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# European collaborative efforts to achieve effective, safe, and cost-controlled dismantling of nuclear facilities

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**Abstract.** This paper aims to give an overview of very recent European coordinate efforts to implement technologies of the “4.0 Industry” in the nuclear deconstruction sector. This objective aims to benefit from the lever of efficiency and reliability represented by innovative technologies on all the value chain of the dismantling, from early characterization to the dismantling operations themselves through engineering studies, waste management, project management and coordination of multiple stakeholders of each project. The outcomes of five projects (INNO4GRAPH, LD-SAFE, PLEIADES, CLEANDEM and INSIDER) are summarized here. They result in a unique data and knowledge common base, as well as in a significant sharing of experience based on dismantling projects already carried out or to come. They also result in designing new tools or methods natively taking into account the needs of a maximum of dismantling operators, as well as new test facilities. This will allow the undertaken joint work and collaboration to be continued. All of this paves the way to further collaborative projects and developments, in order to continue to implement reliable new technologies and processes in European dismantling projects to make future dismantling operations more efficient, safer and more cost-effective.

## 1 Introduction

Due to the energetic political choices of some European countries to phase out nuclear power such as Germany or more recently Belgium on the one hand, and industrial choices regarding the extension or not of their lifetime, on the other hand, an increasing number of nuclear installations and power reactors, in particular, are to be dismantled in the coming decades. Except for graphite reactor dismantling, which remains a technical challenge, the general feasibility of dismantling many reactors (PWR, BWR, HWR, ...) is established. Still, these operations can be optimised in terms of dismantling processes, waste generation, costs and lead times.

The reliability and safety requirements imposed on dismantling sites make it necessary to use mature, reliable techniques that meet all three criteria that are international good practices, local safety, and radiation protection criteria. This necessary precaution is part of the reason why decommissioning operations are still carried out mainly

manually, hence requiring extensive personnel protection measures, engineering controls, and costly and inefficient detailed work planning and monitoring, to achieve the required high safety levels. Moreover, the “poorly reproducible nature” of the operations to be carried out from one site to another also explains a current approach that is still only partially industrial. This state of fact added to a large number of dismantling work sites in the next decades yields a major challenge for research and innovation in the field of nuclear dismantling. It is indeed necessary to rapidly bring to maturity technologies (digital technologies, automatised or semi-automatised robotics, LASER cutting) which will make the dismantling operations more efficient, safer and more cost-effective. This objective is common to the five European projects (INNO4GRAPH, LD-SAFE, PLEIADES, CLEANDEM and INSIDER) which are the topic of this article.

Thinking of technological developments, by analogy with other industrial sectors such as aeronautics, the first thought that comes to mind is the digital “revolution”. The PLEIADES project aims to accelerate this transition towards a more efficient and more widespread use of digital

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tools. Relying on existing and proven tools already used by some actors in the field, PLEIADES aims to make their use more fluid, even efficient and shared.

Furthermore, dismantling activities are based on an essential pillar: characterisation operations. These operations can be considered as a true “red thread” of a dismantling project. A site to be dismantled must indeed be characterised beforehand, to be able to plan and size the dismantling operations, in particular the management and disposal of waste. The complementary characterisations, which are performed during the whole dismantling operations, ensure that the current state conforms with the prediction made before the start of the works. Final characterisations are performed after the final clean-up operations to ensure compliance with the decommissioning objectives. This important activity has its own areas for improvement and challenges that the INSIDER and CLEANDEM projects aim to address.

Finally, the most visible part of the dismantling operations consists of dismantling and removing the equipment that is part of the facility. The LD-SAFE project focuses on the promising LASER cutting, and more particularly on how to ensure the total operational safety of this technology during cutting operations in future dismantling sites. The INNO4GRAPH project aims to define and develop tools that will make it possible to effectively and safely remove the graphite constituting the structure of graphite-moderated reactors (UNGG, Magnox, AGR and RBMK).

The present paper presents a short overview of these projects and their results. If necessary, more information may be found on the website of the projects respectively:

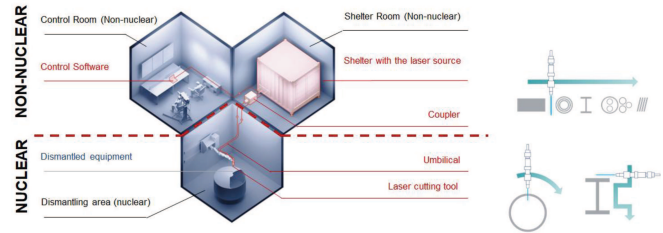
- <https://www.inno4graph.eu/>
- <https://ldsafe.eu/>
- <https://pleiades-platform.eu/>
- <https://insider-h2020.eu/>
- <http://cleandem-h2020.eu/>

## 2 Brief overview of the projects

### 2.1 INNO4GRAPH

The decommissioning of shut-down graphite nuclear reactors worldwide is still in its early stages with many reactors in “safe store” condition. For these reactors, there are still considerable industrial and technical challenges that remain to be tackled, even after more than 30 years of the operational shutdown of the first unit. The complex geometry, design and large dimensions of such reactors make their decommissioning a worldwide industrial and technical challenge. Being 2 to 5 times bigger than a Pressurized Water Reactor (PWR), the decommissioning of an industrial Graphite Unit is also expected to generate 10 to 30 times more waste.

