LD-SAFE

Laser Dismantling Environmental and Safety Assessment

STAKEHOLDERS WORKSHOP REPORT

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P. DAGUIN	D. ROULET	D. ROULET
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1. SUBJECT OF THE DOCUMENT

1.1. Subject of the document

This document corresponds to the 'Stakeholders Workshop Report' requested on the Work Package n°6 of the LD-SAFE project. This version represents the final delivery to the public.

A first version of this deliverable has been delivered at the beginning of the project to provide information about the first technical workshop. The second delivery (final version) contains the feedback of the end technical workshop (which represents an important milestone of the project and will be a measure of its success).

1.2. Workshops objectives

As defined in the LD-SAFE Grant Agreement **[R1]**, two technical workshops are planned with the stakeholders of the project:

1- **At the beginning of the project:** to present the project to the stakeholders and sharing views with them about the use of laser cutting technology for reactor dismantling.

2- **And at the end of the project:** to disseminate the results of the project both to industry, academics and RTOs.

The main stakeholders of the project are:

- The European Commission,
- The LD-SAFE Consortium composed of: ONET TECHNOLOGIES, CEA, IRSN, EQUANS (formerly ENGIE), Vysus Group (formerly Lloyd's Register) and Westinghouse (formerly Tecnatom),
- The Advisory Board.

1.3. Technical Workshops organization

Due to COVID-19 restrictions, the first technical workshop was organized in three phases/events:

- First Technical Workshop (webinar, by videoconference) on the 9th of December of 2020, covering the same topics and target audience. The Webinar presented the objectives and milestones of the project and shared views with the End User Group and Expert Group, thought interactive polls and questions/answers. A questionnaire was also shared with the End User Group, which was fully completed by the 12 members of the End User Group (100%).

  As a result, the objectives set for the workshop were successfully achieved. However, additional events were scheduled for providing the opportunity for face-to-face exchanges and further discussions of the project, as detailed below.

- LD-SAFE Public Workshop in WNE 2021 (Paris, France), on the 1st of December of 2021.

- Presentations of the different Work Packages (mainly WP2 to WP5) in two videoconference sessions with relevant stakeholders, in March 2022.

The second and end technical Workshop was scheduled at Onet Technocenter in Chusclan (France) in a two-day event (the first day for the main stakeholders, industrials, TSO, RTO, operators; the second day for the students, post-graduate scientists, engineers, and researchers). This event was performed the 30th and 31st of May 2024.

2. REFERENCE DOCUMENTS

N°	Reference	Version	Description
R1	945255 (and amendment reference AMD-945255-2)	N/A	Grant Agreement - LD-SAFE

3. TERMINOLOGY

Acronym	Definition
CEA	Commissariat à l'Energie Atomique et aux énergies alternatives
EC	European Commission
EG	Expert Group
EQUANS	EQUANS
EUG	End User Group
IRSN	Institut de Radioprotection et de Sureté Nucléaire
LD-SAFE	Laser Dismantling environmental and SAFEty Assessment
MS	Milestone
OT	ONET TECHNOLOGIES
RTO	Research and Technology Organisations
TSO	Technical Safety Organisations
TW	Technical Workshop
VYSUS	Vysus Group
WH	Westinghouse

4. LD-SAFE SUMMARY

4.1. Project presentation

Introduction

The forthcoming power reactor decommissioning, particularly the Reactor Pressure Vessel and In-ternal, represents an immense challenge due to the acceleration of the project schedules. Improving the dismantling processes and in particular cutting, which is a key operation, is a request from the European end users. Indeed, the main cutting techniques already used (such as mechanical, thermal and hydraulic) present advantages and drawbacks but for sure these conventional cutting techniques have limited effectiveness.

In this context, the European decommissioning market requires the development of innovative cutting technologies in order to improve safety, radiation protection, waste management, time and cost aspects. Therefore, the European Commission selected laser cutting technology as one of the most promising techniques in comparison with the conventional ones currently used. Indeed, following more than 10 years of R&D effort, laser cutting (solid state laser: disk laser or fibre laser with a wavelength between 1.03 and 1.07 µm) represents already a mature and operational technology thanks to laboratory trials and the dismantling of fuel cycle or research facilities.

That is why the LD-SAFE project, which is an Innovation Action project financed within the Horizon 2020 program of the European Commission (Euratom), will assess the maturity of laser cutting technology for dismantling pressure vessels (RPV) and internals (RVI) of Nuclear Power Reactors.

LD-SAFE

An European Consortium composed of 6 companies (Onet Technologies, CEA, IRSN, Westinghouse, EQUANS and Vysus Group) has been granted an H2020 project called "LD-SAFE", focusing on removing the last technical, financial and psychological barriers to propose the laser cutting technology as an alternative to the conventional cutting techniques used for the decommissioning of Nuclear Power Reactors and mainly their internals and pressure vessels.

LD-SAFE project aims to demonstrate that both the in-air and underwater laser cutting technologies are effectively operational for the dismantling of the most challenging components of light-water Nuclear Power Reactors and that, for this application, the laser cutting technique:

- Is as safe as the best cutting techniques currently used, even safer for the workers and environment;
- Does not add any new constraints;
- Is more cost effective to dismantle the challenging power reactor components;
- Is simpler to implement on site and suited to the complex dismantling of reactor internals.

An Advisory Board completes the LD-SAFE organization to provide an external point of view on the project. It plays the role of an ecosystem for providing inputs for running the project and for ensuring the match between project results and market, societal, and environmental needs. It is composed of 3 groups: Expert Group, End User Group and Support Group. These groups represent important participants of the Technical Workshop because they are able to provide inputs to the LD-SAFE Consortium to progress in their technical activities.

Expert Group: Experts on laser safety, conventional cutting techniques for dismantling of reactor pressure vessels and internals, nuclear safety, and dismantling project management. They will monitor and redirect when needed the scientific developments, project management and the strategy for the dissemination of results.

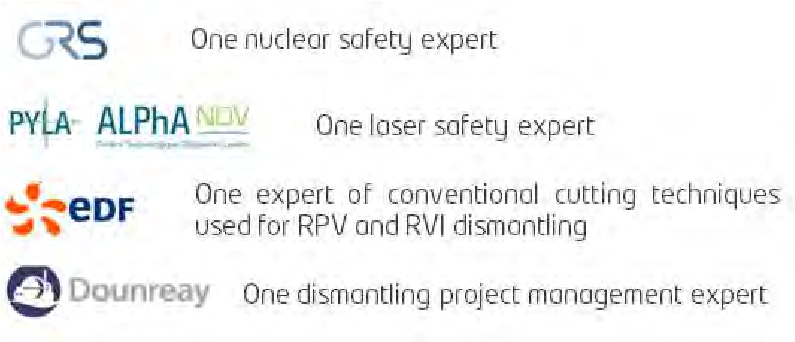


Figure 1: Expert Group composition

End User Group: Dismantling Operators and Contractors, Research & Technology Organizations and Technical Safety Organizations interested in the results of the project. The EUG ensures project activities adequately address the conditions and restrictions of nuclear facilities during decommissioning, and to increase the visibility of the project. The EUG members participate to all Technical Workshops or specific events scheduled by the project.

Figure 2: End User Group composition

Support Group: Groups with activities whose inputs or outputs are connected to LD-SAFE objectives. The members act primarily as observers, although they can share their views and participate in technical workshops.

Figure 3: Support Group composition

4.2. Project Objectives

Objectives

The main objectives of the LD-SAFE project are:

- The validation of the laser cutting technology for the dismantling of the most challenging components of Nuclear Power Reactors in air and underwater;
- The demonstration that laser cutting technologies is a relevant alternative to the conventional techniques used for the segmentation of the Nuclear Power Reactors internals and pressure vessels.

Specifically, considering these main objectives and the pending limitations outlined in the state of the art, this means:

- Demonstration of the technical capabilities of the laser cutting technology to address the key challenges of the dismantling of Nuclear Power Reactors RVI and RPV;
- Environmental and safety assessment for the implementation of laser cutting in nuclear reactor environment and definition of safety provisions according in particular to defense in depth;
- Validation of technology in operational environment, with in-air and underwater demonstrators including the safety system, confirming that TRL 7 is reached (Technology Readiness Level);
- Demonstration of the economic advantage of using the laser cutting technology for RVI and RPV dismantling.

4.3. Technical activities

Main technical activities

To meet the goals and the requested impacts, the project is structured into five technical activities covering a project time of four years:

- Laser technology analysis in operational reactor environment: production of analysis and specifications for the use of laser cutting technology in operational reactor environment.
- Laboratory tests and calculations to assess and mitigate the environmental and safety impacts dedicated of laser cutting technology applied to the dismantling of reactor components. It concerns the characterization of the laser beam residual power, secondary emissions as aerosols and hydrogen generation during underwater laser cutting.
- Protection of the workers and environment: Technology Qualification of the laser system in relation with the protection of the workers and environment will be carried out, and a Technology Qualification Certificate (TQC) and guidelines for the industry for use of laser cutting technology in reactor dismantling environment will be delivered.
- Safety assessment for the implementation of the laser technology: Development of the risk analysis including answers on the safety concerns raised by stakeholders. A generic safety assessment supported by an independent review for laser cutting in reactor environment has been delivered.

- Development of demonstrators for the validation of the implementation and the use of laser cutting technology in a representative reactor environment: the objective of this activity is to validate the implementation of the technology in reactor environment at TRL7.

Analysis of reactor dismantling with laser cutting

At the beginning of the project, an analysis of reactor dismantling techniques including laser cutting has been completed. As starting point, an overview of all the common techniques of cutting the internals of a nuclear reactor has been done which included a description of the use of different techniques and a comprehensive comparison. For proposing new cutting techniques, it is required to know how the dismantling of radioactive structures of nuclear facilities is performed today by looking at the various types of cutting equipment (divided into three types: thermal, mechanical and hydraulic) that have been applied in past dismantling projects. The objective is to present the most common cutting tools for cutting PWR and BWR reactor internals and to build a database to compare them with laser cutting. This comparison highlights the key challenges to be checked during the laboratory tests to assess the risks by using laser cutting technology in reactor environment, but also during the demonstrator at the end.

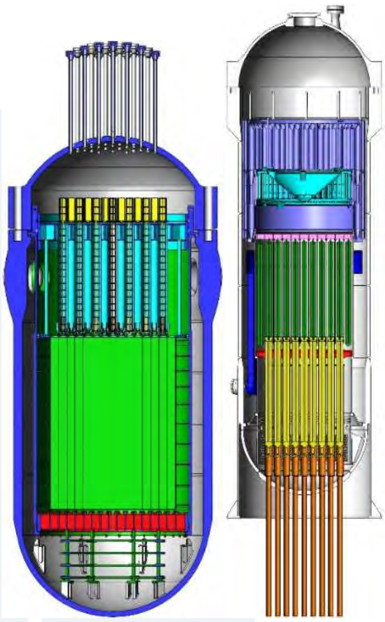


Figure 4: PWR and BWR reactors

Laboratory trials and calculations

Subsequently, and using as inputs, data provided by the previous analysis, laser cutting tests have been carried out in laboratory conditions to assess three safety topics:

- Laser beam residual power (applicable in air cutting)
- Secondary emissions: aerosols (applicable to both in air and underwater cutting)
- Hydrogen gas generation during underwater laser cutting

Laser beam residual power:

Laser cutting process absorbs only a part of the laser power delivered to the workpiece to melt and cut through. The unabsorbed laser power, referred to as residual laser power, propagates in the form of optical radiation beyond the workpiece and is capable of reaching mechanical structures located behind it, commonly known as background structures. Heat generated by the residual laser power can potentially weaken or damage these structures by affecting their mechanical resistance or tightness. This task aims to assess the impact of laser beam residual power and the risk of damage on background structures in the context of dismantling nuclear power reactors. Specific instrumentation was designed and tested to characterize the spatial intensity profile of residual laser beam and its thermal impact on background structures. Since the spatial intensity profile depends on various parameters, such as cutting speed, distances between background structures and work pieces, material type to be cut and its thickness, laser cutting tests are carried out to gather data and plot graphs (build abacus charts) from which it is possible to estimate potential damages for specific workshop configurations. Data supplied by all technical activities, notably indicated that RVI in European Nuclear Park are mainly made of 304L austenitic steel and RPV are fabricated on carbon steel with a layer of 304L stainless steel or Inconel ranging from 4 to 6 mm, and provided the most restrictive configurations of RVI cutting (including analysis of background structure). Furthermore, 304L stainless steel was chosen as the most representative material. First, tests performed in air in these configurations showed that the initiation phase of laser cutting process is critical. When the cut initiates at the edge of the work piece, the extent of damage depends on the distance between the laser beam and the workpiece edge. Secondly residual laser power generates blind kerfs of a few millimeters in depth when the background structure is very close to a thick workpiece that has to be cut (Figure 5). Moreover, tests performed underwater showed the absence of residual laser-power risk due to the absorption of water at the laser wavelength and the scattering of light by air bubbles.

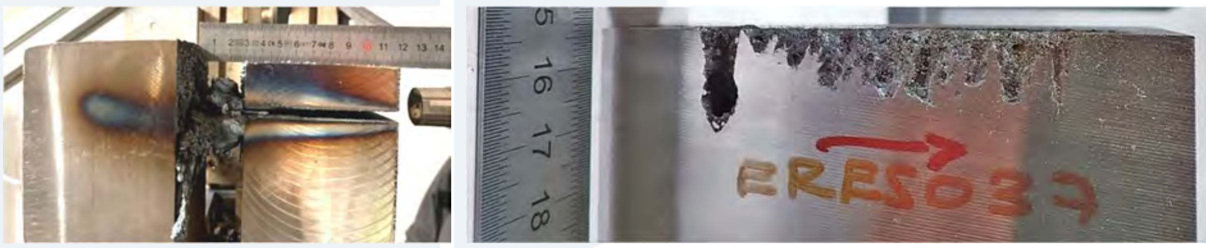


Figure 5. Example of cutting on 304L stainless steel with sample in background (left) and cross-section of the sample in the background showing blind kerf (right)

A new campaign of tests started at CEA facility with tests planned in two phases. First, laser cutting tests are performed on stainless steel plate ranging in thickness from 10 mm to 80 mm. Subsequently, the spatial intensity profile of residual laser beam on a thick graphite plate is measured with the specific implemented instrumentation for this purpose (Figure 6). Second, laser cutting tests are conducted on 304L stainless steel plate serving as both workpieces and background materials. These plates vary in thickness and are located at various distances. The thermal impact of residual laser beam is measured with thermal cameras (Figure 7).

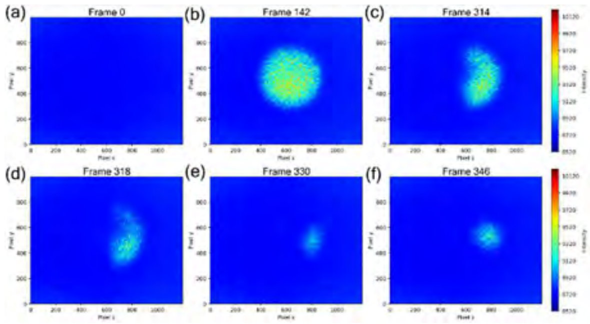


Figure 6. Residual laser power cartography images on a background structure during a laser cutting of a 304L stainless steel sample

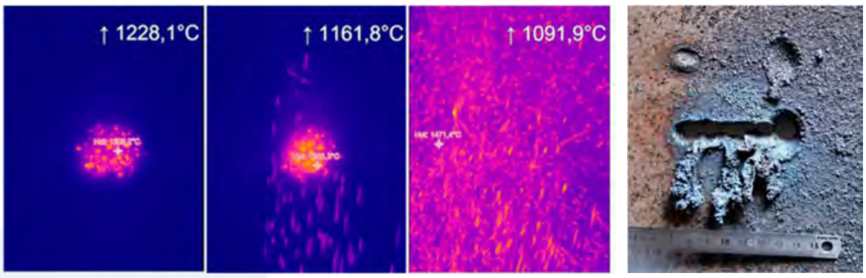


Figure 7. Example of thermal cartography on background structure during a laser cutting and impact at two distinct cutting speeds (a high cutting speed (top) and a low cutting speed (bottom))

Secondary emissions - Aerosols:

The knowledge of the size distribution and the morphology of particles released during cutting operations undertaken for nuclear power plant dismantling activities is important for safety and radioprotection issues. This information allows predicting particle transport and deposition and particle behavior against confinement equipment implemented to ensure the mitigation of radioactive particles dispersion in the facilities and environment. Furthermore, quantitative characterization of the contaminated aerosols is essential to develop and optimize technologies to capture and contain particulate pollutants, mitigating against environmental contamination and human exposure.

Airborne particles emitted during laser cutting of various grades of stainless-steel are submicronic particles with mainly fractal morphology. Extensive results have been acquired on aerosol characterization emitted during laser cutting in air or nitrogen atmosphere and underwater conditions. The repeatability of the airborne particle generation characteristics during laser cutting has been checked extensively during the trials (Figure 8). The repeatability, which is very good, demonstrates the well-controlled conditions for the laser cutting process, for the aerosols sampling and for the aerosols analyses both in terms of aerodynamics and physico-chemical measurements.

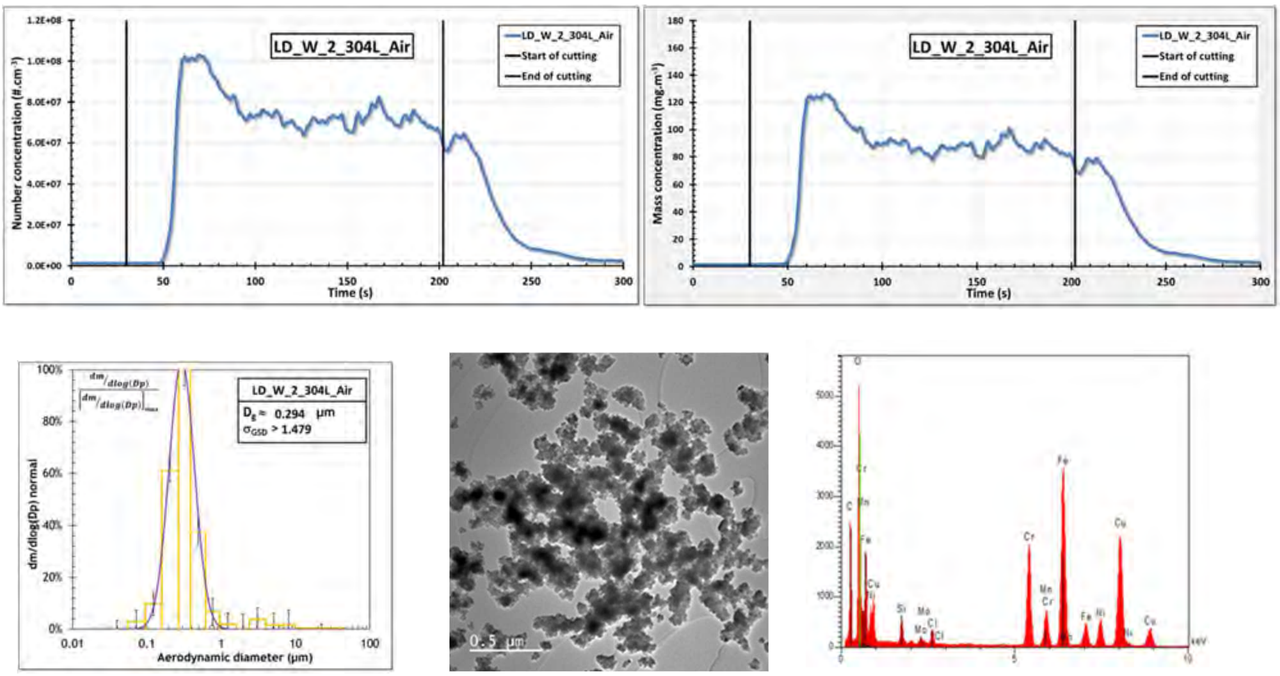


Figure 8: Examples of aerosols characterization emitted during underwater laser cutting of stainless-steel 304L with air assist gas, in terms of particle number and mass concentration, particle size distribution, particle morphology and composition

The main conclusions for laser cutting performed are summarized below:

Non-underwater:

- Aerosol size: weak influence of stainless-steel grade. Nitrogen as assist gas leads to reduce particle size to ~100 nm (~200 nm for air assist gas).
- Aerosol mass generation: weak influence of stainless-steel grade. Nitrogen as assist gas leads to reduce particle mass generation by a factor more than 10.

Underwater:

- Aerosol size: weak influence of stainless-steel grade. Nitrogen as assist gas leads to reduce particle size to ~130 nm (250 nm for air assist gas). Underwater condition leads to a slight increase of particle size compared to non-underwater condition.
- Aerosol mass generation: weak influence of stainless-steel grade as for non-underwater condition (316 slightly less than 304 L). Pool scrubbing at 1 m depth reduces by a factor ~ 2 to 3 the mass generation of particles. Nitrogen as assist gas leads to reduce particle mass generation by a factor more than 5 compared to air assist gas but for underwater condition, mass rate generation is same order or slightly larger for nitrogen assist gas, than for non-underwater condition.

