Demonstration of a Non-Invasive Radiation Measurement Technique to Support the Decommissioning of Nuclear Power Plants – 25529

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ABSTRACT

Contamination profiling of cementitious material is critical for developing comprehensive decommissioning strategies in nuclear environments. Contaminated concrete structures represent a significant fraction of the total radioactive waste expected to be generated, and stored, during decommissioning. Techniques to evaluate the amount of clean and contaminated concrete prior to decommissioning can significantly reduce cost and improve efficiency. This work describes an EPRI sponsored demonstration of the Createc D:EEP system for the in-situ and non-destructive evaluation of contamination depth in cementitious structures at the Électricité de France (EDF) Dungeness B site in the United Kingdom. For this application, a specially designed version of the D:EEP system was developed for underwater use within the Dungeness B Fuel Storage Pond (FSP) to obtain a contamination depth profile within the pool wall. If effective, this technology could significantly enhance traditional radiological characterization and waste estimation methods in nuclear decommissioning.

INTRODUCTION

Non-destructive characterization of contamination ingress in cementitious materials is crucial for the future decommissioning of nuclear sites. Dealing with the UK's nuclear legacy is expensive, with cementitious structures constituting a significant proportion of the overall waste volume. Due to the complexity of this challenge, cementitious waste is often incorrectly assigned to a higher waste stream based on conservative or limited characterization information.

In-situ measurement of entrained radioactivity within the walls of nuclear fuel, and waste storage structures is a universal challenge at nuclear facilities worldwide. During decommissioning activities, the higher contaminated surfaces must be removed, separated from the Low-Level Waste (LLW), and stored as Intermediate Level Waste (ILW). In the UK, the lifetime storage and disposal costs for ILW are around many times more expensive than LLW, therefore proper classification of materials can result in significant long-term savings. Similar cost structures are observed in the US and other countries, whereas accurate characterization of cementitious waste is a global issue, impacting decommissioning strategies and costs worldwide.

Createc's DEEP: Estimating Entrained Product (D:EEP) presents a potentially innovative solution for the non-destructive assaying of cementitious material in-situ. It combines advanced spectral analysis techniques with detailed modelling with the aim to estimate contamination ingress within concrete structures at a much finer granularity than attainable with conventional methods. Given the described advances this technology could provide, the Electric Power Research Institute (EPRI) supported the compilation of a report on the D:EEP technology in 2024 (to be published in 2025) [2]. This introduces the technology, discusses the recent advancements made to the system, and presents a detailed case study of a deployment in a Fuel Storage Pond (FSP, internationally known as Spent Fuel Pool (SFP)) undertaken at a UK nuclear power plant in 2024, the latter being the subject of this paper.

DESCRIPTION

Background

Conventional characterization of cementitious structures relies on the use of physical core samples taken from the structure of the facility. Using industrial coring drills, samples are removed from the facility and analyzed in a laboratory using collimated radiation detectors. This process is state of the art, however poses radiological, structural as well as logistical challenges when decommissioning hazardous environments or characterizing active facilities.

Figure 1 shows an example of a core sample being extracted from the wall of a nuclear facility. This is highly intensive, manual work requiring operators to engage directly with potentially hazardous surfaces. Due to the nature of core drilling, airborne contamination can be a challenge requiring the use of Personal Protective Equipment (PPE) and Respiratory Protective Equipment (RPE) to ensure the safety of operators. This reliance on PPE and RPE represents the least desirable condition under the Hierarchy of Controls.

Figure 1: Example of core sampling on a nuclear facility.

Removing physical samples from a region naturally results in damage to the structural integrity of the facility. This can limit the number of samples that can be extracted. Due to the sparsity of core samples typically taken, gross assumptions are often applied to the neighboring regions, resulting in assumptions of homogeneity between sample locations. This runs the risk of missing elevated regions of localized contamination ingress in areas where radiation transport has occurred at an accelerated rate. Examples include regions where the physical structure of the surface has been compromised by the formation of cracks, flaking of protective paint layers, etc. This can result in over or underestimation of waste volumes and often leads to conservative assumptions being applied to mitigate these uncertainties.

From a logistic point of view, apart from choosing the right equipment, bringing it into and installing it in the radiological controlled environment, maintaining industrial safety as well as equipment contamination minimization protocols, having comprehensive knowledge of carrying out core drills with the intent of characterization requires skills, knowhow and experience. Hiring contractors with experience in the field is therefore an important lesson learned.