The H2020 INNO4GRAPH project is the first international collaboration in order to address common challenges connected to graphite retrieval operations. It started in September 2020 for three years. It gathers 13 entities from five different countries: EDF (Consortium leader), Graphitech, Cyclife Digital Solutions, Enresa, Sogin,



**Fig. 1.** LASER cutting typical configurations for decommissioning application.

LEI, CEA, Tecnatom, Ansaldo Nucleare, Cirten-Polimi, Westinghouse Spain, University of Manchester and ARTTIC.

The INNO4GRAPH project aims to support the operators to define the most optimal ways to decommission graphite reactors i.e., the tools that can help to safely remove radioactive material, and the most cost-efficient solutions for dismantling operations in reactors of such complexity and dimension. This goal will be reached through the development of physical and digital tools and methods to support the decommissioning of European graphite reactors.

To this end, the INNO4GRAPH project takes place in two phases:

- tools and methods will be used during tests and studies upstream of the dismantling operations to:
  - get an excellent knowledge of both the graphite properties thanks to the in-situ measurement of cracks and corrosion and the dismantling tools to be used;
  - evaluate the efficiency of the use of innovative tools in order to define the most adapted scenario for each reactor regarding the local context (technical constraints, regulations, ...) in terms of safety and cost-efficiency thanks to scenario grid analysis, mock-ups for physical tests and digital 3D models.
- Innovative cutting and handling tools will then be made available during the dismantling operations. It is for example the case of LASER cutting technologies, like in the LD-SAFE project.

### 2.2 LD-SAFE

Dismantling the reactor vessel and internals of a nuclear power reactor is probably the toughest task to be accomplished in the decommissioning programme, mainly due to the size of equipment to be cut and removed, but also the high dose and cost related to these operations. A number of “conventional” techniques are currently used by the nuclear industry, but innovation has not yet penetrated these operations due to risk-averse behaviour, reluctant to see new technologies that have not yet proved their advantages on the field. Among the innovative technologies which could be used to enhance such works, the laser cutting technology (see Fig. 1) is probably the most promising one due to its large maturity in the manufacturing industry and great advantages like the cutting performance but also the operability and reduction of secondary waste.

The global objective of the LD-SAFE project is to validate the laser cutting technology in an operational environment in-air and underwater (TRL7) and prove that the technology is mature to address the dismantling of the most challenging components of power nuclear reactors. 6 companies (ONET Technologies, CEA, IRSN, Tecnatom, EQUANS and Vysus Group) are deeply involved to make this demonstration through specific tasks started in August 2020 and to be completed by June 2024.

Safety being one of the major drivers for accepting innovative technologies, the LD-SAFE project will evaluate the safety of the use of laser cutting technology in 4 stages:

- risk analysis under nominal and accidental conditions, which preliminarily demonstrates the safety of its implementation;
- acquisition of laboratory results of hydrogen and aerosol generation, and the possible impact of the residual laser beam;
- generic safety assessment following IAEA methodology, with the additional objective of being easily adaptable to future end-user conditions and reducing their licensing effort;
- followed by an independent safety assessment, to be carried out by IRSN.

### 2.3 INSIDER

The project aims at improving the management of contaminated materials by proposing a methodology that allows us to define and select the best nuclear decommissioning and dismantling operations (D&D) and remediation scenarios, and which produce well-characterized waste for which storage and disposal routes are identified. In particular, the methodology developed in the INSIDER project helps to acquire characterisation data in a Medium and High radioactivity environment, which are the basis for D&D scenario studies compliant with regulations in European countries. This gives access to a reliable vision of the radiological state of a facility (and/or its components) at a relevant confident level, allowing the identification of the different D&D scenario options.

INSIDER proposes a common validation in the entire D&D process, based on three main use cases – nuclear R&D facility, nuclear power plant and post-accidental land remediation.

The project has developed three main strategic objectives:

- define the best sampling strategy for waste production optimization through new/improved statistics approaches for sampling plan establishment; feasibility of realistic cases, including safety and waste management impact; assessment of cost, duration, and impact on waste production.
- Assess the performance of available measurement techniques (methods & tools) to establish a scientific basis for decision-making through validation of quick/cost-effective analytical methods (in lab and in-situ); performance assessment; reference materials production.

- Establish common methodologies to deploy reference guidelines for selected use cases through the first mapping guide for potential support to standardisation commissions, a database of analytical methods and reference materials, training and software module offer.

Three use cases were specified, covering a large majority of D&D installation configurations:

- UC1: Cycle plant: effluent tank in Italy at the ISPRA site of the JRC (Joint Research Centre).
- UC2: Nuclear reactor: biological protection of the BR3 reactor vessel in Mol/Belgium.
- UC3: Post incident: contaminated soil on a CEA site in France.

### 2.4 CLEANDEM

The CLEANDEM project implements some of the learnings of the MICADO project (<https://www.micado-project.eu/>) by developing a mobile unmanned ground platform (UGV) equipped with upgraded highly mature detection technologies for radiological measurements. Indeed, the radiological conditions at the end of life of a nuclear facility vary, from very harsh at the beginning when the facility is close to its nominal working conditions, to nearly non-existent at the time when the facility is decommissioned. Today's need for human resources to conduct operations in the dismantling step is a clear limit with regard to the “As Low As Reasonably Achievable” (ALARA) principle which aims to avoid workers' exposure to radiation as far as it is reasonably feasible. Indeed, according to the level of radiation, the operating time can be limited or impossible and, in presence of contamination, the operators must be protected for their own safety.

Current radiological risk mapping implies exposing operators to the radiological conditions in the environment (i.e., to minimize dose exposure of dismantling operators, we still have to expose operators who will measure where the risks are).