Hydrogen gas generation during underwater laser cutting:

Underwater laser cutting of metallic materials entails specific risks. A cut is achieved thorough the combined action of a focused laser beam on a workpiece and the mechanical action of an assisting gas jet which operates coaxially with the laser beam. The heating associated to this cutting process reaches extremely high temperatures surpassing the material's melting point. This leads to the formation of a heat-affected zone between the melted metal and the unaffected base metal. Under such high temperature the material undergoes changes in its physico-chemical properties within this zone. In addition, cutting underwater induces others physico-chemical processes, such as the oxidation of the ejected material through interaction with assist gas, which is air, and the decomposition of water at high temperatures superior to 1000°C, resulting in the generation of dihydrogen gas (H_2). Dihydrogen gas then mixes with the assist gas supplied to the underwater laser cutting process.

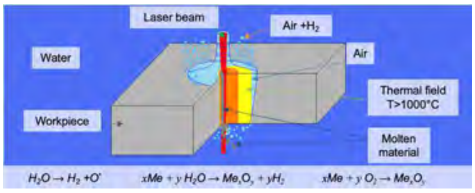


Figure 9. Schematic of hydrogen generation during laser underwater cutting of stainless steel 304L

An initial experimental study was conducted to evaluate dihydrogen gas generation during laser cutting of 304L stainless steel (Figure 10) of various thicknesses in DELIA Facility at CEA Saclay. Specific sampling line and instrumentation were implemented to measure H_2 levels during laser cutting as a function of cutting speed and thickness. Preliminary measurements showed very low concentration of dihydrogen in air, typically less than a few hundreds of parts per million (ppm) at DELIA facility. However, since the concentration of H_2 in air depends on parameters such as the assist gas flowrate and the ventilation flow rate of the facility, these preliminary results, specific to DELIA facility, need to be adjusted using a scaling factor determined for each facility. An analytical study was conducted to understand the physicochemical mechanism of dihydrogen gas generation during underwater laser cutting of 304L stainless steels, in addition to numerical simulation of the thermal fields of the heat affected zone (Figure 11). Furthermore, SEM (Scanning Electron Microscope) and EDS (Energy Dispersive Spectroscopy) analysis were performed to map the chemical composition of generated oxides (Figure 12).

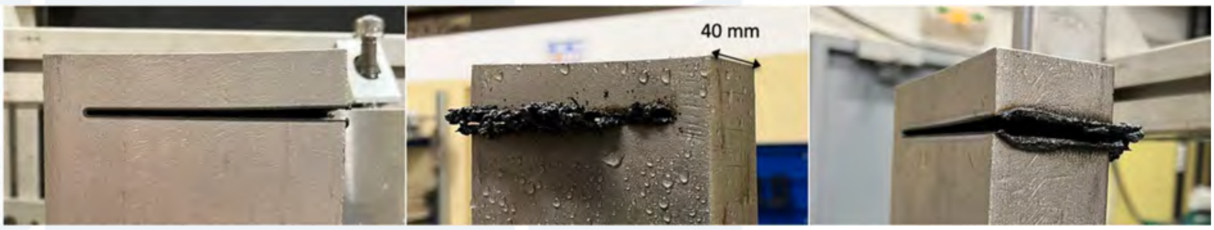


Figure 10. Laser underwater cut performed on a 40 mm stainless steel 304L at 8kW

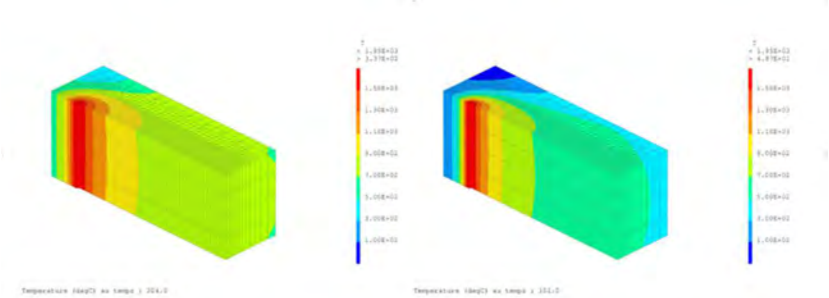
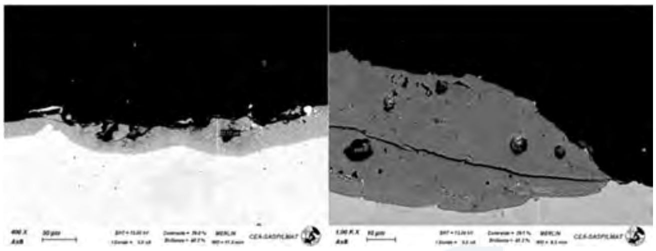


Figure 11. An example of thermal maps for a 40mm thickness plate cut at 8kW and at cutting speed of 2.5 and 5 cm/min



Element	Analysis	% atomic
O	WDS	55.72
Si	EDS	1.11
Cr	EDS	7.55
Mn	EDS	0.77
Fe	EDS	33.01
Ni	EDS	1.62
Mo	EDS	0.22

Figure 12. SEM/EDS and WDX characterization

These initial tests showed a slight increase in the mean level of H_2 volumetric concentration with increasing cutting speed and a small decrease with increasing sample thickness. Additionally, it's worth noting that peak values of H_2 volumetric concentration did not exceed 4500 ppm, significantly lower than the Lower Explosive Limit LEL of H_2 which is 1% (equivalent to 10000 ppm).

Figure 13. H_2 volumetric profile during laser underwater cutting of a 40mm stainless steel plate at 8kW for a speed of 5 cm/min and at 5.6m of water depth

Finally, an experimental campaign of laser underwater test was performed to measure H_2 generation in various conditions such as workpiece thickness, laser power, water level, and assist gas flowrate. The goals were to compare experimental and numerical results, attempt to validate the numerical model for 304L, gather experimental data to construct abacus charts, and consequently, calculate H_2 generation for other configurations.

Protection of the workers and environment

In collaboration with all companies in the LD-SAFE project, a Technology Qualification process has been followed in parallel with the other technical activities. The Technology Qualification process is a systematic risk assessment and verification process that demonstrates to interested parties that the uncertainties introduced by a novel technology, or a new process or application of an existing technology, have been considered and addressed.

At the start of the Technology Qualification process, as set of goals were specified, and as the last step of the process, a certificate is awarded to verify that those goals have been achieved. Based on the learnings throughout this process and other project activities, guidelines have also been derived for protection of the workers and the environment.

<u>Technology appraisal:</u>

The first step of the Technology Qualification process was to perform a technology appraisal in a workshop at the start of the project. This consisted of defining a set of project goals related to the performance of the laser system and to the protection of the workers and the environment. Once all the goals had been defined and agreed upon, the laser system was broken down into individual components, their individual function, and their integrated function within the laser system.

Each component was then given a technology maturity rating based on: 1) the technology readiness level of the component, and 2) its maturity in a nuclear decommissioning environment. The final output of the technology appraisal was a risk matrix that highlighted components where uncertainty and/or risk was at a level that required mitigation. This first step of the Technology Qualification process was documented in a technology appraisal report.

<u>Technology Qualification & Certification:</u>

The technology appraisal report and its risk matrix were used as a foundation to create a set of activities and actions that were assigned to the respective company and its associated work. The objective of these activities was to produce test results or other evidence to the effect that the identified risk has been mitigated or reduced to as low as reasonably possible. Once evidence was available for an activity, it was assessed and scrutinized in order to ensure that the risk has been successfully mitigated.

Upon completion of all activities at a satisfactory level, a Technology Qualification certificate will be provided to demonstrate that all identified risks have been mitigated, hence verifying that the goals that were defined at the start of the Technology Qualification process have been achieved.

<u>Guidelines for the use of laser cutting in reactor dismantling environment:</u>

As part of the project scope related to protection of the workers and environment, guidance notes from the LD-SAFE project have been derived and published in a Guideline. The Guideline incorporates the relevant lessons learnt in the

LD-SAFE project; that is, lessons learnt from laboratory trials, the generic safety assessment, the demonstrator, as well as other technical activities.

The guidance notes have been designed to give end users an overview of how to use lasers correctly, safely and efficiently in decommissioning activities for PWR and BWR nuclear reactors. This includes guidance on activities that need to be performed before, during and after using the laser system for both in-air and underwater cutting.

Safety assessment

As a reminder, the project aims to demonstrate that laser cutting technique allows meeting technical and safety challenges in a more efficient and economical way, and at least as safely as conventional techniques. For this, a safety evaluation following the methodology of IAEA Safety Report Series No. 77, "Safety Assessment for Decommissioning", has been carried out. It includes the results obtained in laboratory tests of the generation of aerosols and hydrogen and of the residual laser beam. The safety evaluation analyzes different laser cutting configurations, both in air and underwater, with special emphasis on the main risks associated with the technology. First, potential dose rates with different shielding and cut depths are analyzed using MAVRIC code (figure 14). Based on aerosol release data, recommendations on static and dynamic confinement systems are made proportional to the risks according to ISO 16647:2018 and considering operational experience of reactor pressure vessel and internals segmentation using thermal techniques. Finally, the risks derived from the residual laser beam due to unwanted damage to components not involved in the segmentation plan are analyzed. All risks and associated safety measures and controls are summarized in a risk matrix for normal conditions and a risk matrix for abnormal and accidental situations.

The generic safety evaluation developed, and which was evaluated independently will facilitate the implementation of laser technology for cutting reactor pressure vessel and internals, and will be available with the aim of being easily adaptable to the specific conditions of end users and reduce the associated licensing effort.

Risk analysis:

A risk analysis was performed following a structured process (IAEA SRS No. 77):

1- Description of the activities and conditions to be evaluated.

2- Identification of the risks for the activities case of study.

3- Evaluation of the potential consequences of the identified risks.

4- Determination of safety measures and controls for reducing the risks to ALARA.

The preliminary identification and evaluation of radiological and non-radiological risks for normal and accidental conditions was performed in a complementary and iterative manner, considering IAEA checklists, a HAZOP study, and a benchmarking of risks identified for other reactor pressure vessel and internals dismantling projects. Potential deviations from normal conditions were screened, identifying three initiating events that were further analyzed: fire/explosions, loss of filtration/local confinement, and drop of loads. The consequences were evaluated in a deterministic manner, qualitatively and quantitatively (predefined radiological inventory), and based on that, a recommendation of design options (for normal conditions) and safety measures (for abnormal/accidental conditions) was done. All the information was summarized in two risk matrixes: one for normal conditions and another one for abnormal or accident situations.

Summary of risks identified:

This report compiles all risks identified in laboratory trials and qualification activities, evaluating its impact on the Generic Safety Assessment. A structured process was followed to ensure major risks included in qualification activities (that are within the framework of the generic safety assessment) were identified and evaluated, and that the risks associated to aerosols and hydrogen generation and residual laser beam take into consideration the outputs of laboratory tests performed. Within this report:

1- Potential dose rates with different shielding and cut depths are analyzed using MAVRIC code.

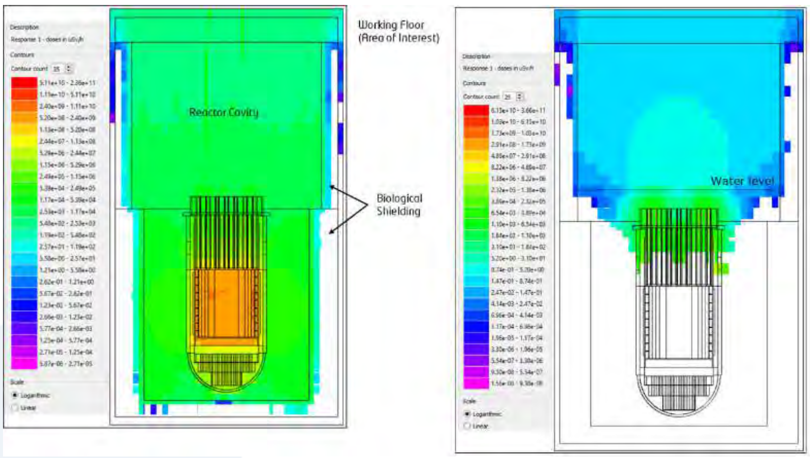


Figure 14: Dose Rates Simulation Optimized for Calculating at Work Zone using MAVRIC. Internals In-air Cutting within the Vessel (left) and 2 meters underwater (right)

2- Based on aerosol release data, recommendations on static and dynamic confinement systems are made proportional to the risks according to ISO 16647:2018, "Criteria for design and operation of confinement systems for nuclear worksite and for nuclear installations under decommissioning" and considering operational experience of reactor pressure vessel and internals segmentation using thermal techniques.

3- The risks derived from the residual laser beam due to unwanted damage to components not involved in the segmentation plan are analyzed.

This activity aimed at providing further guarantee in the completeness of the hazard's identification and screening process.

Generic Safety Assessment:

The Risk Analysis was updated to develop the Generic Safety Assessment, considering the outputs from the summary of risks identified during the technical work of the project. Major assumptions and uncertainties identified in the risk analysis were eliminated or reduced. Due to the generic nature of the assessment, End Users would have to adjust the information to their specific conditions (i.e., radiological inventory and segmentation plan), but it is the aim of this assessment to reduce their licensing effort.

The Generic Safety Assessment includes the recommendations and findings of the Independent Review, providing End Users with a consolidated final version.

Independent review:

A first version of a preliminary independent review of the Generic safety assessment has been performed in 2022. This review led to improve the Generic safety assessment with a second version, which has also been reviewed through a final version of the independent review (released in 2023). The scope and level of detail of the independent verification have ensured they are consistent with the safety stakes associated with the maturity and complexity of the LD-SAFE project. Finally, the outputs of the independent review have been addressed considering:

- Recommendations which have been considered in the final version on the Generic safety assessment,
- Guidelines to the End User, to make sure the interfaces between LD-SAFE and target facility are covered,
- Hypotheses to be verified within the industrial demonstrator.

Case studies / Demonstrator

Finally, a demonstrator has been developed to validate the performance, the ease of use and the compliance about safety of a representative laser configuration which could be deployed in a dismantling project. It has been performed in 2 phases: at first at CEA Marcoule for in-air cutting tests, and then at ONET Technocenter for underwater cutting tests. Based on all previous activities, the studies of in-air and underwater demonstrator studies have been focused on:

- The design and procurement of the complete laser system and the cold representative mock-ups (of the most complex components),
- The adaptation or the building of facilities for the implementation of all laser equipment,
- The demonstration itself by performing laser cutting tests in a representative environment (validation of the performance, the ease of use and the compliance about safety).

Case study for the demonstrators:

The first step represents the development of a case study for the demonstrators to specify the main requirements. The objective was to demonstrate that laser system:

- Complies with standards and regulatory (for the procurement and the use of laser).
- Has a representative configuration for a dismantling project and easy to be deployed, commissioned and used.
- Is mature in terms of performance, ease of use and safety for dismantling RVI components.
- And is a cost-effective solution in comparison with the conventional cutting tools (to reduce cost and time).

This case study allowed to design, procure, install and commission the complete laser system for in-air and underwater cutting tests. The case study for the demonstrators gathers all the project outcomes, inputs and expectations (from the members of the End User Group). It highlights the main challenges to address with the laser cutting technology and the main answers to provide to the future end users, including nuclear safety management. This set of goals to achieve is the baseline for the development of the demonstrator. To enhance this baseline, an overview of the reference environment and cutting scenarios are made. These items showcase typical constraints to be encountered in actual NPP dismantling worksite. Due to the non-radioactive nature of the mock-ups to be cut, some constraints cannot be considered in the case study. Nevertheless, an analysis has been made to include as much item as possible to ensure the best level of representativeness. With all these elements put together, the goals of the case study are implemented into quantified specifications, and the latter into requirements to perform the two demonstrations.

Development of the demonstrators:

A complete laser cutting system has been developed to comply with all in-air and underwater demonstrator requirements identified during the case study. This system is composed of:

- Two 20-foot containers for the implementation of the laser utilities (the first container contains the laser source, its cooling system, and the main electrical cabinets for the distribution of power and for I&C; the second one is dedicated to the compressed air needed for the laser process). These containers are implemented in a 'utility zone' (located outside the facilities to facilitate the implementation of laser equipment due to lack of space in Nuclear Power Plant).
- The fiber coupler which allows having a physical separation of the fiber between the equipment localized in the nuclear area and those which are not. This coupler is implemented closed to the cutting area (but not in active area) called 'interface zone'.
- Laser HMIs to drive and monitor the laser cutting system safely (implemented in a 'controlled room').
- And finally, the cutting zone for the implementation of the laser head and its umbilical.

Mock-ups was designed in order to challenge the technology by anticipating difficulties expected to arise at the stage of operation. Those difficulties were identified, listed and grouped based on the information found in detailed PWR and BWR plans. A design file was written and included a representativeness note, i.e. a list of similarities and differences between the mock-ups and real internals. Construction was carried out with stainless steel 304 with various parts welded or fixed on a base plate, with dimensions and distances representative of real internals.

This laser system was implemented in representative nuclear configuration we could face in the future decommissioning projects. Indeed, the versatile laser cutting system has been implemented at CEA Marcoule for representative in-air cutting tests and then at ONET Technocenter for underwater cutting tests.

Figure 15. Implementation of the laser cutting system and cutting operation at CEA Marcoule and Onet Technocenter

In regards with both demonstrators, general and realistic cutting scenarios for PWR and BWR dismantling activities with laser have been studied. According to these scenarios, test programs will be elaborated with specific attention drawn to feedback collection. In terms of tests, the main ones were dedicated to:

- The performances of in-air and underwater cutting operation (to improve the cutting duration and the availability rate of the laser system),
- The capabilities and versatility of laser to cut all the most complex RVI configurations,
- The safety aspects for the management of laser beam residual power and secondary waste,
- The assessment of the underwater laser system by providing evidence of its use to answer qualification tasks.

Figure 16. Illustration of in-air and underwater cutting operation during demonstrators

Demonstrator results:

Based on the most complex cutting RVI configurations for PWR and BWR, around 200 cutting tests have been performed on cold-mock ups.

In-air cutting operations has been fully successful as every mock-up had been fully cut. This in-air cutting campaign has proven that:

- Every internal of PWR & BWR can be cut in-situ, i.e. inside the reactor vessel,
- Especially, the upper plate can be cut in-situ: in previous dismantling projects, this piece was removed from the vessel to be cut in a dedicated area, involving heavy handling operations and creation of specific cutting location in the reactor pool,

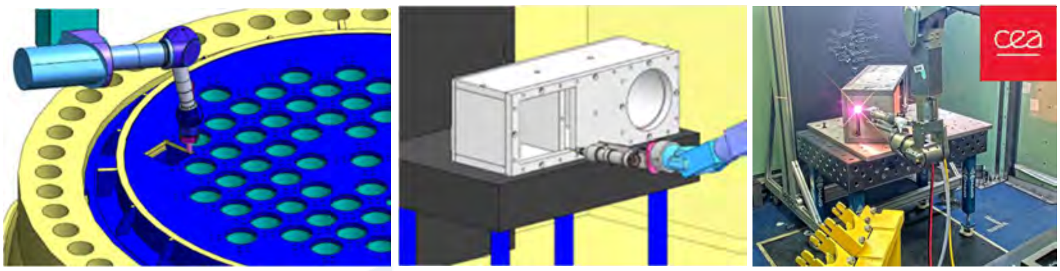


Figure 17. Upper plate mock-up cutting

- Several layers can be cut at the same time thus inducing time savings,

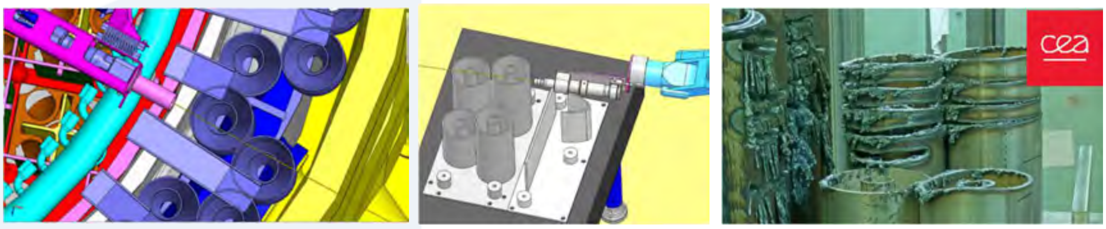


Figure 18. Steam dryer tubes mock-up cutting

And especially:

- Thickness of 100 mm of stainless steel has been successfully cut, which is far more than the maximum thickness of a single piece (68 mm for the upper plate ring),
- Several layers of tubes have been successfully cut, which is a very likely configuration for the dismantling of BWR's steam dryer tubes,
- Successful cuttings with sub-optimal cutting angles have been performed, thus ensuring the congestion inside the reactor vessel isn't an issue for the laser cutting technology,
- Multi-layers cutting operations are possible, for instance in the case of BWR's steam dryer tubes dismantling to increase cutting speeds.

