XS-ABILITY

Accessing hard-to-reach areas with **A**dvanced and **B**reakthrough **I**nnovation for re**L**iable **I**n-situ characterization of a facili**TY**

Deliverable 2.2

Use cases and demonstration specifications

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Author(s)	J.SEYSSAUD
Contributor(s)	E.FANCHINI, A.BIELEN, M.MICHEL
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ABBREVIATIONS AND ACRONYMS

Acronym	Description
D&D	Decommissioning and Dismantling
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
BR1 and 3	Belgium Reactor 1 and 3
PPE	Personal protective equipment
UAV UGV UxV	Unmanned Aerial Vehicle Unmanned Ground Vehicle Unmanned system

EXECUTIVE SUMMARY

The XS-ABILITY project aims to develop and demonstrate a fleet of unmanned systems (UxVs), both ground-based (UGVs) and aerial (UAVs), equipped with advanced radiological sensors, to perform autonomous radiological and physical mapping in complex nuclear environments during Decommissioning and Dismantling (D&D) operations.

These use cases have been selected to reflect realistic D&D challenges and to progressively increase in operational complexity, culminating in a large-scale final demonstration at a representative nuclear site currently being identified.

A representative nuclear facility with complex architecture and realistic radiological characteristics is being considered as the location for the final integrated demonstration. This environment will enable the coordinated deployment of a fleet of UxVs to carry out multi-agent missions involving autonomous navigation, radiological data acquisition, and adaptive mission planning based on real-time sensor feedback.

This deliverable presents the initial specification of use cases intended to validate the XS-ABILITY robotic fleet in realistic D&D contexts. The scenarios outlined here are the result of collaborative discussions among all project partners and reflect our current thinking on mission objectives, target environments, and the radiological and physical measurements envisioned. Although several potential demonstration sites are already under consideration, the purpose is not to finalize the demonstration plan, but to provide a structured overview of the operational contexts in which the system is expected to perform. Each use case accounts for the current capabilities of the individual technological modules and the upgrades planned for their integration, aligns with the hardware and software developments carried out in Work Packages 3 to 5, and serves as a validation framework for the integrated platform defined in WP2. Consequently, the document remains open to adaptation as technical, logistical, and regulatory constraints evolve.

KEY WORDS

Autonomous fleet of UxV and radiologic sensors, nuclear facility, radiological data acquisition, adaptive mission planning, real-time sensor feedback

1. D&D needs

The nuclear industry, now entering a phase of infrastructure aging, is confronted with a large wave of decommissioning projects. As many reactors reach or exceed their operational lifespan of around 40 years, the challenge lies not only in safely shutting down these installations but also in managing the dismantling process in a secure, cost-effective, and technically efficient manner.

D&D operations encompass a wide spectrum of activities—from the dismantling of radioactive equipment and the decontamination of structures, to the treatment, characterization, and safe disposal of nuclear waste. Unlike conventional demolition, D&D is constrained by radiation protection requirements, regulatory frameworks, and the presence of highly activated or contaminated materials. These constraints dramatically alter logistics, work planning, and safety conditions. In particular, the need for accurate and early **radiological and physical mapping** are critical to assess risks, plan interventions, and manage waste classification effectively.

In this context, current practices based on manual surveys with handheld instruments reveal significant limitations: they are time-consuming, expose workers to hazardous conditions, and often lack the spatial coverage or resolution required for detailed radiological characterization. Moreover, large nuclear facilities—often encompassing tens of thousands of cubic meters—pose logistical and practical challenges for exhaustive mapping using conventional techniques. In addition, these manual methods frequently lack sufficient traceability and quality control, which can result in incomplete or unreliable measurement datasets, particularly when conditions change or operators vary.

To address these gaps, **automated robotic systems**—such as Unmanned Ground Vehicles (UGVs) and Unmanned Aerial Vehicles (UAVs) are emerging as promising tools to enhance D&D efficiency, precision, and safety. By integrating radiological and SLAM/Lidar systems, autonomous navigation, and real-time data processing, such systems can drastically reduce human exposure, increase the traceability, quality and coverage of measurements, and optimize intervention strategies throughout the D&D lifecycle—from initial site characterization to final clearance verification.