Having a robot conduct this radiological assessment not only removes the risks to operators, but also removes the unavoidable errors due to organisational and human factors (limited intervention time [to reduce exposition time], repetitive tasks intrinsic to dose rate/contamination mapping, ...).

CLEANDEM aims at reducing human exposure to radiation, as well as the duration and costs of D&D operations while achieving higher efficiency and traceability of the operations. One can notice here that the INNO4GRAPH project shares the same stake in developing remote tools, without compromising in terms of the efficiency of the operations, applied to the dismantling of graphite reactors.

This three-year project, which started in March 2021, will address the need for full-D&D-operations' spectrumable technologies through four main tasks:

- improvement of current radiological measurement technologies (dose rate, neutron/gamma detection and identification, and contamination monitoring).

- Their implementation on a UGV platform, enabling to carry out remote operations and minimise human intervention.
- Build a Digital Twin containing all the radiological information of interest, updated as and when new data is available from D&D operations.
- Field-tests of the CLEANDEM solutions during in-situ operations in real environment conditions based on the scenarios defined by end-users.

To achieve the best consistency with both end-users and stakeholders' expectations, a team is specifically dedicated to Market analysis.

To address these different challenges, leading actors from the nuclear industry and research have joined their expertise and efforts in a pan-European consortium, with 11 partners from France, Italy, Germany and Spain.

## 2.5 PLEIADES

The PLEIADES project (PLatform based on Emerging and Interoperable Applications for enhanced Decommissioning processES) aims at making the decommissioning of nuclear facilities more efficient, by demonstrating an innovative digital decommissioning approach inspired by the BIM (Building Information Modelling) concept.

BIM enables all the information related to a building to be managed through a central 3D model, enhancing information exchanges between different jobs and enabling scenario simulations for testing building or renovation work. CLEANDEM is the first example of BIM use in a digital twin approach. In this approach, the building model is coupled to its physical twin and updated in real-time as soon as the autonomous characterisation system is acquiring new data. By extension to almost all the operations of the dismantling of nuclear installations, PLEIADES will demonstrate how a BIM-like model (containing data required for decommissioning planning) can be used for scenario simulations improving safety, minimising radiation exposure, and optimising costs and schedules. It is also an aim of PLEIADES to provide evidence for its added value and cost-saving through realistic pilot applications in different facility types. In order to achieve these goals, PLEIADES will develop a platform and demonstrate a new methodology for costing, planning, radiation protection and waste management. The platform will include a set of innovative modules, developed by project partners, including 3D simulation-based solutions. Using this platform, PLEIADES will implement use cases based on data from three different nuclear sites: the Santa María de Garoña nuclear power plant in Burgos (Spain), the Halden research reactor in Norway and the BCOT nuclear maintenance facility in Bollène (France).

To structure the data, PLEIADES proposes a decommissioning-oriented ontology that extends the standard Open BIM ontology applied in the building industry. PLEIADES aims at demonstrating a BIM-like modular software ecosystem based on the connection of front-line support tools through an interface built on this decommissioning-specific ontology.

As mentioned in the introduction, the nuclear dismantling community needs mature technologies for efficiently performing a large number of foreseen dismantling operations. PLEIADES will integrate mature solutions from partners that were, individually, already tested in the nuclear or other sectors. The exploitation strategy of PLEIADES is based on capabilities and services offered through the integration and interoperability of the partner's solutions.

The expected results of the project are foreseen to:

- improve safety, specifically by providing improvements in radiological protection, communication between stakeholders and training of workers.
- Reduce costs by enabling better and more standardized costing, as well as higher optimisation of the waste management process.

## 3 Main results of the projects

### 3.1 INNO4GRAPH

The work carried out during the first 18 months of the project has made it possible to produce some initial results and to achieve part of the objectives of INNO4GRAPH.

During the first period, the technical and environmental dismantling requirements of the different European operators were gathered in a report reviewing existing global dismantling scenarios, main reasons for choices etc. This provided a good overview of the graphite decommissioning situation as well as an understanding of similarities and differences. It also allowed identifying discrepancies to be considered in developments during and after the INNO4GRAPH lifetime.

Improved knowledge of graphite properties was achieved by data sharing between graphite NPP operators, identifying what are the most relevant graphite properties needed to conduct a successful dismantling according to different issues and to the sequencing of the project.