In addition to in-air cutting campaign, underwater demonstrator highlighted:

- All internals can be cut in situ too as for in-air. However, the cutting scenario is different due to the difficult capabilities of underwater tools to perform multi-layers cutting.
- In terms of performance, underwater cutting tests highlighted (in a specific configuration) the capabilities of laser to cut 100mm of stainless-steel plate.
- Laser beam residual power is not a danger for structures (around 50mm) and the workers for a short distance (around 50cm).
- In terms of maturity, underwater laser cutting system is mature and all uncertainties regarding the use of underwater laser cutting with performance, ease of use and safely are solved.

For both environments, in-air concentration of aerosols was measured during all cutting operations to confirm laboratory tests results. Moreover, additional collection & filtrations systems (especially in-air) have been used showing the possibility to catch airborne particles as close as possible to the cutting area. Also, feedback about filters replacements frequency have been collected showing the maintenance needs between in-air and underwater cutting. Finally, laser parameters have been assessed to reduce the impact of laser beam residual power and the generation of secondary waste to ensure safe laser cutting operations as much as possible.

These 2 demonstrators confirmed a TRL7 of laser cutting technology for PWR and BWR RVI dismantling, that the system is easy to use and demonstrated laser system availability rate is higher than 95%.

5. FIRST TECHNICAL WORKSHOP

5.1. Objectives

This first technical workshop aimed to present the main objectives of the LD-SAFE project, our organization and the main activities to the main stakeholders (the members of the Advisory Board) at the beginning of the project.

5.2. Sequence

Due to the Covid-19 pandemic, the first Technical Workshop has been held in two steps:

1- A technical workshop with the members of the Advisory Board already involved in the LD-SAFE project (End User Group, Expert Group and Support Group).

   This workshop was held by videoconference (webinar) the 09th of December 2020.

2- An additional workshop to present LD-SAFE and the progress to the public.

   This public workshop took place physically at WNE 2021 (in Paris) the 1st of December 2021.

5.3. Technical Workshop with the Advisory Board (Webinar)

Presentation: this first technical workshop has been performed only with the stakeholders (already involved) of the project (not open to the public because confidential data was included in the presentations shared with the participants).

Participants:

- LD-SAFE Consortium: ONET TECHNOLOGIES, CEA, IRSN, EQUANS, Westinghouse (formerly TECNATOM) and VYSUS GROUP.
- Expert Group: ALPHANOV / PYLA, DSRL, EDF (DP2D) and GRS.
- End User Group: Bel V, DSRL, EDF (DP2D), ENGIE, GRAPHITECH, IGNALINA NPP, JAEA, KTE, LEI, SCK CEN, SOGIN.
- Support Group: VTT.
- European Commission: the Project Officer.

Program/Sequencing:

1- <u>Introduction</u>

   a. Welcome to all participants

b. Webinar introduction (program and interactions with the Consortium)

c. Presentation of the LD-SAFE Project Coordinator (Onet Technologies) and the Project Officer (European Commission)

2- <u>LD-SAFE project and objectives</u>

a. Introduction (context and LD-SAFE project)

b. Objectives (focus and Global ambition)

c. Organization (main information, stakeholders and Advisory Board)

d. Main activities (overview, Work Packages and methodology)

e. Next steps

3- <u>Challenges of reactor components segmentation with conventional techniques</u>

a. Introduction of the Work Package 1

b. Conventional cutting techniques (introduction and overview of common techniques)

c. Reactor components (introduction, BWR and PWR, characteristics, difficulties/challenges)

d. Conclusion

4- <u>Introduction to laser technology</u>

a. Principle of laser cutting

b. Tools development and cutting performances

c. Technology implementation

d. Decommissioning experience and feedback

e. Application to reactor dismantling

5- <u>Presentation of the main technical aspects of the Work Packages 3 and 4</u>

6- <u>Generic Safety Assessment and independent review</u>

a. Generic Safety Assessment Objectives (and timeline)
b. Methodology
c. Independent review

7- <u>Questionnaire</u>

a. Introduction (reminder)
b. Objectives (expectations)

c. Structure (questionnaire)
d. Information (instructions)

8- <u>Webinar closing</u>

a. Greetings to all participants

b. LD-SAFE communication

Duration: 2 hours.

Interactions during the webinar:

- Polls (with multiple choices) launched during the webinar:
    - How many laser cutting applications are currently used in the industrial field?
        - 1 000
        - 10 000
        - 25 000
        - 50 000
        - ⇨ *Answer: today, there are over 25,000 high-power laser cutting applications in the industry.*
    - Based on your experience (or your perception if you have no experience) what is the most widely used cutting technique for dismantling RPV/RVI?
        - Mechanical cutting
        - Thermal Cutting
        - Water jet Cutting
        - ⇨ *Choice the most used from the participants: mechanical cutting.*
    - What are the key technical criteria for Safety Authorities to allow the use of any cutting technology in a given decommissioning project?
        - Ability to be remotely operate
        - Limitation of radiation exposure
        - Minimization of generated waste and discharges
        - Reliability and safe maintainability
        - Compliance of generated waste with packaging, transport and storage
        - ⇨ *Choices the most used from the participants:*

- Limitation of radiation exposure

- Minimization of generated waste and discharges

- Reliability and safe maintainability

- Main questions asked on the chat and answers (from the Consortium) provided during the webinar:
    - RVI and RPV segmentation contracts have already been awarded and some already completed. Did one of the project partners already proposed the laser technology for such operation, and if yes why it has never been implemented?
        - Up to now, from the few segmentation call for tender (for Power Nuclear Reactor), none was opening the possibility to use laser as a cutting technique. When discussions were made to see whether laser could be accepted, the answer was no. Because the technology has already been selected before the tender phase, and was included in the preliminary safety reports with difficulties to be changed afterwards. That's why the LD-SAFE project will prepare and deliver a generic safety assessment to allow the use of laser cutting technology in the forthcoming Power Reactor decommissioning programs.
    - What about saw cutting dust / particles to recover, and secondary waste. Is that also looked at in assessing the different techniques?
        - During the analysis of all the conventional cutting techniques, identification of the benefits and the drawbacks regarding secondary waste has been done (for Band Saw Cutting, Plasma Arc Cutting and Abrasive Water Jet Cutting). The objective is to perform a quantitative comparison of these 3 cutting techniques (which will be useful to compare with laser cutting technology).
    - Are there any data on the resistance of the optical fiber laser and the laser head to radiation? Has the radiation hardness of the fiber optic transmitter been tested?
        - During past decommissioning activities (for instance: the dismantling of the dissolver A of UP1 at CEA Marcoule), no damages have been detected (regarding radiation) on the laser head and the optical fiber (included in an umbilical).
    - How will the end users be involved for the boundary conditions definition?
        - The generic safety assessment should be designed to be easily applicable to an existing nuclear facility. At this stage of the project (first steps), the End Users boundary conditions are not yet included in the generic safety assessment process (for the moment). However, the main boundary conditions from the End User Group will be taken into account in our studies (through questionnaires sent to the End User Group).

Replay:

This webinar has been recorded. The replay has been provided to the participants after this first Technical Workshop.

Key figures:

- Subscribers for the webinar (including speakers): 44
- Attendees (including speakers): 39
- Participation rate: 89%
- Number of rates: 16
- Average rate: 4.5/5

Questionnaire:

Following the first TW (webinar) performed in December 2020 with the stakeholders, LD-SAFE questionnaires have been sent to the EUG members.

The objective is to collect feedback about:

- Their experiences in implementing different remotely operated technologies for the cutting of highly radioactive material (especially regarding safety, radiation protection, waste, cost and time aspects)
- Their comparison of dismantling technologies (for instance about cutting, implementation of the technology, necessary resources, the collection of waste, etc.)

This feedback will be used to:

- Confirm the information gathered and assessed under WP1 and complete gaps in respect with input data
- Identify the End Users expectations about Laser Technology
- Respond to End Users issues as part of the project
- Ensure that:
    - The project starts with the right quality of input data to achieve the targets (and if necessary, by adjusting first deliverables)
    - The project is aligned with the market reality

As inputs, all questionnaires' results (confidential data) will be used in the technical activities of the LD-SAFE project. The blank version of this questionnaire is available in annex.

5.4. Technical Workshop with the public (at WNE)

Presentation: presentation shared to the public during the workshop in December 2021 (at WNE, in Paris). This presentation is available in annex.

Participants: around 40 people participated at this event (including the people who followed this presentation by videoconference).

Program/Sequencing:

1- Welcome & LD-SAFE presentation:
   a. LD-SAFE project
   b. Laser cutting technology
   c. Safety aspects of the project
2- Exchanges (Q/A) / Networking
   d. Discussions about the objectives of the project and our expectations, but also about the laser cutting techniques, our experience with the use of this technology and its advantages.
   e. Presentation of the laser heads (developed by CEA) and the various samples cut with this technology at CEA stand.

Duration: 1 hour.

Replay: this public presentation has been recorded and shared on the LD-SAFE project website: https://ldsafe.eu/ (see news & events tab).

Figure 19. Public presentation of LD-SAFE during the 1st Technical Workshop (at WNE 2021)

5.5. WP2 to WP5 presentations

Presentation: an additional workshop (by videoconference; 2 sessions in March 2022) have been performed with the members of the Expert Group and End User Group to present the project progress of the WP2 (to WP5) to bring us more confidence about the technical execution of the project. It was also the occasion for all partners to express their new feedback/expectations and ask some questions to align the technical content of their tasks.

Participants:

- LD-SAFE Consortium: ONET TECHNOLOGIES, CEA, IRSN, EQUANS, Westinghouse (formerly TECNATOM) and VYSUS GROUP.
- Expert Group: DSRL and GRS.
- End User Group: Bel V, DSRL, GRAPHITECH, IGNALINA NPP, KTE, LEI, Belgoprocess.

Program/Sequencing:

<u>On March, 08th 2022:</u>

1- Introduction
2- WP2 – Laboratory trials and calculations & technical exchanges on TEAMS chat.
3- WP3 – Protection of the workers and environment & technical exchanges on TEAMS chat.
4- Greetings / end of the technical session

<u>On March, 15th 2022:</u>

1- Introduction
2- WP4 – Safety assessment & technical exchanges on TEAMS chat.
3- WP5 – Case studies / Demonstrator & technical exchanges on TEAMS chat.
4- Greetings / end of the technical session

Duration: 1 hour per session.

Interactions during the webinar: main questions asked on the chat and answers (from the Consortium) provided during the webinar:

Laser beam residual power:

o How do you explain there is no effect on the background surface during underwater cutting?

During underwater cutting, and in particular during the approach phase, we don't see damage during this phase due to water absorption (in link with the limited length of the dry cavity).

o Do you try to establish and qualify a physical model for assess the effect on background in different situations?

A physical model to assess and predict the effect on background is under study, but not in the framework of the LD-SAFE project.

o Do you try any "angular" strategy during the approaching phase in order to mathematically increase distance between sample and background ?

CEA haven't tried yet any angular strategies, maybe later. This will also have an impact on the thickness of the sample to be cut. There are better strategies to reduce the impact of residual power such as for example: using less power during the approach phase, and once the sample edge is detected increase the power.

Case study / Demonstrator:

o What is the maximum distance of fiber between the laser source and the laser head?

With TRUMPF laser manufacturer, the maximum length of one fiber is 100m. By using a laser coupler, you can connect two fibers and having a maximum length of 200m (2x100m).

o Concerning the number of graphite reactors in European community, graphite reactors (including french UNGG, MAGNOX, AGR, RBMK) are more than 50.

Today, the LD-SAFE project is focus on the PWR and BWR. However, laser technology can be a solution for the other reactor technologies.

o Do you plan to represent the environment of the piece to cut, I mean the closest piece with the real interval?

A cutting scenario have to be done to identify all the constraints (distances of the laser head and the piece to be cut, accessibility, angle of attack) and to be focused on the most complex configurations.

o Maybe the question of close environment can be simulated using of line programming software to deal with the accessibility (if it is the issue)?

Indeed, that is a solution too.

Replay: This webinar has not been recorded.

Participants: 20 per session.

Questionnaire:

Following this additional TW (webinar) performed in March 2022 with the stakeholders, new LD-SAFE questionnaires have been sent to the EUG and EG members (as indicated above).

As inputs, all questionnaires' results (confidential data) have been used in the technical activities of the LD-SAFE project. The blank version of this questionnaire is available in annex.

6. SECOND (AND FINAL) TECHNICAL WORKSHOP

6.1. Objectives

The second technical workshop aimed at disseminating the results of the project both to the Advisory Board, industry, operators, academics, TSO and RTO.

6.2. Sequence

This end technical workshop was scheduled in two days:

1- The first one was dedicated to the presentation of all technical results of the project. All the main LD-SAFE stakeholders, RTO, TSO, industrials and operators were invited. During this day, a visit of underwater demonstrator including in live underwater cutting operations on RVI representative mock-ups was performed to show the performances, the ease of use and safety aspects. This F2F workshop was done the 30th of May 2024 at Onet Technocenter.

Figure 20. End Technical Workshop (day 1) at Onet Technocenter with the main stakeholders

2- The second day had the same sequence, but the results were presented through poster sessions for the students & young graduates. In addition, brief parts of the final training courses were presented to aware the future workforce of the nuclear decommissioning field. This face-to-face workshop was done the 31st of May 2024 at Onet Technocenter.

Figure 21. End Technical Workshop (day 2) at Onet Technocenter with students and young graduates

6.3. 1st day Workshop – Stakeholders, RTO, TSO, industrials, operators

Participants (organizations represented):

- European Commission
- Onet Technologies and its consultant
- EDF (DP2D)
- GRAPHITECH
- CEA (Marcoule, Saclay and Cadarache)
- IRSN
- DSRL
- MAGNOX
- EQUANS
- ENGIE
- Belgoprocess
- Bel V
- Framatome Germany
- GRS
- Westinghouse (France and Spain)
- ENRESA
- Vysus Group
- PYLA/ALPHANOV
- STAUBLI
- TRUMPF

<u>Note:</u> some members of the Advisory Board couldn't attend the End Technical Workshop (due to unavailability in link with vacations, workload and travel restrictions) although they were invited and well involved in the project since the beginning (1st technical workshop, questionnaire phases, general assembly meetings, etc.).

Program/Sequencing:

- Introduction (Onet Technologies & European Commission: Seif BEN HADJ HASSINE as Project Officer)
- Key relevant applications of laser cutting technology in the decommissioning market (Onet Technologies)
- Decommissioning challenges with laser cutting technology (EQUANS)
- Laboratory trials for safety purposes (CEA & IRSN)
    - Laser beam residual power (CEA)
    - Hydrogen gas generation during underwater laser cutting (CEA)
    - Secondary emissions – Aerosols (IRSN)
- Laser Technocenter Visit Tour & Underwater laser cutting demonstrations (Onet Technologies)

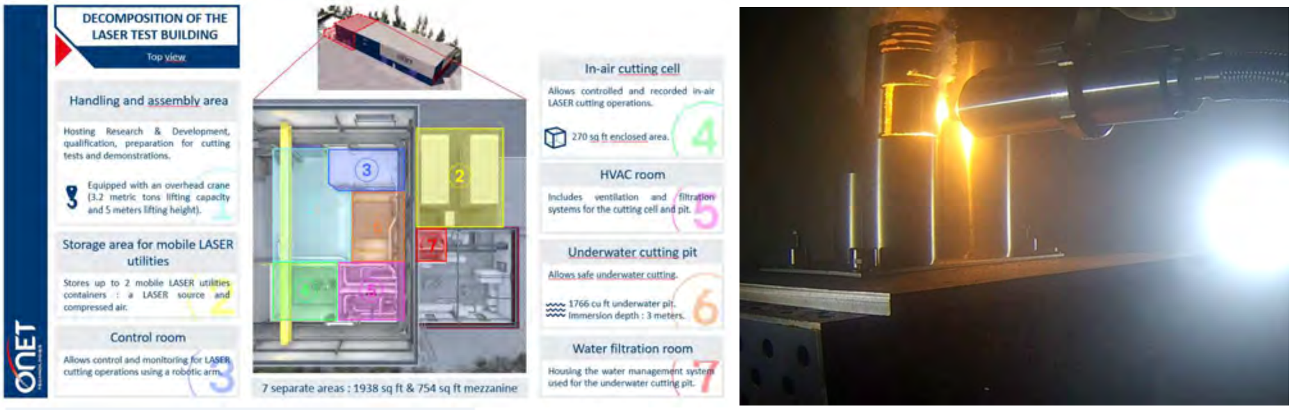


Figure 22. Onet Technocenter map and underwater cutting operation

- In-air & underwater demonstrator results (Onet Technologies)
- Safety assessment, independent review & recommendations (WESTINGHOUSE & IRSN)
- Qualification of laser cutting technology & guidelines for the use in reactor environment (Vysus Group)
- Next steps: future applications and R&D efforts to address commercial reactors decommissioning with laser (EDF)
- Wrap-up (Onet Technologies & European Commission: Seif BEN HADJ HASSINE as Project Officer)

Duration: 1 day.

Number of participants: around 70.

Presentations: public technical presentations are available in annex.

6.4. 2nd day Workshop – Students & young graduates

Participants (organizations represented):

- Onet Technologies and their students/young graduates
- Université de Nîmes
- INSTN
- IRT
- CEA (Marcoule & Saclay)
- IRSN
- EQUANS
- Westinghouse (Spain)
- Vysus Group
- InnoDURA
- MSD
- ACETT

Program/Sequencing:

- Laser Technocenter Visit Tour & Underwater laser cutting demonstration (ONET Technologies)
- Training courses & Serious Game (WESTINGHOUSE & CEA)
- Poster sessions (LD-SAFE activities)
- Wrap-up & closing (ONET Technologies)

Duration: 1 day.

Number of participants: around 70.

Training courses: technical content is available in annex.

6.5. Summary of the end technical workshop

Euratom program (Seif Ben HADJ HASSINE - European Commission): as introduction of the day, the European Commission delivered a quick overview of the ongoing R&D projects of the Euratom program. About LD-Safe, after a remind of the context, the LD-SAFE project officer said that, view from his office in Brussels, the project is going perfectly. This project had an industrial aim which was completed; therefore, there is no direct follow-up. However, a synergy could emerge with other topics / projects at the next call.

Laser cutting technology in the decommissioning market (Damien ROULET - Onet Technologies): after a brief introduction about the origin of the LD-Safe project, the Coordinator indicated that though about 25000 cutting by laser are used in industry since the origin of laser, very few have been achieved in the nuclear sector. Today, the performances of laser cutting in air and under water are already quite satisfactory and should be improved with the power of lasers which increases each year. The laser enables several constraints to be satisfied: cost reduction, safe for the workers and environment, reduction of risks, planning optimization. Moreover, this technology is faster than others. As examples, he showed 3 on-going projects in which Onet Technologies is involved. In conclusion, he mentioned a number of outcomes from LD-Safe: expansion of laser acceptability, new applications, worldwide interest about laser cutting.

Decommissioning challenges (Anton NULENS - EQUANS): as dismantling operator, EQUANS reminded the constraints of nuclear cutting in particular for RPV/RVI and showed the comparison of laser cutting with conventional cutting technologies. Moreover, EQUANS emphasized the most challenging configurations for which laser could be an asset.

Residual power (Lucas BRIZZI - CEA): after a quick introduction of the physical process, and its consequences, CEA presented the tests performed and the results. In conclusion, he made some recommendations for the use of laser cutting in real situations.

Aerosol characterisation (Stéphanie ALAGE - IRSN): IRSN reminded what aerosols are and what are the associated risks. Then, IRSN presented the tests carried out and the results obtained from which they drew some important conclusions:

1) a pool scrubbing of 1m depth reduces by a factor of 2 – 3 the mass generation of aerosols;
2) Steel 304 produces more aerosols than steel 316;
3) Chemical compositions of aerosols depend on the cutting conditions.

Hydrogen generation during underwater cutting (Ioana DOYEN, Pascal PILUSO and Serge PASCAL - CEA): after a remind of laser cutting underwater, CEA presented the tests carried out. They succeeded in cutting 80 mm of 304L stainless steel. CEA finally gave a number of concluding remarks among them it can be noted:

1) Cutting in nitrogen atmosphere is 10 times slower than cutting in air;
2) Instabilities were observed at laser power > 10 kW;
3) H_2 generation occurs mainly at the beginning of cutting (a peak is clearly observed); this peak could be due to oxidation;
4) H_2 generation increases with laser power.

In addition, CEA presented the physicochemical analyses which provide insights that help to understand the mechanism of H_2 generation. Moreover, from these tests, CEA developed a model which can provide an envelope of H_2 generated.

Demonstrator (Pierre DAGUIN & Virasay SOUKPHOUANGKHAM – Onet Technologies): Onet reminded the audience that this part of the project aimed at demonstrating that laser cutting technology is mature for nuclear cutting in air and under water. About 200 cutting tests were performed in various conditions and positions for several samples, including the most challenging ones. The results obtained showed globally a very high efficiency and very good performances in several criteria: cutting speed, ease to use, cost and time, versatility, compliance with safety and regulatory safeguards. These tests showed also that:

- It was not possible to cut several layers underwater in one pass (but possible in-air);
- Aerosols generation is lower than with plasma cutting;

These tests allowed an estimation of secondary waste generated by the process.

