number of samples of this step will need to be sufficient for determination of scaling factors and range of nuclide factors.

If data was collected for biased sampling, the number of samples still required for the unbiased sampling step can be correspondingly reduced, as the biased sampling data can provide some information about the results to be expected after mixing.



The statistical evaluation of results will only be done concerning univariate analysis with respect to the nuclide specific activity concentration. In addition to this, the scaling factors of difficult-to-measure to Cs-137 will be evaluated or confirmed.

In conclusion; biased sampling may be used to confirm inhomogeneity within the tanks, if suggested by non-destructive testing; if not, non-biased sampling only can be used to confirm the trends observed in the pre-existing data, and to supplement it where additional information is needed.

The methodology for sampling strategy optimisation developed within the INSIDER project **proved to be successful** in the application of the UC1 case.

3.7. Case study #2

2

The second case study (UC2) was intended to cover the case of the **decommissioning of a nuclear reactor**. The selected facility for UC2 was the characterisation of the biological shield of the BR3 reactor, under decommissioning at the SCK-CEN site of Mol (Belgium). The reactor was a smaller scale prototype (40 MWth) of a commercial power reactor of the PWR type which was operated from 1962 to 1987.

The heart of the reactor, i.e., the reactor pressure vessel and primary circuit, was located in the reactor building.

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At the time of the exercise, all the main installations had been dismantled, and the focus lied on the building structure itself. One of the most important remaining radioactive waste volumes was considered to be the activated concrete of the bio-shield.

[Figure 7](#) shows a picture of the reactor pool before the removal of the liner (left) and a cross section of the reactor building during exploitation (right).

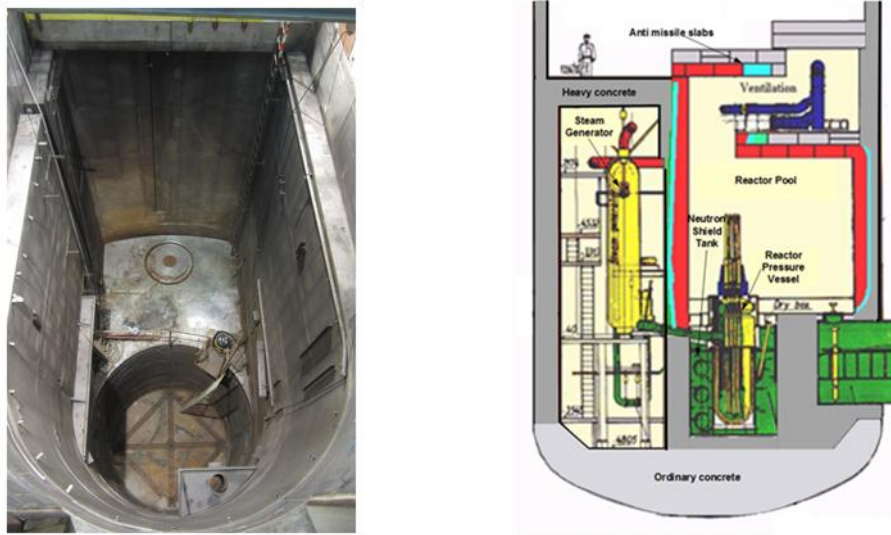


Figure 7. Left: Picture of the reactor pool after dismantling the main components and before dismantling the pool liner

Reference [6] refers in detail to the sampling strategy and data analysis process and results for UC2.

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The list of radionuclides of potential importance was the following: H-3, C-14, Ca-41, Fe-55, Co-60, Ni-63, Ba-133, Cs-134, Eu-152, Eu-154 and Eu-155. This list can be further downsized to Co-60, Ba-133, Eu-152 and Eu-154 in case of unconditional and conditional release. Ba-133 was the radionuclide with the highest concentration present (estimated maximum 20-40 Bq/g on 01/01/2020).

The main goal of the radiological characterisation programme for the BR3 bio-shield was to economically optimise the bio-shield dismantling strategy using a waste-led approach. In order to reach this main goal, the **main objective was divided into three sub-objectives**:

1. create a 3D activity concentration distribution map,
2. quantify and localise the different end-stage volumes,
3. economically optimise volumes in view of the waste-led approach.

