Laser Dismantling Environmental and Safety Assessment

PRESS RELEASE

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European H2020 Research & Innovation Project

LD-SAFE

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INTRODUCTION

To propose an innovative cutting technology to the European nuclear decommissioning market, LD-SAFE demonstrated, over the last four years, the maturity of laser cutting technology, in particular the performance, ease of use and safety. This project contributed to facilitate the acceptance of all future end users to implement and use laser technology for RPV/RVI segmentation (PWR and BWR components).
Because LD-SAFE project is now completed, this press release summarizes project context, objectives, tasks and key achievements.

REMINDERS

The forthcoming power reactor decommissioning, particularly the Reactor Pressure Vessel and Internal, 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 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.

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.

MAIN TECHNICAL ACTIVITIES

The main technical activities covering the four years project was the following:

- Laser technology analysis in operational reactor environment: production of analysis and specifications for the use of laser cutting technology in operational reactor environment.

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- 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: implementation of a Technology Qualification process on the laser system in relation with the protection of the workers and environment. A Technology Qualification Certificate (TQC) and guidelines for the industry for use of laser cutting technology in reactor dismantling environment highlighted execution of this appraisal.
- 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 will facilitate the future implementation of laser cutting technology.
- Development of demonstrators for the validation of the implementation and the use of laser cutting technology in a representative reactor environment both in air and under water.

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 was 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 highlighted the key challenges to be checked during the subsequent laboratory tests to assess the risks by using laser cutting technology in reactor environment, but also during the demonstrator at the end.

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:** laser cutting process absorbs only a part of the laser power delivered to the workpiece to melt and cut through it. The unabsorbed laser power, known as residual laser power, propagates beyond the workpiece as optical radiation and can reach mechanical structures behind it, referred to as background structures. This residual laser power's heat can weaken or damage these structures by affecting their mechanical resistance or tightness. The goals of this study were to characterize and assess the impact of residual laser power and the risk of damage to background structures in the context of dismantling nuclear power reactors. Based on the most challenging configurations, laser cutting tests were conducted to collect data and generate charts estimating potential damage for specific workshop setups based on parameters like cutting speed, distance between structures and workpieces, material type, and thickness. Tests in air revealed

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the critical nature of the laser cutting process's initiation phase. Damage extent is influenced by the proximity of the laser beam to the workpiece edge and the background structure relative to the working piece, potentially causing blind kerfs of a few millimeters deep. Moreover, a characterization of the spatial intensity profile of the residual laser beam on a thick graphite plate and an assessment of thermal effects on 304L background structure located at different positions was performed during and after cutting stainless steel plates of various thickness for different process parameters. Results clearly highlighted that cutting speed was the most influential parameter. Therefore, in constrained scenarios, it is advisable to increase the cutting speed to minimize the residual power. Finally, 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.

- **Secondary emissions: aerosols (applicable to both in air and underwater cutting):** 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 particles transport and deposition and particles 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. Previous data on particles generation during cutting of stainless-steel material with various mechanical and thermal tools were reported. Particles generation related to laser cutting technique and mechanical tools was also extensively studied for simulant of corium. 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 particles generation characteristics during laser cutting has been checked extensively during the trials. 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.

- **Hydrogen gas generation during underwater laser cutting:** laser underwater cutting of metallic materials poses specific risks due to the high temperatures involved in the process. This leads to the ejection of molten material and the formation of a heat-affected zone between the melted metal and the unaffected base metal. At such high temperatures, the physicochemical properties of the materials change, particularly the ejected molten material and surfaces oxidize, leading to the generation of dihydrogen (H2). The objectives of this task were to evaluate dihydrogen generation during laser underwater cutting of stainless steel and provide input data to support safety assessment for implementing laser cutting technology. To achieve this, experimental data of the volumetric concentration of H2 have been collected to create abacus charts considering parameters such as material type, cutting speed, workpiece thickness, laser