Also, Onet showed several important features of laser cutting technologies that were clearly confirmed by the demonstrating tests:

- Cost and time of operation are reduced in comparison with common cutting tools used in decommissioning;
- Risks are also reduced in comparison with other system available on the market.

Onet concluded that the system, as it was developed through the LD-Safe project, which is a robust one, can address any project of dismantling in the EU (and likely worldwide).
To complete these technical presentations, a visit tour of Onet laser technocenter has been done showing the main features of the laser system developed in the frame of LD-SAFE project. It was also the occasion to show real underwater cutting operations to the participants.

Safety assessment (Jesus RUIZ – Westinghouse and Xavier MASSEAU – IRSN): Westinghouse reminded that the objective of this task was to demonstrate that laser cutting technology is, at least, as safe as the best technique currently used. Then, following the process recommended by IAEA, Westinghouse showed the aim was reached.
This was confirmed by an independent review made by IRSN.

Qualification of laser cutting technology and guidelines (Timmy SIGFRIDS – Vysus Group): based on the successful completion of all activities, a Technology Qualification Certificate has been delivered by Vysus Group. Moreover, Vysus presented guidelines which were developed to support end-users of laser cutting technologies in nuclear dismantling.

Overview of EDF decommissioning projects: Through this presentation, EDF shared its opinion, as end-user, on laser cutting technology.
Laser cutting technology is a new innovative technology that could present some advantages for decommission EDF facilities. Because each site has its own specificities, it is needed to adapt the process. He showed the status of decommissioning / dismantling of several NPPs in France of various types: PWR (Chooz, Fessenheim), Graphite-gas (Chinon, Saint Laurent des Eaux), Heavy water (Brennilis), RNR (Creys Malville). He finally underlined the future needs for which laser cutting could be one of the most interesting technologies. In conclusion, he mentioned that, thanks to LD-Safe, laser cutting is already used by EDF for the dismantling of Brennilis, Creys Malville and graphite-gas reactors.

Training courses: because the aim of LD-SAFE is also to promote laser cutting technology to the future workforce of the decommissioning market, schools, students, and young graduates were invited to visit Onet laser technocenter and see the complete mature laser system developed and used in the frame of the LD-SAFE project. Laser cutting experiments were done underwater. In addition, training courses were presented to the students to provide awareness about what are the decommissioning projects at this moment and how laser cutting technology can improve them technically and economically. In addition to the training content, a simulation tool developed by CEA (Serious Game) was presented to show what are the main laser parameters to be managed during cutting operations and what are the consequences of their definition.

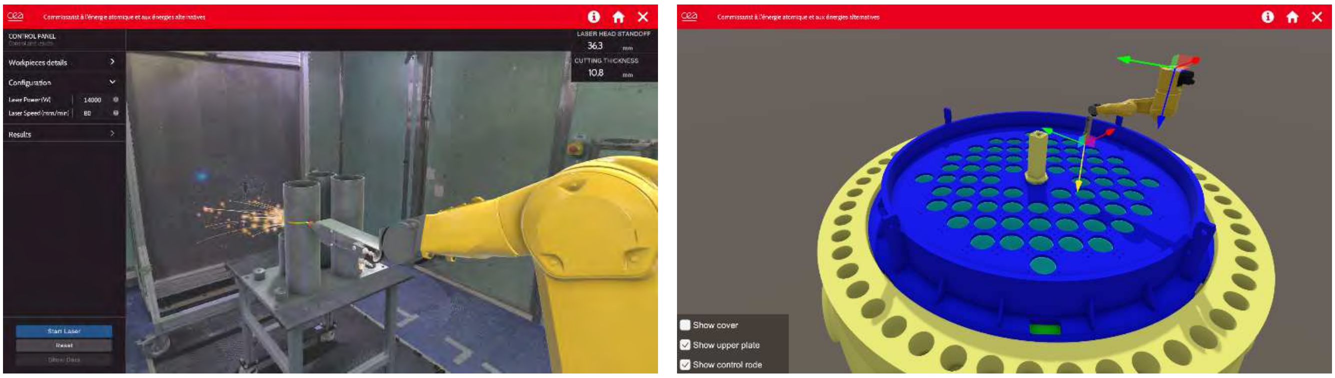


Figure 23. Serious game on the laser cutting process

This serious game was initially developed by CEA in association with an e-learning module to raise awareness of the use of laser cutting for D&D projects[1]. As part of the final workshop for the LD-SAFE project, 2 scenes have been added (Figure 23). The first shows the in-air cutting tests carried out for the project at CEA Marcoule's HERA facility. The second shows a PWR reactor, highlighting the various elements that were cut during the LD-SAFE cutting tests.

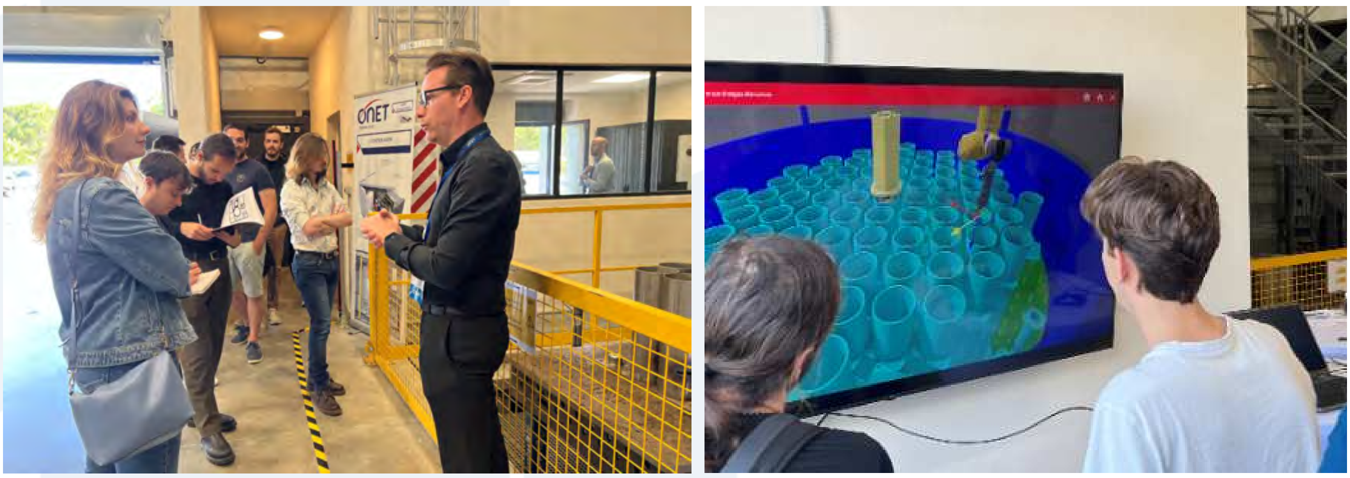


Figure 24. Technical exchanges with students

[1] Testard, V., Clery, L., Perrot, V., Doyen, I., Favrichon, J. How serious games coupled with e-learning methods can provide a basis for training operators in technical concepts: an example with laser-cutting process for nuclear worksite dismantling operations. DEM 2024-Dismantling Challenges: Industrial Reality, Prospects and Feedback Experien.

Questions and discussion: This workshop was the occasion to raise some questions and discuss some issues:

- Comparison or benchmark with other cutting technologies; A better efficiency of laser cutting was demonstrated for several criteria.
- Increase of cutting speed and efficiency with laser power; Laser power is regularly increased but its use is also a question of cost and effectiveness.
- Influence of power distribution in the laser beam;
- Effect of nuclear ageing on material cutting; In the project, only stainless steels were cut but in other framework, cutting of other materials such as ceramics was demonstrated.

7. CONCLUSION

To facilitate the implementation of laser cutting technology in the European decommissioning market, LD-SAFE project highly contributed to share outcomes to the future end users of this technology and to the public.

Indeed, a part of the studies and tests carried out (which include a part of knowledge) have been transferred to the End-users and Public which allow a reduction of the future effort for any customers who could be interested in using the promising laser cutting technology. Indeed, important data have been openly shared through LD-SAFE communication materials. The main stakeholders of the project such as the End User Group and Expert Group members had also access to some confidential data to increase their acceptance on this cutting technology.

The start of the project began with an analysis of the different reactor components to be dismantled in combination with the selection of conventional cutting techniques. This work had for objective to present the most common cutting tools for cutting PWR and BWR reactor internals and building of a database in order to compare them with laser cutting. This comparison highlighted the key challenges to be checked during the LD-SAFE tests in laboratory conditions and for the demonstrators. The related results highlighted the main risks to be addressed in the safety demonstration such as laser beam residual power, secondary emissions and dihydrogen gas generation for underwater cutting.

Based on these results, a Generic Safety Assessment has been developed (and reviewed independently), in consistency with IAEA International Safety Standards, for the implementation and the use of laser cutting technology for the dismantling of reactor pressure vessel and internals (with the aim of being easily adaptable to the specific conditions of end users and reduce the associated licensing effort).

To support the implementation of laser cutting techniques, specific guidelines for the use of laser cutting in reactor dismantling environment (in-air and underwater) have been elaborated which incorporates all LD-SAFE lessons learnt to provide to future end users an overview of how to use lasers correctly, safely and efficiently in decommissioning activities for PWR and BWR nuclear reactors.

Also, a technical validation report which summarizes the main demonstrator's results has been established to show in-air and underwater cutting operations on representative mock-ups of PWR and BWR internals (and highlight the compliance with the Generic Safety Assessment recommendations). This report highlights the maturity and efficiency of the technology by providing evidence of safe implementation and use of laser cutting technology on-site.

And finally, education and training report has been developed to compile and transmit the best practices and knowledge of the use of laser cutting technology in decommissioning of nuclear facilities, in particular the dismantling of the RPV and RVI. In addition, online courses on cutting technologies are available in an online platform to integrate LD-SAFE project results, lessons learned, and experiences, and the state of the art of the laser cutting technology as a cutting tool and its comparison with conventional technologies. This pursues two goals: capacity building of trainees and dissemination of project objectives and results.

Before the end of the LD-SAFE project, laser cutting technology have been already identified as a selected tool for future decommissioning activities, in particular for the French Market. Laser cutting technology is not just recognized at European scale but also Worldwide (many organizations are interested in laser cutting technology state of the art for the preparation of the next dismantling projects; and not just for PWR and BWR scope).

Economically, an investment on laser is more interesting in comparison with mechanical tools (which are the most used in Europe). Moreover, as regards time assessment between laser and mechanical tools, laser will allow to reduce dismantling schedule.

Upon completion of LD-SAFE project, the suitability of the laser cutting technology to address the challenges of the dismantling Nuclear Power Reactor and its capability to improve these projects in respect of safety, radioactive waste, time and cost has been confirmed on the basis of the demonstrators and the other project outputs as the Technology Qualification and the Generic Safety Assessment. Laser cutting technology is not just a promising cutting technique but already a proven technique (TRL7) through all evidence provided during the LD-SAFE project and thanks to all laser projects carried out in parallel at Onet Technologies.

Societally, this craze should make it possible to create new jobs, for instance laser experts and operators for the next decades of the nuclear decommissioning market. The laser product definition and its supply chain are already defined (laser system will become more robust over the time by increasing the knowledge about laser cutting technology in Europe).

To conclude, this project proposed an innovative and integrated approach including laboratory tests, technical development, safety assessment and economical aspects, with the aim of enhancing one of the most challenging tasks of Nuclear Power Reactor dismantling. The results obtained during the project as well as the Technology Qualification Certificate and the guidelines prove that the objective was reached; laser cutting technology is no more a promising technique for nuclear decommissioning, it is a proven, safe and qualified technique. The work done within LD-Safe project will continue to support European nuclear field in remaining a step ahead in the development of this technology aiming to achieve a world first laser dismantling of a Nuclear Power Reactor.

8. ANNEX

8.1. EUG questionnaire (blank version)

LD-SAFE

Laser Dismantling Environmental and Safety Assessment

QUESTIONNAIRE

End User Group

Number of Pages: 22

Distributed to: End User Group (Advisory Board)

A	21/12/20	Initial version
Revision	Date	Description of Changes
P. DAGUIN	D. ROULET	D. ROULET
Written	Reviewed	Approved

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1. SUBJECT OF THE DOCUMENT

1.1. Introduction

This document corresponds to the LD-SAFE 'Questionnaire' to fill in by members of the End User Group (Advisory Board). The scope is Reactor Pressure Vessel and its internals.

1.2. Objectives

The objective is to collect feedback about:

- Their experiences in implementing different remotely operated technologies for the cutting of highly radioactive material (especially regarding safety, radiation protection, waste, cost and time aspects)
- Their comparison of dismantling technologies (for instance about cutting, implementation of the technology, necessary resources, the collect of waste, etc.)

This feedback will be used to:

- Confirm information we already have in our first WP1 deliverables and complete gaps in respect with input data
- Understand what End Users can expect about Laser Technology
- Respond to your issues as part of the project
- Make sure:
    - We start the project with the right quality of input data to achieve our target (by adjusting our first deliverables)
    - We are aligned with the market reality

1.3. Structure

This questionnaire is divided in 3 parts:

- Global questions including multiple choice questions with an area dedicated to comments
- A datasheet focused on complex reactor components. It includes specific criteria: physical and radiological characteristics, environment of the component, segmentation and waste management processes. You will mention the name of the component you consider as complex to cut and indicate your data, comments and expected improvement with the laser technology (if any).
- A technology comparative analysis focused on 3 conventional technologies (Mechanical Cutting which includes Band saw/disk grinder/Milling cutter, Abrasive Water Jet Cutting and Plasma Arc Cutting). In this part, you will indicate your experience/feedback for these conventional technologies regarding different aspects: Feasibility and suitability, Safety, Performances / Key

factors, and waste. You will also indicate your data which represents the state of the art for each cutting techniques (if any). Finally, you can have the possibility:

- To do an overall appraisal of each cutting technique by indicating the main advantages and drawbacks.
- To indicate your expectations regarding laser technology (the benefits but also the drawbacks).

1.4. Instructions

How to fill in the questionnaire?

- The questionnaire can be filled in digitally (in this Word version).
- Instructions will be specified for the 3 parts.
- Your experience depends on your own organization. **You will not be able to answer all the questions/criteria**. This is the complementarity of all questionnaires which will help us.
- If you have documents that can directly answer to some questions of the questionnaire, you can send them to us (if it is possible).

Confidentiality of data:

- The questionnaires filled in will not be shared between all End Users.
- All data you consider as confidential has to be indicated in red in the questionnaire.
- Signing a Non-Disclosure Agreement is required.

2. QUESTIONNAIRE

2.1. Global Questions

Instructions:

The following questions concern dismantling activities of nuclear power reactors internals (RVI) and pressure vessels (RPV).
If you consider a question not applicable to your organization or not relevant, please indicate N/A or N/R

GLOBAL QUESTIONS

Q1

Do you think dismantling RPV/RVI represents a cutting challenge in decommissioning programs?

☐ Yes
☐ No

Comments (if any):

Q2

Have you ever considered using laser technology for dismantling RPV/RVI?

☐ Yes
☐ No

If not, why?

Q3

Based on your experience and/or knowledge (or your perception if you have no experience) what is the most widely used cutting technique for dismantling RPV/RVI?

☐ Mechanical cutting
☐ Thermal Cutting
☐ Water jet Cutting

According to the cutting technique chosen, which tool is the mostly used (**circle your answer**)?

Mechanical cutting: Shearing - Sawing - Grinding - Blasting - Milling.

Thermal cutting: Oxygen cutting - Plasma Arc Cutting - CAMX-Processes - Laser Beam Cutting.

Water jet Cutting: Abrasive Water Injection Jet (AWIJ) - Abrasive Water Suspension Jet (AWSJ)

Q4

What is your preferred cutting environment to dismantle RPV/RVI?

☐ In air
☐ Underwater
☐ Both In air and Underwater
☐ Not yet decided

If not yet decided, why?

Q5

How many cutting tools and handling systems do you use (or intend to use) for dismantling RPV/RVI (in average)?

Number of cutting tools (if you intend to use 2 different tools from a same technology, please count each of them):

Number of handling systems (crane, manipulator, pole, bespoke mechanical systems, etc.):

Number of back-up systems:

Q6	**According to your experience or knowledge, what are the key technical criteria for Safety Authorities to allow the use of any cutting technology in a given decommissioning project?**
	Key criteria for Safety Authorities (the choice can be multiple): ☐ Ability to be remotely operate ☐ Limitation of radiation exposure ☐ Minimization of generated waste and discharges ☐ Reliability and safe maintainability ☐ Compliance of generated waste with packaging, transport and storage Other:

Q7	**What are your main constraints / difficulties in your dismantling activities?**
	☐ Cutting environment (in air or underwater) ☐ Accessibility of tools and/or handling systems (for cutting) ☐ Control and monitoring of the operations (e.g. moving the system remotely, visualizing the operation, etc.) ☐ Space needed to implement the tools and their utilities in controlled area ☐ Maintenance and replacement of spare and wear parts ☐ Filtration / dust and fume collection ☐ Radioprotection and safety of the workers ☐ Coactivity Other:

Q8	**What are the most impactful steps about cost and time?**
	☐ Studies/Design/segmentation plan ☐ Manufacturing/Testing/Operators Training ☐ Installation/Commissioning ☐ Cutting operations ☐ Maintenance (preventive and corrective) ☐ Waste management ☐ Protection of workers / safety aspects Other:

Q9	**According to your experience or knowledge, what is the most complex component to cut (for PWR / BWR)?**
	Regarding its physical/radiological characteristics, environment, waste generation, cost and time operation (several components possible) To list (if possible): Can you provide us an example of datasheet? ☐ Yes ☐ No

Q10	**According to your experience or knowledge, which steps represent a challenge for reducing dismantling cost?** ☐ Cutting duration ☐ Operation and Maintenance costs (including consumables) ☐ Corrective maintenance costs (troubleshooting, repairs) ☐ Number of tools and handling systems ☐ Implementation of the cutting system (as a whole) / space available ☐ Drying (of the segmented components) ☐ Waste characterization and packaging ☐ Waste logistics (handling, interim storage, transport) ☐ Human resources Other:
Q11	**How do you carry out the secondary waste collection for each cutting technology used (in air and underwater)?** Provide some examples: Examples: - Cutting chips: underwater pumping or in-air vacuuming + filtration - Dust (in air): local collection by vacuum system + filtration / containment with general HVAC - Sludge (underwater): local collection by suction system + filtration / global water treatment system
Q12	**According to your experience or knowledge, what is the duration (ratio) of cutting operation compared to other operations (handling, cleaning and decontamination)?** Approximately:
Q13	**In addition to the radiological spectrum, total activity and dose rate, are you aware about other limitations for the transportation of nuclear waste coming from RVI/PRV decommissioning (Type B Packages for ILW waste)?** ☐ Absence of liquid (drying needed) ☐ No mobile piece/dust ☐ No filtering media (other than metal) ☐ Each single item must be characterized separately Other:

2.2. Datasheet – Reactor component (RPV/RVI)

Instructions:

The objective of this datasheet is to focus on the most complex component(s) to cut in the scope of Reactor vessel internals (RVI) and pressure vessels (RPV) following several criteria:

- ***Physical characteristics***
- ***Radiological characteristics***
- ***Environment of the component***
- ***Segmentation and waste management processes***

In order to fill in correctly this datasheet, please find below the instructions.

*1-In link with the **Question 9** of the Global Questions, please indicate the **name of the component** you consider the most complex to cut in the table.*

*2-If you have data to provide us, please complete the '**DATA**' and '**COMMENTS**' columns for each criterion. Also, we will have the possibility:*

- *To indicate your main comments regarding each criterion*
- *To propose additional criteria (if any) which you consider important and which should be taken into account in the LD-SAFE project (**available cells**)*
- *To provide us your own datasheet of this component*
- *To leave the cell empty if you don't have information regarding specific criteria*

*3-You can also mention if a specific challenge connected to these criteria could be solved by the laser technology or if an improvement is expected ('**EXPECTED IMPROVEMENT WITH THE LASER TECHNOLOGY**' column). In this column, you can also indicate expected benefits but also the drawbacks.*

*4-In each column, if the information is confidential, please indicates it in **red color**.*

5-if you consider doing the same exercise with other components, please do copy-paste the table below in this document (as often as necessary).