The **constraints** were limited to the following:

- **Safety**: The expected activation levels were relatively low (maximal activity concentrations up to 50 Bq/g). The radiation levels after removing the liner were very limited (100 nSv/h up to a few μ Sv/h). As the activity concentrations was low, the contamination hazard was relatively low as well.
- **Planning and budgetary restrictions** limited the number of core drilling samples to 30. The number of gamma spectrometry measurements per core were limited to 10.
- **In situ (non-destructive) measurements** were only possible on the inner or outer surface of the reactor pool walls. Moreover, acquiring results in terms of activity concentrations was extremely challenging due to the activity distribution profile depending on the depth and angle.
- **For sampling and ex-situ measurements** the amount (mass, volume, number) was limited compared to the total volume of the bio-shield. Sampling was hampered by the presence of thick reinforcement bars. Due to the wet drilling, precautions were needed to prevent cross contamination.

The following **pre-existing data** was made available:

- original 2D plans and 3D models based on the original 2D plans (not “as-built”),
- operational history,
- results from neutron activation calculations; and
- results from historical sampling and characterisation programmes.



Although the pre-existing data was rather heterogeneous, as it resulted from different campaigns with different goals, the amount of information and consistency seemed sufficiently adequate to justify performing a preliminary analysis for informing the sampling design. The consensus was that it could at least lead to the achievement of the first objective: the estimation of the 3D activity concentration distribution.

During the **exploratory data analysis**, a significant degree of focus was placed on the multivariate aspect, and the potential relation between the liner activity concentrations and those in the concrete. It was already very clear from the start that there would be a **complex trend** related to the distance from the neutron source, and the depth in the concrete, and that **characterisation** of this trend would be the **main aim in this phase**.

Data analysis was **focussed on modelling the complex trend of Ba-133 activity concentrations**, using the class of generalised linear models and potentially generalised additive models if the former would not provide sufficient flexibility. Different features are available for use as regressors in this case: the spatial coordinates, the distance to the reactor fuel, the depth within the concrete, and others.



Since the liner Co-60 activity concentration was only available at the measurement locations, a generalised additive model was used to basically interpolate these measurements on the inner surface of the bio-shield, as a smooth function of the projected x and z coordinates, and the corresponding distance to the fuel.



A linear model did not suffice, because of the non-linear relation of the Co-60 activity concentration with some of the considered regressors. For similar reasons, the trend modelling for the Ba-133 activity concentrations was done with a generalised additive model as well, using a smooth function of the liner Co-60 activity concentration and the depth within the concrete. At this stage the objectives were not achieved, so the preliminary analysis simply served the purpose of informing the sampling design.

After removing the liner, an in-situ total **gamma surface mapping** was performed, consisting of about **300 individual measurements** using a planar plastic scintillator. This roughly amounted to about one measurement per square meter, using **regular grid sampling** to achieve full coverage.



The sampling design mainly consisted of systematic sampling (equal probability of selection/probabilistic) supplemented with judgemental, selected sampling locations (specific structures such as the “waste bin” and the refuelling channel and close to the location with the maximal activation level).

In addition to this, the expected trend extreme locations were selected as well, and relying on the symmetry of the activation to maximise the results with a minimum number of samples. This **combination of sampling approaches** basically ensured:

- covering all the concrete elements, to reduce the risk of missing anything,
- including (approximately) the minimum and maximum values across the entire bio-shield, but also within every element, reducing the required amount of extrapolation during the data analysis,
- investigating specific features for which it is known that they deviate from the general trend.



30 samples were taken by wet core drilling, to be segmented and the segments to be analysed by gamma spectroscopy. Furthermore, 6 were taken, homogenised and sent to laboratories for destructive analyses.

The **main outcomes** from the statistical guideline applied to **UC2** case can be summarised as:

The definition of clear and quantifiable objectives prior to starting the exercise allowed the development of an effective sampling plan including the selection of appropriate measurement techniques and the up-front definition of criteria for the measurements.

Performing a radiological characterisation program in two or three stages can be efficient and effective to tackle areas with higher uncertainties. Historical data, sometimes gathered with other objectives, can optimise the characterisation process.

The main **UC2 objective** was to **estimate** the **volume categorised** as **conditional release**. The **sensitivity analysis** showed that a **global uncertainty of 13%** (best estimate compared to 95th percentile) on the volume categorised as conditional release **was more than satisfactory**.

In conclusion, the methodology for sampling strategy optimisation developed within the **INSIDER project** proved to be successful in the application to the UC2 case.

3.8. Case study #3

3

The third case study (UC3a) was intended to cover **post accidental site remediation**. The selected facility was a location in a nuclear research centre with soil contamination from a liquid solution due to the dissolution of spent fuel. Therefore, the soil was contaminated with actinides (alpha emitters) and fission products (beta/gamma emitters).

The **contamination level** was **generally very low**, typically **below 100 Bq/kg**, but **with hotspots** up to hundreds of Bq/g.



Access to the site for in-situ cartography could not be granted, so the exercise was limited to the development of the sampling strategy.