To address these challenges, Createc developed a Non-Destructive Depth Profiling (NDDP) technique, D:EEP, with the aim of measuring waste items in-situ at a much finer granularity than currently achievable using physical sampling techniques. The technology uses a proprietary spectral analysis technique on data recorded with a Cadmium Zinc Telluride (CZT) spectrometer to provide a non-intrusive picture of the penetration of contamination within a concrete surface. The spectrometer is essentially uncollimated, only requiring shielding to remove background and ensure that the spectrum recorded is that of the surface being analyzed. The system is designed for rapid deployment, producing minimal airborne contaminants during surveys (as opposed to coring). With this, the technology aims at scanning large areas with greater speed compared to core drilling, while minimizing the time workers spend in hazardous environments through ALARA principles.

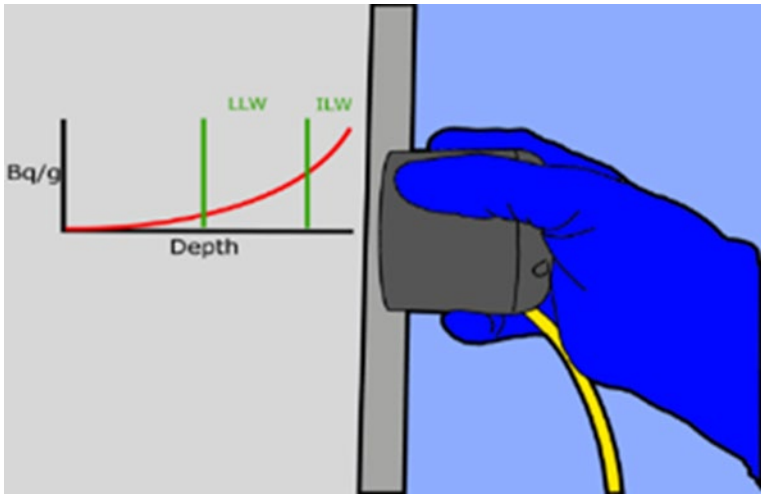

Figure 2: Schematic image of the Createc Non-Destructive Depth Profiling system.

Createc's NDDP is designed to ascertain the depth of contamination of multiple gamma-emitting isotopes, up to a maximum depth of 150mm. Figure 2 presents a diagrammatic illustration of the technique, highlighting the physical structure and deployment of the sensor technology, alongside a simplified representation of the final output of a D:EEP analysis.

One of the potential benefits of the such a technology is the independence of the sensor and deployment mechanism. The sensor is completely agnostic of the deployment mechanism and can be fitted to any system capable of holding the front face of the sensor flush against a surface for the duration of the measurement. This may enable bespoke deployment options to be developed to suit the individual needs of each survey.

Examples of deployment mechanisms utilized by Createc throughout the development lifecycle can be seen in Figure 3. These mechanisms range in complexity and capability from a desktop standalone detector to a fully automated x-y scanning frame. This is not an exhaustive list of previous deployments, however it illustrates the deployment variety possible based on Createc's experience.