Datasheet - Reactor component (RPV/RVI)

Component name:

CRITERIA	IMPORTANCE	DATA	COMMENTS	EXPECTED IMPROVEMENT WITH THE LASER TECHNOLOGY
Physical Characteristics				
Global appraisal:				
Material / Combination of different materials if any	*Impact on cutting technology* *Impact on secondary waste (oxides, dusts, etc.)* *Presence of mix of material (e.g. sandwich) can be challenging*			
Thickness (min - max)	*Impact on cutting performances*			
Geometry description (external dimensions and shapes)	*Impact on cutting sequence*			
Volume description (e.g. hollow parts ?)	*Impact on cutting technology*			
Available cell (to add criteria if necessary)				

Datasheet - Reactor component (RPV/RVI)

Component name:

CRITERIA	IMPORTANCE	DATA	COMMENTS	EXPECTED IMPROVEMENT WITH THE LASER TECHNOLOGY
Radiological Characteristics				
Global appraisal:				
Specific Activity [Bq/kg]	*Some high-irradiated components are difficult to cut mechanically (radiation hardening)* *Activity of secondary waste (chips, swarf, dust, slag)* *Impact on Dismantling and Waste Management Strategy*			
Dose Rate (specifying the distance from the component and the environment, i.e. in air or underwater)	*Potential impact on tools* *Impact on Dismantling and Waste Management Strategy*			
Presence of surface contamination (loose or fixed and specifying whether the component was decontaminated, e.g. by Full System Decontamination)	*Resuspension in the environment*			
Available cell (to add criteria if necessary)				

Datasheet - Reactor component (RPV/RVI)

Component name:

CRITERIA	IMPORTANCE	DATA	COMMENTS	EXPECTED IMPROVEMENT WITH THE LASER TECHNOLOGY
Environment of the Component during segmentation				
Global appraisal:				
Accessibility (available area to access the cutting location)	*Impact on cutting tool and carrier*			
Environment (in air / underwater and depth)	*Impact on cutting technology*			
Environment description (around the component - nearby structures, equipment, components - building services such as HVAC, RP, water treatment systems, etc.)	*Impact on cutting technology and management of secondary waste (e.g. HVAC or RP constraints)*			
Available cell (to add criteria if necessary)				

Datasheet - Reactor component (RPV/RVI)

Component name:

CRITERIA	IMPORTANCE	DATA	COMMENTS	EXPECTED IMPROVEMENT WITH THE LASER TECHNOLOGY
Segmentation and Waste Management Processes				
Global appraisal:				
Dismantling step (when and why)	*To know what other components remain when this one is segmented and why this component is cut at that moment*			
Possibility to disassemble the component (e.g. bolted) or not (e.g. welded)	*Impact on dismantling sequence and cutting technology*			
Dismantling location (where: in situ, pool, etc. and why)	*To understand the drivers, e.g. for deciding to segment in pool or in situ (Due to space? Due to RP ?)*			
If not in situ, description of the environment (in air/UW - nearby structures, equipment, components - building services)				
Cutting technique(s) used (Mechanical, Abrasive Water Jet Cutting, Plasma Arc Cutting, etc...)	*To know the most common technique used, although this may change from a project to another.*			

Datasheet - Reactor component (RPV/RVI)

Component name:

CRITERIA	IMPORTANCE	DATA	COMMENTS	EXPECTED IMPROVEMENT WITH THE LASER TECHNOLOGY
Number of pieces of cutting equipment used to cut this component. Even if only one family of cutting technologies is used (e.g. mechanical), please count the pieces of cutting tools (e.g. different saws).	*To understand the versatility of the cutting tools used and the specificities of the components regarding different tools to address the segmentation.*			
Segmentation plan (Number of cuts, length of cuts, etc.)	*Impact on the cutting technology*			
Handling means needed (for disassembly, cutting, packaging / standard or bespoke)	*Handling means versus segmentation plan*			
Waste container used for the packaging (type / family)	*To understand the drivers to select the waste package in relation with the segmentation plan (e.g. interesting to cut smaller or not? importance of making precise shapes or not, etc.)*			
Waste routes for the primary and secondary waste	*Does the segmentation of this component generate any waste for which no waste route exist on the site (e.g. fines, filters, etc.)*			
Any specific challenge	*E.g. requirement to cut at a precise location (such as section of upper internals from the vessel head)*			
Available cell (to add criteria if necessary)				

2.3. Technologies comparative analysis

Instructions:

The objective of this spread sheet is to focus on 3 conventional technologies (Mechanical Cutting which includes Band saw/disk grinder/Milling cutter, Abrasive Water Jet Cutting and Plasma Arc Cutting).
In this part, you will indicate your experience/feedback for these conventional technologies regarding different aspects:

- ***Feasibility and suitability***
- ***Safety***
- ***Performances / Key factors***
- ***Waste***

In order to fill in correctly this sheet, please find below the instructions.

*1-At first, please indicate the **main specifications** of your tools for which you provide the data (e.g. size, power, etc.). Should you prefer to provide answers for another technology (e.g. Circular saw instead of Disk grinder), please do so and change the name of the tool.*

*2-If you have data to provide us, please complete the '**DATA**' and '**COMMENTS**' columns for each criterion and cutting techniques (some examples are indicated in the first lines). Also, we will have the possibility:*

- *To indicate your main comments regarding each criterion*
- *To propose additional criteria (if any) which you consider important and which should be taken into account in the LD-SAFE project (**available cells**)*
- *To provide us documents which will answer to some criteria*
- *To leave the cell empty if you don't have information regarding specific criteria*

3You can also:

- *Indicate your point of view regarding each criterion: Do you agree with our LD-SAFE project comment (Yes or No, Why)?*
- *Indicate your expectations regarding laser technology in the ('**EXPECTATIONS FOR LASER TECHNOLOGY**' column) if any.*
- *Do an overall appraisal of each cutting technique by indicating the main advantages and drawbacks at the end of the table.*

*4-In each column, if the information is confidential, please indicates it in **red color**.*

Technologies Comparative Analysis (for the Dismantling of RPV/RVI)

CUTTING TECHNIQUES		State of the art					YOUR POINT OF VIEW	COMMENTS	EXPECTATIONS FOR LASER TECHNOLOGY
		Mechanical Cutting			Abrasive Water Jet Cutting (AWJC)	Plasma Arc Cutting (PAC)			
		Band saw	Disk grinder	Milling cutter					
SPECIFICATIONS		*Size:* *Power:* *Etc.*	*Size:* *Power:* *Etc.*	*Size:* *Power:* *Etc.*	*Size:* *Power:* *Etc.*	*Size:* *Power:* *Etc.*			
CRITERIA	ENVIRONM.	DATA							
Feasibility and Suitability for the Segmentation of RPV and RVI									
Global appraisal:									
Maturity [Qualitative Answer] *Could you please provide your perception of the maturity of the technology for dismantling RPV or RVI, making your choice in the list below:* *1.* ***Fully mature*** *(commonly used, since a long time)* *2.* ***Proven*** *(use demonstrated but improvements are still in progress)* *3.* ***New*** *(not yet actually used, still in development)* *If you have some ideas about the developments which are yet to be carried out to improve the technology, you can mention them in comments*	In Air	*e.g. Fully mature*	*e.g. Fully mature*	*e.g. Fully mature*	*e.g. Fully mature*	*e.g. Fully mature*	**Do you agree with? (Yes / No)**		
	Underwater	*e.g. Proven*	*e.g. Proven*	*e.g. Proven*	*e.g. Proven*	*e.g. Proven*			
Our point of view regarding this criterion: Cutting tools proven for the intended application, used in the same operational environment in the industry before.							*e.g. Yes*	**Why?** *Your comment*	
Versatility [Qualitative Answer] *Could you please provide your perception of the versatility of the technology for dismantling RPV or RVI, making your choice in the list below:* *1.* ***High*** *(can be used to address most of the segmentation scope)* *2.* ***Medium*** *(used on a rather large but targeted part of the scope)* *3.* ***Low*** *(used on a limited scope or for specific cutting tasks only)*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Cut with one tool components of various physical properties (different material or materials modified by radiations, containing hollow parts, etc.), thus reducing the number of tools / systems needed for the project.							*e.g. Yes*	**Why?** *Your comment*	

Efficiency [Qualitative Answer] *Could you please provide your perception of the efficiency of the technology when operating on its part of the segmentation scope, making your choice in the list below:* *1.* **High** *(efficiency gives flexibility to the segmentation plan, not constraining)* *2.* **Medium** *(balanced pros and cons, average compared to other technologies)* *3.* **Low** *(using the technique constraints the segmentation plan, constraining technique impeding efficiency)* *In comments, you could list the aspects which make the technique efficient or constraining.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Do not constrain the segmentation plan due to technological limitations (allows performing less -or more- cuts, depending on what is preferred). Operates with few needs or constraints (reduced handling means, precise positioning, necessary instrumentation and controls, etc.).							*e.g. Yes*	**Why?** *Your comment*	
Technological Limitations [List of exceptions] *Could you please list the materials or components, if any, which according to your knowledge, cannot -or do not- cut with this technology during segmentation of RPV/RVI.* *Comment to briefly explain why.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Avoid the need for bespoke solutions to address limited but specific parts of the scope.							*e.g. Yes*	**Why?** *Your comment*	
Maximal thickness of cut [Value in mm] *Could you please indicate the maximum thickness of stainless steel which, according to your knowledge, can be cut with the technology.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Capable of cutting material in the range of the high thicknesses of RPV and RVI components.							*e.g. Yes*	**Why?** *Your comment*	
Available cell (to add criteria if necessary)									

Safety									
Global appraisal:									
Radiation Protection [Value - Proportion of works carried out remotely in %] *For the use of this technique, including operation and maintenance, could you please provide an assessment of the* ***works carried out remotely (%)*** *(i.e. workers operating the system from an area with no radiation exposure or contamination risk).* *In comments, you could specify which operations must be carried out hands-on, or remotely but still in the working area.*	In Air	*e.g. 30%*	*e.g. 30%*	*e.g. 30%*	*e.g. 60%*	*e.g. 60%*	**Do you agree with? (Yes / No)**		
	Underwater	*e.g. 50%*	*e.g. 50%*	*e.g. 50%*	*e.g. 90%*	*e.g. 90%*			
Our point of view regarding this criterion: Internal exposure of workers is the main risk for dismantling activities. Avoiding hands-on human activities, by increasing the proportion of works carried out remotely, is the most efficient way to reduce this risk.							*e.g. Yes*	**Why?** *Your comment*	
Failure of equipment in the work area [List of risks] *Could you please indicate the main risks of failure in the work area associated with the use of this technology (e.g. blockage of blade in the cut component).* *In comments, you could indicate if specific provisions to mitigate the risks and to allow the rescue of the equipment are necessary.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Failure and rescue of equipment in the work area is a source of risk for the operators and must be reduced.							*e.g. Yes*	**Why?** *Your comment*	
Protection of Systems Structures or Components in the surroundings of the cutting area [Value - Unit of distance] *Could you please indicate whether SCCs in the surroundings of the cutting area must be protected against any impact of this cutting technique (e.g. projections, residual beam/jet behind the cut, etc.) and if yes indicate an estimate of the* ***shortest distances (m)*** *between the position of the cutting tool and the SCCs which must be protected. If not, please indicate N/A.* *In comments, you could describe a concrete example particularly relevant which you would like to be taken as an example for a demonstration.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: For safety reasons the absence of impact on SSCs located nearby the cutting area may have to be demonstrated.							*e.g. Yes*	**Why?** *Your comment*	
Generation of aerosols [List of Safety Requirements] *Please note that the question of the quantity and size of aerosols generated by the cutting techniques is asked below in the section Waste.* *According to your knowledge, could you please indicate what are your safety requirements in respect of aerosols generation when this cutting technique is used, such as composition (specific radionuclides, e.g. 60Co), limits (mass and/or sizes), collect and mitigation means (local or by building's systems), etc.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Reduce generation of radioactive aerosols and contamination hazard (related not only to the quantity but also to the size of the aerosols generated).							*e.g. Yes*	**Why?** *Your comment*	

Generation of gas and bubbling [List of Safety Requirements] *For underwater cutting works, and according to your knowledge, do you have any concern and/or safety requirements regarding the release of compressed air (or inert gas) in the cutting environment in relation with topics such as bubbling or impact on the ventilation?* *In addition to the above topic, could you please indicate if you have any concerns and/or safety requirements regarding the generation of hazardous gases during the cutting, such as hydrogen.* *In comments, you could provide data associated with the safety requirements in this respect (e.g. flow rate, concentration, etc.).*	Underwater Only						**Do you agree with? (Yes / No)**		
Our point of view regarding this criterion: Techniques generating bubbles might concern operators, due to the potential transfer of contaminants to the surface. This is true for any technic using gas: Assist gas (for plasma or laser) but also pneumatic mechanical tools, etc.							*e.g. Yes*	**Why?** *Your comment*	
Water Contamination [Value - Unit of concentration] *Could you please indicate whether the cutting technique increases water contamination during use and, if available, provide the concentration reached and/or the limit as per safety requirements (e.g. mass of particles in a volume of water).* *In comments, you could indicate whether monitoring and purification systems are required.*	Underwater Only						**Do you agree with? (Yes / No)**		
Our point of view regarding this criterion: Keep better water clarity and better visibility during underwater cutting is an important safety aspect in addition to being required to allow the operations.							*e.g. Yes*	**Why?** *Your comment*	
Specific Safety Topics [List] *Could you please list any safety topics, other than the ones above, inherent to the use of this technology for RPV and RVI dismantling and which require a demonstration in the framework of the Safety Assessment.*	In Air						**N/A**		
	Underwater								
Available cell (to add criteria if necessary)									

Performances / Key factors

Global appraisal:

Cutting speed (feed rate) [Value in unit of length by unit of time] *Could you please give us some data about acknowledged* **feed rate (e.g. mm/min)** *with this technology. If possible, complement this data with the parameters of the cut, such as the* **cutting tool specifications**, *the* **material cut** *and the* **thickness cut.** *Should you have more relevant data (other material or thickness), it will be welcome. Please feel free to add lines to these criteria or attach other answers to your questionnaire at your convenience.* *If you lack data for some of the technologies, you may provide a qualitative answer instead:* *Fast (increasing the cutting speed would not be so beneficial, as it is not a limiting factor)* *Medium (increasing the cutting speed would be beneficial)* *Slow (the cutting speed is a real limiting factor, impacting other aspects such as the segmentation plan)*	In Air	*e.g. 50mm/min*	*e.g. 60mm/min*	*e.g. 75mm/min*	*e.g. 80mm/min*	*e.g. 90mm/min*	**Do you agree with? (Yes / No)**		
	Underwater	*e.g. 25mm/min*	*e.g. 30mm/min*	*e.g. 35mm/min*	*e.g. 40mm/min*	*e.g. 40mm/min*			
Our point of view regarding this criterion: Improvement of the cutting speed to reduce the duration of the step of segmentation of the RPV and RVI.							*e.g. Yes*	**Why?** *Your comment*	
Footprint [Value in unit of surface area] *Could you please provide the total* **footprint (surface area occupied, e.g. in m2)** *of the system for this cutting technology in the work area (e.g. reactor building, cover floor over the pool).* *In comments, you could indicate whether the space occupied is an issue (e.g. high proportion of available space) and whether part of the system is installed in remote areas where the available space is not an issue.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Space available in the reactor building and pool cover floor is limited. The footprint of the system in the dismantling area is key because of the lack of space.							*e.g. Yes*	**Why?** *Your comment*	
Robustness and Reliability [Value in Availability Rate %] *Could you please provide the* **Availability Rate (%)** *of this technology during RPV and RVI segmentation, i.e. the percentage of time during which the technology is operational (thus deducting the stops for failures, maintenances, etc.).* *If you are lacking data you may provide an estimate or a qualitative answer instead (High, Medium, Low).* *In comments, you could give details such as the percentage of time dedicated to maintenance or wear parts replacement. Provide brief descriptions of the main reasons of failures, if any.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Improve the reliability and availability rate of the cutting system, considering maintenance and wear parts replacement. Improved robustness and reliability is beneficial to the safety of the workers.							*e.g. Yes*	**Why?** *Your comment*	

Resistance to Radiations [Value in Sv/hr and/or Gy] *Could you please indicate if the tool or part of the cutting system is required to be qualified to resist to radiations. Please provide the* **qualification dose rate and/or total absorbed dose** *(as relevant) or indicate "none" if there is no qualification required.* *In comments, you could indicate whether shielding is used instead or if the tool or part of the cutting system needs actual radiation hardening.*	In Air							**Do you agree with? (Yes / No)**		
	Underwater									
Our point of view regarding this criterion: Resistance to radiations is a key factor for the availability of the technology								*e.g. Yes*	**Why?** *Your comment*	
Cost for the segmentation of RPV and RVI [Value in EUR] *Could you please provide the* **overall cost (or budget, assessment; order of magnitude)** *for the use of this technology for the segmentation of RPV and RVI, including CAPEX and OPEX (i.e. not only the cost of the cutting system, but also its operation including maintenance, consumable, workforce, etc.).* *Please specify the scope which you considered in your assessment, such as RVI only, one or more reactor units, etc.* *If several types of technologies are used for the same scope (e.g. mechanical and AWJC), could you please add an estimate ration of the works carried out with this technology.* *In comments, you could add any detail which you agree to share, such as CAPEX and OPEX separately, cost of maintenance, or any other relevant cost breakdown.*	In Air							**Do you agree with? (Yes / No)**		
	Underwater									
Our point of view regarding this criterion: Reduce the cost for the dismantling of a power nuclear reactor, segmentation of RPV and RVI being often one of the most costly steps and subject to uncertainties.								*e.g. Yes*	**Why?** *Your comment*	
Time for the segmentation of RPV and RVI [Value in Months] *Could you please provide the overall* **time (actual or planned)** *needed for the segmentation of RPV and RVI, including design, procurement, deployment and operation of the system until completion of the works.* *Please specify the relevant parameters used for you assessment, such as scope considered (same as above for costs), work in single or several shifts and number of resources.* *If several types of technologies are used for the same scope (e.g. mechanical and AWJC), please add an estimate ration of the works carried out with this technology.* *In comments, you could add any detail which you agree to share, such as the duration of the main phases.*	In Air							**Do you agree with? (Yes / No)**		
	Underwater									
Our point of view regarding this criterion: Reduce the time for the dismantling of a power nuclear reactor, segmentation of RPV and RVI being often on the critical path of the project.								*e.g. Yes*	**Why?** *Your comment*	
Available cell (to add criteria if necessary)										

Waste									
Global appraisal:									
Primary waste handling [Qualitative Answer] *Could you please indicate if you see any advantages -or drawbacks- inherent to the use of this technology in respect of handling of the primary waste, making your choice in the list below:* *1.* **Advantages** *(using this technique limits the need for handling means, allows standard handling means)* *2.* **Neutral** *(balanced pros and cons, average compared to other technologies)* *3.* **Drawbacks** *(requires several, bespoke, handling means)* *In comments, you could provide the type of handling means which have to be used when cutting with this technique.*	In Air	*e.g. Advantages*	*e.g. Neutral*	*e.g. Neutral*	*e.g. Neutral*	*e.g. Neutral*	**Do you agree with? (Yes / No)**		
	Underwater	*e.g. Neutral*	*e.g. Drawbacks*	*e.g. Advantages*	*e.g. Advantages*	*e.g. Advantages*			
Our point of view regarding this criterion: Avoid the need for bespoke mechanical systems to handle the cut component and segmented pieces (primary waste), such as need to transport, lift, rotate, fix, etc.							*e.g. Yes*	**Why?** *Your comment*	
Primary waste packaging [Qualitative Answer] *Could you please provide your perception of the advantages -or drawbacks- of the technology in respect of facilitating the packaging of the segmented RPV or RVI components, making your choice in the list below:* *1.* **Advantages** *(enables optimized packaging, eases compliance)* *2.* **Neutral** *(balanced pros and cons, average compared to other technologies)* *3.* **Drawbacks** *(does not allow optimized packaging, introduces risk of non-compliance)* *In comments, you could provide the reasons of your rating, the average percentage of packages' filling achieved with this technology, the necessary control means inherent to this technology required to guarantee the packages' compliance, etc.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Reduce the quantity of waste packages (by optimizing the filling). *Guarantee the compliance of the waste package with the regulatory criteria (e.g. controlled filling of the waste package to avoid introduction of forbidden material or uncharacterized pieces, such as fines, loose slag, etc.).*							*e.g. Yes*	**Why?** *Your comment*	

Secondary waste generated during the cut [Values in unit of mass or unit of mass per surface of cut and Characterization] *During the cutting, the mass removed from the component and added by the cutting tool, will contribute to the generation of secondary waste, which can be described as per the following families:* *- Gases and aerosols* *- Particles (fines, sludges)* *- Solids (coarser chips, swarfs, slags)* *For the relevant types of secondary waste, could you please provide:* *- The* ***mass generated*** *with the reference for your value, i.e. total mass for one reactor unit or for one specific component, or mass by unit of surface cut (surface being the length x thickness).* *- The* ***characterization*** *including description, main modes of the size distribution and waste classification as per your regulation.* *If you lack data to provide the above values, please describe quantitatively the secondary waste generated (none, low, medium, high).*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Reduce the quantity of secondary waste generated by the cutting operations, which is often considered as key criteria to select cutting technologies due to the technical difficulty and cost for managing this waste.							*e.g. Yes*	**Why?** *Your comment*	
Collection of the secondary waste generated during the cut [description of method / equipment] *Could you please describe how you collect the secondary waste generated by the cutting technique (e.g. local or building collection system) and how you manage the waste (processing and packaging).* *Please indicate if this is a particularly challenging and/or has a high cost and time impact.* *In comments, If the collection system itself generates significant amount of secondary waste (e.g. filtering media), could you please describe the type of waste and quantities.*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Reduce the quantity of secondary waste generated by the cutting operations, which is often considered as key criteria to select cutting technologies due to the technical difficulty and cost for managing this waste.							*e.g. Yes*	**Why?** *Your comment*	
Secondary Waste generated during dismantling of the segmentation system [Value in unit of mass and waste classification] *Upon completion of the segmentation of the RPV / RVI, the cutting system itself, along with spare or wear parts and consumable, may have to be disposed as radioactive waste.* *Could you please provide an average - or estimate - of the total mass of waste generated, along with its classification as per your regulation.* *In comments, you could add a description and specify, for instance, whether parts of the cutting system can be reused, on the same site (other unit) or a different site (other NPP).*	In Air						**Do you agree with? (Yes / No)**		
	Underwater								
Our point of view regarding this criterion: Although this is not ILW, disposal of the cutting system after its dismantling generates additional waste management costs which could be reduced.							*e.g. Yes*	**Why?** *Your comment*	
Available cell (to add criteria if necessary)									