Reference [7] refers in detail to the sampling strategy and data analysis process and results for UC3a. For **site remediation purposes**, the main **objectives** of characterisation are:

1. The **global estimation of statistical quantities**, such as average activity concentration value for the whole area
2. **3D distribution map of activity concentration and waste segregation**. The analysis of depth profiles combined with the horizontal distribution leads to 2D/3D representations depending on the dataset spatial organisation. Appropriate geostatistical methods need to be carefully selected given the spatial continuity of the phenomenon and the database configuration (linearity, stationarity, multivariate, trend etc.).

This case was affected by the following major **constraints**:

- **Accessibility**: for security reasons the location was subject to vetting, so no in-situ measurements were allowed.
- **Confidentiality**: the sensitivity of the case (environmental contamination) limited the access to existing data and possibility to perform additional measurements.

Availability of **pre-existing data** was also extremely limited for confidentiality reasons. The concerned nuclear facility was devoted to radiochemistry on trans-uranium elements. The contaminated soil area was located beneath this building, just below a former tank room.

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In order to improve the radiological assessment of soils below the tank room, different sampling campaigns were conducted, consisting in 7 horizontal drill holes. Preliminary direct measurements were performed along the cores. They consisted in gamma and X scanning (gross counting) on a regular 5 cm mesh, to serve as a semi-quantitative characterisation of the gamma content of soil samples.

The **main nuclides for laboratory analyses** included:

- **Np-237** and **Pa-233** for **gamma emitters**.
 - Other gamma emitters such as **Co-60**, **Eu-152**, **uranium** and **thorium** chains **were not present** (or were observed at very low levels, close to detection limits).
 - **Cs-137** and **Am-241** were detected on some samples.
- **Sr-90** for a beta emitter.
- In addition to this, the different **plutonium isotopes** (**238**, **239+240** and **241**) were quantified using appropriate alpha measurements.

As there was no possibility for new samples and new in situ measurements, the **existing dataset was considered as the final one for UC3a**. However, non-destructive measurements and new samples could have been performed on the existing cores.

There was no sampling design definition for the other use cases, but the statistical analysis promised to bring interesting and relevant conclusions due to the number of available samples. Global and local estimates were calculated instead. In addition to this, sensitivity to dataset extension was studied as 2 zones could be identified: the inner area with the highest activity levels (corresponding to the 50 cm sampling resolution along the cores) and the accessibility area (with a 1 m mesh).

As it seemed to be relevant, 3D contamination, areas with high estimation uncertainties as well as extrapolation areas, were finally identified. They would have been used for recommendations of new samples in the case of a site with possible additional investigation.

Despite the dataset limitations for the definition of the sampling plan, as described before, the large number of samples enabled a sound sensitivity analysis. Sub-dataset will be extracted from the full dataset in order to quantify the impact on the estimates and their related uncertainties. Different possibilities can be applied, such as:

- reduction of sample number per drill hole,
- reduction of drill hole number,
- integrating correlation between nuclides by reducing some laboratory analyses.

The **major outcomes from UC3a** can be summarised as:

Sampling strategy is strongly impacted by the characterisation objectives.

The statistics and geo-statistics methods used in the application case can provide several kinds of results, such as quantiles of total activity on the one hand, and classification of contaminated materials according to the risk to exceed a given threshold (such as French IRAS requirement) on the other hand.

These outputs are key results to develop, manage and optimize D&D scenarios.

Geo-statistics proved to be very effective for the analysis of collected data and in order to provide estimates of contaminated materials for different radiological thresholds or total radiological inventory. However, there was not a defined standard or guide to define the number of measures/boreholes/samples and their location as it strongly depended on the spatial structure of the contamination.

Drilling points should be placed throughout the area to avoid extrapolation. The spatial distribution of in-depth investigations should cover the entire site to characterise it globally.

From the point of view of waste volume management, transition zones are more critical since it is difficult to categorise them with respect to the reference thresholds. Uncertainty being the most important in these areas for proper delineation (and limiting misclassification errors), the sampling distribution should favour them over other areas that only require confirmation of contamination or non-contamination.

3.9. Case study #4

4

The fourth case study (UC3b) was added as supplemental analysis of irradiated graphite of a nuclear research reactor. The selected facility for UC3b was the moderator/reflector block of G2, a prototype gas-graphite reactor localised at the CEA centre of Marcoule that was operated for 22 years until 1980.