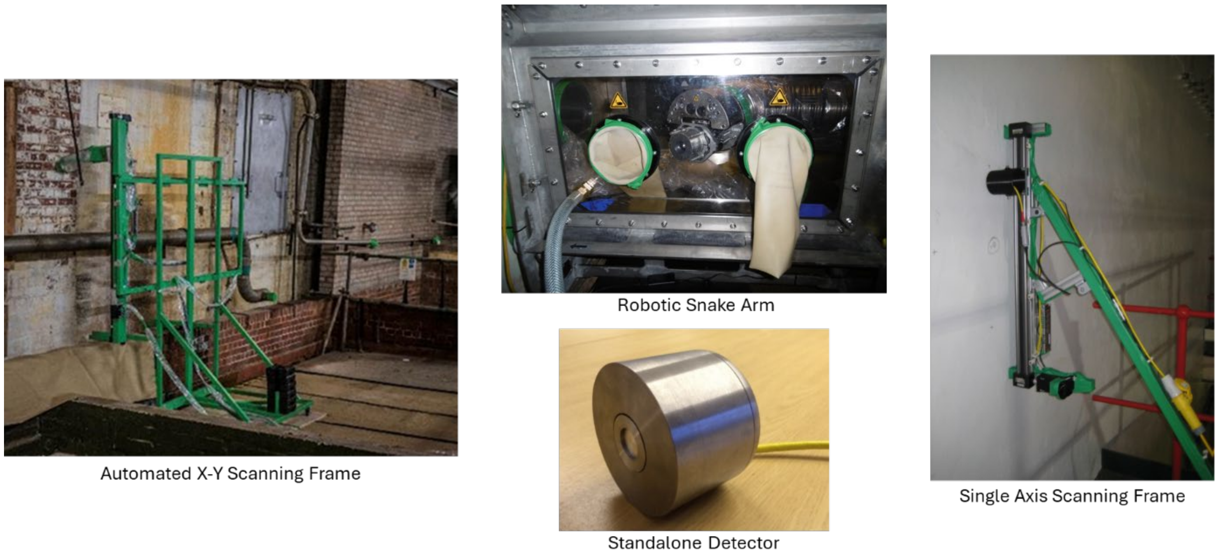

Figure 3: Examples of the deployment mechanisms utilized during past D:EEP deployments.

For the purpose of this study, in collaboration with EDF Energy Nuclear Generation Ltd, UK (EDF), the D:EEP sensor was redesigned in 2023 to enable underwater in-situ measurements in active FSP’s. Details of the latest generation sensor are provided in a later section. Following the redesign work, a trial demonstration of the technology was scheduled at the EDF Dungeness B power plant, one of EDF’s second-generation Advanced Gas Cooled Reactors (AGR) currently undergoing defueling following the cessation of power production operations.

Technical Description

To further understand the capabilities of D:EEP, it is essential to explore its underlying principles. The approach is primarily a γ-ray spectroscopy technique utilizing the variation in spectral features as a function of attenuation through a medium to retroactively understand the distribution of radioactivity within that medium. It builds on the principles of γ-radiation attenuation through matter, specifically the understanding that x-rays and γ-rays of different energies will experience different levels of attenuation for a given thickness of attenuating material. Additionally, as γ-rays travel through a given medium, the probability of certain interaction methods increases. This results in a substantial variation in the relative proportions and intensities of spectral features as a function of depth for radiation source terms within cementitious media.

A simplified representation of this is provided in Figure 4, where three regions of a typical spectrum are highlighted:

1. X-ray region dominated by low energy x-ray emissions from radionuclides. For example, Cs-137 emits characteristic x-rays in the 32 keV range.
2. Compton continuum dominated by scattered photons from higher energy γ-ray emissions.
3. Gamma photopeak dominated by photoelectric absorption of characteristic γ-rays. For example, Cs-137 emits a characteristic γ-ray at 661.7 keV.

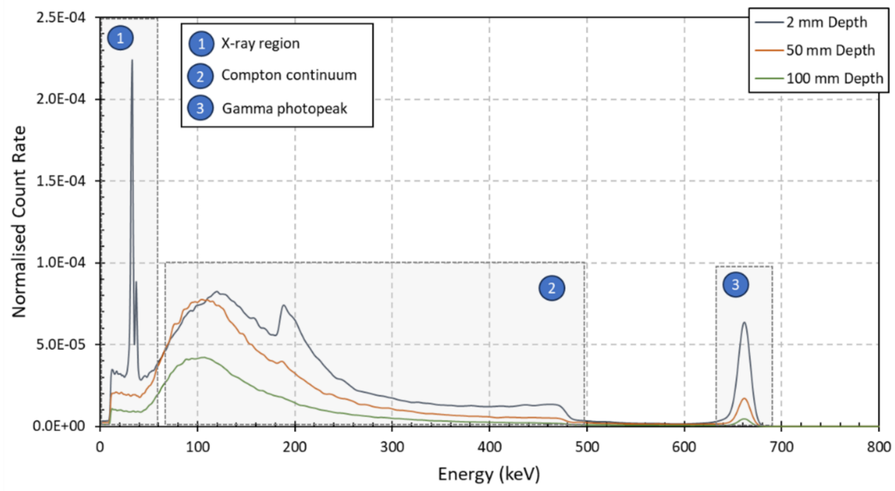

Figure 4: Demonstration of the spectral variation observed in simulated Cs-137 spectra at varying depth within a concrete medium.

As the thickness of concrete between the source term and the detector increases, the relative intensities and profiles of these features vary. The behavior of the x-ray efficiency relative to the γ-ray efficiency is the basis of the simplest depth profiling techniques. This ratio provides a relatively limited, yet easily measurable insight into the depth of contamination within a medium. The variation of this ratio as a function of depth can be seen in Figure 5, which illustrates the relationship between the parameters. This technique can be useful for radionuclides such as Cs-137, which emit measurable x-rays and γ-rays at substantially different energies.