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power, water level, and assist gas flowrate. Sample cuts were analyzed with a Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS) to map the thickness and chemical composition of the oxide layer formed during and after cutting. Additionally, an analytical study was conducted to understand the physicochemical mechanism of dihydrogen gas generation during underwater laser cutting of 304L stainless steel. This study aimed to establish parametric laws, provide parameters for numerical simulations of the thermal fields generated during cutting with parameters, and calculate the amount of H2 generated for a given test configuration. A method for bounding conditions was demonstrated. Experimental campaigns was carried out to build the abacus charts of H2, under various conditions, including increased laser powers up to 16 kW and thicknesses up to 80 mm. The main results highlighted peak values of H2 volumetric concentration not exceeding 4500 ppm, significantly lower than the Lower Explosive Limit (LEL) of H2, which is 1% (equivalent to 10000 ppm).

The cutting test campaigns on these three safety topics highlighted safety challenges to be implemented in the Generic Safety Assessment.

PROTECTION OF THE WORKERS AND ENVIRONMENT

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.

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.

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 had been successfully mitigated.

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Upon completion of all activities at a satisfactory level, a Technology Qualification certificate 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.

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

At first, a risk analysis was established following a structured process (IAEA SRS No. 77 based on IAEA WS-G-5.2). 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 RPV/RVI 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 the other for abnormal or accident situations. Also, a compilation of all risks identified during laboratory tests and qualification activities have been performed, evaluating its impact on the Generic Safety Assessment.

Then, a Generic Safety Assessment has been developed, considering the outputs from the summary of risks, as well as a lot of other information that became available within other project activities. Major assumptions and uncertainties identified in the risk analysis were solved 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). It is expected that the Generic Safety Assessment will provide an added value to facilitate the safety demonstration of the laser use by the end-user in the frame of the licensing process.

Finally, an independent review performed of the Generic Safety Assessment has been done to ensure the appropriateness of the identified safety measures. The scope and level of detail of the independent review was commensurate with the safety stakes associated with the maturity of the laser technique and challenges of RPV/RVI dismantling tasks. Recommendations are provided to the End User to ensure the interfaces between LD-SAFE and target facility are covered, as well as recommendations to be considered within the safety assessment (including hypotheses to be verified within the industrial demonstrators).

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DEMONSTRATORS

As last part of the project, in-air and underwater demonstrators have been developed.

At first, a case study for the demonstrators was performed to specify the main requirements. The objective was to demonstrate that the laser system:

- Complies with standards and regulatory requirements (for the procurement and the use of laser),
- Has a representative configuration for a dismantling project and is 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).

Then, a complete laser cutting system was developed to comply with all in-air and underwater demonstrator requirements identified previously. This system was composed of:

- Two 20-foot containers for the implementation of the laser utilities These containers were 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 close 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 the laser head and its umbilical implemented in the cutting zone.

This laser system was implemented in a representative nuclear configuration that could be faced in 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.

In regards with both demonstrators, general cutting scenarios for PWR and BWR dismantling activities with laser have been studied. According to these scenarios, test programs were 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 address qualification tasks.

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

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In-air cutting operations have 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,
- Several layers can be cut at the same time thus inducing time savings.

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 is not an issue for the laser cutting technology,
- Multi-layer 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-layer 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.

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% and optimal cutting speeds have been assessed to ensure cutting time reduction.

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.

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

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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.

Based on these results, a Generic Safety Assessment has been developed (and reviewed independently), in consistency with IAEA 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 developed, incorporating 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, online courses 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. They 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.

Before the end of the LD-SAFE project, laser cutting technology has already been selected as 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

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evidence provided during the LD-SAFE project and thanks to all laser projects carried out in parallel at Onet Technologies.

Societally, the development of laser cutting technology will 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.

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FOLLOW US

Please continue to visit our LD-SAFE project website (https://ldsafe.eu/) to have access to all public deliverables such as:

- Guidelines for the use of laser cutting in reactor dismantling environment
- Generic Safety Assessment
- A Technical validation report
- Online course on cutting technologies

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