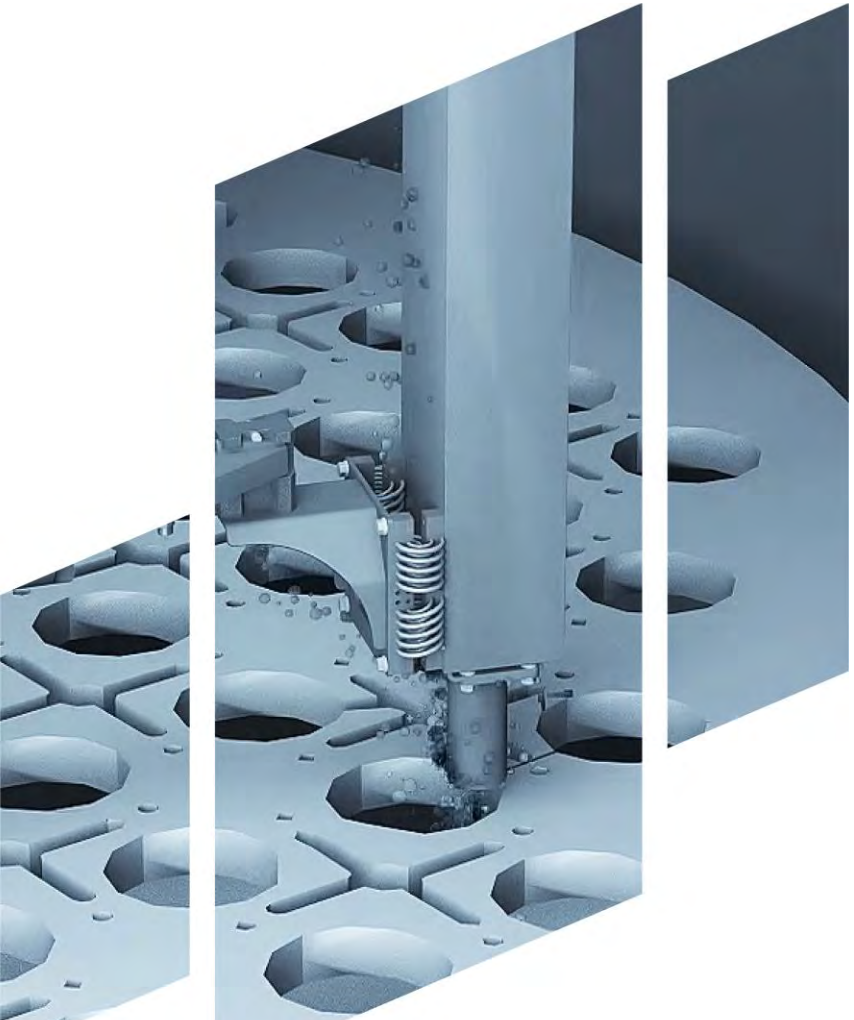
8.5. Training course content (presented to the students)

Laser Cutting for Nuclear Reactor Dismantling

LD-SAFE TRAINING COURSE



Date: 31st May 2024

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European Commission

Horizon 2020
European Union funding
for Research & Innovation

Laser Cutting for Nuclear Reactor Dismantling

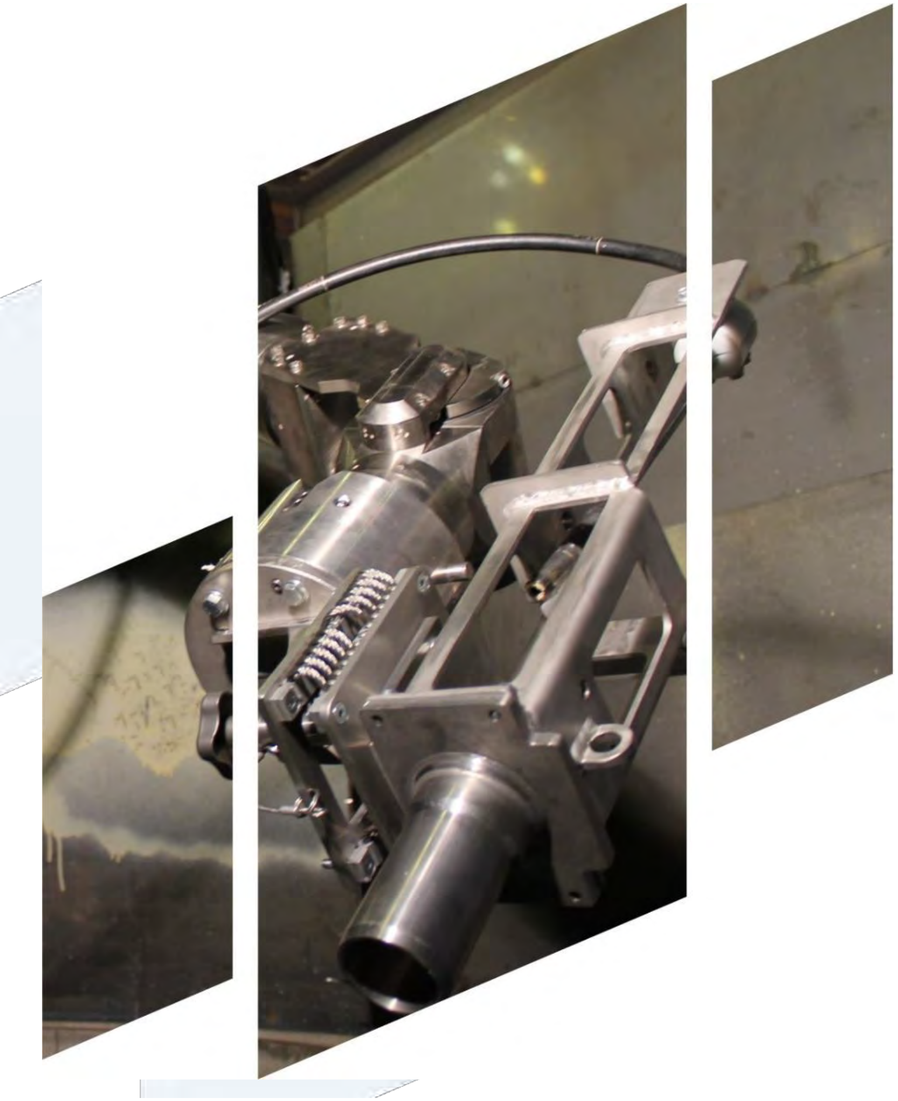
LD-SAFE Training Course

CONTENT

1. Introduction to Laser Cutting for Nuclear Decommissioning
2. Laser Cutting Technology
3. Conventional Cutting Techniques – Comparative Analysis
4. Reactor Pressure Vessels and Internals Segmentation in Nuclear Reactors
5. Safety Aspects
6. Technology Qualification and Demonstrators
7. Conclusions

Laser Cutting for Nuclear Reactor Dismantling

LD-SAFE Training Course



1. Introduction to Laser Cutting for Nuclear Decommissioning

- *Context of nuclear decommissioning*
- *Challenges of RPVI and RVI dismantling*
- *Laser cutting - Previous experiences*
- *LD-SAFE Project and associated objectives*

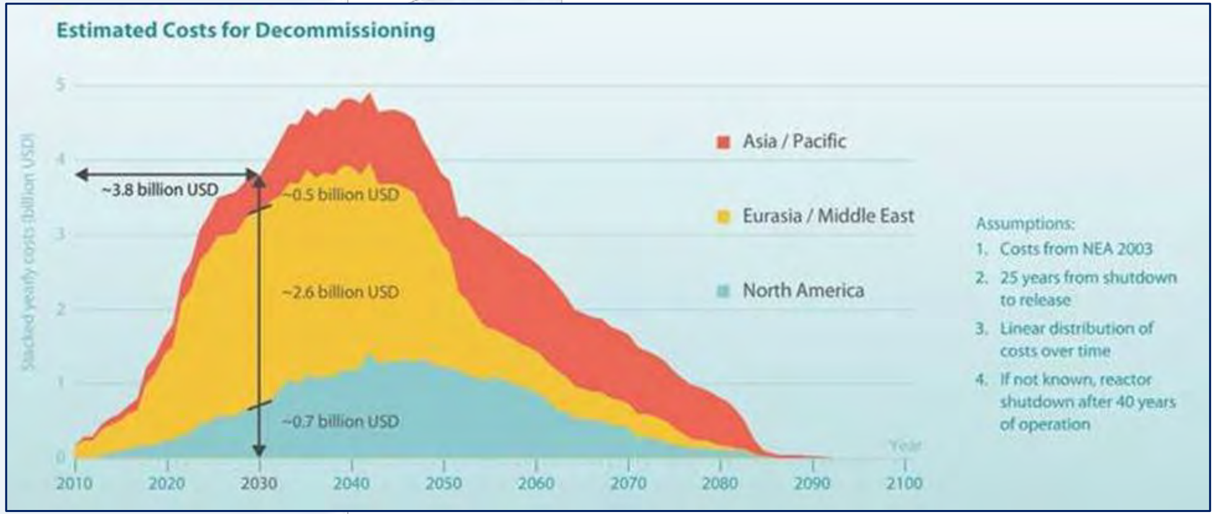
Introduction to Laser Cutting for Nuclear Decommissioning

Context of nuclear decommissioning

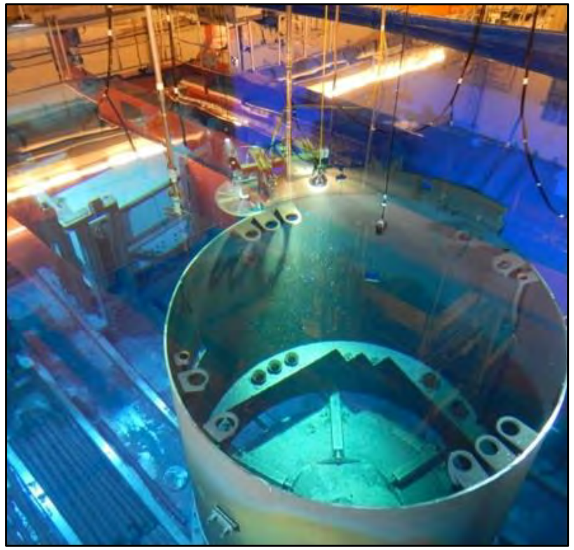
Up to now, only a few Nuclear Power Plants (NPPs) have been fully decommissioned.

For the immediate future, the field will imply a big effort, but also, represents an opportunity for improvement:

- There is need for improvement of processes, especially key activities such as **Reactor Pressure Vessel (RPV) and Internals (RVI) segmentation**.
- Removal of the main components of the RPV/RVI is one of the most challenging tasks in the decommissioning of NPPs (high thicknesses, high activation, space constraints…).



Decommissioning Case Studies.
Source: IAEA



Core shroud of RVI at Barseback-2 (BWR).
Source: Westinghouse

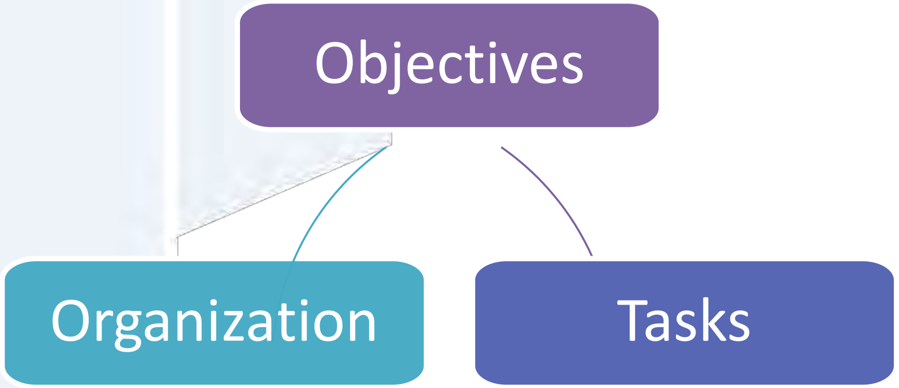
Introduction to Laser Cutting for Nuclear Decommissioning

LD-SAFE Project and associated objectives

Room for innovative technologies that improve safety, radiation protection, waste management, time, and cost.