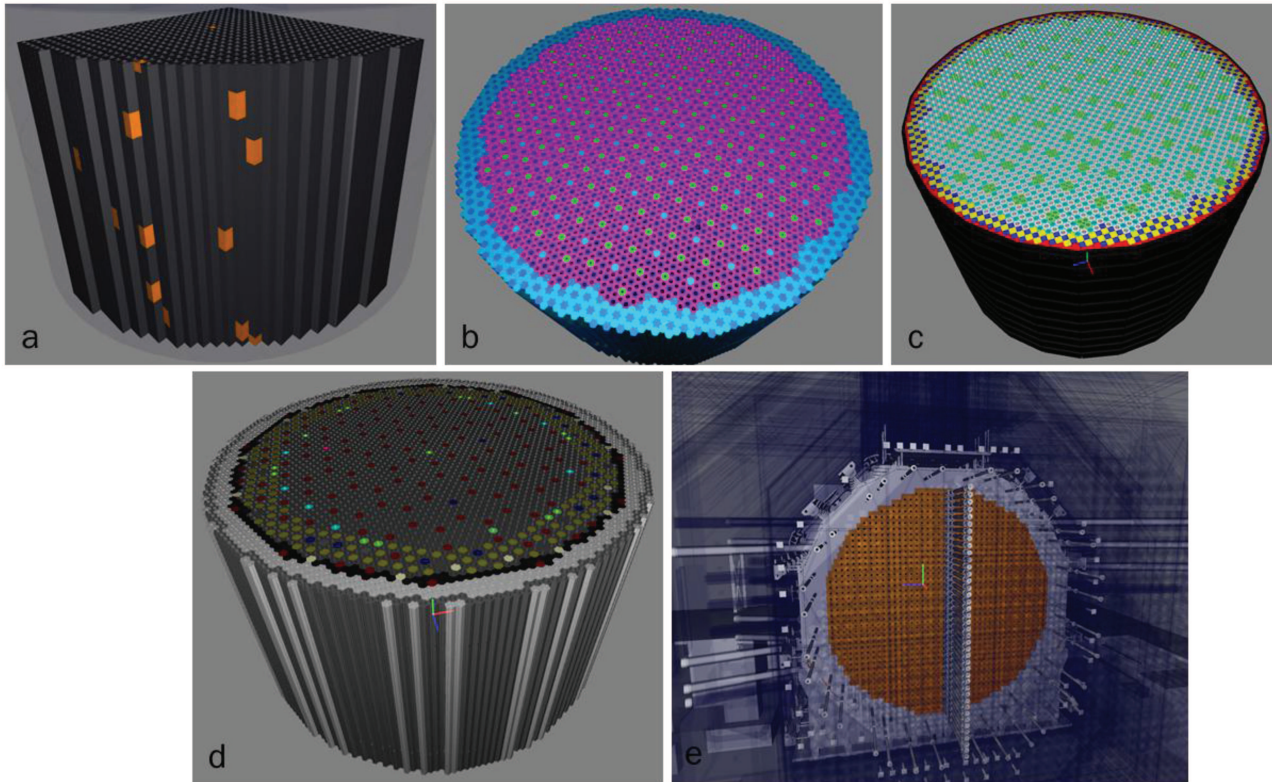
The DEMplus<sup>®</sup> for Nuclear software is a digital tool which allows simulation scenarios in a 3D virtual environment, enriched by radiological, physical, waste streams and labour costs information. It is also used in PLEIADES, as one of the applications of the Platform for enhanced Decommissioning processes. In INNO4GRAPH, DEMplus<sup>®</sup> for Nuclear has been upgraded with a new module dedicated to Graphite reactors which will allow to capitalisation graphite core data, to use if needed, external calculation models and to perform sensitivity study on the decommissioning scenario.

3D models of each reactor (Latina, Chinon A2, G1, Ignalina, Vandellos 1 – see Fig. 2) have thus been integrated into the DEMplus<sup>®</sup> software. This will allow graphite retrieval simulation in the second period of the project.

Studies are also in progress on methodology to measure the mechanical properties of graphite as well as on the in-situ measurement of cracks and corrosion.

The development of tools and methods to define the most adapted scenario for each reactor is another main





**Fig. 2.** Graphite core reactor 3D models integrated on DEMplus<sup>®</sup>. (a) Ignalina, (b) Vandellós I, (c) Latina, (d) Chinon A2, (e) G1.

objective of the project which is in progress. EDF's graphite industrial demonstrator (Fig. 3) will facilitate the uptake and further development of these tools. It will also be the place where operators from all around the world will be able to test them, train themselves and share experiences.

Among these tools and methods, one can mention:

- a multi-criteria grid analysis developed to allow graphite NPP operators to decide about their best dismantling scenario based on an objective evaluation of existing options taking into consideration risks and opportunities on different items.
- A representative and full-scale Chinon A2 NPP mock-up of the graphite stack designed and available for tests in the industrial demonstrator built by EDF in the township of Chinon in France.
- Definition of a testing methodology to assess the risk of bulk oxidation of the graphite during cutting operations [1].

### 3.2 LD-SAFE

#### Analysis of reactor dismantling with laser cutting

An analysis of the different reactor components in combination with the selection of conventional cutting techniques has been carried out including a comparison in



**Fig. 3.** EDF's industrial demonstrator.

regards to safety, secondary waste minimization, reliability and maintainability, and cutting performances. Specifications for the laser cutting system have been written to describe and explain the technology associated with the goals to be achieved in terms of cutting performance. A summary of safety-related challenges raised by laser has also been delivered.

Finally, this task has been completed by identifying the most challenging piece to be cut into the reactor and

describing the specifications for the mock-up in relation to the conventional technique band saw.

### Laboratory trials and calculations

Experimental data are needed to support the safety demonstrations and define the technical countermeasures to be implemented when using laser cutting for reactor decommissioning.

Works have been implemented on the laser beam residual power, through the design of an experimental set-up to characterize laser beam residual power.

The secondary emissions (aerosols) topic is also key in the safety demonstration and the definition of the measurement needs and aerosol metrology has been done with the first results obtained on aerosol generation during laser cutting using nitrogen vs. air.

Finally, the experimental set-up for hydrogen gas generation during underwater laser cutting has been qualified with specific instrumentation for real-time hydrogen and oxygen gas monitoring.

The experimentations are ongoing with expected results in 2022 and 2023.

### Protection of workers and environment

The Technology Qualification (TQ) of the Laser System in relation to the protection of the workers and of the environment in a nuclear decommissioning environment is ongoing with significant achievements so far with the final objective to develop a guideline for the industry for use of laser cutting technology.

The Goals for the Technology have been established against which the Technology Qualification will be assessed.

