INSIDER UC2: the BR3 biological shield preliminary results and future work

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Abstract. Aiming at economical optimization, the characterisation of the biological shield of the Belgian Reactor 3 is one of the three use cases intended to validate the integrated characterization methodology developed within the INSIDER project. Pre-existing data were used to define the sampling design strategy. The additional sampling and analysis program consisted of total gamma measurements at the inner surface of the biological shield (secondary data) and gamma spectrometry measurements on drill core samples (primary data). The newly acquired data is supplemented with the historical available data. The full data set currently consists of a total of 283 secondary and 379 primary data points. Preliminary calculations already provide a clear-cut representation of the three different end-stage classes: unconditional clearance, conditional clearance and radioactive waste. On the short term, the current model will be further refined and completed with proper risk evaluation. On the longer term, we envisage a global uncertainty calculation and sensitivity analysis of the entire process.

1 Introduction

The EURATOM work program project INSIDER (Improved Nuclear Site characterization for waste minimization in Decommissioning under constrained EnviRonment) aims at improving the management of contaminated materials arising from decommissioning and dismantling (D&D) operations. The methodology is based on advanced statistical processing and modelling, coupled with adapted and innovative analytical and measurement methods.

The INSIDER partners selected three case studies in order to validate the improved integrated characterisation methodology. The biological shield of the Belgian Reactor 3 (BR3) has been chosen for the second case (UC2) dealing with the decommissioning of a nuclear reactor. The reinforced high-density concrete (also known as heavy weight or barite concrete) has been exposed to neutrons during reactor operation and is therefore activated.

The main goal of the radiological characterization program is to economically optimize the biological shield dismantling strategy, using a waste-led approach. In order to reach this main goal, we established three sub objectives:

– create a 3D specific activity distribution map;
– quantify and localize the different end-stage volumes; and
– economically optimize volumes in view of a waste-led approach.

Constraints are related to typical nuclear safety issues (radiation and contamination hazards) and in addition to access limitations and classical safety hazards. Due to planning and budgetary reasons, the amount of samples by core drilling was limited to 30. In situ (non-destructive) measurements are only possible on the inner or outer surface of the reactor pool walls. Moreover, acquiring results in terms of specific activities is challenging due to the activity distribution profile that depends on the depth and angle.

Section 2 of this paper describes how the method developed within the INSIDER Work Package 3 (sampling and strategy) was implemented for UC2. The preliminary results are given in Section 3. Section 4 summarizes some preliminary conclusions and reflects on the future work.

2 Method

The strategy used is being developed and will be further adjusted within Work Package 3 [1]. Following the current approach, we used the different diagrams for the data analysis and sampling design strategy. After defining the objectives and assessing the constraints, available information was analysed and checked against the objectives. This check consisted of the following steps: pre-processing, an exploratory step and the actual data analysis, and post-processing to transfer the obtained results into end-stage volumes. Apart from the available

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plans of the biological shield and the operational history of
the reactor operation, results from neutron activation
calculations and former characterization programs were
available. From the different neutron activation calcula-
tion exercises performed, we noticed the following:
– The specific activity obtained differs considerably from
sample measurements for the main radionuclide present
(Ba-133), while Ba is one of the main elements present in
the concrete.
– Specific activity ratios of other radionuclides to Ba-133
differ considerably between different calculations, con-
sidering different chemical compositions of the concrete
(trace elements).

Radiological measurements performed in the past on
drill core samples, gave a first idea on the most important
radionuclides present (Ba-133, Eu-152, Co-60 and Eu-154)
and the activation profiles at a few specific locations.
Neutron calculations and radiological analysis showed that
the potential presence of difficult to measure nuclides (i.e.
H-3, C-14, Ca-41, Fe-55 and Ni-63 in the reinforcement
bars) does not influence the decision-making process for
defining the end-stage material volumes for conditional and
unconditional clearance.