LASER CUTTING

Most challenges are addressed within a European research and innovation project called **LD-SAFE, “Laser Dismantling Environmental and Safety Assessment”,** which is focused on the use of laser cutting technology for dismantling nuclear power plants.

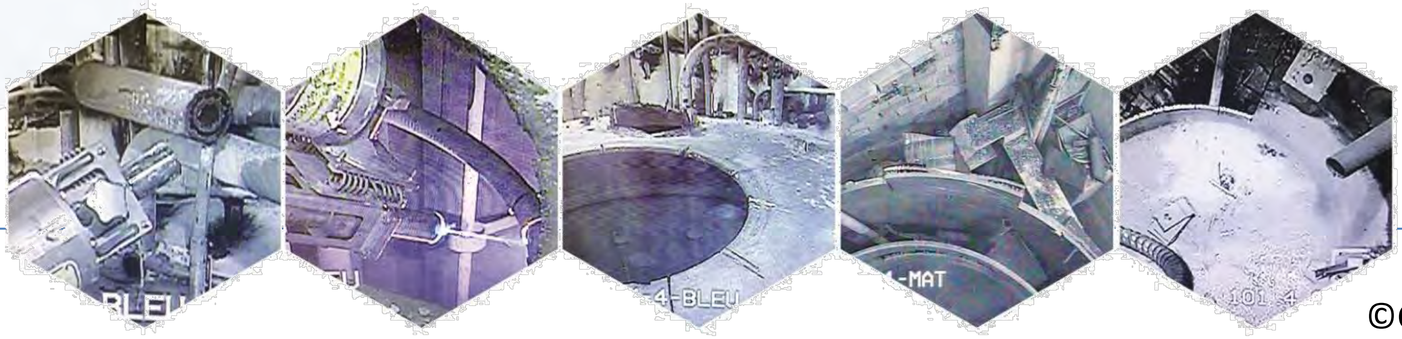


Introduction to Laser Cutting for Nuclear Decommissioning

Laser Cutting - Previous Experiences

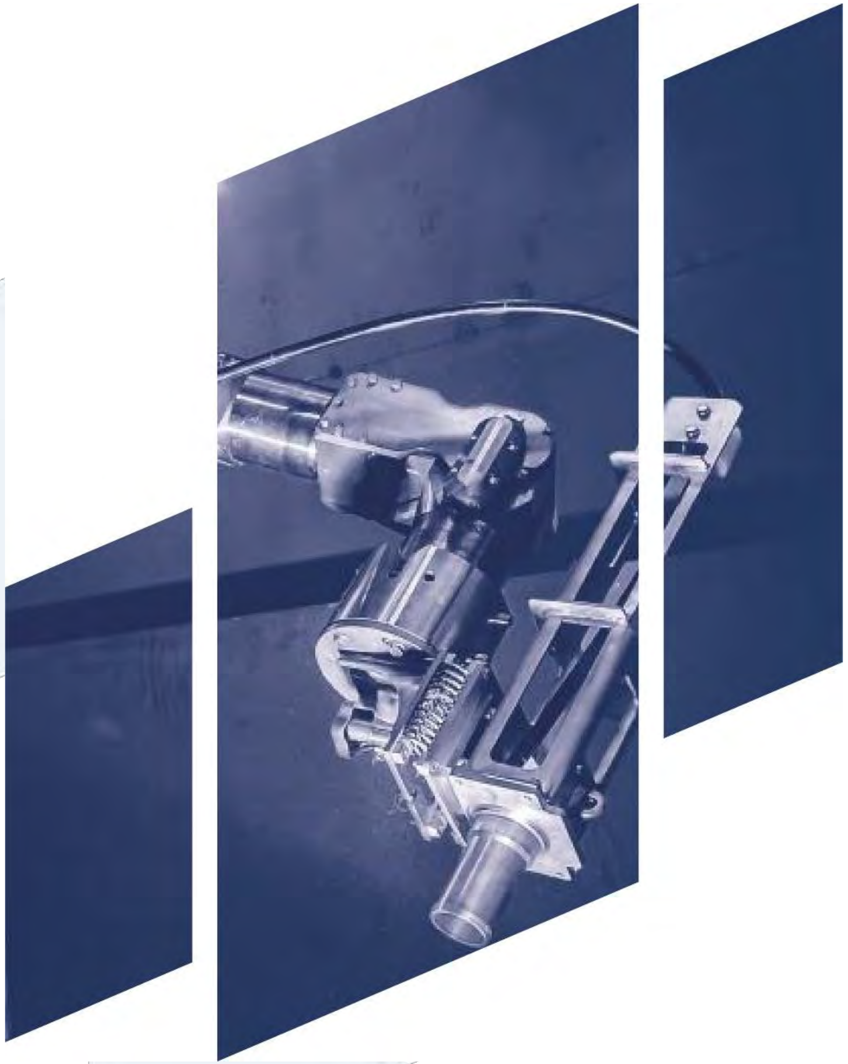
Why Laser Cutting?

- Widely known in the conventional industry for cutting and welding.
- More than 10 years of Research and Development in laboratory trials.
- Tested with satisfactory results in various materials.
- Versatile tool for complex shapes such as tubes, plates, or multi-thickness.
- Already implemented in dismantling activities for fuel cycle and research facilities (Robot Laser Snake at DRAGON experimental reactor, CHARLI robot at SUPERPHENIX, radwaste laser cutting in La Hague, laser cutting of dissolution tank in Marcoule).



Laser Cutting for Nuclear Reactor Dismantling

LD-SAFE Training Course



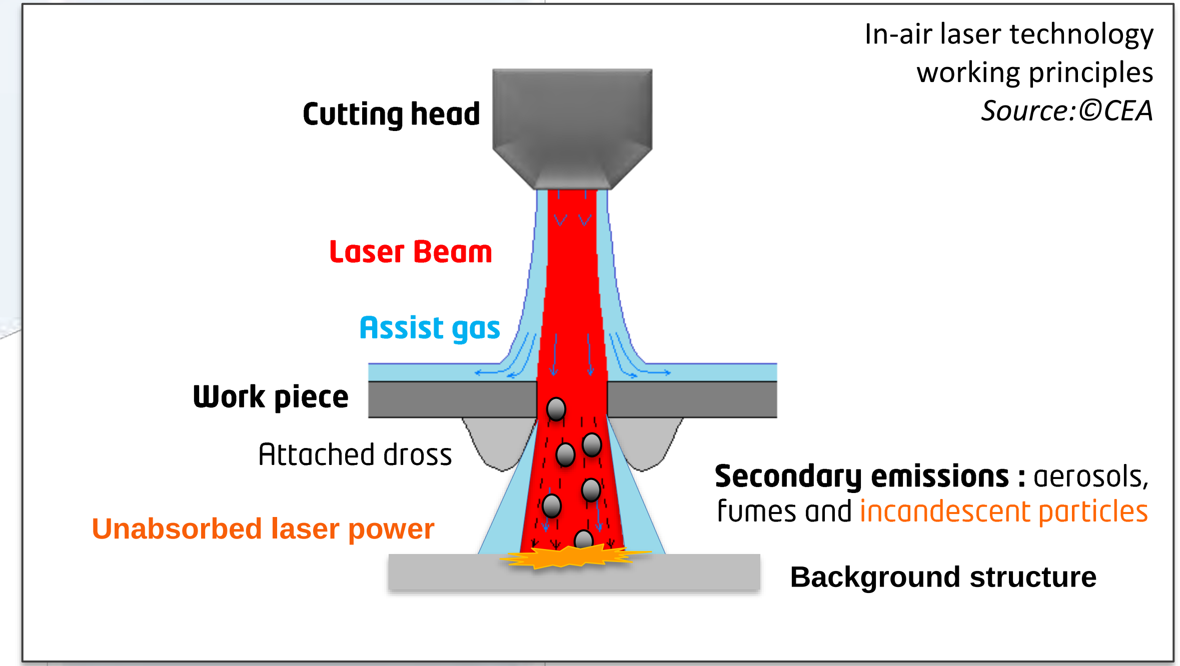
2. Laser Cutting Technology

- *Working principles*
- *Components of the laser cutting system*

Laser Cutting Technology
Working principles

In-air laser cutting working principles:

- **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.



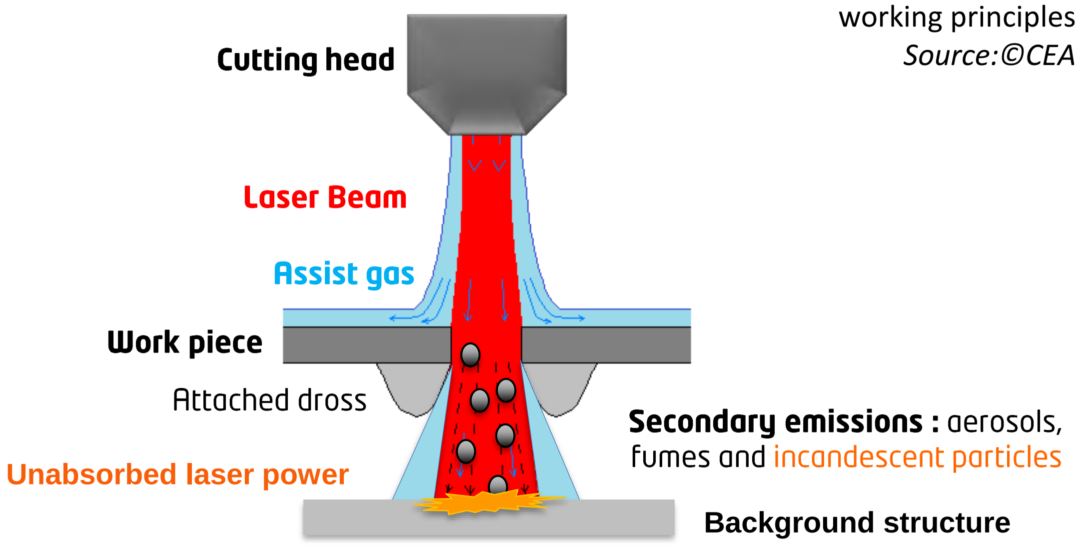
Laser Cutting Technology

Working principles

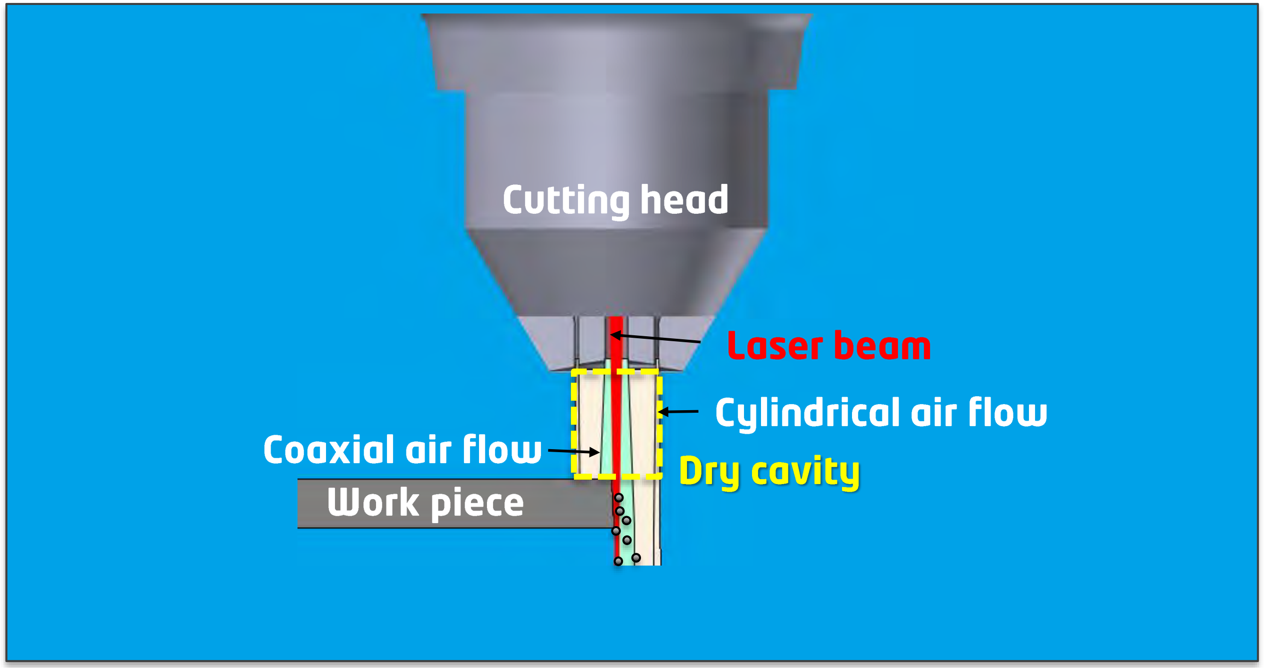
Underwater laser cutting based on **dry cavity concept:**