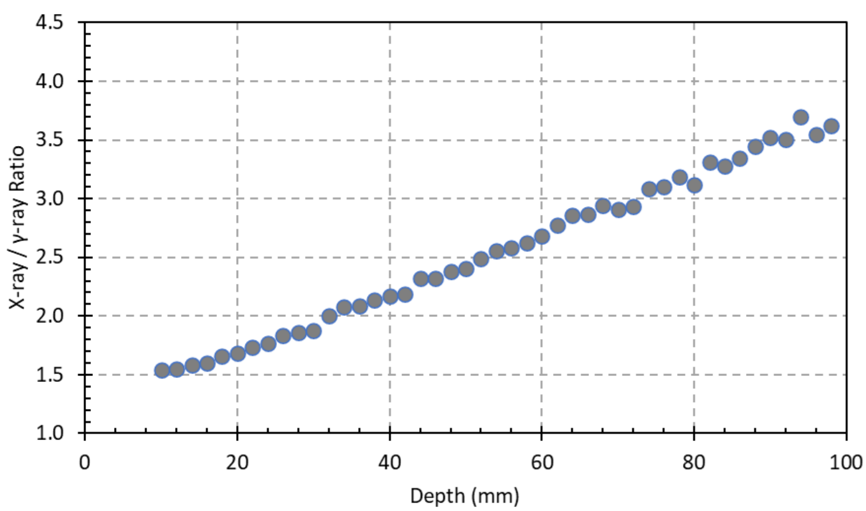

Figure 5: Ratio of x-ray to γ-ray intensities as a function of depth.

Alternative techniques have also been developed which utilize the ratio of i) events in the 'Multiple Compton Scattering' region directly below the photopeak, to ii) the photopeak. The theory is that the ratio of events undergoing small-angled scattering within the attenuating medium to photopeak events will vary as a function of depth. This method is more flexible than the aforementioned technique related to x-rays and γ-rays attenuations, however, it still relies on a small proportion of the spectral shape.

D:EEP builds on the entire spectrum for comparison, and can be used to study most radionuclides which emit γ-radiation. It makes use of detailed particle transport simulations to predict the theoretical response of a detector to radiation within a medium, generating a database of spectral responses at varying depths for a given radionuclide, and physical medium. This aims to provide a much greater fidelity when analyzing measured spectra and has the added flexibility of studying any distribution of contamination within the medium. Furthermore, it is designed to study radionuclides across a wide range of emission energies; from Am-241 (59.5 keV) to Co-60 (1332 keV). A detailed investigation was undertaken in collaboration with Sellafield Ltd, UK in 2024 to study the sensitivity of the technology to a wide range of environmental and radiological conditions [3].

Hardware

D:EEP builds on a simple hardware solution requiring minimal components to function. At its core, a gamma spectrometer with the associated pulse processing electronics is required. Further components include; a pre-amplifier, Multi-Channel Analyzer (MCA), a control laptop, and shielding to support background radiation distinction.

The background rejection shield, constructed from tungsten, ensures the ambient radiation background has little effect on the measurement. This enables measurements to be taken in high background environments. The 'standard' configuration has a collimator manufactured to attenuate 99.9% of the 661.7 keV γ-ray from Cs-137, however, this can be reconfigured for different environments, if required.

Following years of testing and development, the core components have been refined to improve the sensitivity of the system. The current design consists of the following:

Table 1: Description of components installed in the current collimator design for the D:EEP system.

Component	Description
Cadmium Zinc Telluride (CZT) Spectrometer	Intermediate Resolution Gamma Spectrometer for detection of x-and γ-rays from the sample of interest.
Tungsten collimator	Hemispherical design to shield the CZT detector from background radiation not associated with the sample of interest. Low degree of collimation in the forward direction. The thickness has been optimized for use in facilities with a dominant γ-radiation background consisting of Cs-137.
Copper / Tin Graded Shield	Graded shield positioned between the detector and collimator to reduce the average energy of x-rays reaching the detector originating from γ-radiation interacting with the collimator material.

Due to the growing demand for in-situ underwater measurements, a underwater housing was designed, manufactured, and tested in collaboration with EDF in 2023. A schematic of the newly designed system is presented in Figure 6 with the key features discussed in Table 3.