Overall Apraisal of the Technology						
In case of using this technology for the dismantling of RPV/RVI, could you please describe your overall experience (e.g. which projects)?						**Short responses are expected for each technology**
Describe your overall feedback throughout the process (design, safety analysis and licensing, installation and commissioning, operation, etc.)						
Whether you use this technology or not, could you please indicate its main advantages according to your knowledge?						
Main drawbacks according to you						

8.2. Additional EUG & EG questionnaire (blank version)

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Laser Dismantling Environmental and Safety Assessment

VIDEOCONFERENCE

SESSION WITH THE ADVISORY BOARD - MARCH 08TH 2022

WORK PACKAGE #2 - LABORATORY TRIALS AND CALCULATIONS

Number of Pages: 3

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A	02/02/2022	Initial version
Revision	Date	Description of Changes
I. DOYEN	S. PAILLARD	S. PAILLARD
Written	Reviewed	Approved

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European Commission | Horizon 2020 European Union funding for Research & Innovation

PARTICIPANT	ORGANIZATION	NAME
TOPICS	**COMMENTS / QUESTIONS** **(following the presentation)**	**ANSWERS** **(to be completed by the Advisory Board member)**
Comments / feedback	**Open answers**	
Question 1	Based on your knowledge, what are the safety requirements regarding the integrity of the vessel wall when cutting internals in situ (potential damages of the vessel wall)?	Safety requirements to list (e.g. scratches depth):

Questions to the Consortium	**Open questions**	
New expectations	***Regarding the use of laser cutting***	

LD-SAFE

Laser Dismantling Environmental and Safety Assessment

VIDEOCONFERENCE

SESSION WITH THE ADVISORY BOARD - MARCH 08TH 2022

WORK PACKAGE #3 - SAFETY OF WORKERS & THE ENVIRONMENT

Number of Pages: 4

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A. CALOGIROS	C. SWIFT	C. SWIFT
Written	Reviewed	Approved

This project has received funding from the Euratom H2020 programme 2019-2020 under grant agreement No 945255

PARTICIPANT	ORGANIZATION	NAME
TOPICS	COMMENTS / QUESTIONS (following the presentation)	ANSWERS (to be completed by the Advisory Board member)
Comments / feedback		
Question 1	For the Guidance Notes, what specific guidance are you looking for in this document, related to health and safety and protection of the environment? ☐ Planning the segmentation ☐ Cleaning / decontaminating cutting zone ☐ Installation ☐ Operation of laser system ☐ Limitations of the laser system ☐ Collection and disposal of cut pieces Anything else:	☐ Planning the segmentation ☐ Cleaning / decontaminating cutting zone ☐ Installation ☐ Operation of laser system ☐ Limitations of the laser system ☐ Collection and disposal of cut pieces Anything else:

Question 2	What are your main concerns around safety of the workers and the environment when using laser technology for reactor segmentation? Is there anything specific you would like assurance or further investigation on?	Open answer:
Question 3	What topics would you consider important, and would like to see them included in end user training?	Comments:
Question 4	Based on your experience, could you share any instances where you have had any accidents or near misses (regarding worker or environmental safety) in nuclear decommissioning activities during dismantling of a reactor? If yes, what changes did you learn or implement to prevent future occurrences?	☐Yes ☐No Details: Lessons Learned:

Questions to the Consortium	**Open questions**	
New expectations	***Regarding the use of laser cutting***	

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Laser Dismantling Environmental and Safety Assessment

VIDEOCONFERENCE

SESSION WITH THE ADVISORY BOARD - MARCH 15TH 2022

WORK PACKAGE #4 - SAFETY ASSESSMENT

Number of Pages: 4

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J. RUIZ	T. RECIO	T. RECIO
Written	Reviewed	Approved

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PARTICIPANT	ORGANIZATION	NAME
TOPICS	**COMMENTS / QUESTIONS** **(following the presentation)**	**ANSWERS** **(to be completed by the Advisory Board member)**
Comments / feedback	**Open answers**	
Question 1	Based on your experience, do you think that cutting configurations that were preliminarily considered are representative for most end users? That is: 1. Cutting of the internals underwater and outside the vessel 2. Cutting of the vessel in-air ☐ Yes, they would probably fit most end users cutting configurations and it would be relatively easy to adjust to other situations. ☐ No, other configurations may need to be considered. If not, please, indicate the cutting configurations that you consider missing and the reason for that:	☐ Yes ☐ No If not, please, indicate the cutting configurations that you consider missing and the reason for that:

Question 2	For normal segmentation conditions, different risks were identified: • external exposure • internal exposure • effluents and secondary waste • waste management • hazardous materials exposure (i.e., potential generation of carbon oxides, nickel carbonyl…) • maintenance operation Based on your experience, do you consider any other risks relevant?	Open answer:
Question 3	For normal segmentation conditions, several design options were considered for reducing the risks caused by airborne releases to ALARA: ☐ dust/aerosols collection system ☐ contamination control confinement (airlock) ☐ auxiliary water filtration systems ☐ others: remote operation, area radiation monitoring, effluents monitoring, building off-gas system monitoring/filtration. Based on your experience, do you consider any of these design options unrealistic, unnecessary or non-operative? Would you consider any other design option?	Design options unrealistic (UR), unnecessary (UN) or non-operative (NO) ☐ dust/aerosols collection system ☐ contamination control confinement (airlock) ☐ auxiliary water filtration systems ☐ others Other design options:

Question 4	Radiological consequences of three initiating events were assessed in detail: • Fire/explosion • Loss of airborne filtration systems during cutting activities or rupture of the contamination control confinement (airlock) • Drop of loads Based on your experience, do you consider any other event sufficiently relevant for a detailed analysis?	Open answer:
Questions to the Consortium	**Open questions**	
New expectations	***Regarding the use of laser cutting***	

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Laser Dismantling Environmental and Safety Assessment

VIDEOCONFERENCE

SESSION WITH THE ADVISORY BOARD - MARCH 15TH 2022

WORK PACKAGE #5 - CASE STUDIES / DEMONSTRATOR

Number of Pages: 5

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P. DAGUIN	D. ROULET	D. ROULET
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European Commission | Horizon 2020 European Union funding for Research & Innovation

PARTICIPANT	ORGANIZATION	NAME
TOPICS	**COMMENTS / QUESTIONS** **(following the presentation)**	**ANSWERS** **(to be completed by the Advisory Board member)**
Comments / feedback	**Open answers**	
Question 1	Based on your experience, do you think the **upper plate** and the **bottom plate** are the **most complex components** to cut (in terms of geometry, thicknesses, accessibility, etc.)? ☐Yes ☐Only one of them. Which one: If not, others choices (2 maximum to choose): ☐Guide tubes / Control rods ☐Thermal shield ☐Core barrel (and baffle structure) ☐Lower Core Support Assembly ☐Vessel wall (not only in link with the thickness)	☐Yes ☐Only one of them. Which one: If not, others choices (2 maximum to choose): ☐Guide tubes / Control rods ☐Thermal shield ☐Core barrel (and baffle structure) ☐Lower Core Support Assembly ☐Vessel wall (not only in link with the thickness)

Question 2	Based on your knowledge and/or experience, what are the most important criteria (regarding representativeness) for the choice of mock-ups? And what are the boundaries in terms of representativeness?	Open answer:
Question 3	Based on your experience, what is the maximum distance (length for cables/hoses) between (in meters)? ☐The Control Room and the Utility zone: ☐The Utility Zone and the Interface zone: ☐The Interface Zone and the Cutting zone:	☐The Control Room and the Utility zone: ☐The Utility Zone and the Interface zone: ☐The Interface Zone and the Cutting zone:
Question 4	Based on your experience, what is the best place to implement the laser utilities (in general included in a container)? ☐Inside the reactor building ☐Outside the reactor building And why? What are your constraints (for instance: limitations about the distances, available footprint, maintenance, etc.)	☐Inside the reactor building ☐Outside the reactor building Why: Constraints:

<table>
<tr>
<td>Question 5</td>
<td>
Based on your knowledge, what is the ratio (%) of cost spent for activities indicated below?

Or which ones are the most important from your point of view?

☐Licensing process
☐Studies/Design/segmentation plan
☐Manufacturing/Testing
☐Operators training
☐Installation/Commissioning
☐Cutting operations
☐Maintenance (preventive and corrective)
☐Drying (of the segmented components)
☐Waste management (characterization, packaging and logistic)
☐Protection of workers / safety aspects
</td>
<td>
Ratio (%) to indicate
<table>
<tr><th><u>Steps</u></th><th><u>Ratio</u></th></tr>
<tr><td>Licensing process</td><td></td></tr>
<tr><td>Studies/Design/segmentation plan</td><td></td></tr>
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<tr><td>Waste management (characterization, packaging and logistic)</td><td></td></tr>
<tr><td>Protection of workers / safety aspects</td><td></td></tr>
</table>
</td>
</tr>
</table>

Question 6	During the LD-SAFE demonstrator, what are the most important technical aspects you would like to see with the use of laser cutting technology (to list by priority)? ☐Cutting speed and maximum thickness achieved ☐Secondary waste generated ☐Reliability and versatility of laser system ☐Maintenance ☐Visibility during underwater cutting ☐Impact of the laser beam residual power ☐Performance of safety systems / Management of aerosols and gases ☐Protection of workers / safety aspects ☐Training / procedures	1 - 2 - 3 - 4 - 5 - 6 - 7 - 8 - 9 -
Questions to the Consortium	**Open questions**	
New expectations	***Regarding the use of laser cutting***	

8.3. First Technical Workshop – General presentation at WNE 2021

LD-SAFE

WNE 2021 – Workshop 2
Project presentation

Author: LD-SAFE Consortium

Date: Dec. 01, 2021

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945255

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Summary

CONTENT

1. INTRODUCTION
2. CUTTING TECHNIQUES
3. LASER CUTTING
4. LD-SAFE
5. SAFETY ASPECTS
6. CONCLUSION

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Introduction

Decommissioning of a power reactor

- Commonly scheduled to be completed over a **long period (over 20 years for PWR/BWR in general)**
- Change in strategy (**immediate dismantling** after permanent shutdown)
- **New challenges** (acceleration of the decommissioning project schedules)
- Need to improve the **dismantling processes** and **existing techniques**

➢ **Key operation to improve: cutting of Reactor Pressure Vessel and Internals**

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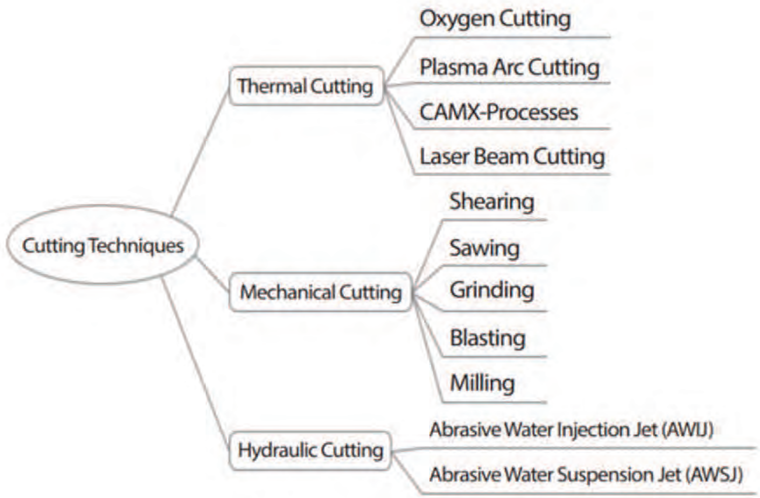
Cutting techniques

Main categories / Main tools used

- Thermal cutting (Plasma Arc Cutting)
- Mechanical cutting (Band Saw Cutting)
- Hydraulic cutting (Abrasive Water Jet Cutting)



Classification of remote handling technologies

Comparison / Limitations

	Plasma Arc cutting	Band Saw cutting	Abrasive Water Jet cutting
Advantages	Large dimensions Fast Less maintenance on site	Cut large thicknesses All materials Limited contamination	Complicated shape All materials Few air pollution
Drawbacks	**High degree of filtration** Slower underwater Electrically conductive material	**Slow (cutting speed)** Maintenance Wear part replacement	**Water treatment** High cost Required space

For cutting RPV/RVI in-air and underwater

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Cutting techniques

Need

- Development of **innovative technologies**
- Improve **safety**, **radiation protection**, **waste management**, **time** and **cost** aspects

Why adapting laser cutting technology for RPV and RVI?

- **Key benefits** in comparison with conventional cutting techniques
- More than **10 years of R&D (laboratory testing)**
- **Mature** and **operational technology** for dismantling activities (already used for fuel cycle / research facilities)

Examples of operational experience

- *Dissolvers of **UP1 MAR200** fuel reprocessing facility at CEA in France*
- *Piping at Creys-Malville NPP (**SUPERPHENIX** prototype fast reactor)*
- *Radioactive waste evaporator at **La Hague** site*

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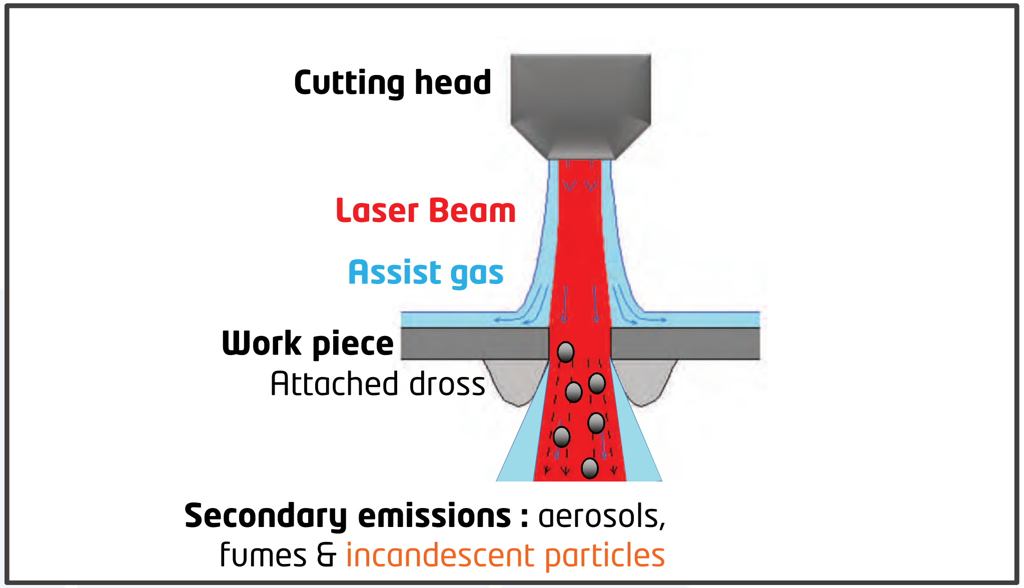
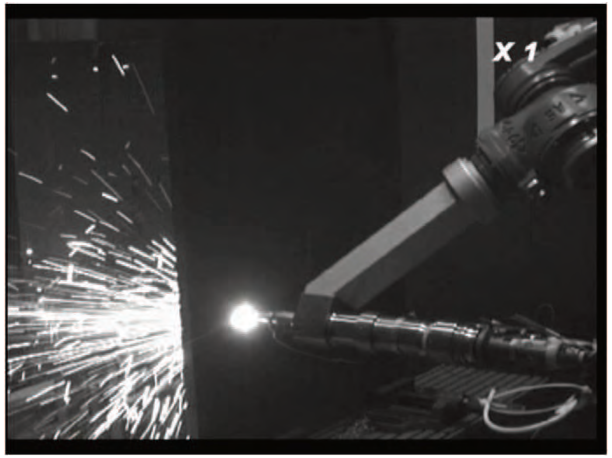
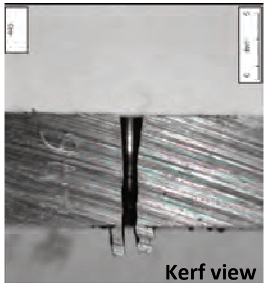
LASER CUTTING IN AIR







- **High intensity laser beam** heats and melts locally the sample
- **Pressurized assist gas** ejects the molten material
- Laser beam or sample manipulation generates a narrow kerf

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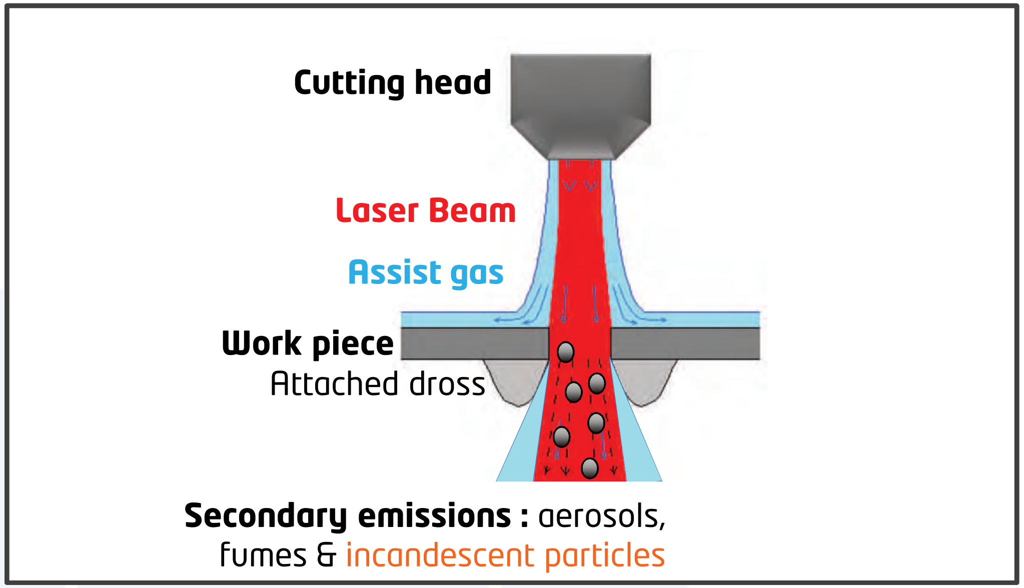
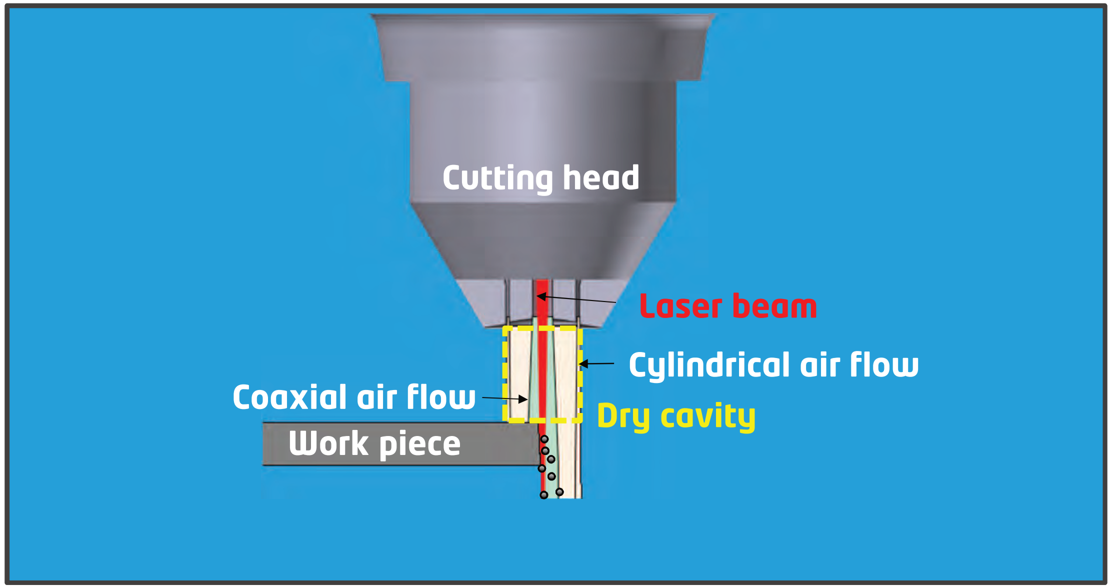
LASER CUTTING UNDERWATER