An effective use case for validating the XS-ABILITY solution should combine several key characteristics representative of real D&D challenges. These include architectural complexity, a mix of decontaminated and monitored zones, the presence of confined and elevated spaces, and varied radiological conditions—whether real or simulated. Such environments enable realistic testing of the fleet's capabilities in terms of autonomous navigation, sensor integration, communication, and adaptive mission planning.

The selected scenarios must allow the simulation of critical D&D tasks such as hotspot detection, mapping of hard-to-reach or even inaccessible areas. These challenges reflect common issues encountered in most if not all decommissioning projects, including limited historical data, traceability gaps, and difficult working conditions in high-radiation or restricted-access areas.

Overall, a suitable use case should provide a comprehensive operational, technical, and radiological framework to demonstrate the robustness, versatility, and replicability of the XS-ABILITY system across different nuclear facilities in Europe and beyond.

In alignment with these goals, the XS-ABILITY project proposes a **modular robotic fleet** capable of autonomous operation in hazardous nuclear environments. The fleet will be validated through representative and complex scenarios, with a final full-scale demonstration planned at one or more selected sites. Among the proposed locations are the G2 reactor at the CEA Marcoule site and the Belgian Reactors 1 and 3 at SCK CEN in Mol.

2. Illustrative Mission Scenario

The mission involves conducting comprehensive radiological and physical mapping within specific areas of a facility over a one-week period, including equipment setup, data acquisition, and system demobilization.

Two distinct types of missions are covered under this objective:

- **Dismantling Mission:**
  Aimed at preparing the physical dismantling of facility components, this mission focuses on identifying and characterizing radiological hotspots. It requires high-resolution **3D gamma mapping**, **in-situ gamma spectrometry**, and **gamma imaging** to determine the location, intensity, and nature of radiation sources.
- **Decommissioning Mission**:
  This mission is intended to support regulatory declassification of facility zones. It focuses on **low-level surface contamination mapping** to verify that contamination levels are below the clearance thresholds required for decommissioning. A specific vertical wall will be selected for detailed characterization.

Each mission type employs tailored methodologies and instrumentation depending on its objectives — either detailed hotspot characterization for dismantling, or broad-area contamination assessment for decommissioning.

2.1 Dismantling Mission

The dismantling mission aims to perform a complete 3D gamma mapping and identify radiological hotspots to support dismantling operations. A key aspect of this scenario is the ability to operate in an environment that is partially or entirely unknown — with little or no prior architectural data such as CAD models or BIM information. The mission starts with an exploratory gamma survey to autonomously generate a 3D radiological map and measure ambient dose rates (10 µGy/h to 1 Gy/h) across the area, enabling the detection of potential hotspots. Once detected, these areas will be investigated in more detail using gamma imaging and in-situ gamma spectrometry to characterize the nature and intensity of the sources. In parallel, surface contamination mapping—beyond low-level background noise—will be conducted to detect and localize residual radioactive deposits on walls, floors, or equipment. The approach is designed to be adaptable to a variety of environments, including complex structures, and is expected to rely on aerial and ground-based platforms. Mission performance will be assessed through mapping speed, data accuracy (both spatial and radiological), and overall area or volume coverage.

2.2 Decommissioning Mission

The decommissioning mission focuses on mapping low-level surface contamination to support the regulatory clearance of selected facility areas. As with the dismantling mission, this scenario assumes limited,unreliable, old, or no prior knowledge of the environment — no architectural drawings or digital models (e.g., CAD or BIM) are required to initiate the operation. A specific wall or surface will be selected as a reference area for detailed radiological characterization, aiming to verify that residual contamination levels are below clearance thresholds defined by relevant regulatory standards.

The mission will employ sensitive instrumentation — potentially one or a combination of tools — capable of detecting surface contamination at very low levels. These systems must be adaptable to unknown environments and able to generate accurate contamination maps autonomously. Precision in surface data acquisition is critical, as results will serve to support decisions on zone declassification and regulatory clearance.