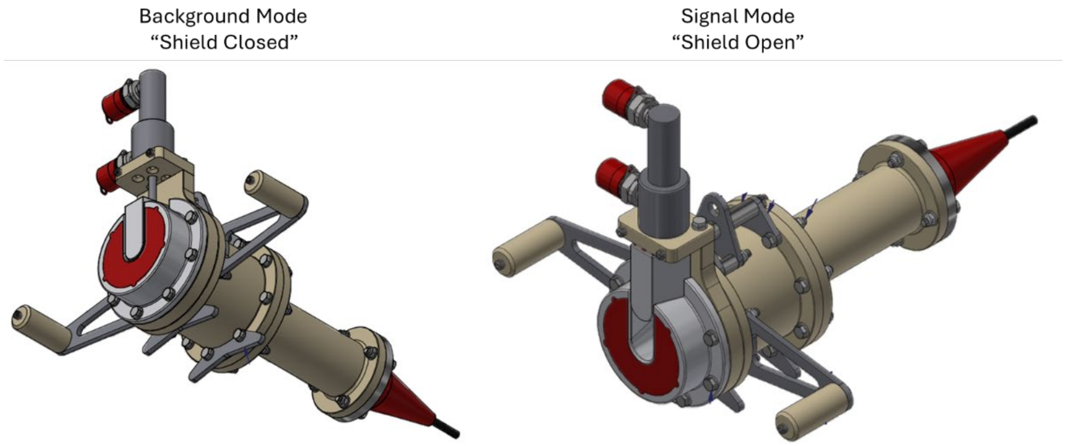

Figure 6: D:EEP underwater housing with integrated hydraulic background shield showing both operational modes: Background and Signal.

Table 2: Description of the key features for the new D:EEP collimator housing.

Feature	Description
Waterproof housing	Outer housing containing the detector, collimator, and pre-amplifier. Waterproof housing designed to a depth of 10 m. Doubles as a protective housing for use in high contamination environments, as well as designed to enable decontamination.
High radiation hardness	Material choices (PolyEther Ether Ketone (PEEK) / stainless steel) selected to provide high radiation tolerance for use in high radiation environments. Ensure a low risk of material degradation from radiation exposure over the lifetime of the product.
Hydraulic actuated background shield	Integrated background shield designed to raise or lower using remotely operated hydraulic system. This enables the operator to remotely alternate between background and signal measurements.
Material Compatibility	Materials used in the construction of the housing have been through rigorous checks with EDF to ensure chemical compatibility with the fuel elements stored in storage ponds.
Guide Wings	Adjustable lateral positioning wings to ensure a consistent offset for the detector, while providing rotational stability when remotely deployed. Acts to protect the front face of the sensor from abrasion damage.

DISCUSSION

With the aim of demonstrating the underwater capabilities within a nuclear environment, the D:EEP sensor was deployed in an active FSP at the EDF Dungeness B power plant. As many FSPs in the UK are mainly coated (instead of having a steel liner) the purpose of this study was to demonstrate the engineering and logistical feasibility of applying the technology under water in active storage pools. The ability to characterize active storage pools could be of immense benefit as it would support for the estimation of waste volumes and remediation depths early in the transition process. It is noted here, that no traditional characterization of the storage pond walls was performed throughout this deployment, thus the efficacy of the underlying characterization technology was not verified in this case.

Pre-Deployment Summary

As described, the D:EEP sensor is agnostic of the deployment housing, allowing bespoke solutions to be engineered to address the deployment challenges of specific environments. The underwater deployment at the EDF Dungeness B FSP required characterization of a 1 m^2 (10.76 ft^2) section of the pond wall located on a central island, see Figure 7 (left). A manipulator crane platform, capable of moving along the length of the pond, was identified as a potential deployment location, (see Figure 7, right).

Figure 7: Photos of the EDF Dungeness B FSP showing: left) the wall of interest in the red dotted area and, right) the deployment platform.

The deployment mechanism was required to meet the following specifications:

1. Able to safely deploy the sensor to a depth of 3 m (9.84 ft) over the edge of the crane platform, while allowing for positional adjustment in the plane of the platform (i.e. to/from the wall).
2. Able to adjust the height of the sensor vertically along the wall, while provide feedback on the position relative to the waterline.
3. Able to hold the sensor in a fixed position against the surface for the duration of a measurement.

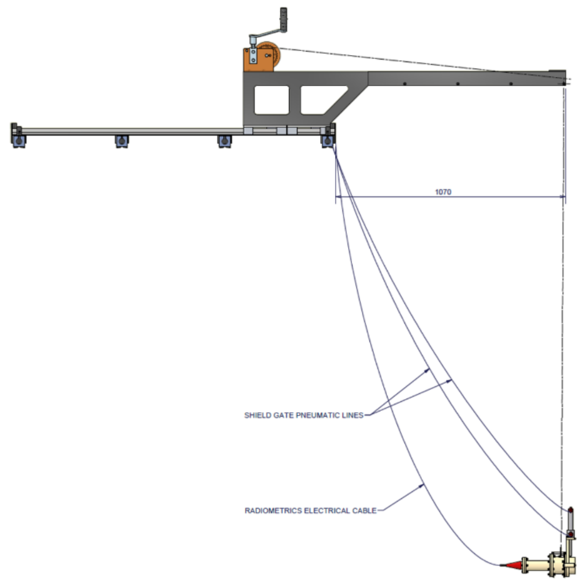

Figure 8: Schematic of the D:EEP variable boom deployment system.