For dismantling and decommissioning operations carried out on this facility, the initial characterisation focused on the graphite volume presented in [Figure 8](#). This is a horizontal prism of 9.53 m by 9.40 m, 9.05 m long and with a core radius of about 4.7 m. The G2 graphite is composed of 1000 tons of moderator surrounded by 302 tons of reflector. Also in this case, the exercise was limited to the development of the sampling strategy.

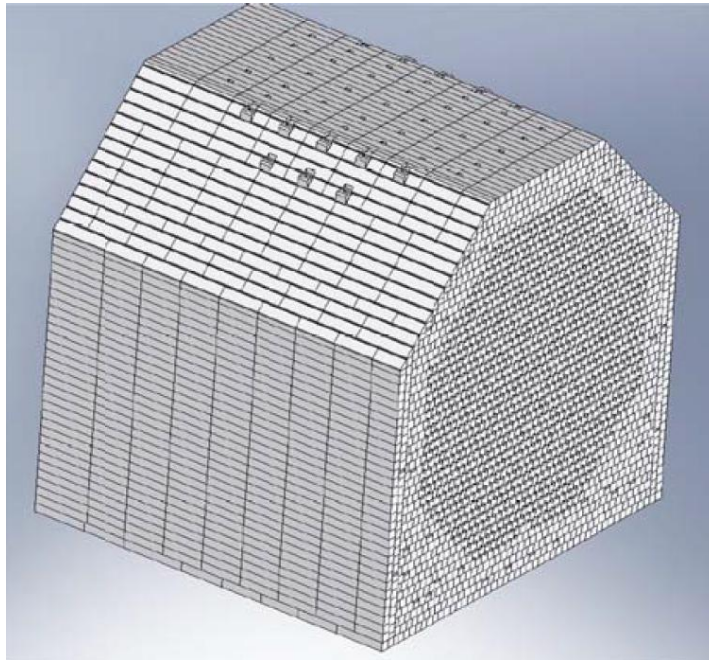


Figure 8. Schematic view of the G2 reactor

The **main objective** of the exercise is to provide a **radiological inventory** for the **graphite volume**. Some key nuclides were considered of major interest for specific nuclides in a waste repository perspective. A secondary objective was waste oriented with the classification of volumes according to different thresholds.

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Pre-existing data consisted of a few localised punctual samples and two core drills (one vertical and one horizontal) taken in the '90s. As there was no possibility for new samples and new in situ measurements, the existing dataset was considered as the final one.

The **data analysis** was performed using statistical methods and geo-statistical tools and was fully described in the specific annex of project deliverable D3.7 [8]. The **main outcomes** have been simply **summarised below**:

- The **radiological inventory** could be computed using **three different data processing techniques**:
 - **direct spatial fitting**,
 - through the **spatial correlation** (variogram) for certain nuclides (C-14 for instance),
 - through **multivariate spatial correlation** to integrate a spatial fitting to reduce estimation uncertainties.
- **Comparable results were shown due to the good spatial continuity of the activation phenomenon**, even if the number of data was quite limited.
- For **total inventory**, **additional data in non-sampled areas was not expected to impact significantly the total activity** as most activated parts are already sampled and contribute the most to the output result, **but improvement on uncertainty may be found** (risk curves become more vertical).
- **Through using more precise waste classification criteria for the different nuclides** (long-lived, reference activity levels), some specific areas in the graphite block may be pointed out for additional investigations. However, the use of a sound activation model may serve as efficiently.

4. KEY TAKEAWAYS

The key takeaways from the **INSIDER project's** experience of utilising **STRATEGIST**, a tool for statistical analysis of plant characterisation data, are recorded in this section. First a high-level overview of the key takeaways has been provided here, including potential benefits to the target audience arising from the KP, and lessons learnt and recommendations have been summarised in the subsequent subsections.

This KP has outlined a generic strategy for handling problem definition, data analysis and sampling design in the field of initial nuclear site characterisation. It has also provided an overview of commonly used data analysis and sampling design methods, applicable in this field. This document can serve as a blueprint for the **STRATEGIST** web-based tool by presenting the strategy in a more user-friendly way.

Furthermore, the strategy has been thoroughly tested in practice through the three different test cases cited in the body of text.

An efficient and correct plant characterisation process allows to better estimate the radiological conditions of the plant and of all subsystems and components. This leads to an optimisation of the dismantling operations in order to minimise the doses to the workers. Moreover, the operator will be able to:

- select the most suitable decontamination and dismantling procedures,
- evaluate the amount and classification of radioactive waste and clearable material,
- optimise the waste treatment processes.

This can bring significant benefits during the decommissioning works in terms of savings in human and financial resources and execution time.

4.1. Lessons Learnt

Seven (7) lessons learnt from the **INSIDER project's** experience of utilising **STRATEGIST**, a tool for statistical analysis of plant characterisation data, are recorded in this subsection.