According to references [1][2], clearance levels apply primarily to bulk materials and vary depending on the radionuclide. For example, general thresholds include:

- **1 Bq/g** for most naturally occurring radionuclides;
- **10 Bq/g** for potassium-40 (^{40}K);
- **0.1 Bq/g** for artificial radionuclides such as cesium-137 (^{137}Cs) and cobalt-60 (^{60}Co);
- **1 Bq/g** for strontium-90 (^{90}Sr).

These limits are based on the principle that any exposure from cleared materials should result in an individual dose below 10 microsieverts (µSv) per year — considered negligible for health protection.

Key performance indicators will include the accuracy and resolution of the radiological mapping, the efficiency of spatial navigation in constrained environments, and the robustness of collected data (ambient dose rates, etc.). The use case will provide critical insights into the operational capabilities of the XS-ABILITY systems under real world scenarios, validating their potential for broader deployment in nuclear decommissioning and inspection.

3. Marcoule G2 Reactor Use Case

The G2 reactor is part of the foundational legacy of France’s nuclear program. Located at the **Marcoule Nuclear Centre**, in the Gard region of southern France, G2 was one of three industrial-scale reactors (G1, G2, G3) constructed in the 1950s as part of a national strategy to develop **autonomous nuclear capabilities**, both for energy and defense purposes

3.1 Origin and Purpose

In the aftermath of World War II, France established the **Commissariat à l’énergie atomique (CEA)** in 1945 with the objective of mastering nuclear science for strategic sovereignty. By the early 1950s, national authorities opted to pursue a reactor technology based on **natural uranium fuel**, **graphite moderation**, and **gas cooling**, since enriched uranium and heavy water were not readily available in Europe. This led to the development of the so-called **“G” series reactors**.

G1, the first prototype, diverged in 1956. G2 followed closely, with construction starting in 1956 and first criticality achieved in **July 1958**. Its twin, G3, went operational in 1959. Together, G2 and G3 represented a leap toward industrial-scale **plutonium production** for the French nuclear deterrent program, while also contributing to the national grid with significant electricity generation—**over 600 million kWh annually** from G2 and G3 combined.

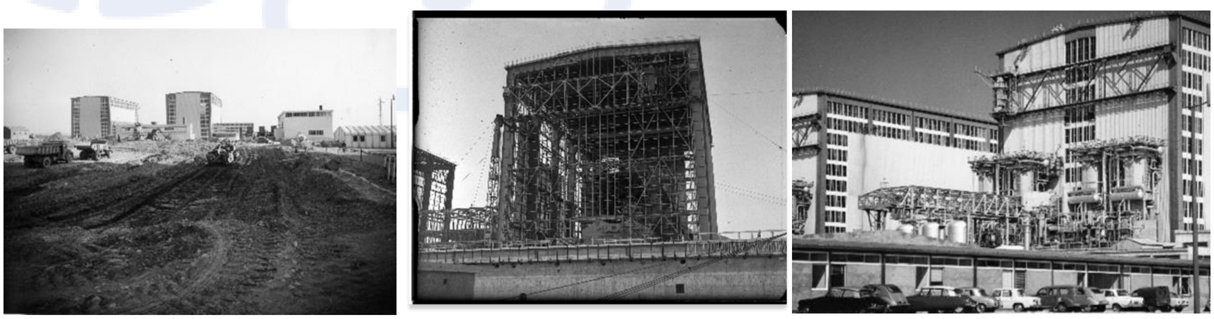

Figure 1: G2 and G3 reactors construction

3.2 Technical characteristics

G2 was an **air-cooled, graphite-moderated reactor** using natural uranium as fuel. It had a **thermal output of 250 MW** and was among the earliest reactors in Europe to adopt **CO_2 gas under pressure** (15 atm) as the cooling medium, a technical innovation at the time. The reactor featured a **graphite moderator block weighing 1,200 tonnes**, with **1,200 horizontal fuel channels** and **51 vertical control rod channels**. Fuel was clad in a magnesium-zirconium alloy and could be loaded and unloaded while the reactor was running, using a gravity-assisted system.

Its **biological shielding** and **prestressed concrete reactor vessel** were unprecedented for the time, employing steel cables to maintain structural integrity against internal pressure—an architectural and engineering feat that would influence future reactor designs across Europe.