Based on **dry cavity concept** → **Laser beam propagates in air** between the laser head & work piece & in the kerf
→ With no laser power loss due to the water absorption

☺ **Radiological protection**
Aerosols trapping by water (75 gain at 0.5 m water depth and 400 at 4 m)

😐 Reduced process tolerance
No possibility of multi thickness cut

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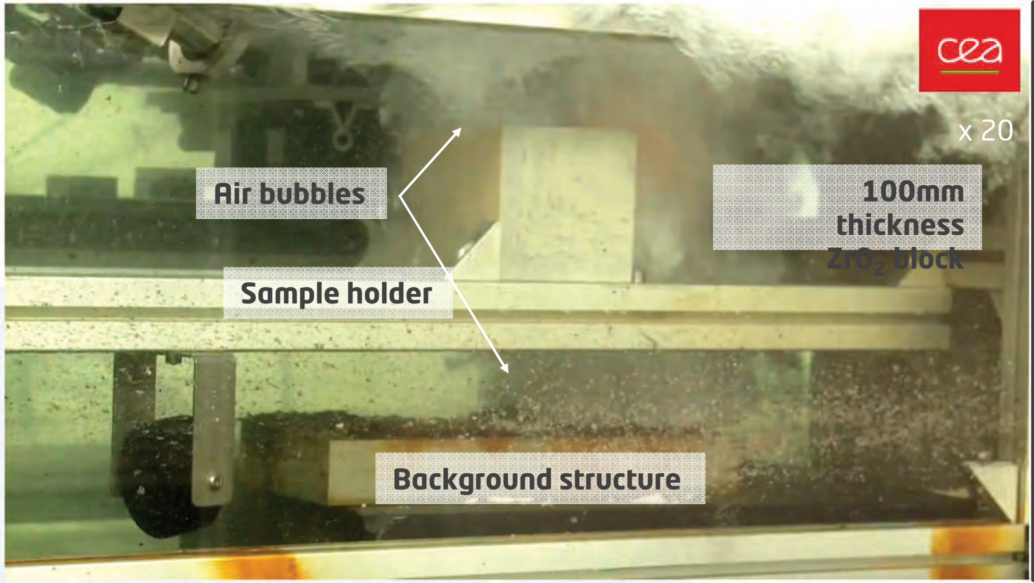
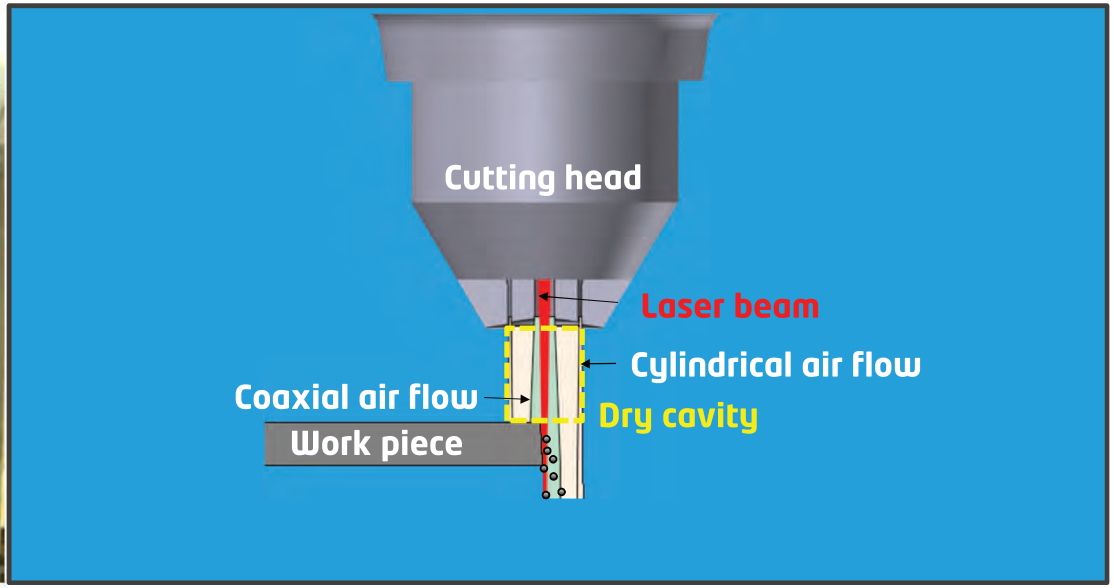
LASER CUTTING UNDERWATER





Based on **dry cavity concept** → **Laser beam propagates in air** between the laser head & work piece & in the kerf
→ With no laser power loss due to the water absorption

☺ **Radiological protection**
Aerosols trapping by water (75 gain at 0.5 m water depth and 400 at 4 m)

😐 Reduced process tolerance
No possibility of double thickness cut

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LASER CUTTING TOOLS DEVELOPED BY CEA

IN AIR LASER CUTTING TOOL

- **Air-cooled head**
- **Successfully used for UP1 dissolver dismantling**
- **High tolerance cutting process**
- **Industrial head : 41.7 x 7.6 x7.2 cm, 6.3 kg w/o**

Straight Head up to 14 kW

90° Angle Head - up to 8kW

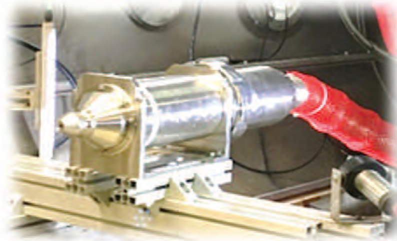
UNDERWATER LASER CUTTING TOOL

- **Operation under water - up to 5.6 m proved**
- **Robust and efficient shutter (stop bubbles for video observation)**
- **Easy umbilical cable connection**
- **No electronic components integrated**
- **Safety functions integrated**
- **Operational prototype - watertight :**

60 cm long, 15 cm diameter, 20kg w/o

Up to 16 kW

- **2 specific laser heads**: for in air operation & for underwater operation
- Designed for nuclear dismantling facilities to work in severe conditions and harsh environment
- High laser power capability: up to 16 kW
- Compact tools => work in cramped area
- Good robustness & high positioning tolerance, in particular for the in air cutting head



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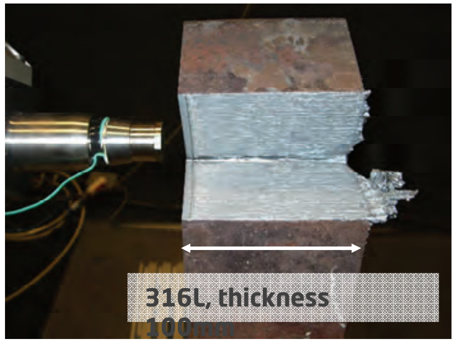
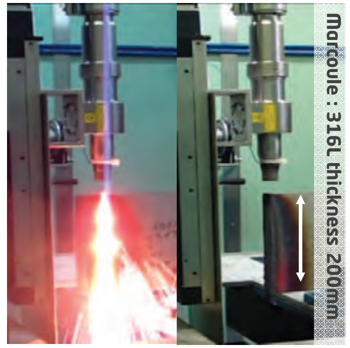
LASER CUTTING CAPABILITIES: STEEL

- **8kW + pressurized air → 100mm thick 316L**

  ~ 1 cm/kW when starting at the edge

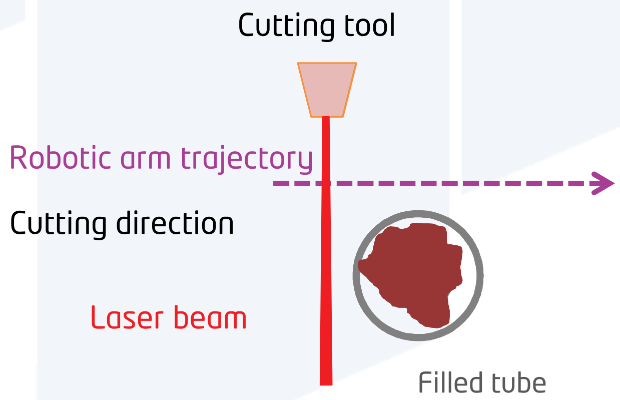
- **14 kW → 200 mm thick 316L (CEA Marcoule)**

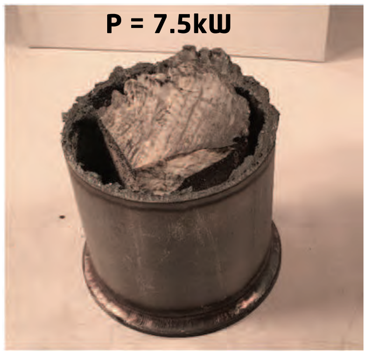




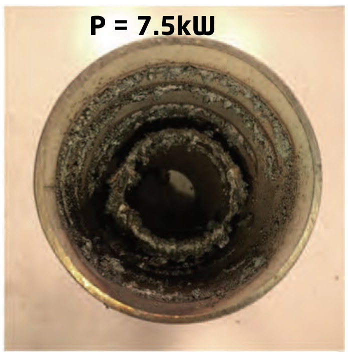
- **COMPLEX GEOMETRIES & MULTI THICKNESS CUT**

Straight trajectory of the robotic arm – does not follow the surface shape

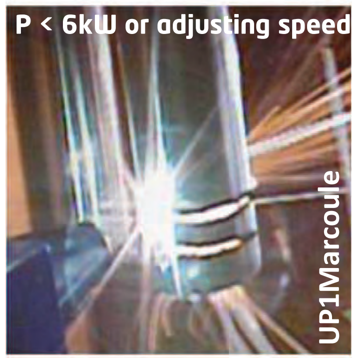




316L Ø 80mm,
3mm thickness + ZrO_2 block



316L Ø 80mm & Ø 40mm
thickness 3mm



316L Ø 80mm
thickness 7mm

316L Ø 80mm
thickness 3mm

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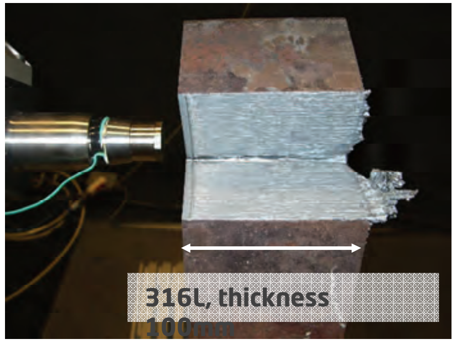
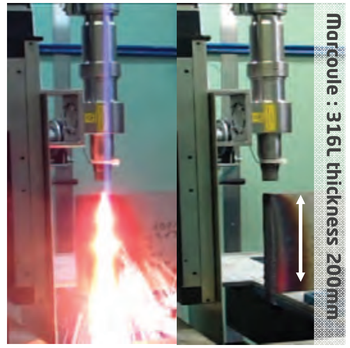
LASER CUTTING CAPABILITIES: STEEL

- **8kW + pressurized air → 100mm thick 316L**

  ~ 1 cm/kW when starting at the edge

- **14 kW → 200 mm thick 316L (CEA Marcoule)**

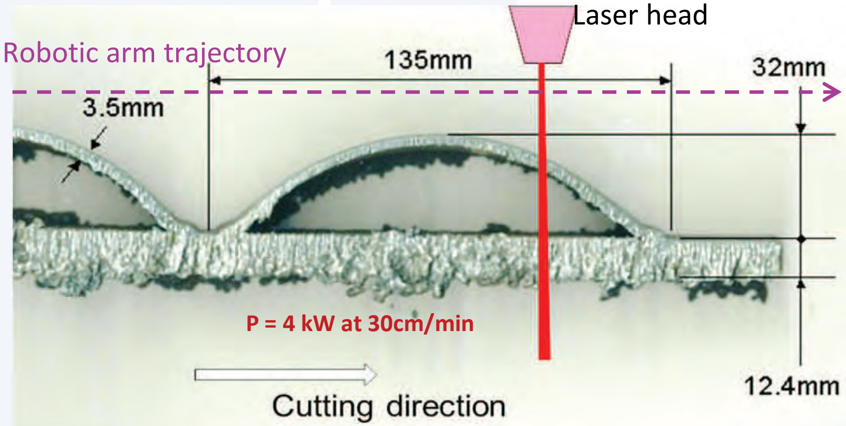




- **COMPLEX GEOMETRIES & MULTI THICKNESS CUT**

  Straight trajectory of the robotic arm – does not follow the surface shape

  Capability to cut simultaneously more than just one plate



2.5cm/min	30cm/min	10cm/min	10cm/min

Uranus 65 steel

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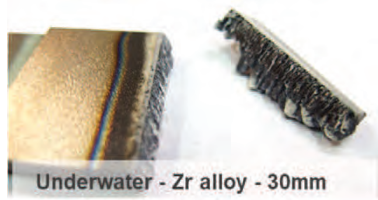
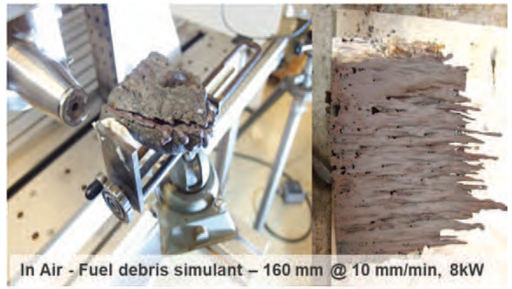
LASER CUTTING PERFORMANCES

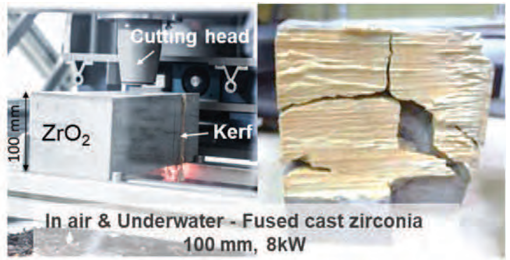
Laser cutting performances tested up to now

Configuration	Material	Thickness (mm)	Laser Power (kW) vs. Cutting Speed Limit (mm/min)			
			4	8	10	14
In-Air	Steel and Stainless Steel	20	175	350	500	700
		40	20	125	150	225
		60	-	40	55	120
		100	-	7.5	25	50
		120	-	-	8.5	32.5
		200	-	-	-	2.5
Underwater	Stainless Steel	40	Not tested	70	Not tested	100

➢ **Increased cutting speeds are expected in the coming years due to the availability of higher power laser sources**


Underwater - Zr alloy - 30mm


In Air - Fuel debris simulant – 160 mm @ 10 mm/min, 8kW



In air & Underwater - Fused cast zirconia 100 mm, 8kW

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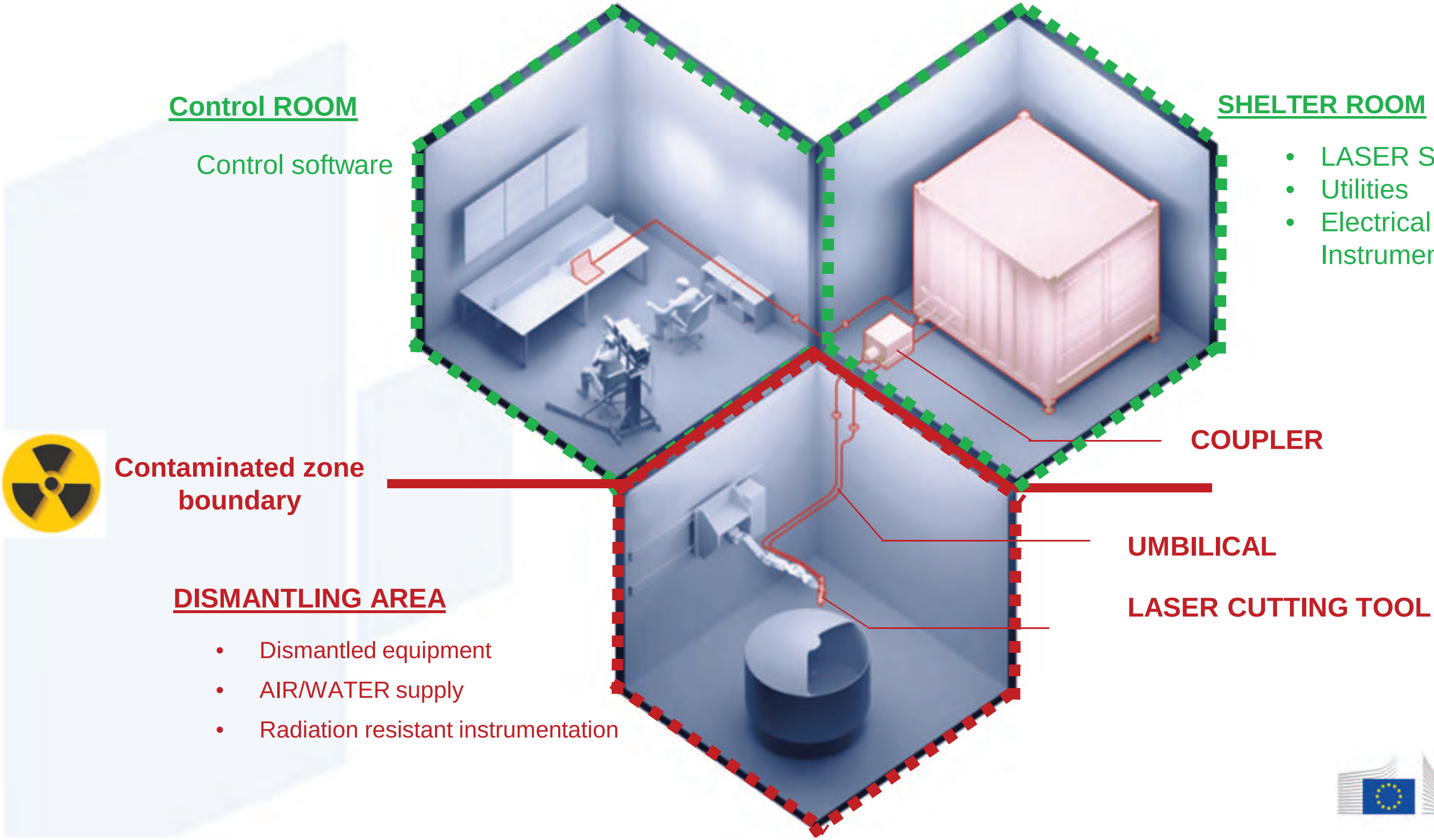
ON-SITE IMPLEMENTATION FOR DISMANTLING ACTIVITIES



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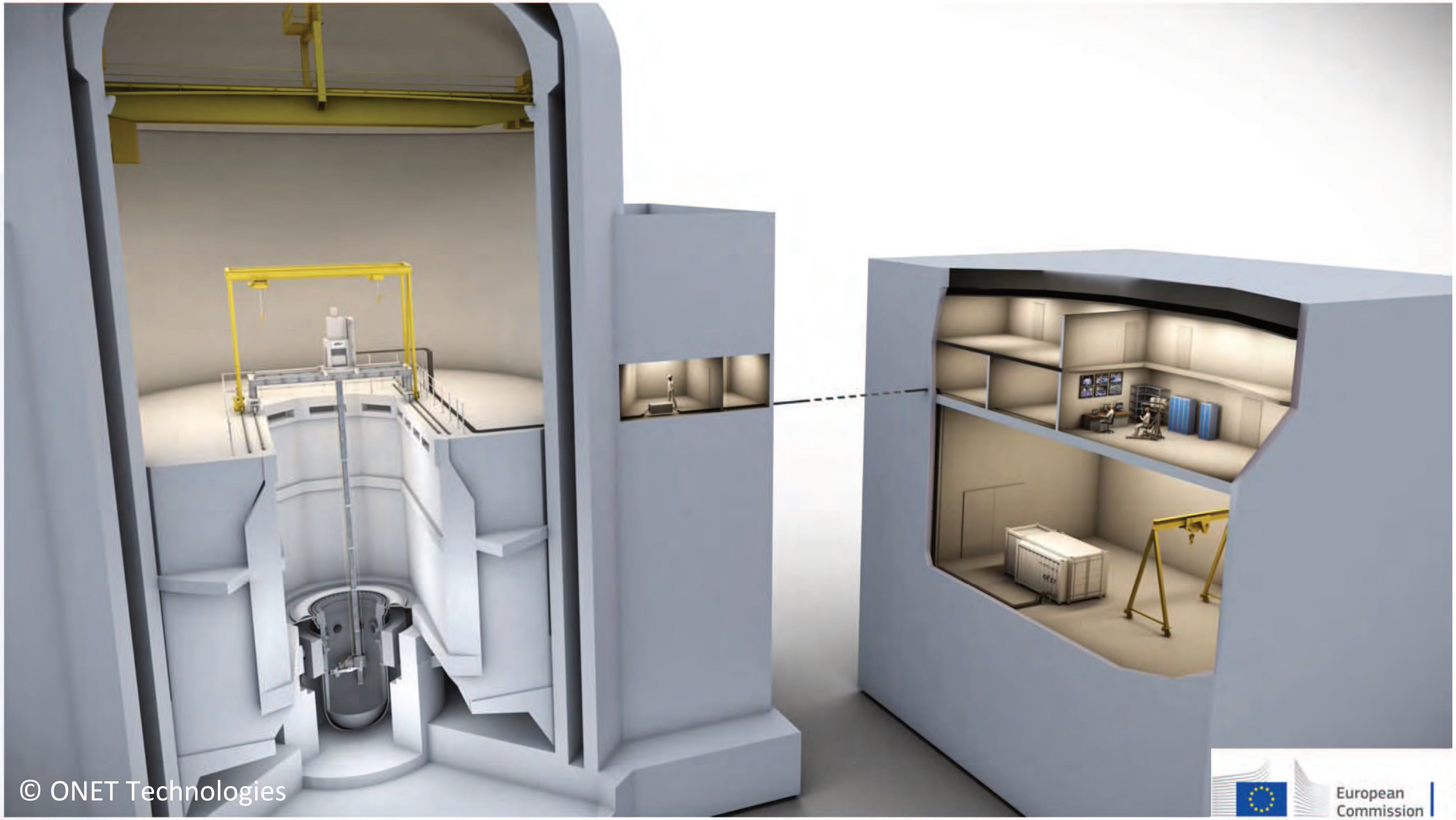
ON-SITE IMPLEMENTATION FOR DISMANTLING ACTIVITIES