→ **Laser beam propagates in air** between the laser head and the work piece and in the kerf

→ With no laser power loss due to water absorption



Underwater laser technology working principles
Source:©CEA



Laser Cutting Technology

Implementation

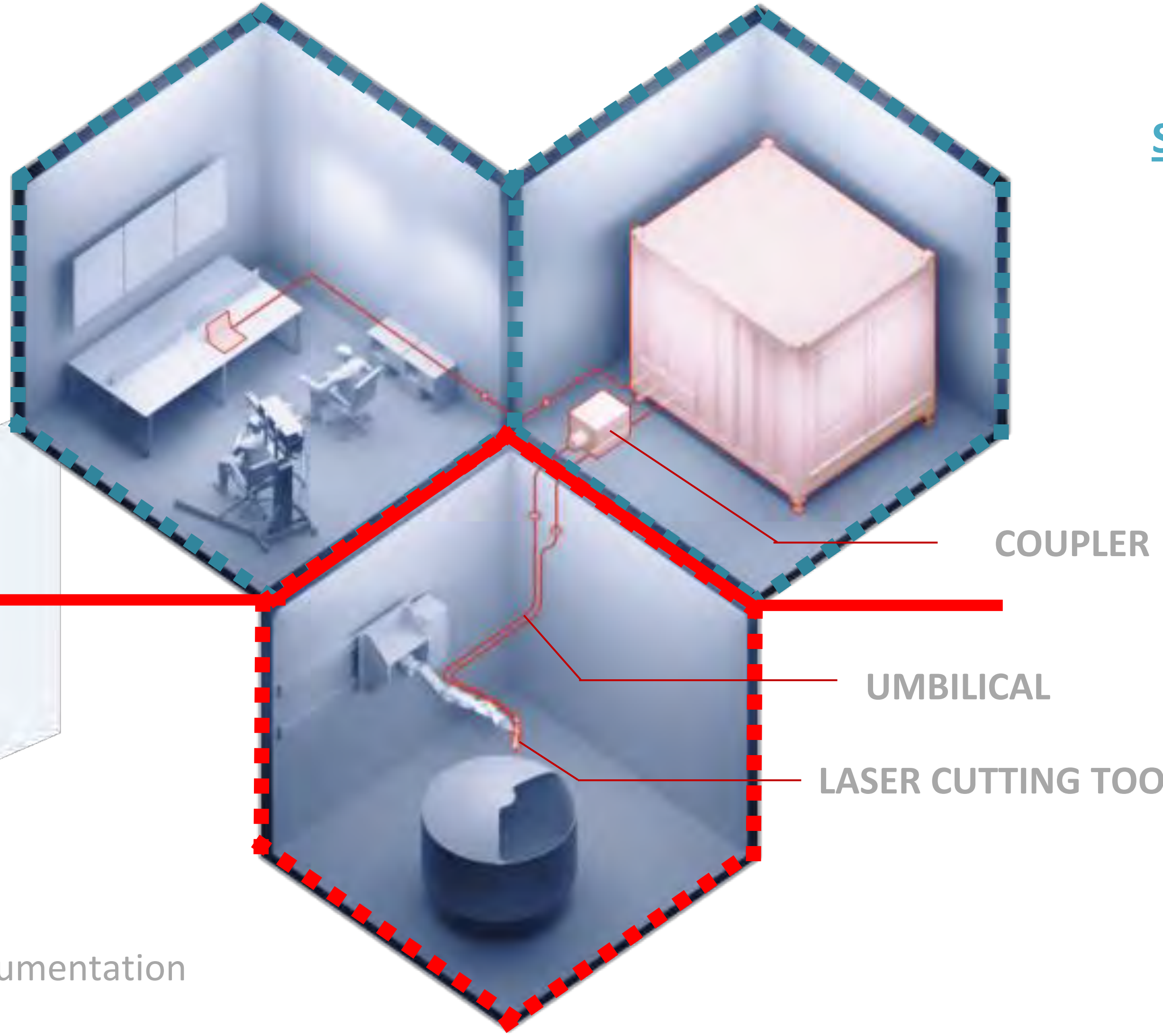
Already deployed at MAR200-UP1, CEA Marcoule

Control ROOM

- Control software
- Monitoring

SHELTER ROOM

- LASER Source
- Utilities
- Electrical Control & Instrumentation



Contaminated zone boundary

DISMANTLING AREA

- Dismantled equipment
- AIR/WATER supply
- Radiation resistant instrumentation

Laser Cutting Technology

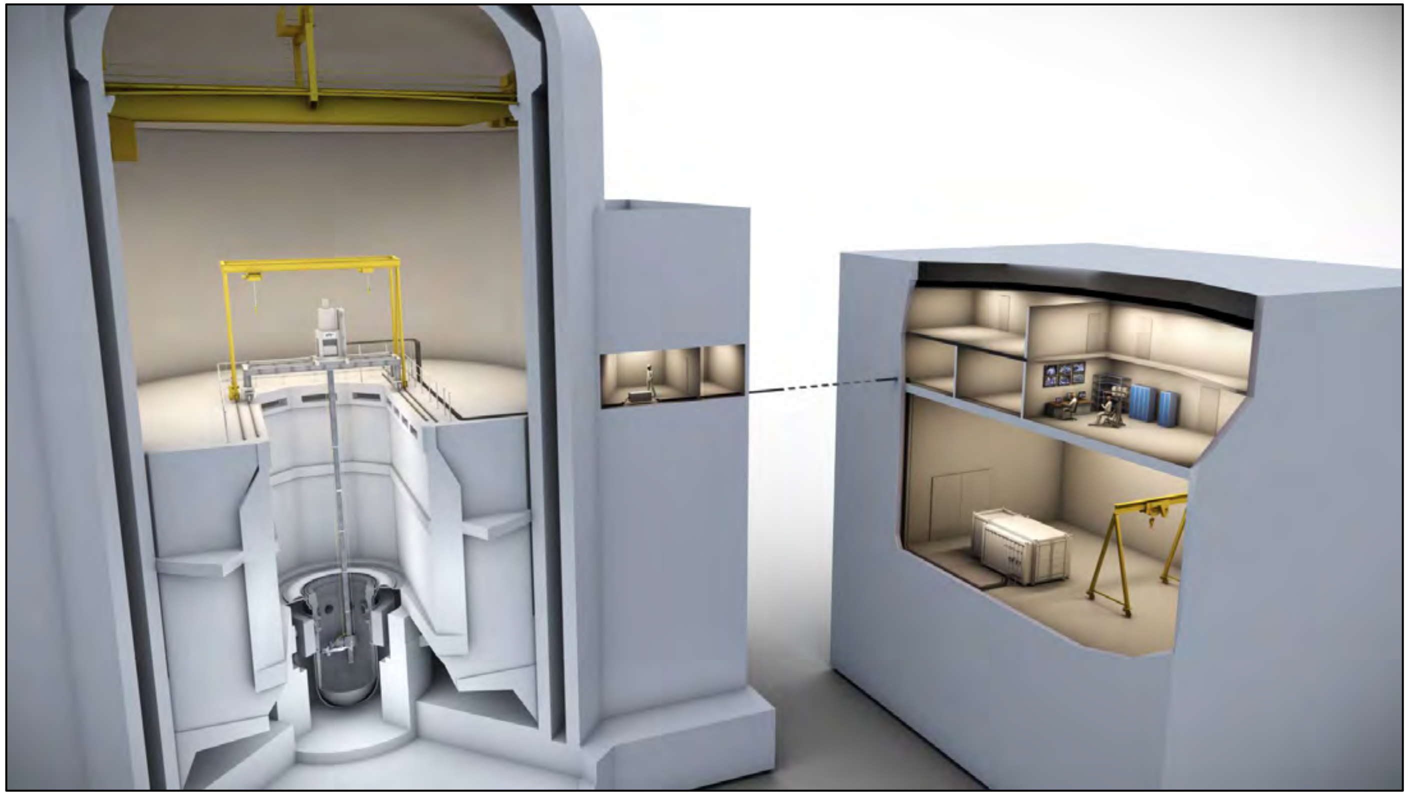
Components of the laser cutting system

MAIN COMPONENTS

- **Laser Technology Process Equipment**

Laser Source	Cutting Head	Optical Fiber & Coupler
Fluid Distribution	Control units	

- **Manipulator**: specific to work zone conditions and configurations.



Laser Cutting Technology

Components of the laser cutting system

LASER SOURCE

It generates the laser beam, which travels to the laser head through the optical fiber.

Laser power is adjustable:

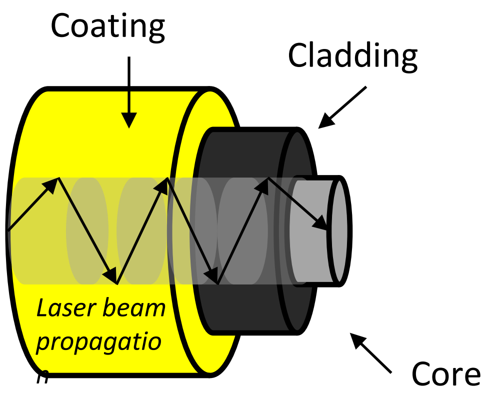
- Typical range: 320W to 16 kW
- Studied in LD-SAFE: up to 16 kW
- Projections for near future: 50kW

L.DCom®, under CEA license

OPTICAL FIBER

It transports the high-power laser beam throughout the glass core.

The reflectivity difference between core and cladding helps to maintain the beam directed.



LD SAFE
Laser Dismantling Environmental and Safety Assessment

Laser Cutting Technology

Components of the laser cutting system

In-air cutting
laser head

Source of image: *CEA*

LASER CUTTING HEAD

- Directing the laser beam and assist gas for cutting the piece.
- It is connected to an **umbilical cable**, containing the optical fiber and two additional lines:

Air supply, serving several purposes:

1. Cooling the cutting head;
2. Blowing the molten material away;
3. Opposing the entry of pollutants into the laser head.
4. For underwater cutting, generating the **dry cavity**.

Water supply for laser head cooling.