The sampling design process followed the strategy
developed in Work Package 3. The samples have been
taken by wet core drilling in June 2018, followed by slicing
and analysing during the second half of 2018. The
additional characterization results will enlarge the
dataset, which will again be analysed and checked against
the objectives. Deliverable D3.5 [2], covering the sampling
plan for UC2, describes the process to be followed in detail.

Apart from the samples taken and analysed aiming to
design the 3D specific activity distribution map, additional
concrete samples at two different locations were taken and
provided to the National Physical Laboratory (NPL) as
part of Work Package 4 (reference materials and
radiochemistry). NPL is taking care of the homogenization
and distribution of sub-samples to various EU labs
belonging to the INSIDER consortium in view of a
benchmarking exercise for Work Package 6 (performance
assessment and uncertainty evaluation. We also provided
inactive concrete for the production of reference samples
(Work Package 4) and organization of an interlaboratory
comparison (Work Package 6).

Furthermore, five EU measurement teams have
performed an in situ measurements comparison exercise
within Work Package 5 (in situ measurements) in the BR3
reactor pool consisting of dose rate, total gamma and
gamma spectrometry measurements at different locations
in the biological shield.

3 Results

3.1 Preliminary data analysis based on pre-existing
data

In a first approach, Co-60 concentration levels in the pool
liner and results from a few historical drill core samples
were used (Fig. 1). During the exploratory data
analysis, we focused on the multivariate aspect, and the
potential relation between the liner specific activities and
those in the concrete. For the borehole analysis, we had Ba-
133 results at all locations, but the other remaining
radionuclides were not always available. Hence, we decided
to fall back to a univariate problem. Since the liner data is
more systematically distributed over the inner surface of
the biological shield, we of course tried to account for it in
this stage.

For the preliminary data analysis, we used
generalized additive models. The liner Co-60 specific
activity was interpolated on the inner surface of the
biological shield, as a smooth function of the projected x
and z coordinates, and the corresponding distance to the
former fuel. For the trend modelling for the Ba-133 specific
activities, we used a smooth function of the liner Co-60
specific activity and the depth within the concrete. Figure 2
illustrates the results of the preliminary data analysis. As
the data on which this analysis is based is very limited, and
e.g. a proper quantification of the uncertainties on the
results was not even considered relevant at this stage, it
was very clear that the objectives were not achieved at this
point. The preliminary analysis just served the purpose of
informing the sampling design.

3.2 Sampling design and additional data gathering

After removing the liner, we performed an in situ total
gamma surface mapping, consisting of 303 individual
measurements using a contamination monitor (type: CoMo
300G plastic scintillator of 300 cm$^2$ surface, manufactured by Nuvia Instruments). This roughly amounted to about one measurement per square meter. We used regular grid sampling (Fig. 3) to achieve full coverage, as the idea was to use these data as secondary information for the specific activities within the concrete, in a similar way as how the liner data was used for the preliminary data analysis.

Following the basic principles described in [1], the sampling design mainly consisted of systematic sampling (equal probability of selection/probabilistic) supplemented with judgemental selected sampling locations (specific structures such as the storage container and the refuelling channel and close to the location with the maximal activation level). In addition, the expected trend extreme locations were selected as well, and we rely on the symmetry of the activation to maximize the results with a minimum number of samples. Figure 4 shows the sampling plan.

The combination of these different sampling approaches basically ensures that:
- We cover all the concrete elements, to reduce the risk of missing anything.
- We include (approximately) the minimum and maximum values across the entire biological shield, but also within every element, to reduce the required amount of extrapolation during the data analysis.
- We investigate specific features for which it is known that they deviate from the general trend.

The presence of thick reinforcement bars hampered the sampling. We choose wet drilling, implying precautions to prevent cross contamination. The cores (diameter 72 mm, length of about 90 cm down the first outer reinforcement bars) were segmented. Analysis of the segments (thickness 5–10 mm) by high-resolution gamma spectroscopy was...
performed in two consecutive steps. A total of 195 segments originating from the 30 drill core samples were analysed.