3.3 From production to decommissioning

G2 operated successfully until **1980**, fulfilling both civil and military missions. Following shutdown, the reactor entered the **decommissioning phase in 1986**, under the supervision of CEA's Military Applications Directorate. The first phase, completed by 1996, involved the removal of external systems and radiological decontamination of auxiliary structures. Roughly **4,000 tonnes of metallic waste** from the CO_2 circuits were processed on-site and sent to ANDRA facilities.

The second phase of dismantling, focused on the reactor block itself, was intentionally delayed to allow **natural decay of cobalt-60**, thus minimizing radiation exposure for future operations. This final phase is aligned with the broader French national strategy for dismantling graphite-moderated reactors and managing legacy nuclear waste, including **graphite and long-lived radionuclides.**

Figure 2: G2 Dismantling operation

3.4 A site of scientific and communication signification

In 1996, France became the first nuclear-armed state to commit to the **dismantling of its fissile material production facilities**. G2 thus evolved from a secretive Cold War-era installation into a **symbol of transparency and disarmament**. In 2008–2009, G2 hosted visits from international diplomats, disarmament experts, and journalists, demonstrating France's irreversible commitment to dismantlement and non-proliferation.

To preserve this legacy and support public communication, CEA inaugurated the **Escom G2 showroom** in 2011 . Built within the former reactor hall, the 300 m² exhibition space now showcases France's dismantling expertise through thematic modules on disarmament, fuel cycles, and decontamination technologies. It also serves as a platform for international outreach and training, while maintaining partial access to the original industrial infrastructure.

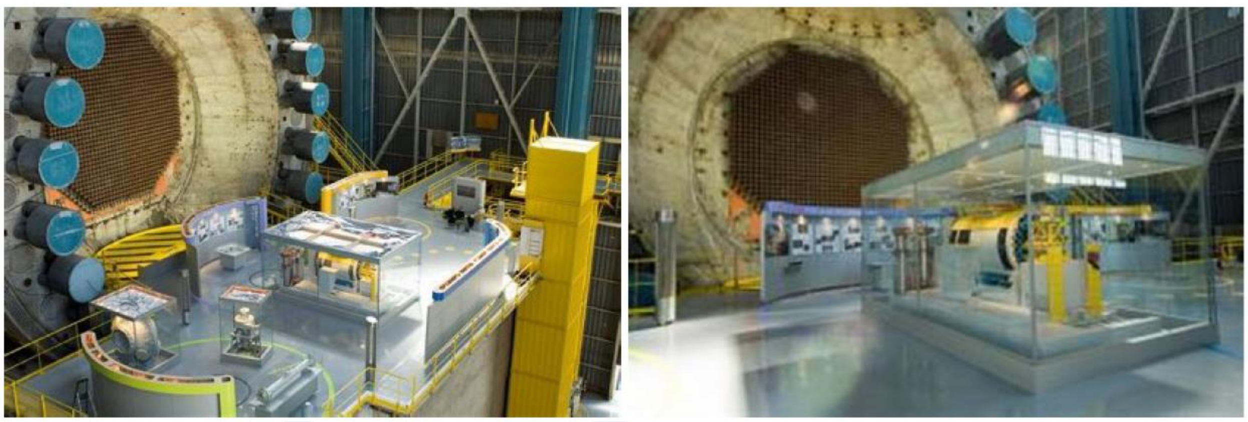

Figure 3: General view of showroom (left) and focus on reactor mock-up (right)

3.5 Current organization

The operational structure at the G2 reactor site is based on a clear division of roles between the contracting authority and specialized subcontractors. The CEA acts as the site contract manager, with full authority and responsibility for supervision and regulatory compliance. The day-to-day operations and technical maintenance of the site are entrusted to a consortium of subcontractors which serves as the technical operator responsible for maintaining the facilities in safe and operational conditions.

Site operations and maintenance are ensured by specialized companies contracted for mechanical, electrical, and general facility services. This professional organization guarantees a safe and controlled environment, facilitating the deployment of external projects such as XS-ABILITY under realistic nuclear conditions.