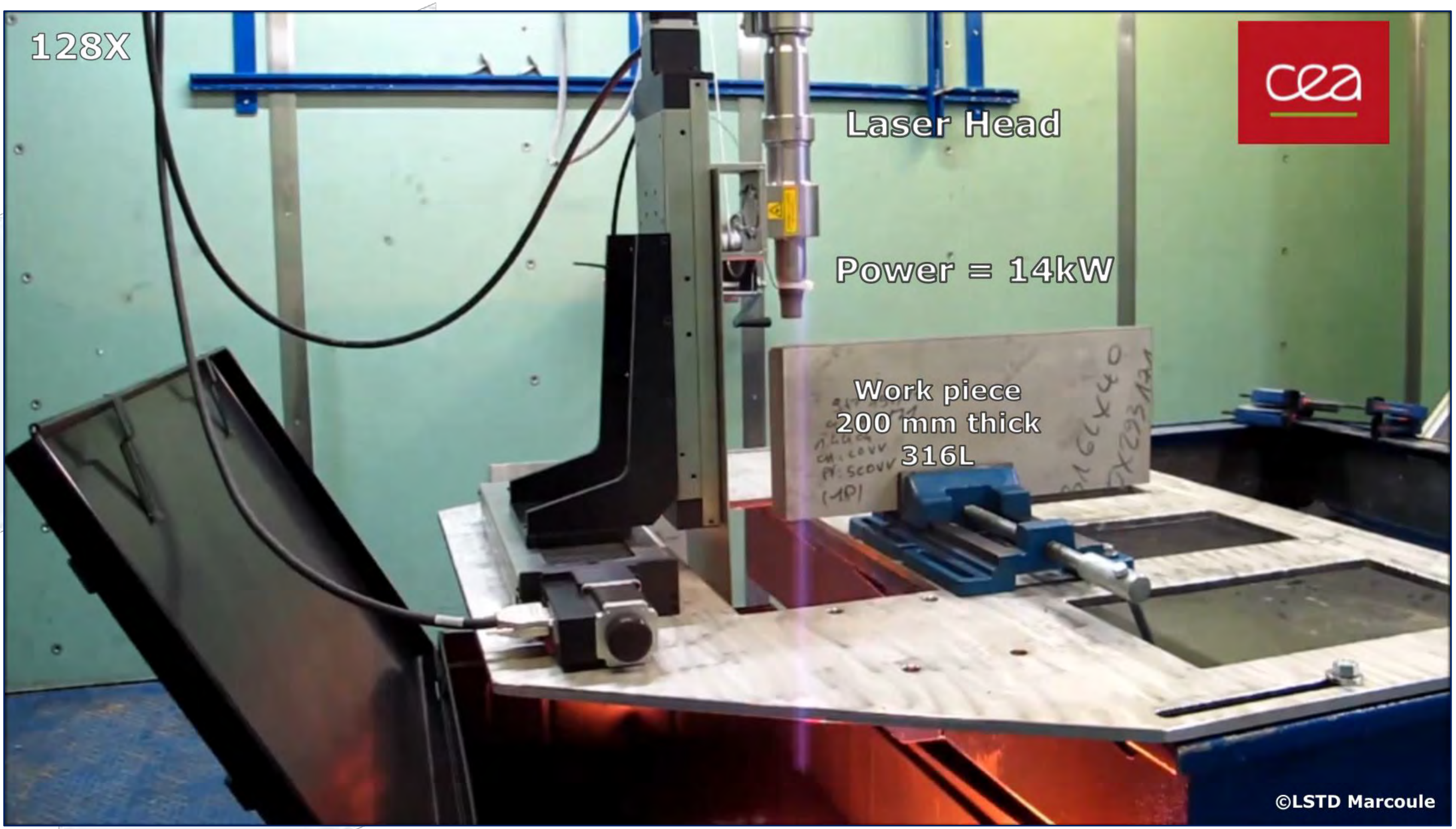
CONTROL UNIT

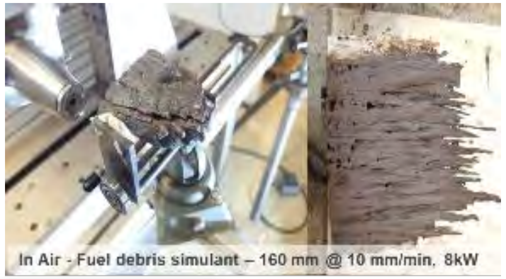
Equipment and software that controls the laser cutting-system.

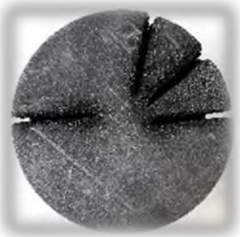
L.DCom®, under CEA license

Laser Cutting Technology

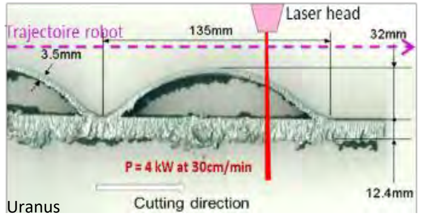
Cutting performances and other relevant aspects







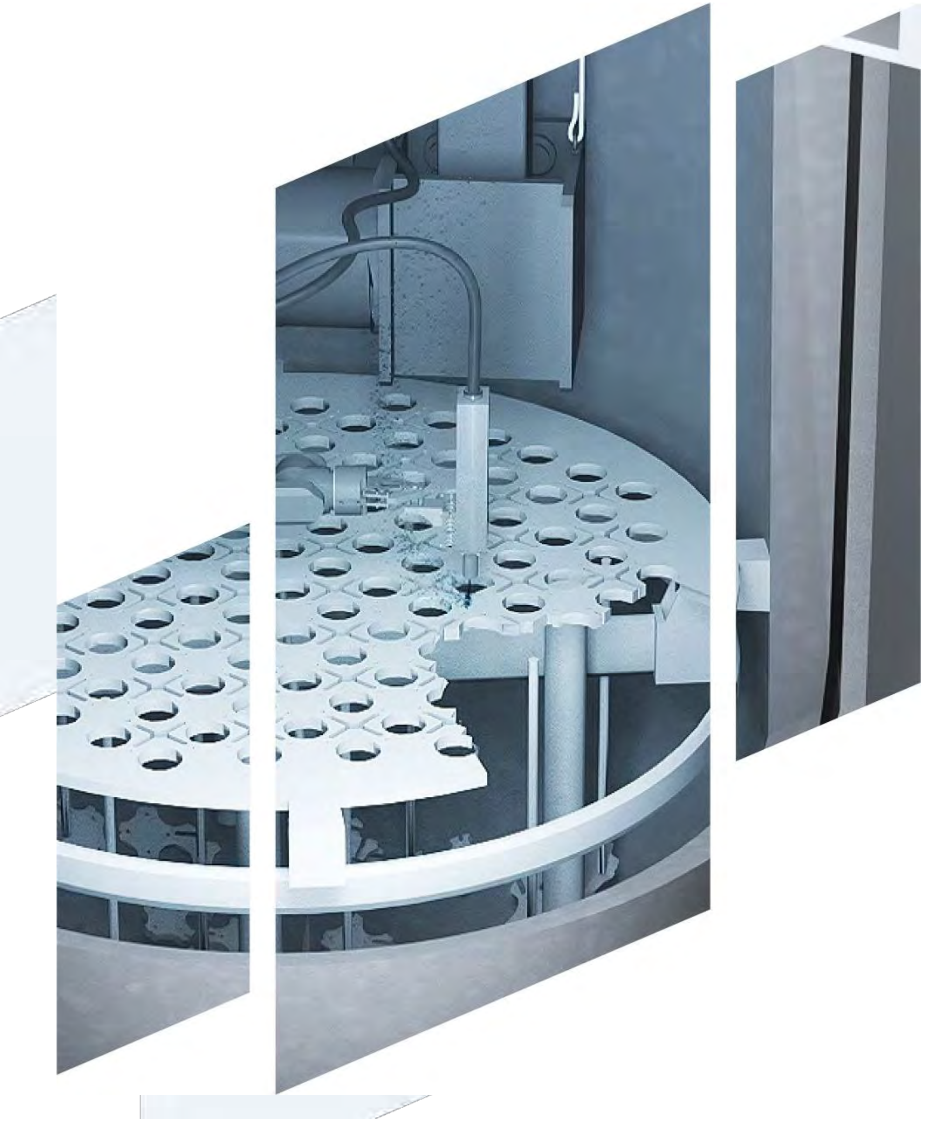
Multipass cutting:
60 mm thick graphite @ 8kW



Note: Underwater laser technology state-of-the-art:
Up to 80mm (8 to 16kW). 100mm reached in specific configuration.

Laser Cutting for Nuclear Reactor Dismantling

LD-SAFE Training Course



3. Conventional Cutting Techniques – Comparative Analysis

- *Conventional techniques to dismantle nuclear reactors*
- *Comparative analysis with the laser cutting technique*

Conventional Cutting Techniques – Comparative Analysis

Conventional techniques to dismantle nuclear reactors

Great number of conventional cutting technologies, being the main selection factors:

- Occupational safety and optimization for radiation protection
- Secondary waste minimization
- Reliability and maintainability
- Process safety
- Easiness to operate
- Cutting capacity

Note: A large number of tools (up to 10) and handling systems (up to 6) are used in a dismantling project (and potentially a combination of all types).

Thermal Cutting

- Oxygen Cutting
- Plasma Arc Cutting (PAC)
- CAMX-Processes
- Laser Beam Cutting

Mechanical Cutting

- Shearing
- Sawing
- Grinding
- Blasting
- Milling

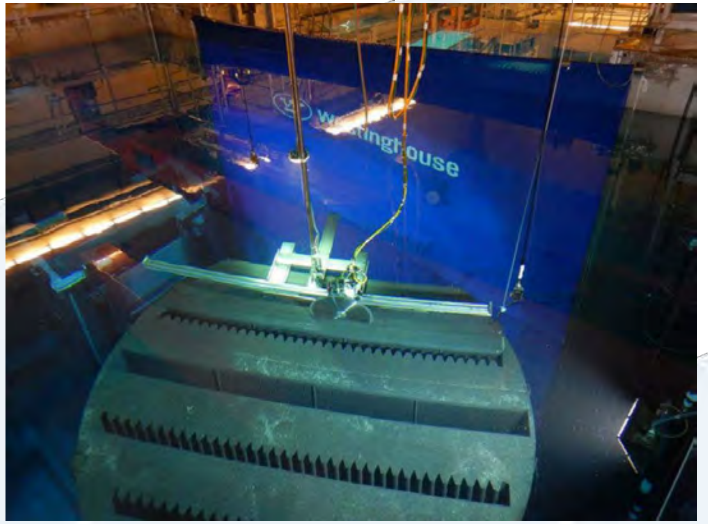
Hydraulic Cutting

- Abrasive Water Injection Jet (AWIJ)
- Abrasive Water Suspension Jet (AWSJ)

Conventional Cutting Techniques – Comparative Analysis

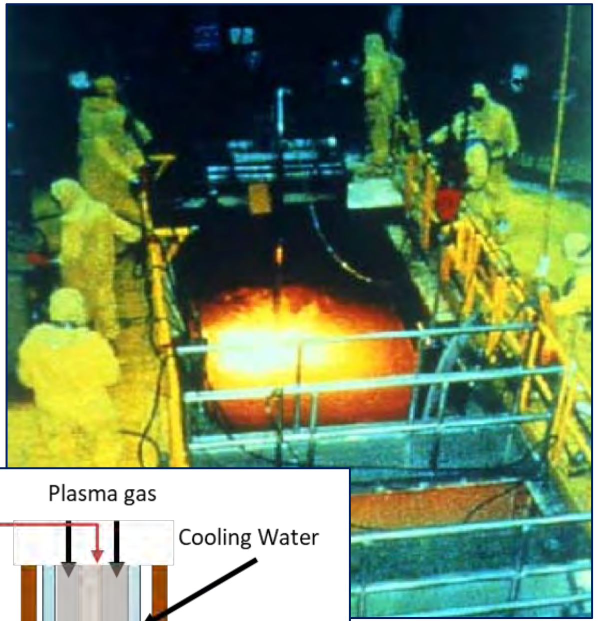
Conventional techniques to dismantle nuclear reactors

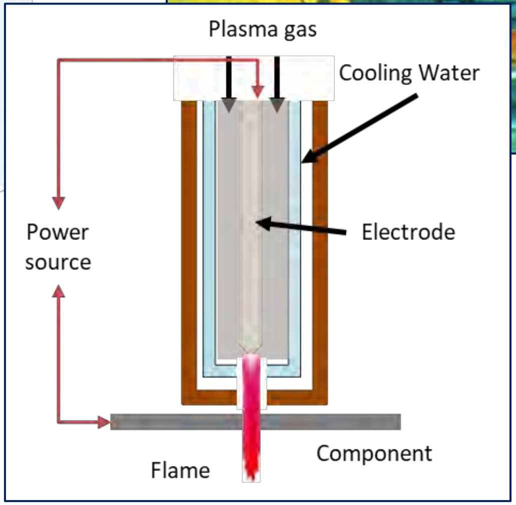
MECHANICAL CUTTING



Disc saw cutting of Barsebäck-2 steam dryer. Source: Westinghouse.