A simple mechanical solution was developed consisting of a variable boom, coupled with a wire rope winch. A schematic of this is presented in Figure 8, showing the boom at full extension with the D:EEP sensor attached to the end of the winch. The boom enabled fine vertical and transversal adjustment of the detector offset relative to the wall, with the depth below the platform controlled by a high-geared winch to ensure controlled, precise deployment of the sensor head. Overextension of the boom, beyond the plane of the wall, acted to ‘pull’ the sensor head into the wall, ensuring stability during measurement and mitigating the effects of external forces such as those arising from currents in the pool water.

Deployment Summary

The deployment at EDF Dungeness B site took place on July 2024. A detailed characterization plan was not required as the results of this study were to be used as a proof of capability, and to provide a qualitative estimate of the contamination profile within the pond concrete structure. Due to these requirements, a simple 3 x 3 grid of measurement locations was proposed (see Figure 9) to demonstrate all facets of the system, covering measurements above, at, and below the waterline to a maximum depth of 0.5 m (1.64 ft).

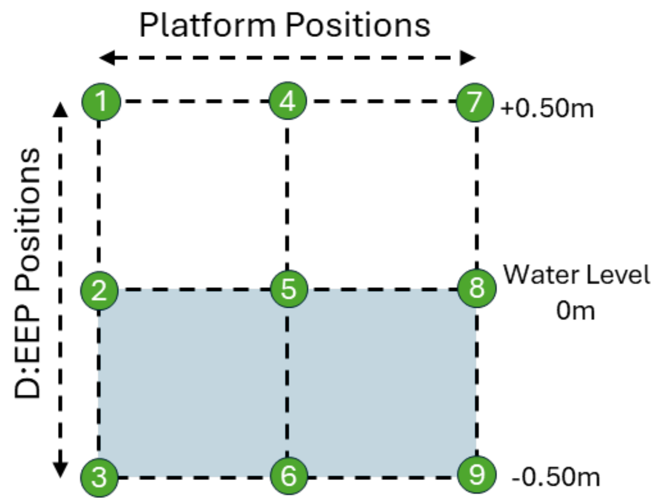

Figure 9: Schematic layout of the proposed measurement locations on the indicated pond wall (see Figure 7).

The deployment took place over 2 days, with 4.5 hours of total active measurement time. The equipment was positioned atop the crane platform as shown in Figure 10, with the D:EEP sensor facing the the measurement location. For each position in Figure 9, two measurements were taken: i) a 'background' measurement with the hydraulic actuated shield in the down position; and ii) a 'signal' measurement with the hydraulic actuated shield in the up position, see Figure 6. Photographs of the sensor positioned above, at, and below the waterline are shown in Figure 11.

Figure 10: Photograph of the D:EEP sensor deployed at the waterline in the Dungeness B (DNB) FSP. The deployment boom can be seen positioned atop the red platform.

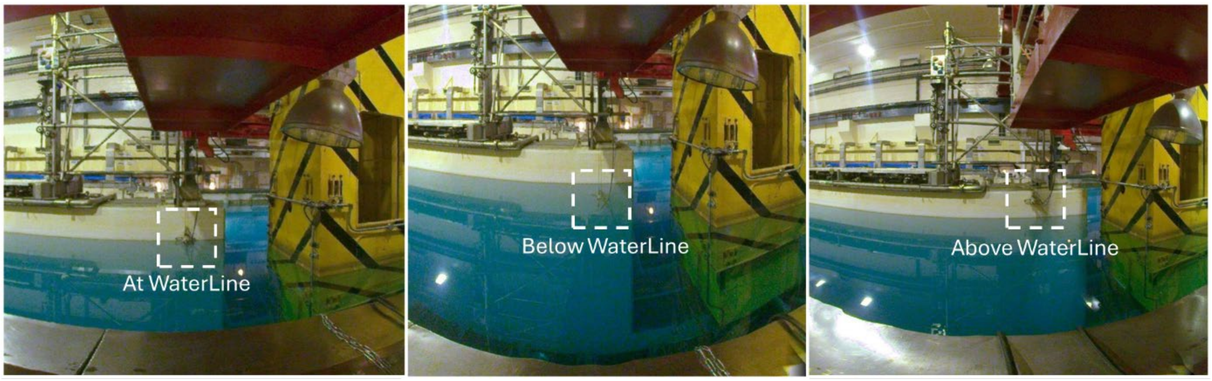

Figure 11: Photographs of the D:EEP sensor deployed at each of the three vertical positions in the DNB FSP.