The full system decomposition (main components/subcomponents) has been implemented along with their TML (Technology Maturity Levels) and IML (Integration Maturity Levels) resulting in a Technology Qualification Plan shared with all partners: tasks to be completed to reduce the technology uncertainties by qualification activities including planning and management of TQ Plan.

### Safety assessment

As a first step for the development of the safety assessment, a preliminary risk analysis was carried out in 2021, which includes the identification of risks, potential consequences, and the recommendations for associated safety measures and controls, all synthesized in a matrix of risks for normal conditions and in case of an accident.

This preliminary analysis will serve as the basis for the generic safety analysis, to be developed in later stages of the project, an analysis that will be available to the End Users of the European market, thus facilitating the possibility of including this technology in the safety assessments during the initial phases of decommissioning projects.

### Involvement of end-users and dissemination

The project is committed to keeping strong connections with future end-users of the technology and enhancing the

dissemination and promote education activities based on the exploitation and communication of the outputs of the project.

A group of 17 end-users and supporting companies have been established with a first workshop held in December 2020 to share the project objectives and gather inputs from the end-users. Questionnaires have been gathered and analysed, they will enable to compile of input data and precise the expectations of the end-users.

The project members have also been actively involved in nuclear conferences during 2021, in France, Spain and Germany concluded at the WNE with a large audience at the workshop held on December 1st 2021 in Paris.

## 3.3 PLEIADES

### Requirements mapping for the design of the PLEIADES concept

The project started with an analysis of the needs and requirements. This gap analysis started with an online survey for gathering input from a large international audience. It provided details about user needs, expectations (of potential users towards emerging digital support concepts like the one developed in PLEIADES), requirements, key performance indicators, as well as blockers and enablers (impacting on possibilities for the adoption of the digital support systems proposed by PLEIADES).

Identified needs mostly focus on:

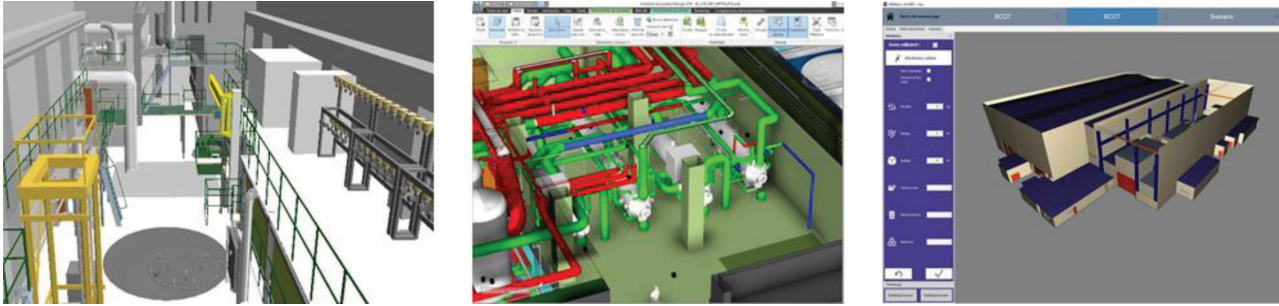
- 3D/BIM-based inventory management with a focus on radiological risks.
- Scenario simulation for analysis/optimisation of work plans.
- Safety and risk management.
- Waste route planning.
- Monitoring of work implementation.

Expectations are related to benefits in terms of cost reduction, dose exposure reduction, schedule improvement (speed), time/effort for regulatory/review approval, waste reduction/optimization, training effectiveness and more flexible planning.

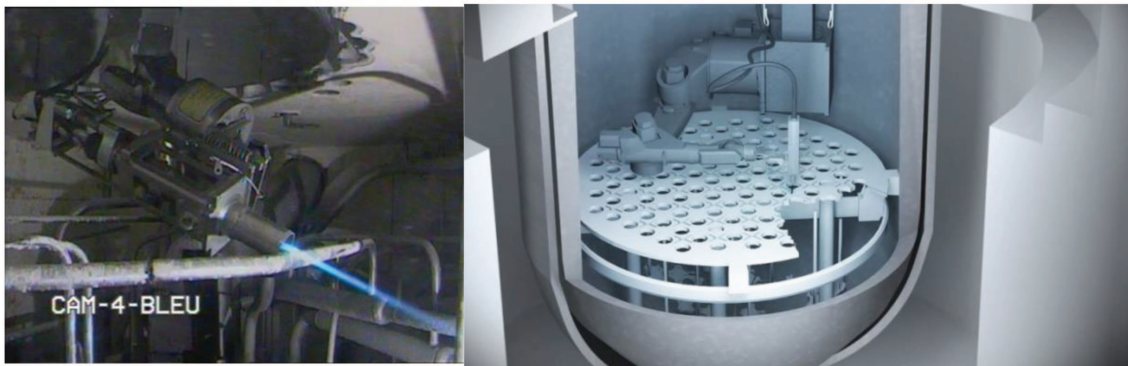
### Generation of a core nuclear decommissioning specific ontology

As many of the software tools being integrated into PLEIADES already exist and bring along their own history of terms and concepts, it was concluded that a pure terminology-based approach is not suitable. Hence the idea of a common ontology was developed. An ontology is a collection of concepts and the underlying properties that connect these concepts. PLEIADES has defined an ontology specifically designed to represent nuclear-decommissioning projects. The PLEIADES platform and data management will rely on this ontology.

The PLEIADES ontology has also been aligned with results from international organizations, ensuring basic compatibility with international knowledge resources (such as communities of practice or databases).