3.6 Zones of interest descriptions

After several on-site visits, two locations appear to meet the project's requirements. These include the hall of the G2 reactor and its foundation.

The hall area – It offers a large surface (L60 × W40 × H50 m) and is easily accessible, with no issues related to radiological contamination. The environment is dusty, and the large volume may present challenges for comprehensive mapping. The area is at ambient temperature and lighting conditions, and is accessible via a short metal staircase of approximately ten steps.

Figure 4: G2 hall

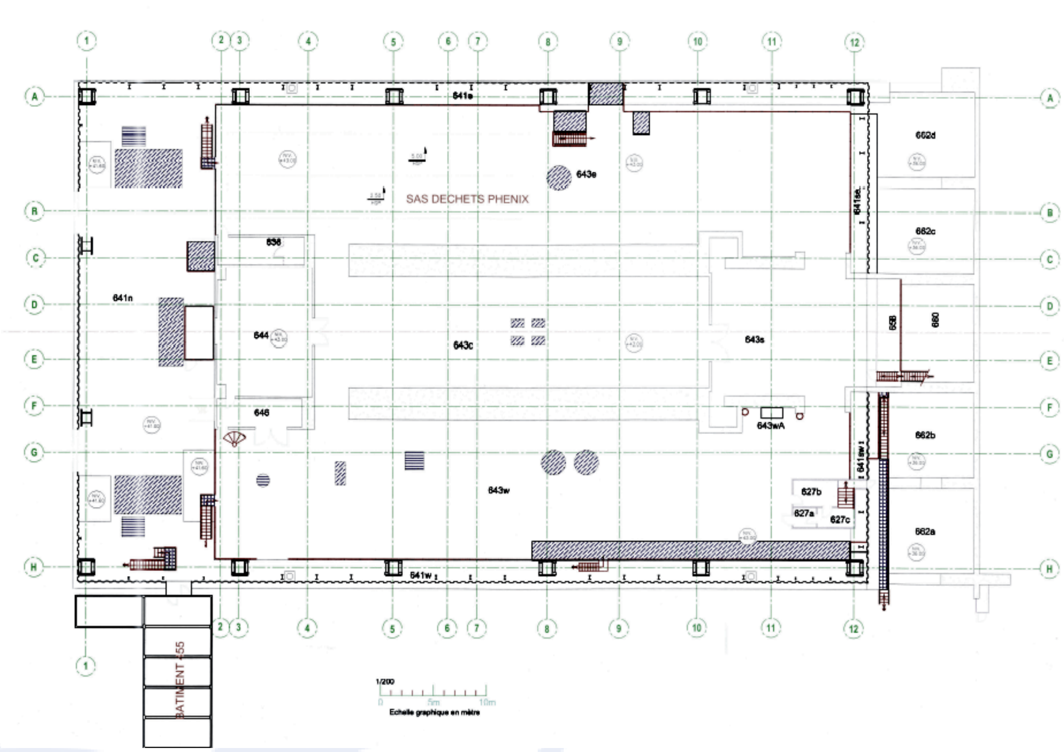

Figure 5: G2 hall map

Foundation area – This zone consists of multiple interconnected concrete cells with thick walls, making communication and movement difficult, but offering good conditions for focused and controlled testing. We can choose to concentrate on a specific corridor or even a single concrete cell, depending on project needs.

The environment is dusty, with artificial lighting. Access is provided via a freight elevator for equipment and a long metal staircase (5 m). There are potential traces of contamination, but no significant dose rate has been measured. Sealed sources may be used to simulate realistic radiation conditions if required.