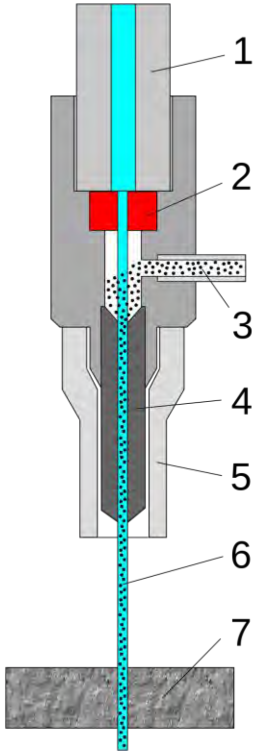
THERMAL CUTTING



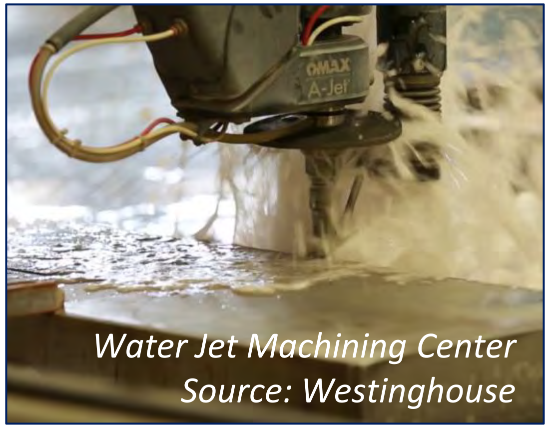


PAC at Fort St. Vrain Reactor Source: Westinghouse

HYDRAULIC CUTTING



1. High-pressure water inlet; 2. Jewel; 3. Abrasive; 4. Mixing tube; 5. Guard; 6. Cutting water jet; 7. Cut material



Water Jet Machining Center Source: Westinghouse

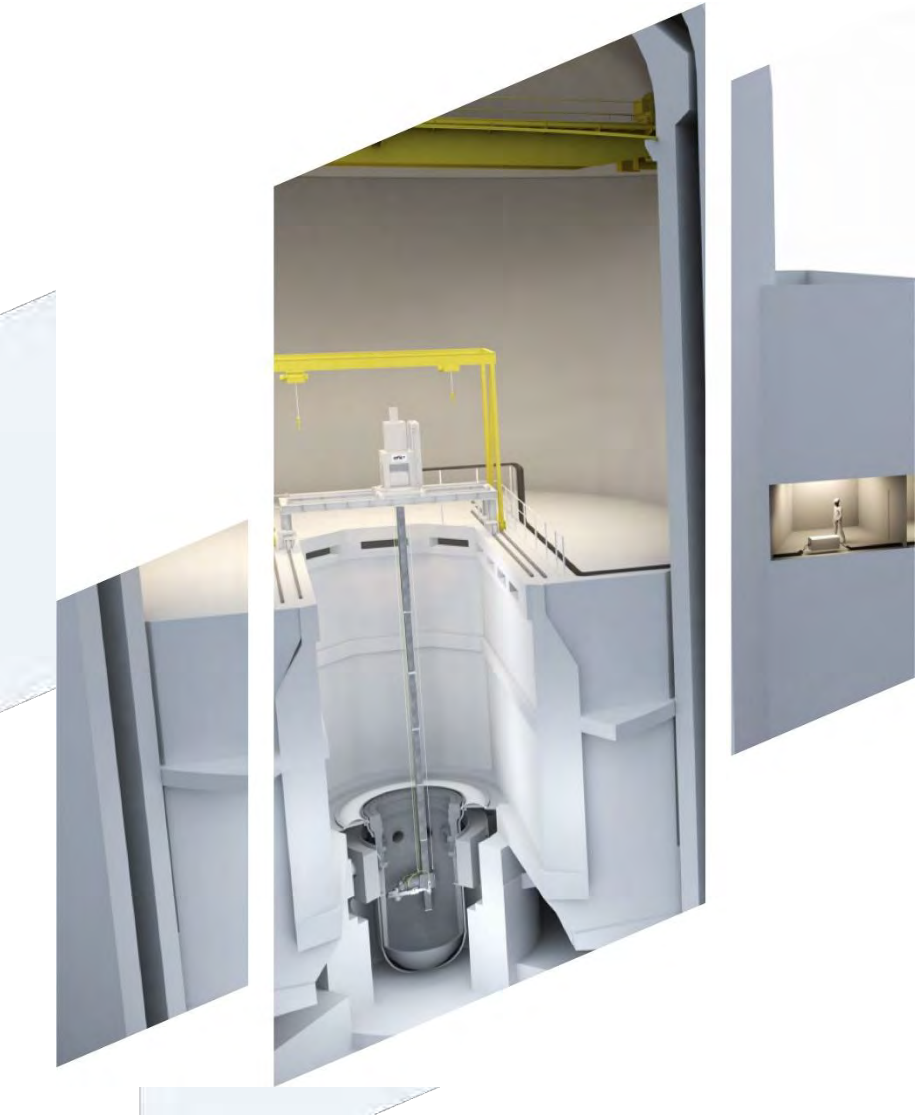
Conventional Cutting Techniques – Comparative Analysis

Comparative analysis with the laser cutting technique

COMPARATIVE ANALYSIS

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

Conventional cutting techniques



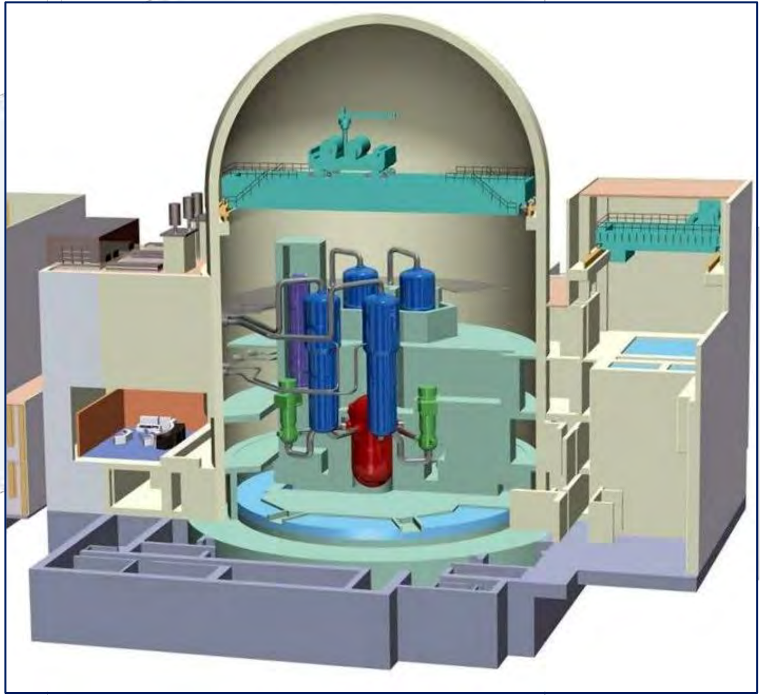
4. Reactor Pressure Vessels and Internals Segmentation in Nuclear Reactors

- *Reactor pressure vessel and internals*
- *Segmentation plan*

RPV/RVI Segmentation in Nuclear Reactors

Reactor Pressure Vessel and Internals

Reactor Pressure Vessel (RPV) and Reactor Vessel Internals (RVI) of Light Water Reactors are contained within the Reactor Building.



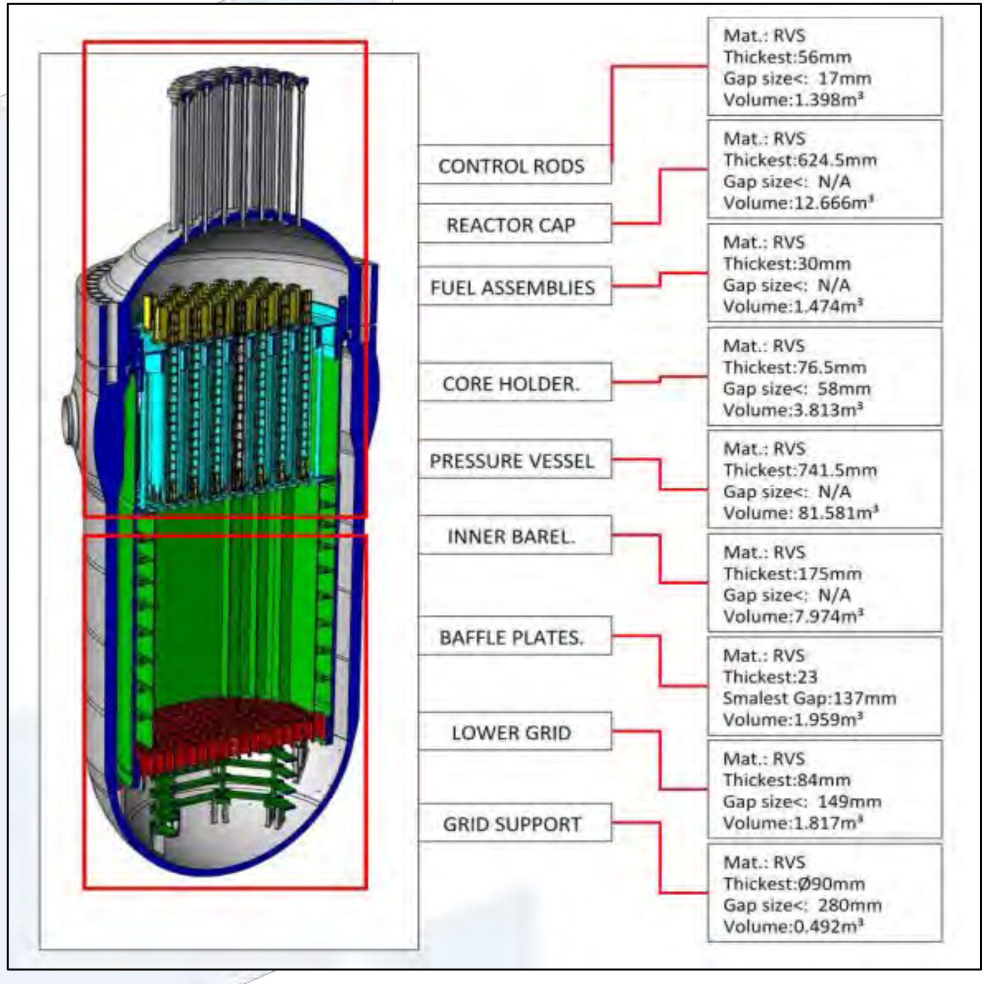
Typical Pressurized Water Reactor (PWR) Containment. RPV/RVI highlighted in red.
Source: U.S. NRC

Reactor Pressure Vessel	Reactor Vessel Internals
• **Simple structure, with large thickness (>150 mm, 300 mm in some areas)** • Cylindrical structure with two hemispherical heads, the bottom one welded and the upper one removable. • Made of Carbon Steel with small Inconel or Stainless-Steel layer (around 4 mm).	• **Complex structure, with variable but relatively thinner thicknesses.** • Designed to support core, align fuel, and direct water flow. • Major components are of Stainless-Steel. • Differentiated parts, which specific design depends on the reactor type (PWR/BWR).