**Fig. 4.** 3D models of the nuclear facilities provided by IFE (left), ENRESA (middle) and EDF (right).



**Fig. 5.** Laser cutting technology applied to pipe in UP1 CEA facility and cutting and planned application of laser cutting technology in reactor environment (3D view).

### Preparation of the prototype validation tests and demonstrations

The consortium has developed user stories to be used as a basis for validation tests to demonstrate the capabilities of the PLEIADES prototype system.

Six user stories were developed in such a way that their implementation in the PLEIADES prototype system will demonstrate capabilities corresponding to most expectations identified previously. They focus on the comparison of alternatives for radiological characterisation, dismantling and decontamination of building surfaces as well as management of risks, regulatory requirements and waste management.

The required data, 3D model features and procedures have been identified for each user story. The 3D models and other facility information are provided by the three partners of the PLEIADES consortiums (IFE-Norway, ENRESA-Spain and EDF-France) that are responsible for the sites selected for the PLEIADES demonstration (respectively, Halden Research Reactor, Santa María de Garoña power plant and Base Chaude Opérationnelle du Tricastin (BCOT)), see [Figure 4](#).

### PLEIADES platform architecture specification and development

With the objective of increasing interoperability, the PLEIADES platform architecture has been defined and guided by the following criteria: respond in a commonly accepted and flexible way to the technological heterogene-

ity of the software tools in the PLEIADES ecosystem, guarantee that the solution meets data security requirements, while still being demonstrable within the timeframe of the project.

The PLEIADES architecture (see [Fig. 5](#)) aims at maximizing the collaboration between the different software modules. It is expected that this collaboration will not happen through direct communication between the different tools, but rather via data exchange to/from a common database with a specific focus on a system design that will take advantage of the common ontology.

The architecture is divided into the client-side and the server-side infrastructure.

The client side includes the interface developed in the domain of each partner's software included in the platform. Expected tools are indicated in [Figure 6](#) (DEMplus<sup>®</sup> for nuclear, already mentioned in project INNO4GRAPH for example).

The server-side infrastructure stores the data and secures the data exchanges. It is divided into the front end (that covers the intelligent features) and the back end (that manages the BIM-like data and ontology-based structured data).

### 3.4 CLEANDEM

In the project's first year, the Technical Specifications and Concept of Operations have been set, as well as the in-situ operations against which robots are to be challenged.



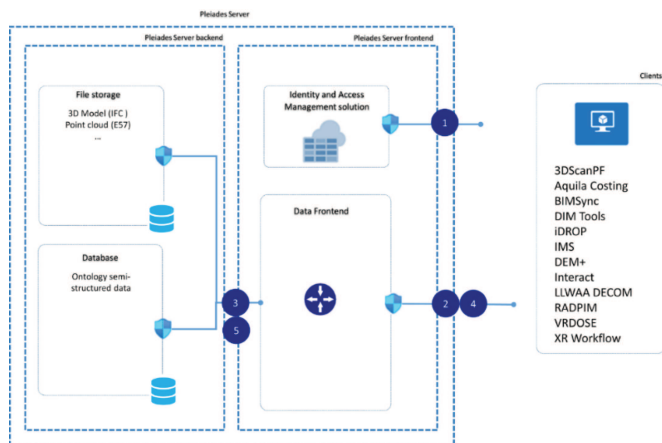


Fig. 6. PLEIADES platform high-level architecture.



Fig. 7. CLEANDEM robotic solution system.

These have allowed the teams to start their developments or eventually resumed them to upgrade them to meet the expected standards of the highly important matter which is the dismantling and decommissioning of nuclear sites.

The system shall be Universal Robot's UR 5e arm mounted on Robotnik Automation's RBVOGUI platform (Fig. 7).

The currently identified location to be the test and demonstration site for the developed technologies shall be located in Saluggia, Italy. No more details can currently be given on it at the moment according to CLEANDEM's project stage.

### 3.5 INSIDER

The general strategy supported by the INSIDER project for the initial characterisation of remediation sites consists of two complementary phases:

- (1) the development of a coupled and iterative approach Sampling/Measurements (and uncertainties)/Data analysis – Mapping.
- (2) The implementation of a structured metrological scheme by using Reference Materials of representative (as far as possible) matrices of the site as well as

inter-team and inter-laboratory comparisons on real or simulated matrix reference materials.

This strategy is based on advanced statistical approaches, both for the design of the sampling plans and the analysis of the data. The application guide for these statistical approaches [2] and the resulting STRATEGIST (Sampling Toolbox for Radiological Assessment To Enable Geo-statistical and statistical Implementation with a Smart Tactic) web tool (see Fig. 8) provides both an overview of the methodology and a step-by-step guide to its implementation in specific cases. The STRATEGIST tool is an open-access tool (<https://strategist.sckcen.be/>) that allows the promotion of all these developments carried out within the INSIDER project.

In situ measurement campaigns, according to pre-established sampling plans, remain essential and are at the heart of the approach. Two guides were drawn up and consolidated following the campaigns conducted as part of the project's benchmarking. The first guide concerns the requirements for implementing the measurement methods [3]. The second proposes an approach for the validation of the in-situ methods implemented [4]. A web-based tool named INSPECT (In Situ Probe SElection Tool) was developed to assist in the selection and implementation of in situ measurements in the case of sites in a constrained environment [5].

Concerning the metrological approach of the project, two certified reference materials were produced with matrices specific to the characterisation problems of D&D worksites, namely high-density concrete and effluent-type solution. They were specially manufactured within the framework of the project by European National Metrology Institutes, NPL, CMI and LNHB (CEA). In particular, the “concrete” Certified Reference Material (CRM) is a unique material obtained from real inactive material taken from the BR3 site.