LiDAR scans were performed at each platform position to generate 3D geospatial maps of the FSP. Given the uncertainties of the lateral bridge displacement, the exact lateral position of the D:EEP sensor was later calculated from the geospatial maps for each measurement. The LiDAR data was later used to demonstrate the potential for integrating the results of D:EEP surveys into 3D models. A snapshot of the final model is presented in Figure 12.

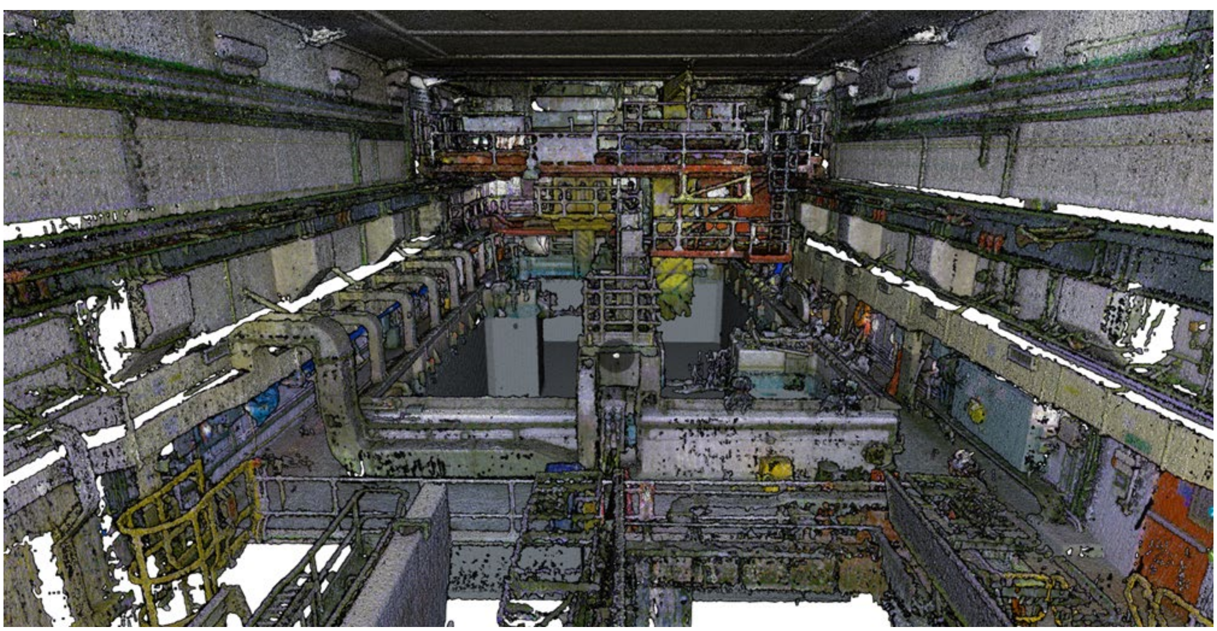

Figure 12: Snapshot of the FSP LiDAR model.

Results Summary

The data collected at Dungeness was analyzed to understand the general trends and behaviors present with an emphasis placed on understanding the background measurement variation as a function of position in the pond concrete structure. The raw background-subtracted count rates were plotted to highlight broad activity concentrations across the measurement area, with the results for Cs-137 presented in Figure 13. This data shows how the activity concentration above the waterline is significantly reduced compared to that at, and below the waterline. The activity levels appear to increase as the depth increases, however there was insufficient data to make a more confident comment on the likely continuation of this trend at greater depths. For this purpose, at least a second underwater measurement would have been required to determine the gradient between to underwater measured points.

Analysis of the spectra collected above the waterline showed consistency with the general background radiation levels of the environment, with no evidence of contamination on the walls. This result matched expectations since the pool water will have had limited contact time with the surface above the waterline, thus reducing the potential for contamination as well as subsurface diffusion (in case of FSP paint layer breach).

The results at, and below the waterline showed evidence of elevated radiation levels above the background and were processed through the D:EEP algorithms. The observed and D:EEP analyzed spectrum as well as the resulting depth profiles are presented in Figure 14.