Figure 6: G2 foundation

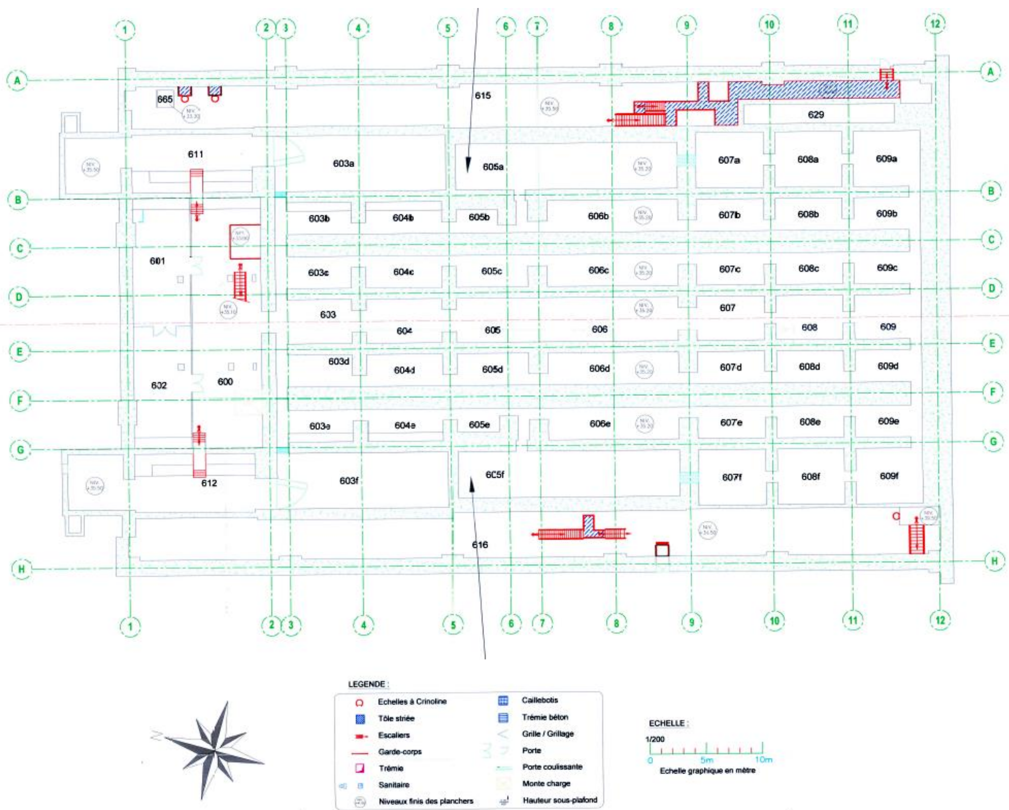

Figure 7: G2 foundation map

Communication between the two areas (Hall 643E and Foundation 605A) is possible via a hatch approximately 1.5 meters wide.

Regarding safety aspects, fire suppression systems are available near machinery and other electrical equipment. Personnel must wear appropriate work attire, including personal protective equipment (PPE), adapted to the site conditions. The drone flight area will be clearly demarcated, with strict no-entry rules for personnel during operations. A potential flight restriction over certain zones may apply and should be confirmed with the facility. Additionally, emergency stop systems are present on all moving equipment to ensure rapid intervention if needed. Access authorizations process for non-French workers from the consortium is still under review.

4. Belgium Reactor use case

4.1 BR1 – Belgian Reactor 1

The BR1, located at SCK CEN in Mol, holds historical and scientific significance as both Belgium's first nuclear reactor and the oldest operational reactor in the world. Commissioned in 1956, BR1 is an air-cooled, graphite-moderated research reactor loaded with fuel rods consisting of natural uranium encased in aluminum cladding. It operates at a maximum thermal power of 4 MWth. It is originally designed to support studies in reactor physics and neutron behaviour, as well as the production of radioisotopes. BR1 has evolved into a multipurpose platform for a wide range of nuclear science applications. These include material irradiation, the calibration of nuclear measurment equipment, nuclear behaviour analysis under controlled conditions, and specialized training for new generations of nuclear experts.

Within the XS-ABILITY project, particular interest is directed toward the ventilation building of BR1, which provides a challenging environment for the testing and validation of advanced robotic platforms, including both ground-based systems and drones. This facility features a large-volume area with engines and ventilators (Figure 8a), as well as confined spaces with dense infrastructure (Figure 8b), such as piping, pumps and low ceilings, that are not easily accessible by conventional means.

A valuable aspect of this environment is the presence of residual radioactivity during reactor operation. Activated ar-41 leads to measurable radioactivity in the ventilation shafts. In addition, localized hotspots with dose rates up to 5 µSv/h and stored radioactive components contribute to a dynamic and variable radiological landscape. These conditions make the facility an excellent test site for evaluating robotic systems' capabilities in terms of radiation, autonomous navigation, sensor integration and data acquisition in a real-world nuclear environment.