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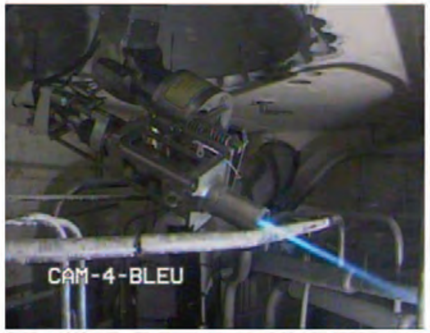
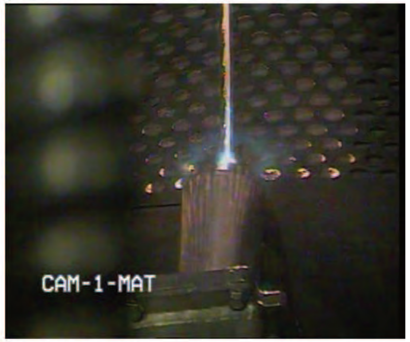
LASER CUTTING KEY BENEFITS FOR DISMANTLING

- **Safe** for the workers (remote operations)
- **Time** reduction and **cost** efficiency in operation
- **Effortless** cutting with high performance
- Ability to cut **complex geometries**
- **Contactless** which eliminates the risk of tool blockage
- **Minimization of the secondary waste** (aerosols and mass removed)
- **Cleaner** than most of other thermal techniques (especially for dust & fumes)
- **Robustness** and **reliability**, **no maintenance** or wear parts replacement in controlled area



Up to **200mm in thickness** in air (14kW laser power)



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LD SAFE

Laser Dismantling Environmental and Safety Assessment

LD-SAFE

H2020 program

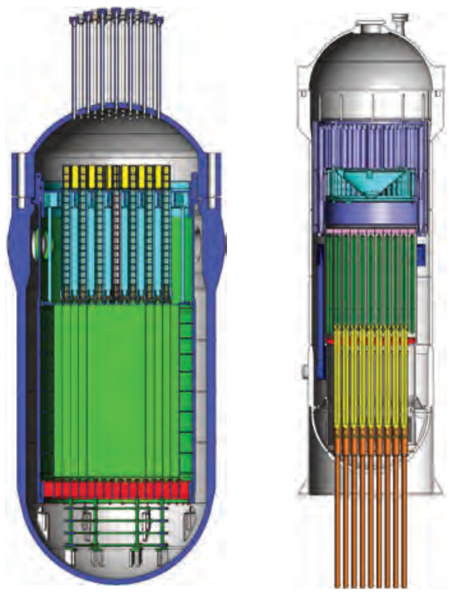
ONET TECHNOLOGIES · tecnatom · cea · IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE · Vysus Group · EQUANS EMPOWERING TRANSITIONS

Not yet widely used in the nuclear decommissioning industry?

- Laser considered as new technology (**never used** for power nuclear reactor dismantling)
- Compliance with **safety requirements** need **to be checked**

Most challenging task

- Dismantling Reactor Pressure Vessels and Internals (**RPV and RVI**) of Power Nuclear Reactor



PWR *BWR*

LD-SAFE (H2020 program)

➢ To demonstrate in-air and underwater laser capabilities, safety, economic advantages and suitability for power nuclear reactor dismantling activities.

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LD-SAFE
Organization

ONET TECHNOLOGIES · tecnatom · cea · IRSN · Vysus Group · EQUANS

H2020 program

- **R + D + i project**
- Funding by **EC (Euratom)**
- **4 years** (July 2020 to June 2024)

Consortium

ONET TECHNOLOGIES - France	🇫🇷
EQUANS (ENGIE) - Belgium	🇧🇪
CEA - France	🇫🇷
VYSUS GROUP - Sweden	🇸🇪
IRSN - France	🇫🇷
TECNATOM - Spain	🇪🇸

Overall organization

1 Project officer — **European Commission** (HORIZON 2020)

6 partners — **Consortium**

3 groups — **Advisory Board**: EG/EUG/SG

Expert Group (EG)
End User Group (EUG)
Support Group (SG)

End User Group: ENGIE · AE · BELGOPROCESS · KTE · SCK CEN · EDF · GRAPHITECH · JAEA · BEL V · SOGIN · Dounreay

Support Group: JEPIC · EPRI · European Commission · VTT · Bundesamt für die Sicherheit der nuklearen Entsorgung

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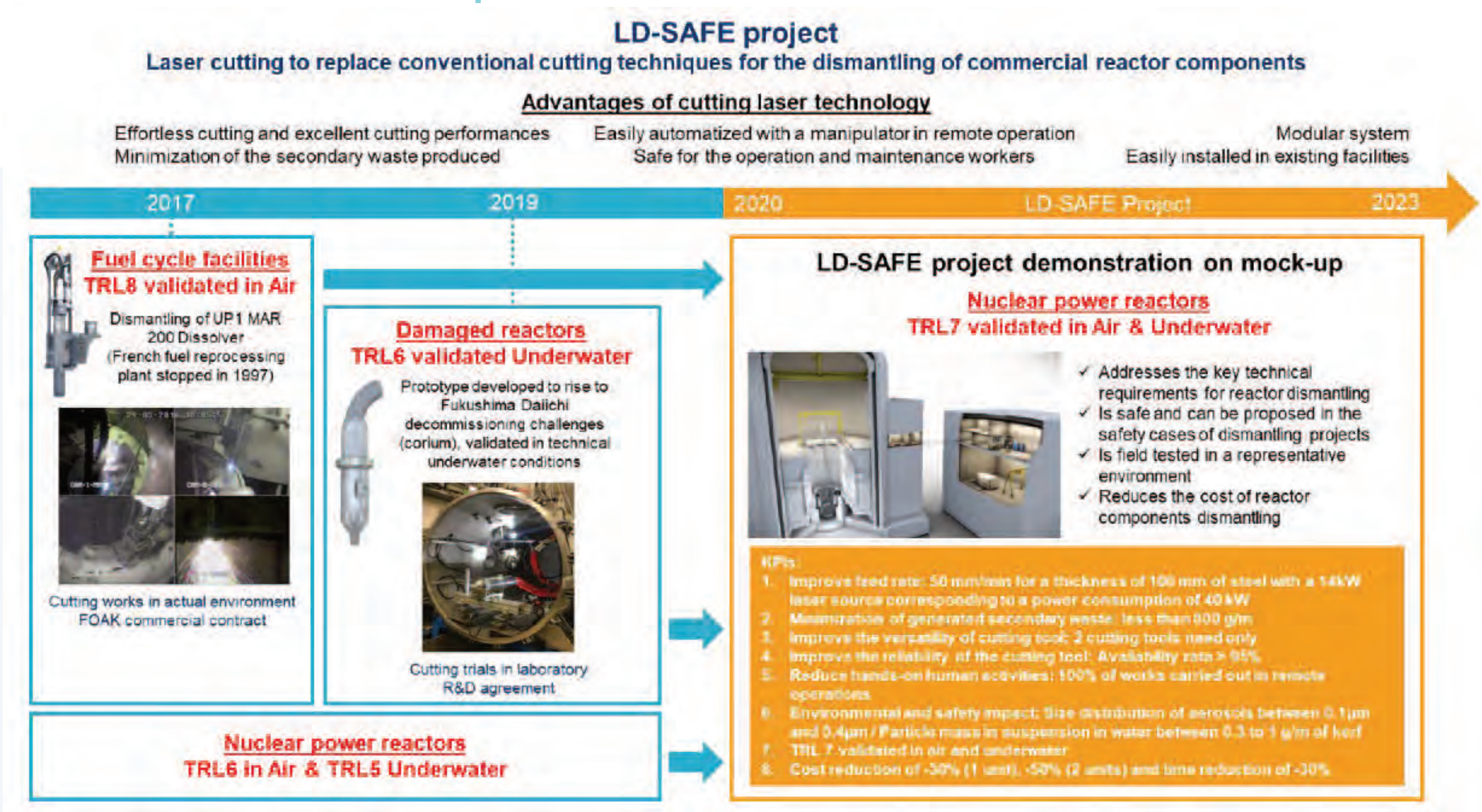
LD-SAFE

Concept



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Main technical activities

Laser Cutting Development → Environmental and worker protection → Safety Assessment → Decommissioning of nuclear facilities

Laser Cutting Development

Analysis of the reactor dismantling with laser cutting

ONET TECHNOLOGIES, EQUANS

Laboratory tests and calculations:

-Laser beam residual power
-Hydrogen gas generation during underwater cutting

cea

-Aerosols

IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

Environmental and worker protection

-Technology qualification

-Guidelines for the industry for the use of laser cutting

Vysus Group

Safety Assessment

-Risk analysis
-Generic Safety Assessment

tecnatom

-Independent review

IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

Decommissioning of nuclear facilities

Demonstrator in two phases: in air and underwater

Validation of the implantation and the use of the laser cutting technology in operational environment

ONET TECHNOLOGIES, cea, EQUANS

+ End-users

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Progress

Laser Cutting Development	Environmental and worker protection	Safety Assessment	Decommissioning of nuclear facilities

Milestone completed:
Specifications for the dismantling of reactor components agreed (inputs for the other activities).
100%

Laboratory tests:
-Design of experimental setups
-Implementation & qualification of specific instrumentation
-Purchase of representative samples
-Preliminary experientations/analysis
25%

Milestone completed:
Qualification activities in the Technology Qualification Plan are defined and scheduled

Qualification activities:
-Appraisal of laser system maturity
-Technology Qualification Plan
-Monitoring qualification activities progress (on-going).
40%

Safety assessment:
-Risk analysis with regards to safety
-Compilation of inputs from previous activities (on-going).
25%

Demonstrators:
-First studies for the definition of the complete laser system for the 2 phases of the demonstrator (on-going)
15%

+ End-users

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Public outputs

Laser Cutting Development

- Analysis of the different reactor components in combination with the selection of conventional cutting techniques (available) — ONET Technologies, EQUANS
- Laboratory tests and calculations — *Confidential deliverables* — CEA, IRSN

Environmental and worker protection

- Guideline - use of laser cutting in reactor dismantling environment (31/12/2023) — Vysus Group

Safety Assessment

- Generic Safety Assessment (31/08/2023) — Tecnatom, IRSN

Decommissioning of nuclear facilities

- Technical validation report (30/06/2024) — ONET Technologies, CEA, EQUANS
- Stakeholders workshop report (31/05/2024) — Advisory Board

Dissemination

- Project website and Social Networks (available)
- Education and training report & Online course on cutting technologies (30/06/2024)

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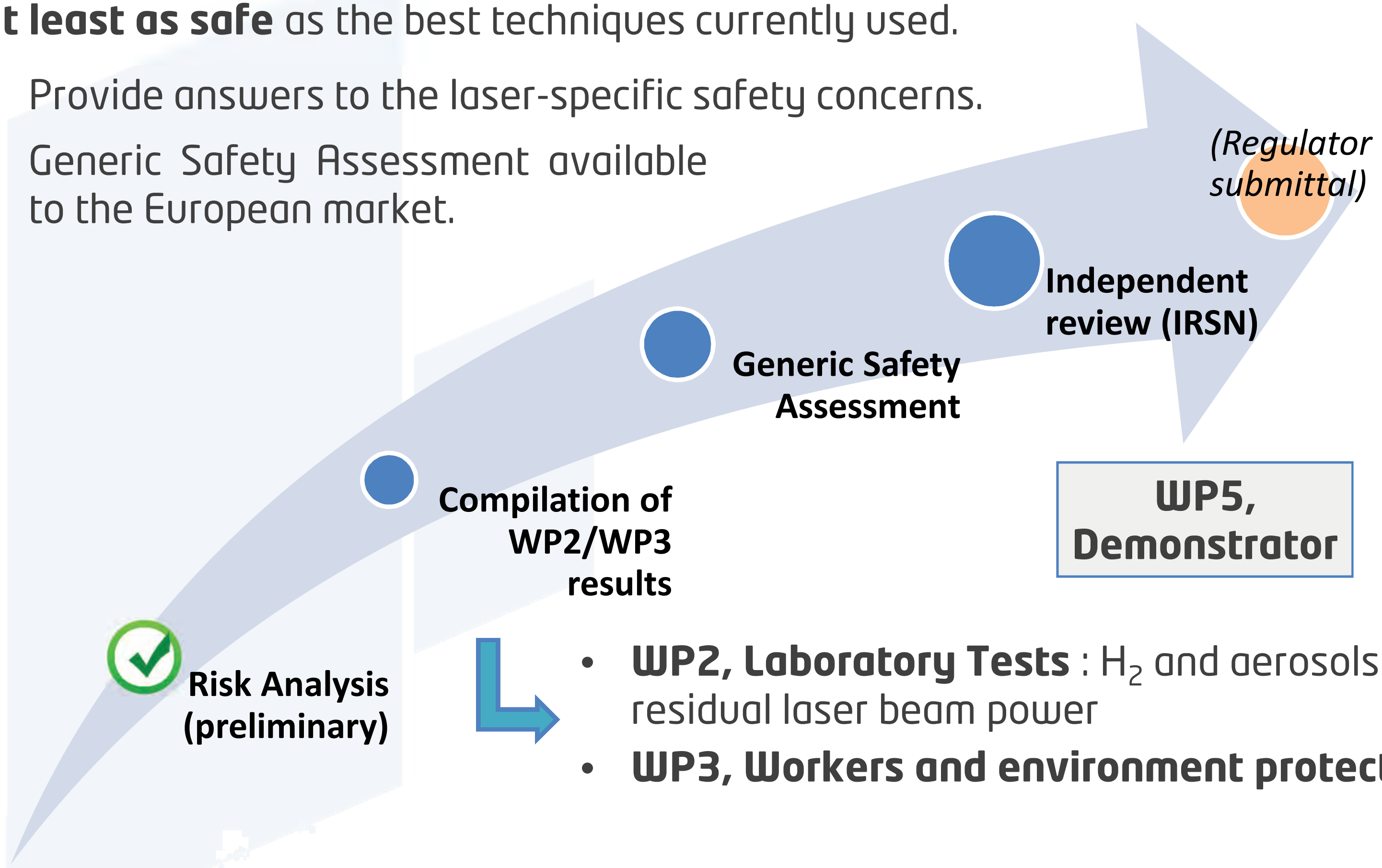
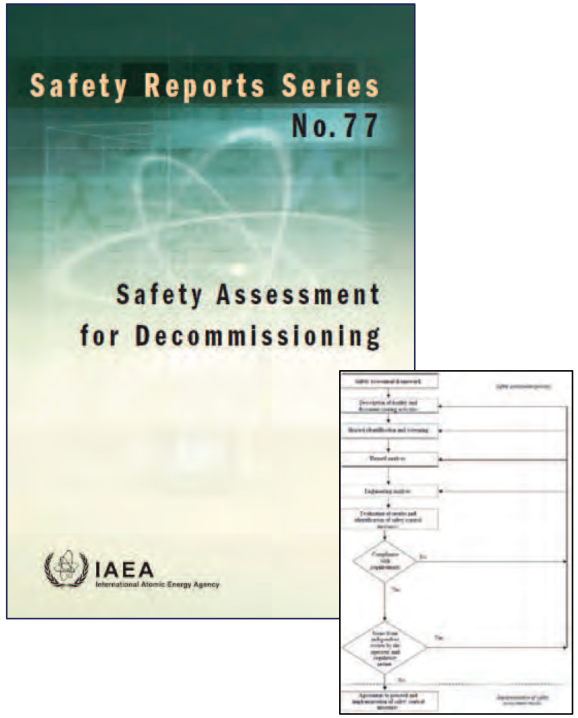
Safety aspects

Objective – **Demonstrating** that laser cutting of RPV and RVI is **at least as safe** as the best techniques currently used.

- Provide answers to the laser-specific safety concerns.
- Generic Safety Assessment available to the European market.



- **WP2, Laboratory Tests** : H_2 and aerosols generation, and residual laser beam power
- **WP3, Workers and environment protection**



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Safety aspects

Preliminary risk analysis performed

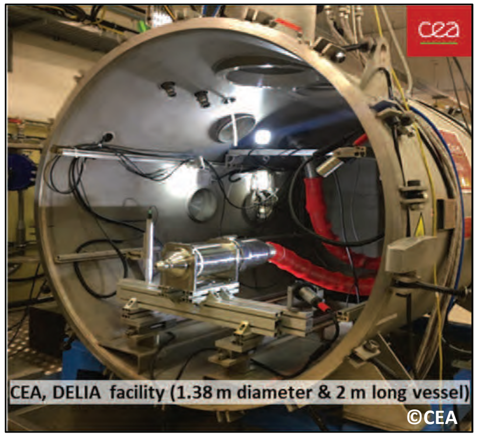
- Identifying and evaluating radiological and conventional risks,
- Identifying safety systems, measures and controls,
- Identifying uncertainties.

Summarized in **Risk Matrixes** for Normal and Accident Conditions

Results should be understood as a **preliminary indication of the level of safety** that can be achieved.

For demonstrating its safety implementation, further information should be gathered:

- **WP2.** Tests and calculations of hydrogen and aerosols generation, and of residual laser beam power (performed in DELIA Facility at CEA Saclay).
- **WP3.** System maturity and integration analysis.
- **WP5.** Demonstration of laser cutting technology safety and efficiency in mock-up (reactor components and conditions simulation).



CEA, DELIA facility (1.38 m diameter & 2 m long vessel) ©CEA

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Safety aspects

Risk Matrixes for Normal and Accident Conditions - "Safety Envelope"

Normal segmentation conditions

			Unoptimized Conditions				Safety Measures and Controls
Situation	Associated Activities	Potential Causes	Probability (1)	Dose to Workers	Dose to Public	Environment	Design options
External Exposure Normal conditions	All activities	Activities in radiation and contaminated areas.	All along the process	Very high if no measures are taken due to highly activated materials	Low	N/A	Remote Operation, robust design, easy installation & decontamination. Shielding, dosimeters, and other Radiation Protection (RP) procedures and controls. Area Radiation Monitoring. Water Level Monitoring. Building off-gas system monitoring and filtration. Training.
Internal Exposure Normal conditions	Segmentation activities	Airborne releases during RPV/RVI cutting. Sublimation of ruthenium to gaseous form (in-air cutting).	All along the process	Very low		N/A	Remote Operation. Dust/aerosols collection system. Contamination Control Confinement (Airlock). Area Radiation Monitoring. Building off-gas system monitoring and filtration.
Effluents and secondary waste Normal conditions	Segmentation activities	Airborne releases, dross generation, and water contamination during RPV/RVI cutting.	All along the process	N/A	N/A	Very Low	Protection of cavity floor. Effluents Monitoring. Auxiliary water filtration systems.
Waste management Normal conditions	Radioactive waste handling and fluxes	Cutting pattern choice	All along the process	Very low	N/A	N/A	Minimize waste generation. Shielding. Online removal of waste. Optimization of waste location considering personnel walking paths.
Hazardous materials exposure Normal conditions	Segmentation activities	Potential generation of hazardous chemical compounds during cutting operations, such as ozone, carbon oxides, nickel carbonyl, nitrogen oxide and toluene. Hexavalent chromium generation during stainless steel cutting.	All along the process	N/A	N/A	Toxicity	Dust/aerosols collection system. Contamination Control Confinement (Airlock). Area Radiation Monitoring.
Maintenance operation Normal conditions	Maintenance (nozzle replacement, support equipment - platform-...)	Maintenance activities, repairs, and replacements.	All along the process	Low	N/A	N/A	Robust design, easy and scarce maintenance. RP procedures and controls. Protective personal equipment.

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Conclusion

Expected impact

- ❑ To support the **European industry** by enhancing the decommissioning sector based on EU safety culture and know-how.

- ❑ To propose an **innovation** (in terms of safety, economic and technical aspects)

➢ **Achieving a world first laser dismantling of a power nuclear reactor!**

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Thank you for your attention!

Q&A

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