Statistical processing of inter-team and inter-laboratory comparisons based on these CRMs and Reference Materials (RM) of real samples taken from two different Use Cases sites (BR3 reactor and ISPRA effluent tank) provides valuable information on method performance and measurement uncertainties in real cases. This information is essential to improve confidence in the characterisation results. The approach for establishing the uncertainty budget for the initial characterisation of a site prior to its decommissioning and the application to the different Use Cases of the project are described in [6,7].

In terms of dissemination, the Insider project has set up a dedicated SoK (State of Knowledge), located on the European Commission's website. The tool for managing the SoK is the web-based Community “Managing decommissioning and radioactive waste management knowledge” at the JRC Science Hub.

The future exploitation of this work in France and Europe through common methodologies and guides requires a transfer of knowledge and results from the project to international standardisation bodies, ISO, ASTM, IAEA, AFNOR/BNEN, etc. Based on the initial mapping of existing documents, recommendations have

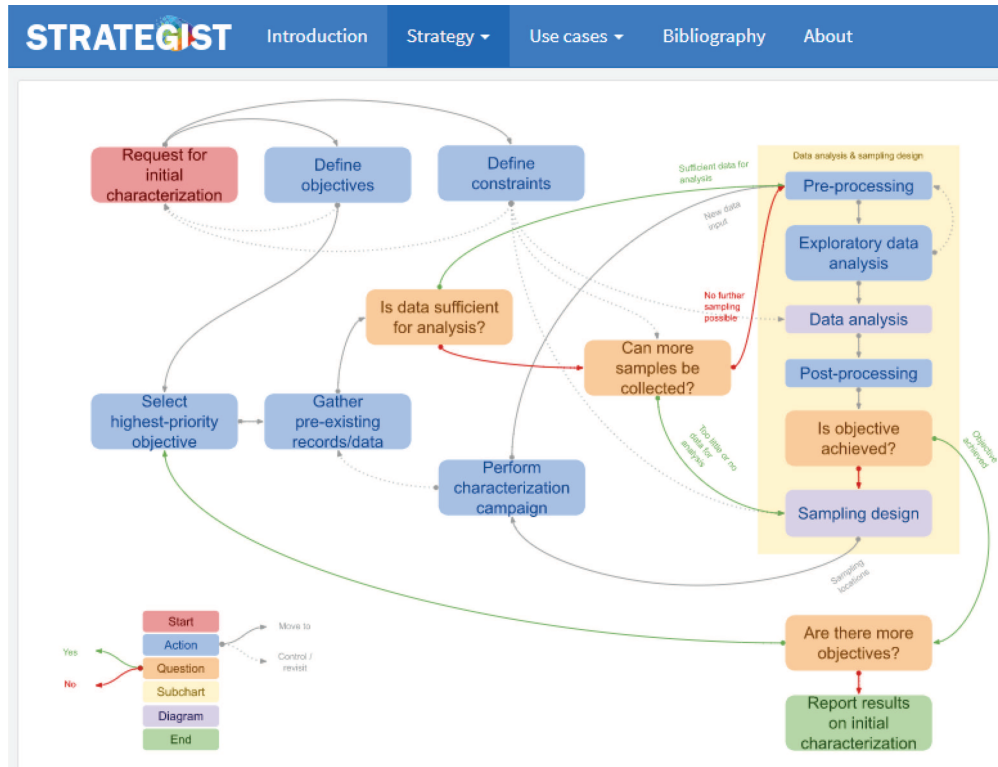


Fig. 8. Strategist Web tool.

been made [8] identifying the technical themes to be prioritized for future proposals for standards.

## 4 Conclusions and perspectives

The INSIDER project is now terminated and could be potentially continued in a European EURATOM framework to extend the methodology developed in the project to other D&D or waste site characterisation issues (also based on the roadmaps from the European projects EURAD and SHARE).

The LD-SAFE tasks will continue for the next two years more specifically the case study development and the construction/operation of the demonstrator. At the end of LD-SAFE, the suitability of the laser cutting technology to address the challenges of the dismantling power nuclear reactor and its capability to improve these projects in respect of safety, radioactive waste, time and cost will be confirmed based on the demonstrators and the other project outputs as the Technology Qualification and the Generic Safety Assessment. The next step should be the first deployment on a reactor decommissioning site as a world first.

Also continuing, the INNO4GRAPH project will now develop innovative cutting and handling tools which may be tested in the industrial demonstrator to make them available during the dismantling operations; while PLEIADES will develop and demonstrate a platform integrating many tools for dismantling operations.