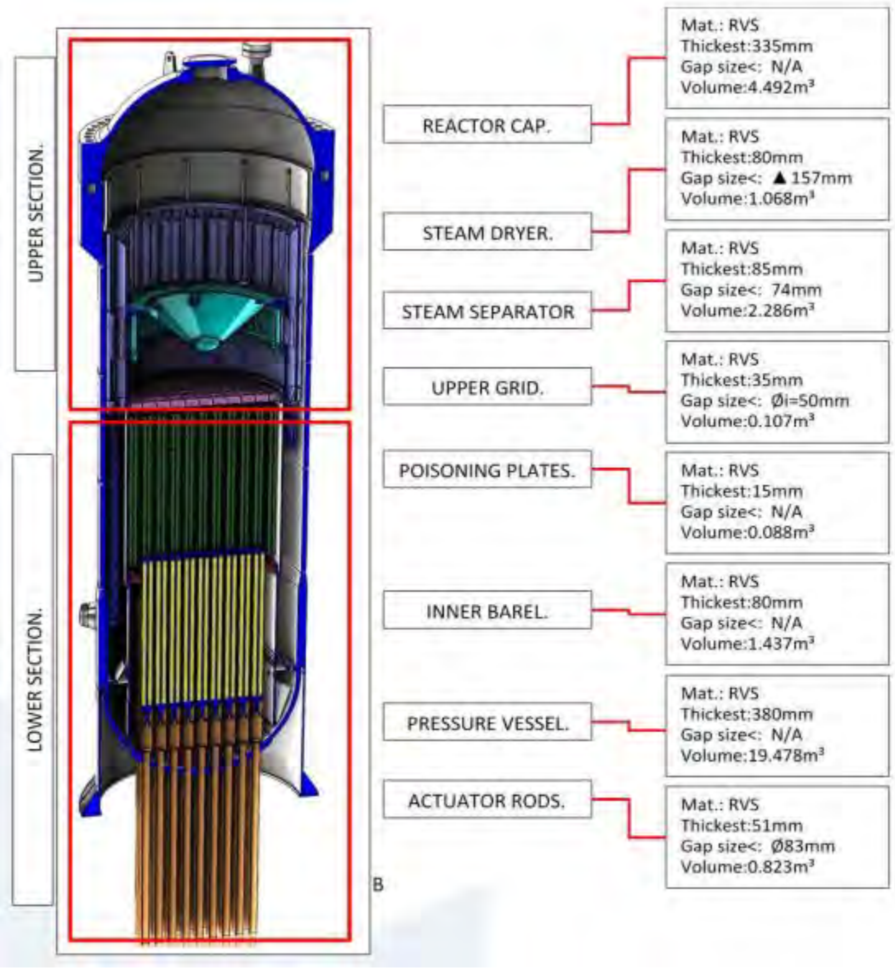
RPV/RVI Segmentation in Nuclear Reactors

Reactor Pressure Vessel and Internals

Pressurized Water Reactor (PWR)



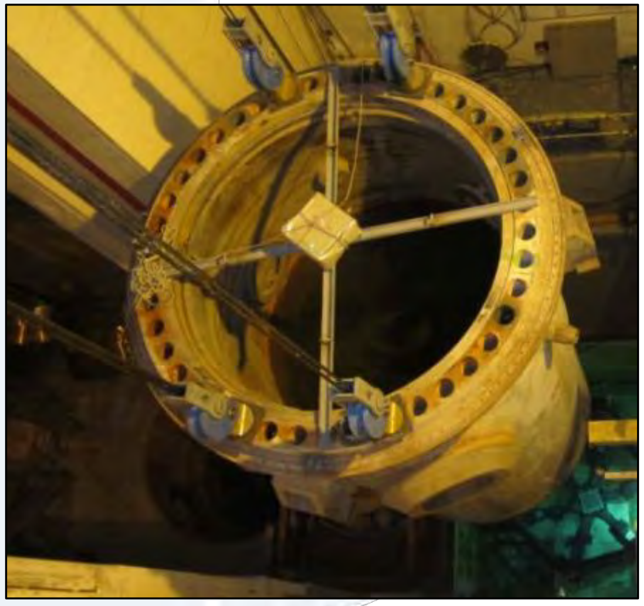
Boiling Water Reactor (BWR)

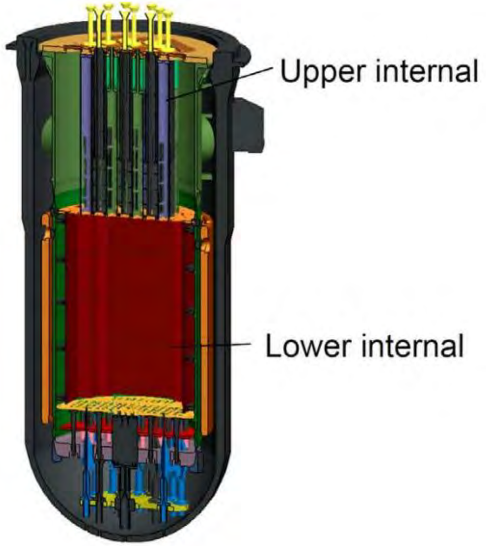


RPV/RVI Segmentation in Nuclear Reactors

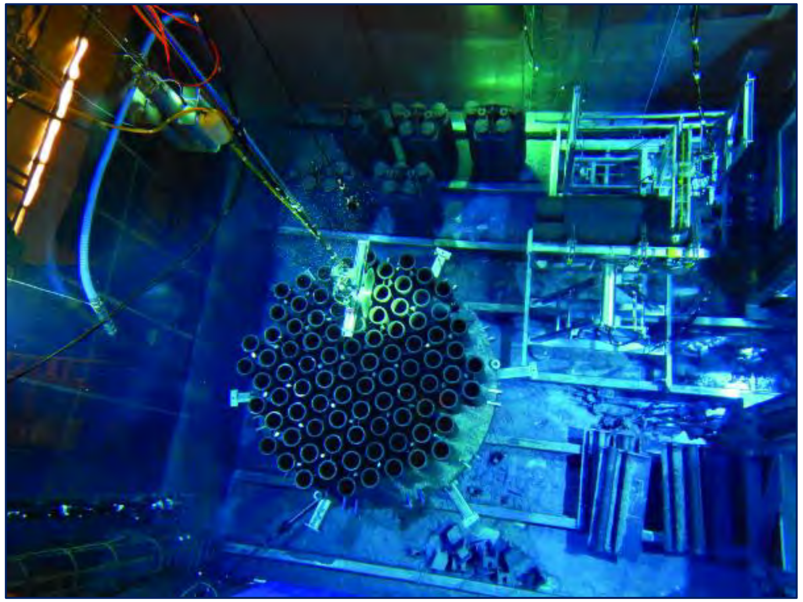
Reactor Pressure Vessel and Internals

RPV of Jose Cabrera NPP





RVI of Jose Cabrera NPP



RVI of Barsebäck NPP (steam separator cutting, Westinghouse)

RPV/RVI Segmentation in Nuclear Reactors

Reactor Pressure Vessel and Internals

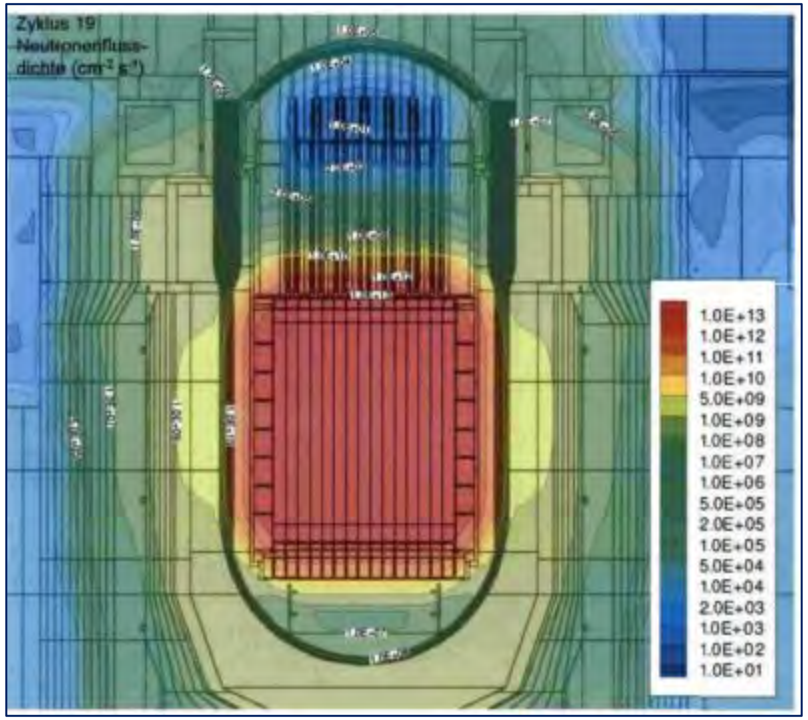
<u>Radiological Constraints</u>

- Highly activated components due to operation neutron flux.
- Maximum activation levels are found in the internals, in the mid-section (core shroud), coinciding with the central core region.

Removal of <u>**highly activated components**</u> is usually the most challenging part, due to Radiation Protection constraints.

KEY CAPABILITIES OF LASER CUTTING

- Remote cutting
- Adaptability to different cutting directions for optimizing radioactive waste packages.
- In situ cutting operations without bespoke mechanical systems (i.e., cranes, tables…).



Example of neutron flux within the RPV/RVI RPV.
Source: Occupational ALARA Planning for RPV Dismantling at Kori Unit 1, KEPCO International Nuclear Graduate School, Hameaji-ro et. Al.

RPV/RVI Segmentation in Nuclear Reactors

Segmentation Plan

TYPICAL SEGMENTATION STEPS

1. Reactor Vessel Head removal/cutting
2. Internals staged removal from vessel to cutting location for subsequent underwater cutting
3. **CUTTING PROCESS OF INTERNALS** (top-down process)
4. Possibility to relocate the RPV to a defined cutting location
5. **RPV CUTTING** (IN-AIR OR UNDERWATER)

3

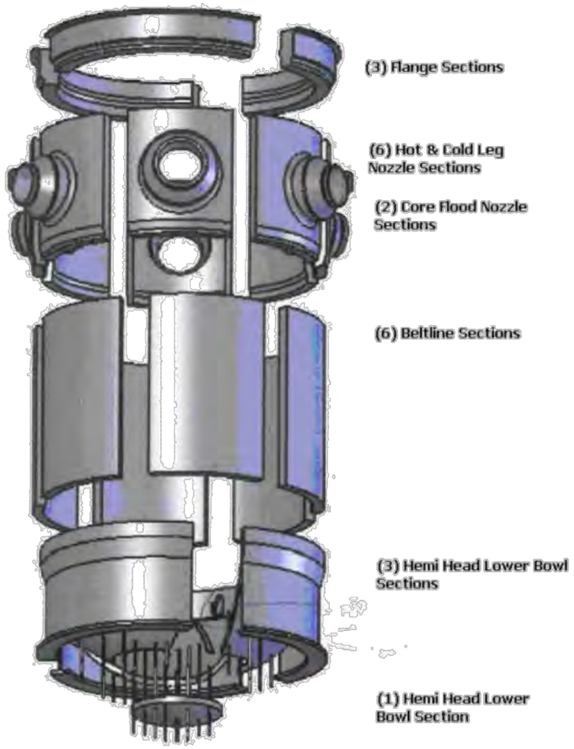
- Steam Separator & Dryer Assemblies (BWR) / Upper Core Support (PWR)
- Top guide & poisoning plates (BWR) / Control rods guide tubes (PWR)
- Core plate & control rods & fuel channels (BWR) / Upper core support grid plate (PWR)
- Poisoning plates / Baffle, core shroud and lower core support grid plate

RPV/RVI Segmentation in Nuclear Reactors

Segmentation Plan

Segmentation plan is completely conditioned by national criteria and requirements regarding waste management strategies, routes, and associated packages.

Trojan Reactor final disposal in one piece without segmentation.
Source: American Ecology



Rancho Seco segmentation by AWJ and diamond wire saw.

Source: EPRI

Segmentation plan of José Cabrera upper core barrel.