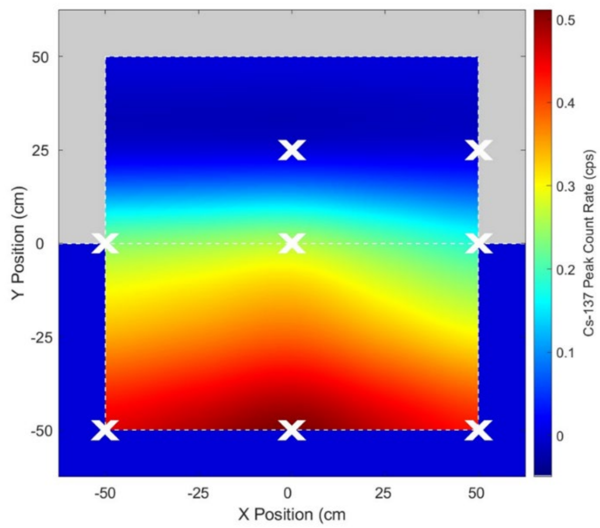

Figure 13: Heatmap of the Cs-137 count-rate as a function of position on the measurement surface.

The results of the depth profiles for Cs-137 suggest that the contamination ingress in the pond walls was restricted to the paint layer, with the depth profile falling rapidly in the first few millimeters ([mm]=[in]/25.4). This matched the expectations from the EDF technical team and provided confidence in the assumptions EDF is using in their current decommissioning strategies. This information, combined with the activity concentrations, provides an indicative estimate of the total waste volumes to be generated.

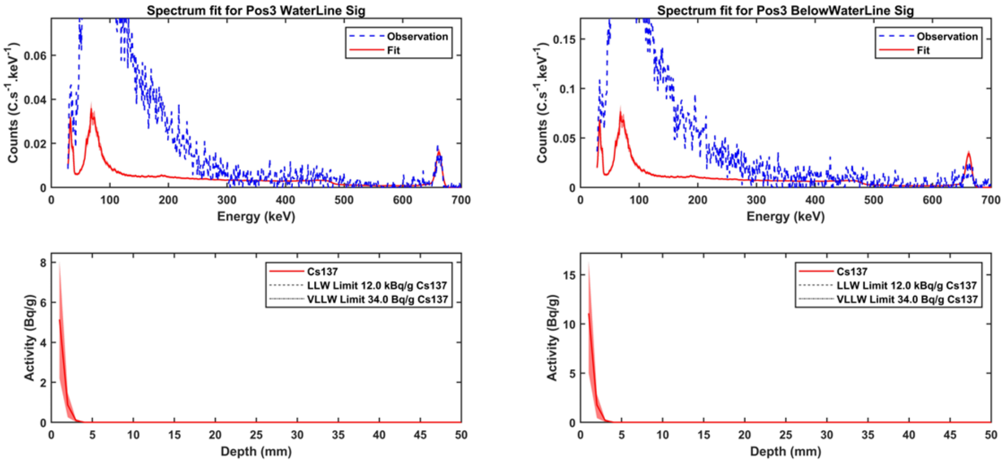

Figure 14: Results of the averaged D:EEP analysis for measurements at, and below the waterline showing the resulting depth profile for each position: (top) the measured spectrum alongside the reconstructed spectrum, and (bottom) the resulting depth profile based on the D:EEP analysis for Cs-137 (denoted as "fit" on the top).

CONCLUSIONS

The D:EEP technology has been presented as a potential alternative to conventional techniques for characterization of cementitious structures. D:EEP provides an innovative approach for profiling the contamination ingress within concrete, while this paper focuses on the demonstration to deploy the D:EEP sensor in active underwater environment. A generic housing for deployment across the UK EDF fleet was developed and a bespoke deployment mechanism was developed to enable remote deployment of the sensor from an overhead crane platform. In collaboration with EDF Dungeness B, the sensor has been deployed in an active FSP to demonstrate the capability of the sensor to collect spectroscopic information at, above, and below the waterline, while being able to distinct background radiation from culminated one.

Although the demonstration data was only of qualitative quality, the results corroborated prior assumptions that the contamination ingress on the pond walls was restricted to the surface paint layer. No evidence of contamination ingress beyond the first few mm's ([mm]=[in]/25.4) was detected. This information, combined with the activity concentrations provides an indicative estimate of the total waste volumes to be generated. Use of this technology throughout the EDF AGR fleet is proposed to assist in the generation of future decommissioning strategies for FSP's.

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