The BR1 ventilation building will serve as a representative use case within XS-ABILITY, with the primary goal of identifying and characterizing radiological hotspots. The operation will begin with a global gamma survey, aimed at generating a 3D radiological map and measuring ambient dose rates throughout the targeted areas. Detected hotspots will be further investigated using gamma imaging and in-situ gamma spectrometry to determine the spatial distribution, isotopic composition, and intensity of the sources. Additionally, the area with engines and ventilators may be used for large-volume mapping.

Figure 8: BR1 ventilation building. a) Large-volume area with engines and ventilators (top view); b) Dense infrastructure, such as piping, pumps and low-ceilings (bottom view)

4.2 BR3 – Belgian Reactor 3

The BR3, located at SCK CEN in Mol, Belgium, was the first PWR in Europe and stands as an important milestone in Europe's nuclear power history. It was taken into service in 1962, it operated until its permanent closure in 1987. The reactor not only served as an innovative prototype for subsequent nuclear reactors in Doel and Tihange, but also captured the attention of the European Commission, which designated it as a pilot project to show the technical and economic feasibility of dismantling a nuclear reactor under real conditions. The BR3 decommissioning project has enabled exploration, testing, evaluation, and qualification of various techniques for the decommissioning and decontamination of nuclear facilities. The main challenge associated with D&D operations is finding the balance between safety and economic feasibility. In this regard, BR3 proves to be a unique and invaluable learning platform, offering insights into this delicate balance.

At this moment, the project is in its last stage: restoring the site in its original state. This implies a careful examination of the surfaces of the controlled areas. In this context, there arises a compelling need for automation driven by several reasons. Automation mainly becomes imperative for assessing areas that are challenging to access, such as the high walls and ceilings in the reactor building. Other reasons are the currently employed methodologies that necessitate either a two-fold measurement process or the deployment of two separate operators, both of which are resource-intensive, and ensuring the absence of radioactive hotspots, with a limited averaging approach, typically covering one square meter at a time.

Notably, the walls of the reactor building itself intricate logistical challenges (since most of the activated and contaminated materials are removed the radiological risks are limited). These walls are approximately 15 meters in height and have limited ground area to support scaffolding or other means to physically reach all areas. Placing conventional measurement equipment in close proximity to these walls is not only costly but also demands extensive labour hours. In light of these considerations, the deployment of UAVs, commonly known as drones, emerges as a transformative innovation for scanning the high walls. These UAVs can efficiently access and assess these hard-to-reach locations. Furthermore, UGVs assume a crucial role in simplifying access to less complex spaces, ultimately enabling UAVs to reach otherwise inaccessible areas. Generally, this offers an integrated and productive synergy between various robotic platforms equipped with multiple sensors.

In conclusion, the BR3 decommissioning project serves as a compelling case study that highlights the importance of automation, especially in the assessment of challenging environments, and the strategic use of advanced technologies to enhance efficiency and effectiveness during the final stages of nuclear facility decommissioning.