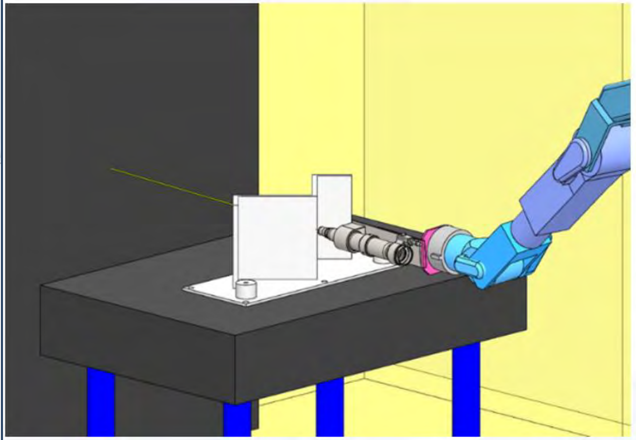
Source: Westinghouse

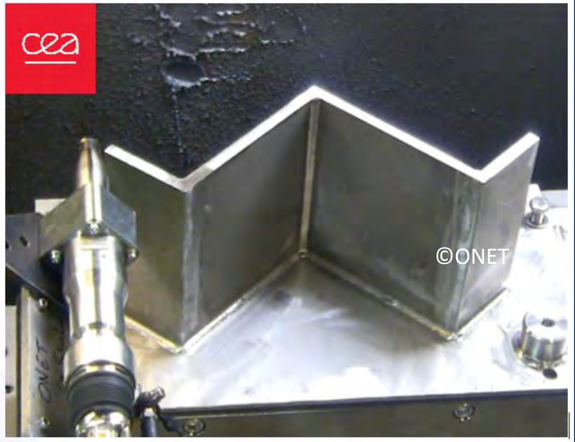
RPV/RVI Segmentation in Nuclear Reactors

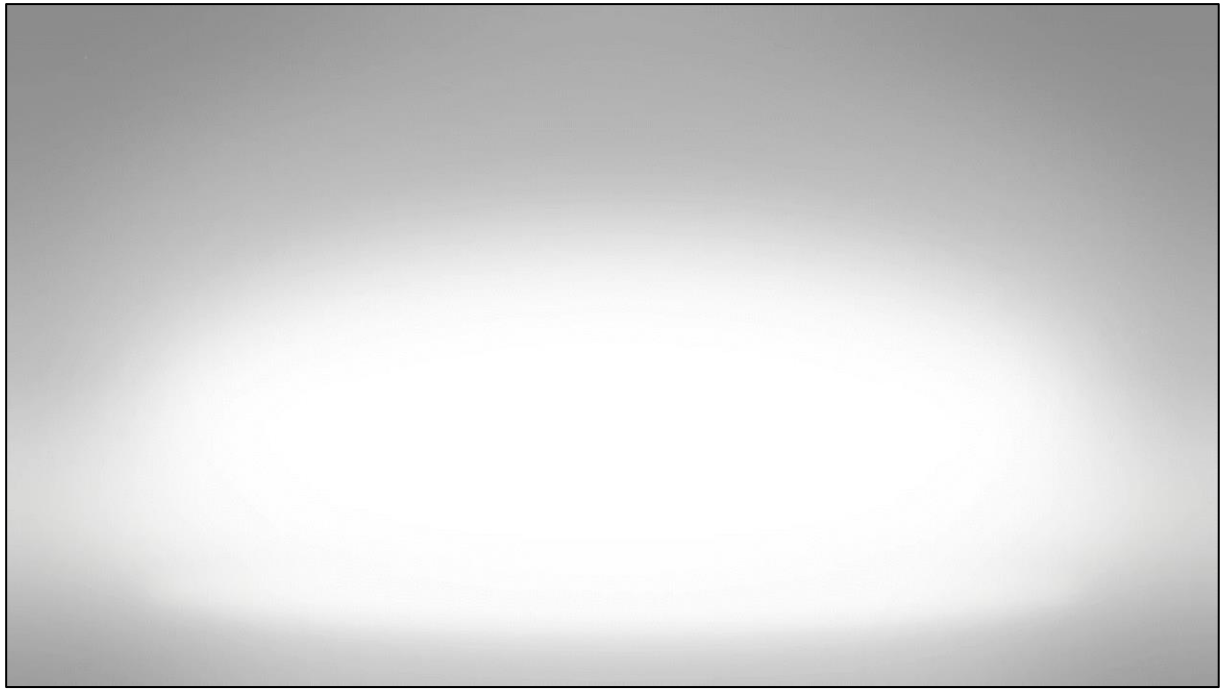
Segmentation Plan

LASER CUTTING PRESENTS KEY ADVANTAGES

- Cutting flexibility (i.e., variety of angles of attack allowing optimizing filling grade).
- Only one cutting tool can do the job (i.e.,, underwater laser head can do operations in-air and underwater).
- Potential to avoid the relocation of components to another cutting location.







In-air cutting scenario (top-down strategy), which it is linked with the underwater demonstrator tests.
For underwater laser cutting, the scenario may be adjusted as necessary (i.e., avoiding multi-thickness cutting).

Laser Cutting for Nuclear Reactor Dismantling

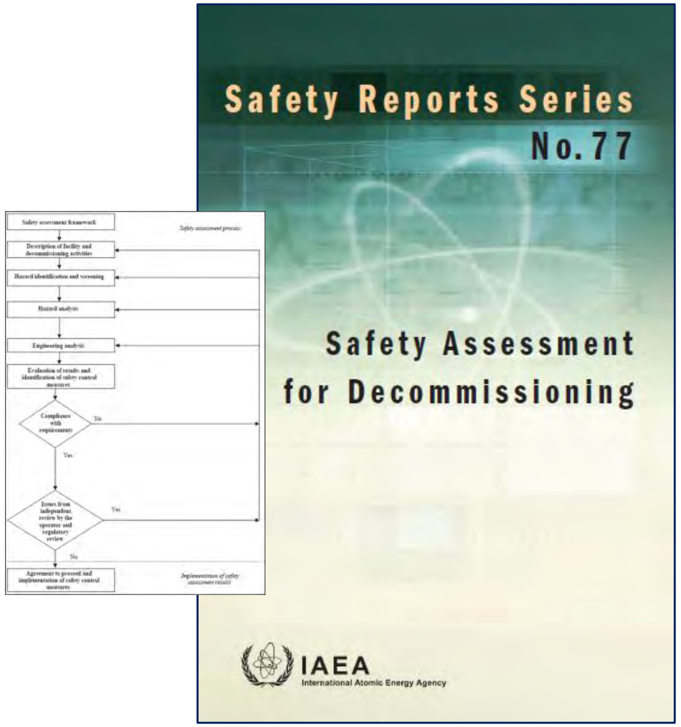
LD-SAFE Training Course

5. Safety Aspects

- *Generic Safety Assessment*
- *Evaluation of Specific Risks*
  - ➢ *Residual Power Laser Beam*
  - ➢ *Aerosols generation*
  - ➢ *H2 generation*
- *Safety Conclusions*

Safety Aspects

Generic Safety Assessment



A Generic Safety Assessment was developed following [IAEA methodology.]

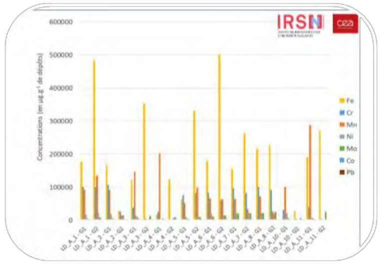
The evaluation included:

- Hazard Identification and Analysis
- Engineering Analysis
- Independent Review, performed by IRSN

Three specific risks were evaluated in detail, dedicating great efforts to performing laboratory tests and calculations.

Residual laser beam power

(for in-air cutting)



Generation of aerosols

(for both in-air and underwater cutting)

Generation of Hydrogen

(for underwater cutting)

Safety Aspects

Evaluation of Specific Risks – Residual Laser Beam Power

Residual Laser Beam Power (laboratory tests performed by CEA)

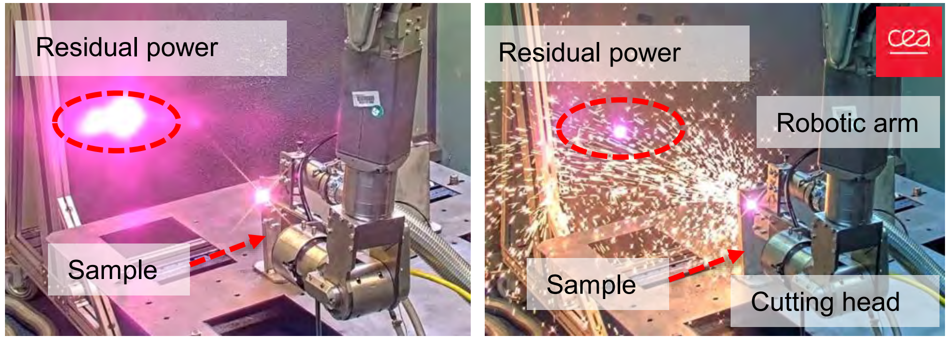
Associated risk, only for in-air laser cutting, since:

- Part of the laser beam propagates and may reach background structures.
- Incandescent particles are generated.

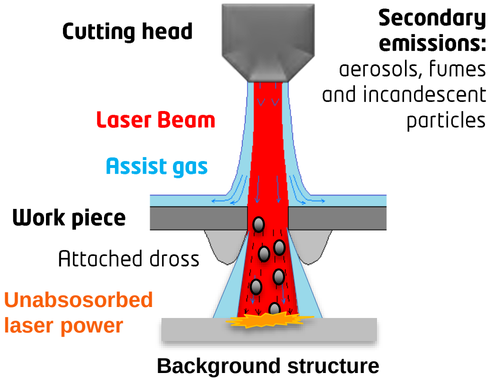
Key aspects:

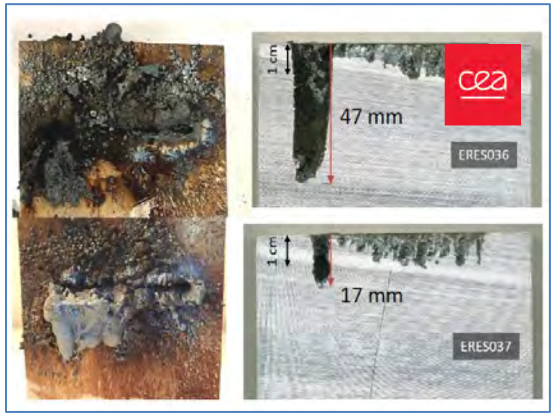
- Damage to background structures depend on several factors (material, power, speed…). It can produce a blind kerf of a few millimeters.
- The initiation/end of laser cutting are critical phases - Deposit of 100% of energy.
- No risk for underwater cutting – laser beam diffusion.

Associated risks (in-air) cannot be discarded. It requires ad-hoc analysis based on specific segmentation plan.



Examples of the laser cutting process and its secondary effects
Source: *CEA*





Residual laser beam effect on two background samples.
Source: CEA.

Safety Aspects

Evaluation of Specific Risks – Aerosols Generation

CEA, DELIA Facility, aerosol sampling line

<u>Aerosols Generation (laboratory tests performed by IRSN)</u>

Generation of aerosols is a recognized common issue to the thermal cutting processes.

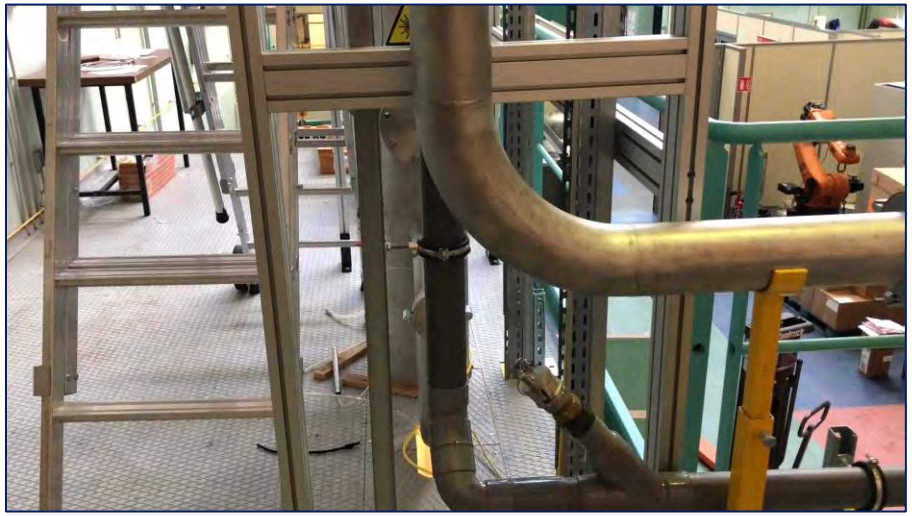
Key considerations:

- For in-air cutting, laser presents lower mass aerosols generation than other thermal techniques (i.e., PAC).
- For underwater cutting, aerosols release is reduced by means of water scrubbing. However, this scrubbing effect is quite limited for laser cutting.

Laboratory tests outputs:

- Release rates (total mass releases obtained by IRSN and physic-chemical results from CEA).
- Particle size distribution.

Aerosols generation has a great impact on **Contamination Control Arrangements (static/dynamic confinement systems)** as to avoid dispersion of contamination within the facility and keep internal exposure of workers in negligible levels.