The dataset on which the current model is based at time of writing contains 662 data lines (Tab. 1). This contains both primary and secondary data. Of all the in situ total gamma measurements 283 are used as secondary data. The primary data consist of 184 historical measurements (based on low and high resolution gamma spectroscopy) and 195 new measurements (high resolution gamma spectroscopy). Figure 5 gives a visual representation of the current dataset.

### 3.3 Data analysis new data included

At present, further data analysis and checking of the objectives is ongoing. Figure 6 shows the example of a horizontal slice of the BR3 biological shield indicating the forecasted class: unconditional clearance, conditional clearance or radioactive waste. This kind of output is indispensable for the colleagues in charge of developing the dismantling strategy. Volume estimations are not yet reported in this stage. In the first place, result calculation needs further development and refinement.

### 4 Conclusions and future work

The strategy developed within Work Package 3 of the INSIDER project is currently being applied on the characterization of the biological shield of the BR3 reactor. The current results show that the process, methodology and tools used are very powerful in combining results of various types of data, developing sampling design, performing data analysis and treatment and providing results representation.

The current result representation needs further refinement. Some examples:

- In the sampling plan, we tried to include the maximum value. Due to the presence of an activated reinforcement ring at the level where the maximum specific activity in the concrete was expected, it was not possible to sample this area. Moreover, the results of the in situ gamma spectroscopy measurements in this area might be influenced by this component. In the present results representation, the specific activity for this area has been extrapolated. Additional measurement data will be collected after removal of the ring.

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**Table 1.** Overview of the different types and corresponding amounts of data points, at the time of writing, in the unfiltered dataset, gathered for constructing the 3D model.

| Data type   | Number of points | Unit                              |
|-------------|------------------|-----------------------------------|
| Primary     |                  |                                   |
| Existing    | 184              | Bq/g (for one or more isotopes)   |
| New         | 195              | Bq/g (for one or more isotopes)   |
| Secondary   |                  |                                   |
| Existing    | None used        |                                   |
| New         | 283              | cps (from contamination monitor)  |
| **Total =** | **662**          |                                   |

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*Fig. 4. Sampling plan for the BR3 biological shield (30 drill core samples).*
The presence of a small contamination in one corner on the pool floor, close to the former storage container, was reflected in a part of the total gamma in situ measurements. The contamination needs to be removed and the total gamma measurements in this area need to be repeated.

Current values shown are the best estimates. Uncertainty calculations and the use of confidence levels are not yet implemented. On the other hand, an averaging out over 1 ton of material could be taken into account in order to minimize the risk.

In order to evaluate the risk we will perform cross validation calculations.

Towards the end of the INSIDER project, we envisage a global uncertainty calculation and sensitivity analysis of the entire process from initial characterization towards the assessment against objectives (Work Package 6). The results of the in situ and laboratory intercomparison and benchmarking exercises (see Sect. 2) could serve as important input.

Return of experience from the BR3 case will, together with the other two use cases, lead to a guide on the data analysis and sampling design strategy that has been developed within Work Package 3 of the INSIDER project.

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**Fig. 5.** Current dataset for the BR3 biological shield: in situ total gamma measurements (left, contamination monitor) and gamma spectroscopy on segments/samples (right, boreholes).

**Fig. 6.** Example of a horizontal slice of the BR3 biological shield indicating the forecasted classes and the corresponding 3D location (left; data for $z = 0.5$ m, right; existing primary data points are shown in blue, new primary data points in red and the location of the slice at a reference height of 0.5 m is marked in green).
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Author contribution statement

S. Boden and B. Rogiers developed the described strategy and performed the data analysis. B. Rogiers performed most of the computational data analysis. R. Vandyck, G. Verstrepen and W. Broeckx organized and performed the measurement and sampling campaigns, while N. Mangelschots managed the data gathered from the measurement campaigns. All authors discussed the results and provided feedback. S. Boden and W. Broeckx wrote the manuscript together with B. Rogiers.

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