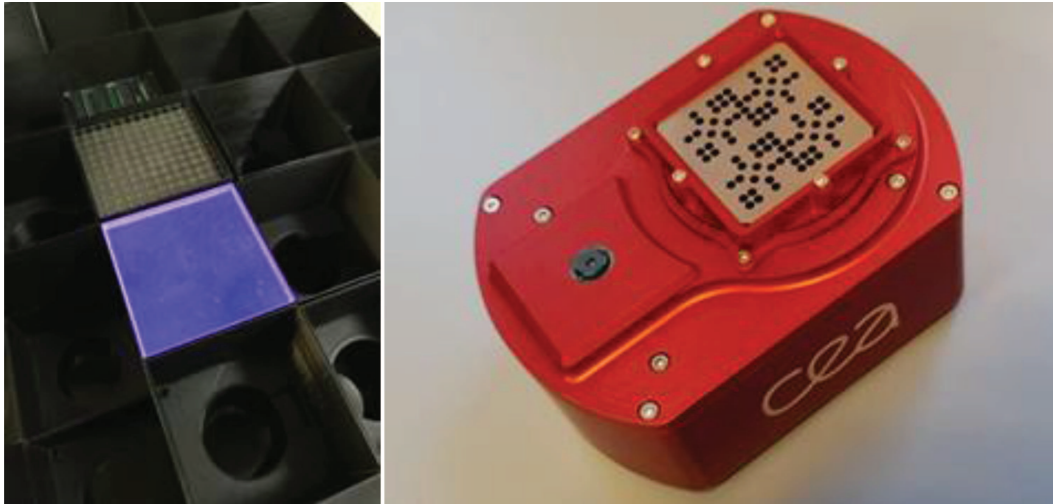
CLEANDEM is now at halfway and, following the Technical Specifications, CONOPS and preselected tests and demonstration sites, the project team is developing technical solutions to address the characterization needs in D&D (notably reducing operator's exposure and reducing the overall time and costs of operations). CLEANDEM is thus clearly addressing an issue of D&D and will allow important improvements in terms of characterisation quality for the operators.

CLEANDEM developments will allow to radiologically characterize D&D environments which will then be implemented in a 3D model of their Digital Twin, all the while avoiding human exposure to radiations enabled by remotely operating the robot and its embedded sensors.

Moreover, the remotely-operated robot and technologies developed in the frame of CLEANDEM will allow low-cost dose rate and contamination mapping, directly for accessible grounds, walls or pipes, but also the airborne contamination. The developed technologies will also allow for distant measurement, either by identifying radiological hotspots through gamma spectrometry imaging or with distributed OSL optical fibres, combined with shape sensing, which will be capable to reconstruct a 3D dose-rate map of usually unreachable locations.

Even if many developments still are in their early stage, some visuals can be shown of the pixelated surface contamination monitor, the Nanopix coded-aperture gamma imager with spectrometric abilities developed by CEA (see Fig. 9)

The 5 projects supported by the European Commission over the period all have the common goal to



**Fig. 9.** Contamination Monitoring System and Nanopix gamma imager with spectrometric abilities developed by CEA to be implemented in the CLEANDEM robotic system.

implement technologies of the “4.0 Industry” in the nuclear dismantling sector. This objective aims to benefit from the lever of efficiency and reliability represented by these technologies, which must make it possible to:

- improve the reliability of the knowledge of the installations to be dismantled;
- minimise dose rates to workers, making the “as low as reasonably achievable” very low; To make it reasonably achievable, more intensive use of remotely carried out operations is necessary, and the rate of this operation must be increased. This will be made possible by mastering these 4.0 industry technologies and their implementation in the nuclear dismantling field;
- facilitate and make the exchanges/sharing of information between the stakeholders of a dismantling project more efficient.

Beyond the traditional technical locks which are on the way to the implementation and the adoption of this type of technology, two other challenges are common to all the projects presented here:

- tools and methodologies must be applicable to a maximum of projects in different countries and contexts. It is commonly agreed that it would be often more efficient, but not always possible, to adapt a proven technology or methodology from one country to another, rather than developing a new method or technology *ex nihilo*. It is also of great interest to develop as many as possible versatile tools, in order to reduce the time-consuming approach of equipment or switching of tools etc. However, the more complex the design, the less reliable and the less simple the maintenance. It is thus necessary to tackle this contradiction in the research and the implementation of new technologies in nuclear dismantling practices. This challenge is even bigger when considering the next major point that is to be considered at the same time.
- Indeed, drastic proof of both the safety and reliability of these new technologies are required for being accept-

able in nuclear activities. A special effort has therefore been made in each of the projects to establish and take into account the developments, and the different regulatory, technological and societal contexts of each European country.

Due to these constraints, the works so far made in the five projects result in:

- a unique common data and knowledge base, as well as a significant sharing of experience on dismantling projects already carried out or to come.
- New tools design or methods natively taking into account the needs of a maximum of dismantling operators (rather than a design centred only on one operator or one facility or one dismantling project). Consequently, ten different European countries are involved in the five projects, plus Switzerland, Ukraine, United-Kingdom and Japan.
- New test facilities have also been put in place and will allow the joint work undertaken to be continued.

All of this paves the way to further collaborative projects and developments, in order to continue to implement safe, reliable and efficient new technologies in European dismantling projects. Based on this technical excellence, Europe is currently building a high-performance nuclear dismantling sector, generating activity and skilled employment in various sectors (engineering, robotics, digital, design of equipment and special machines etc.).

### Conflict of interests

The authors declare that they have no competing interests to report.

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### Data availability statement

Data associated with this article cannot be disclosed due to intellectual property and industrial protection reasons.

### Author contribution statement

The author's respective contributions to the full paper are listed: N. Malleron acted as the coordinator of the full paper. M. Guerin and P. Lefevre contributed to the paper by providing specific information on the INNO4GRAPH project (Sects. 2.1 and 3.1). D. Roulet contributed to the paper by providing specific information on the LDSAFE project (Sects. 2.2 and 3.2). C. Rivier, contributed to the paper by providing specific information on the INSIDER project (Sects. 2.3 and 3.3). M. Michel, contributed to the paper by providing specific information on the

CLEANDEM project (Sects. 2.4 and 3.4). M.-B. Jacques contributed to the paper by providing specific information on the PLEIADES project (Sects. 2.5 and 3.5). Common sections of the full paper (Sects. 1 and 4) have been written collaboratively with the contribution of all the authors.

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