#LL-1 Define and prioritise objectives before selecting sampling methods

The INSIDER case studies demonstrated that the success of a characterisation campaign is strongly dependent on establishing clear, measurable and prioritised objectives at the outset. Objectives should drive the selection of measurements, sampling density, data analysis techniques and acceptance criteria rather than the reverse. This ensures that resources are directed towards generating information that supports decision-making and avoids unnecessary data collection.



#LL-2 Exploit prior information before collecting new data

Historical records, operational history, previous surveys, modelling results and existing measurement data can significantly improve the efficiency of characterisation programmes. In several use cases, preliminary analysis of existing information informed sampling design, reduced uncertainty and limited the need for additional measurements. Making effective use of available knowledge can reduce cost, programme duration and worker exposure



#LL-3 Characterisation is most effective when treated iteratively

Radiological characterisation should not be viewed as a single campaign. Instead, data collection, analysis, interpretation and sampling design should be repeated as new information becomes available. Iterative approaches allow uncertainties to be progressively reduced and enable resources to be focused on the areas of greatest importance or risk.



#LL-4 Sampling design must reflect the contamination characteristics

The case studies showed that no single sampling strategy is universally applicable. The optimal approach depends on contamination distribution, spatial structure, accessibility, objectives and available resources. Therefore, selection of sampling methods should be evidence-based and tailored to site-specific conditions.



#LL-5 Uncertainty management is as important as data collection

A key lesson from the INSIDER methodology is that understanding and quantifying uncertainty provides confidence in decision-making. Sensitivity analyses, uncertainty estimation and transparent reporting enable operators to understand the reliability of conclusions and identify where further investigation is justified.



#LL-6 Statistical and geostatistical tools provide significant value when integrated with engineering judgement

The project demonstrated that advanced statistical techniques could improve characterisation outcomes, optimise sampling programmes and support waste classification decisions. However, these tools are most effective when combined with expert knowledge of facility history, operational conditions and decommissioning objectives.



#LL-7 Knowledge retention and accessibility enhance programme efficiency

Transforming expert methodologies into structured guidance and accessible digital tools helps preserve specialist knowledge and enables wider adoption of good practice across organisations. The STRATEGIST tool illustrates how KPs can convert complex expertise into practical support for future projects.

4.2. Recommendations

Eight (8) global recommendations (Rs) have been provided based on the experience of utilising the **STRATEGIST** tool for statistical analysis of plant characterisation data, with a view of informing future similar works.



#R-1 Treat characterisation as an iterative decision-support process

Characterisation programmes should be planned with provision for multiple investigation and analysis cycles. Decisions on additional measurements should be informed by uncertainty analysis and the extent to which objectives have been met, rather than following predetermined sampling quotas.



#R-2 Establish clear objectives, constraints and success criteria at project initiation

Operators should formally define characterisation objectives, constraints, priorities and required outputs before field activities begin. This provides a sound basis for selecting suitable analytical and sampling methods and improves overall programme efficiency.



#R-3 Maximise the use of existing knowledge and organisational memory

Historical records, previous characterisation campaigns, operational experience and modelling outputs should be systematically reviewed before undertaking new measurements. Knowledge management practices should ensure that this information remains accessible to future projects and organisations.



#R-4 Integrate statistical thinking throughout the characterisation lifecycle

Statistical and geostatistical methods should be applied from the earliest planning stages through to final reporting. These approaches support optimisation of sampling effort, quantification of uncertainty and defensible decision-making.



#R-5 Focus additional investigations on areas of highest uncertainty and decision significance

Where resources are constrained, supplementary sampling should target transition zones, hotspots, areas requiring extrapolation and locations that most influence waste classification or remediation decisions



#R-6 Use digital knowledge products to improve consistency and knowledge transfer

Methodologies, workflows and lessons from characterisation projects should be captured in reusable guidance, tools and training materials. Interactive tools such as STRATEGIST can help standardise the application of good practice and reduce reliance on individual experts.



#R-7 Promote transparency in reporting assumptions, methods and uncertainties

Characterisation reports should clearly document what was measured, which methods were applied, the assumptions used and the associated uncertainties. Transparent reporting improves stakeholder confidence, facilitates regulatory review and increases the future value of the knowledge generated.



#R-8 Capture and share optimisation benefits as organisational knowledge

Future projects should systematically record the benefits achieved through optimised characterisation, including reductions in measurements, worker dose, cost and schedule impacts. These outcomes provide valuable evidence for continuous improvement and support wider adoption of knowledge-led approaches across the decommissioning sector

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