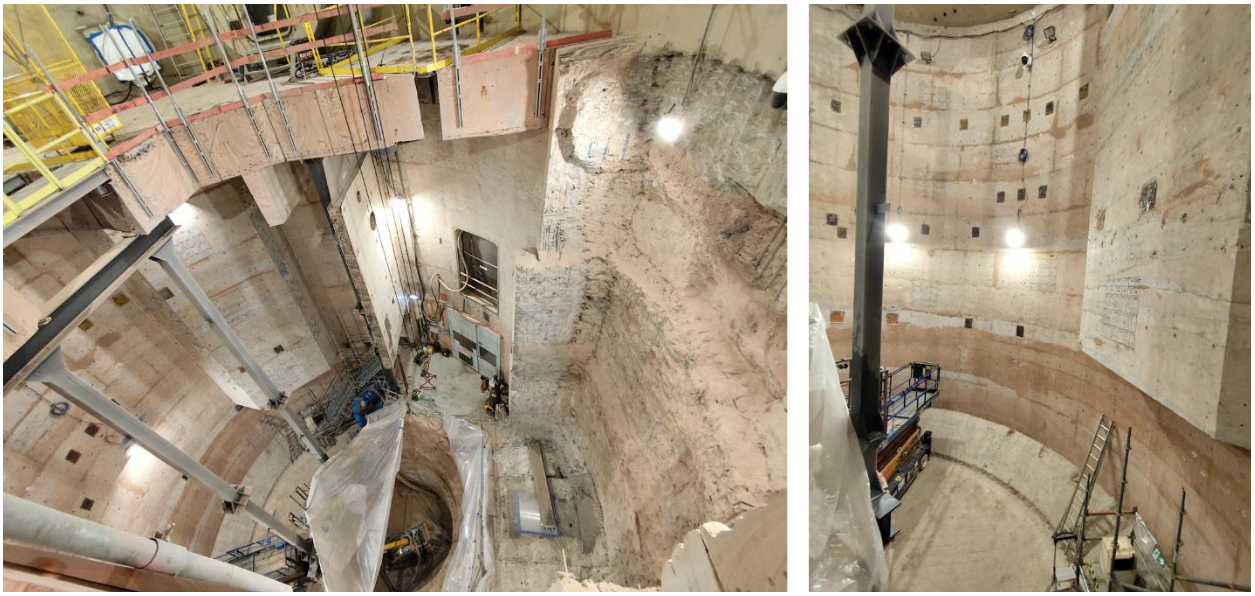

Figure 9: BR3 - Decommissioning in progress

5. Conclusion

To ensure a comprehensive and realistic validation of the XS-ABILITY developments, the selection of use cases has been guided by a structured set of comparison criteria. These criteria address both the operational challenges of nuclear decommissioning and the technical objectives of the project.

Each use case was evaluated based on its relevance to typical D&D operations, environmental complexity, presence of real or simulated radiation, and the diversity of technologies that can be tested. Additional considerations include site accessibility, demonstration potential, replicability, and the alignment with core technical objectives of the project.

Furthermore, the ability to measure performance in a clear and quantifiable manner, as well as to scale scenarios progressively in complexity, were considered essential for a robust evaluation process.

These criteria ensure that the selected use cases not only provide realistic and demanding testing environments, but also serve as representative scenarios for broader deployment across the nuclear sector. They form the foundation for demonstrating the added value, versatility, and maturity of the XS-ABILITY system in operational D&D contexts.

Evaluation Criteria	G2 – Reactor + Foundation	BR1 – Ventilation Building	BR3 – Dismantled PWR
Relevance to D&D Operations	✅ Very high — realistic decommissioning setting	✅ High — confined operational facility	✅ High — final clearance phase
Environmental Complexity	✅ High — mixed indoor/outdoor, structural zones	✅ High — confined spaces, infrastructure density	⚠️ Medium — open but vertical access challenges
Presence of Radiation	⚠️ Simulated or residual (sealable sources)	✅ Present during operation	⚠️ Low — most contamination removed
Technological Diversity Possible	✅ Full	✅ Full	⚠️ Partial UAVs and surface robot for vertical surfaces

Site Accessibility (Personnel)	⚠️ Moderate — controlled access, formal clearance needed	✅ Easier access through SCK CEN procedures	✅ Controlled but already open for D&D
Site Accessibility (Equipment)	✅ Elevator for foundation	⚠️ Many stairs	⚠️ Limited floor space for large setups
Demonstration & Communication Potential	✅ High — historical and symbolic site	⚠️ Internal demo possible, limited visibility	✅ High — historical and symbolic site
Replicability to Other Sites	✅ Medium — unique reactor architecture	✅ Medium — ventilation-specific use case	✅ High — clearance and wall scanning use case
Alignment with Project Objectives	✅ Full — matches autonomous multi-robot coordination goals	⚠️ Partial — tests mobility, limited fleet coordination	⚠️ Partial- no UGVs

Table 1: Radiological Investigation by Site

- ✅ = Strong/fully met
- ⚠️ = Partial / limited
- ❌ = Not applicable or not feasible

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