Aerosols generation laboratory tests setup.
Source*: IRSN & CEA*

Safety Aspects

Evaluation of Specific Risks – Hydrogen Generation

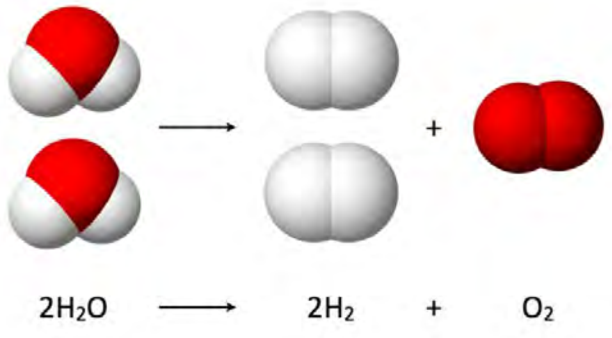
Hydrogen Generation during underwater laser cutting (laboratory tests performed by CEA)

Underwater thermal cutting processes result in H2 generation due to water radiolysis.

For laser cutting, the **risk** of fire or explosion due to H2 is **considered negligible** for stainless steel (as the main component of RVI) due to the following reasons:

- Generation peaks of laboratory tests did not exceed 600 ppm (0.06%): 15 times less than the limit value (1%) and much lower than flammability limit (4%).
- Typical large air volumes in cutting environment and renewal air flows for contamination control make local H2 build-up risk negligible.
- Recommendation of automatic/manual shutdown. If ventilation is loss, laser cutting (and H2 generation) stops by automatic/manual trigger.

This was confirmed in the demonstrator, providing further confidence of the results.



Running test at CEA.

Safety Aspects

Safety Conclusions

As per the generic safety assessment results (available to the European market), it would be demonstrated that laser cutting of RPV and RVI can be performed at least as safe as the best techniques currently used. For that:

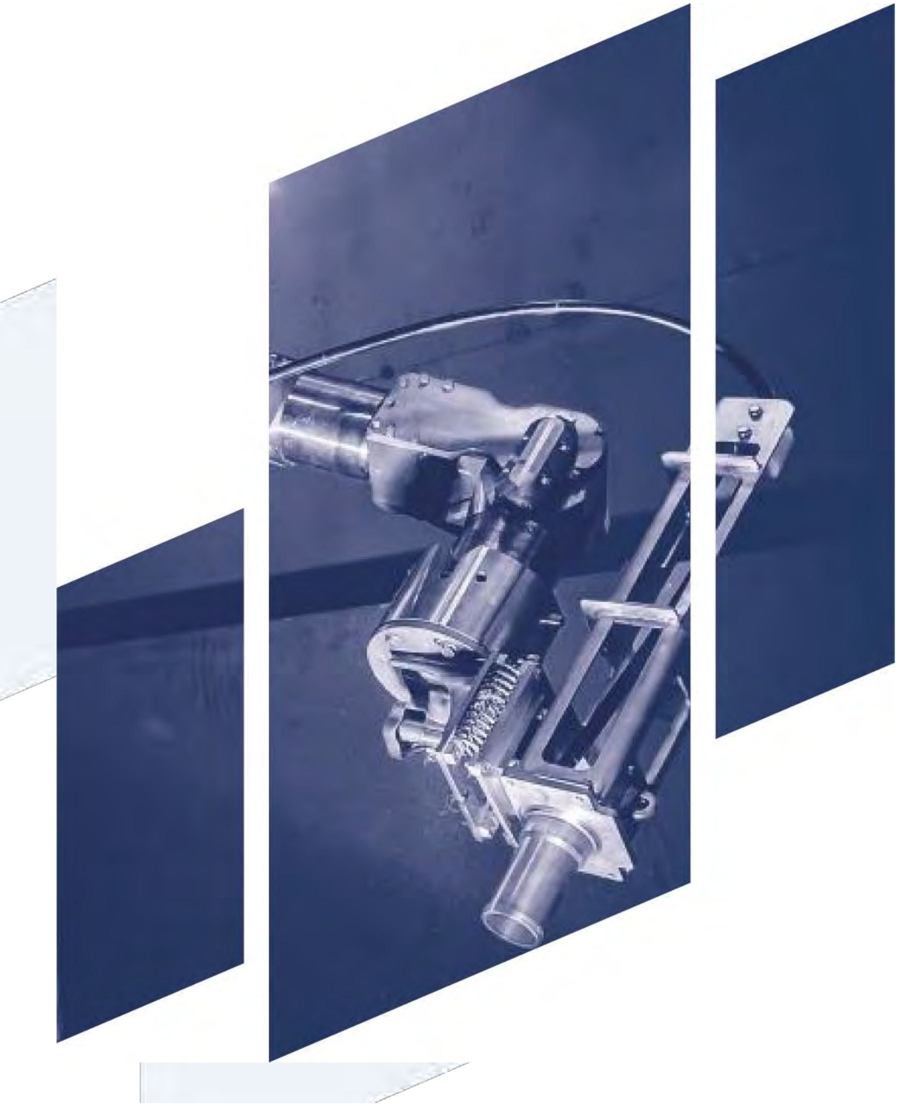
- Attention should be paid to the hazards identified.
- The recommendations on safety measures and controls should be observed, including those to the potential End Users of the technology. I.e.:
  - Contamination control arrangements following ISO 16647:2018
  - Recommendations on relevant **parameters** to be monitored and those that may trigger automatic shutdown.

Parameter or Automatic Shutdown Logic	Risk Prevented / Detected	Reference Value
Low air flow rate in ventilation and filtration system, either from local collection system or overall contamination control envelope ventilation arrangements.	Dispersion of contamination. Fire/Explosion (H2 generation).	Considering manufacture recommendations and confinement design requirements. For instance, for achieving an air renewal rate complying with ISO:16647 or with the assumptions of safety evaluations (i.e., air renewal rate of 5 h^{-1} considered in Annex VI).
High differential pressure (ΔP) in HEPA Filters.	Dispersion of contamination. Fire/Explosion (H2 generation).	Filter manufacturer recommendations and/or standard safety practices.
Filtration efficiency	Dispersion of contamination.	Standard safety practices (i.e. 1000 - 3000 filtering efficiency coefficient)
Low differential pressure (ΔP) between cutting area and reactor building (if negative pressure is required).	Dispersion of contamination.	Considering confinement design requirements (i.e., ISO:16647 minimum negative pressure of 20 Pa)
High temperature (i.e., loss of cooling) in laser source, coupler, or laser head.	Fire.	As per manufacture recommendations.
Signal of rupture of fibre (electrical signal)	Fire.	N/A
Programmed stop mechanisms to avoid unintentional cuts or unwanted collateral aggressions. I.e.: • Exceeding stationary time of robotic arm/laser head with laser active. • Exceeding moving time with laser active. • Prohibited movements and/or coordinates of the robotic arm.	Fire. Laser beam and residual power.	As per operational feedback (i.e., demonstrator) and actual segmentation plan.
Release of laser trigger button, requiring continuous and deliberate manual trigger of the laser beam from the operator.	Fire. Laser beam and residual power.	N/A
Compressed air stop when laser or ventilation system is switched off.	Dispersion of contamination. Confinement overpressure.	N/A
Other equipment malfunctions, such as low pressure in air flow (compressed air). Note: this type of parameters may not require automatic shutdown if equipment integrity is not jeopardized.	Equipment Malfunction.	As per manufacture recommendations and operational feedback (i.e., demonstrator).

SAFETY is an absolute **PRIORITY**

Laser Cutting for Nuclear Reactor Dismantling

LD-SAFE Training Course



6. Technology Qualification and Demonstrators

- *Introduction*
- *Technology Qualification*
- *In-air Demonstrator*
- *Underwater Demonstrator*

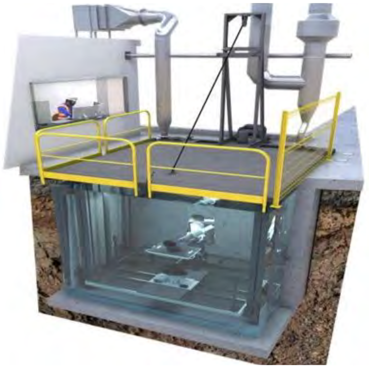
Technology Qualification and Demonstrators

Introduction

In order to qualify and validate the implementation of the technology in reactor environment the following was performed:

Technology Qualification

In-air Demonstrator

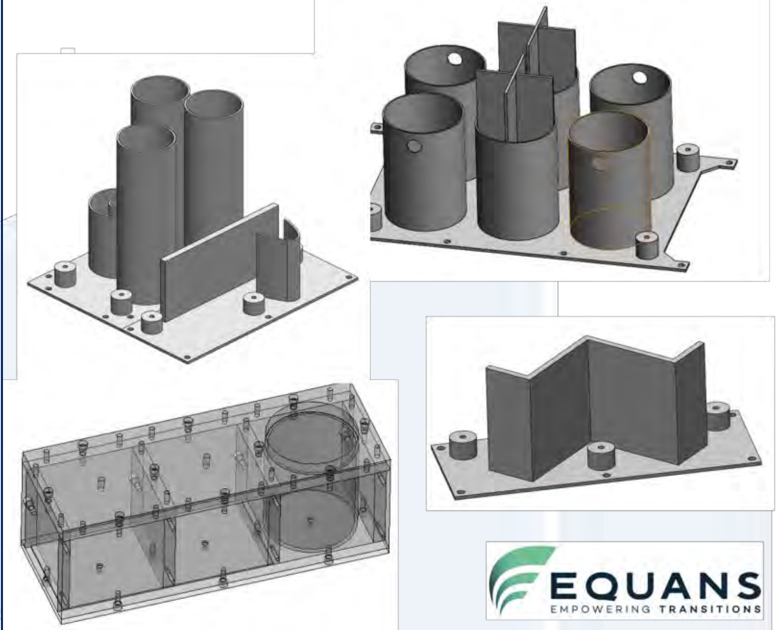


Underwater Demonstrator

Representativeness of segmentation activities was achieved with **mock-ups** representing reactor components (materials and shapes) and by reproducing adequate safety countermeasures.

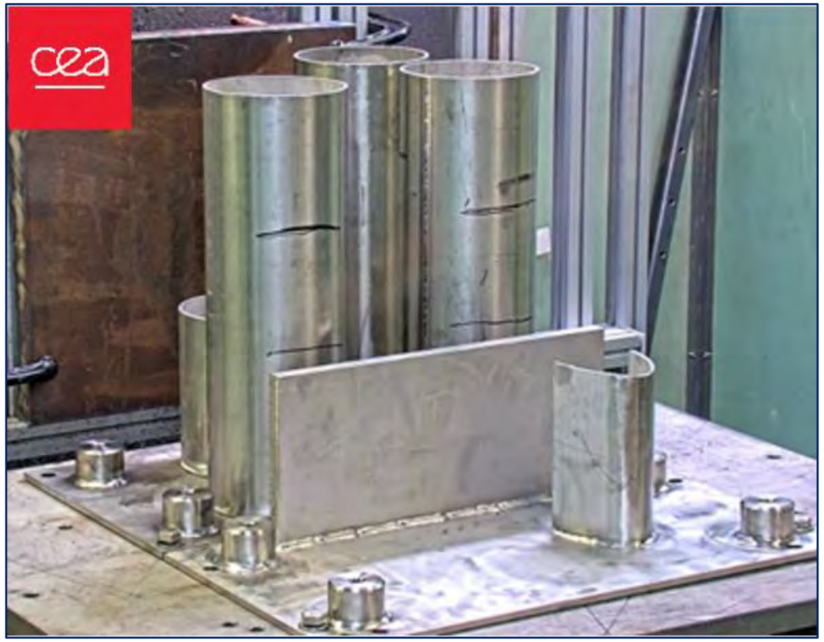
Technology Qualification and Demonstrators

Introduction



Modular Mock-ups representing:

- *BWR Steam Dryer and Core Cover (upper left)*
- *BWR Control rods and Control Rods Guide Tubes (upper right)*
- *PWR Upper Plate (lower left)*
- *PWR Core Shroud (lower right)*

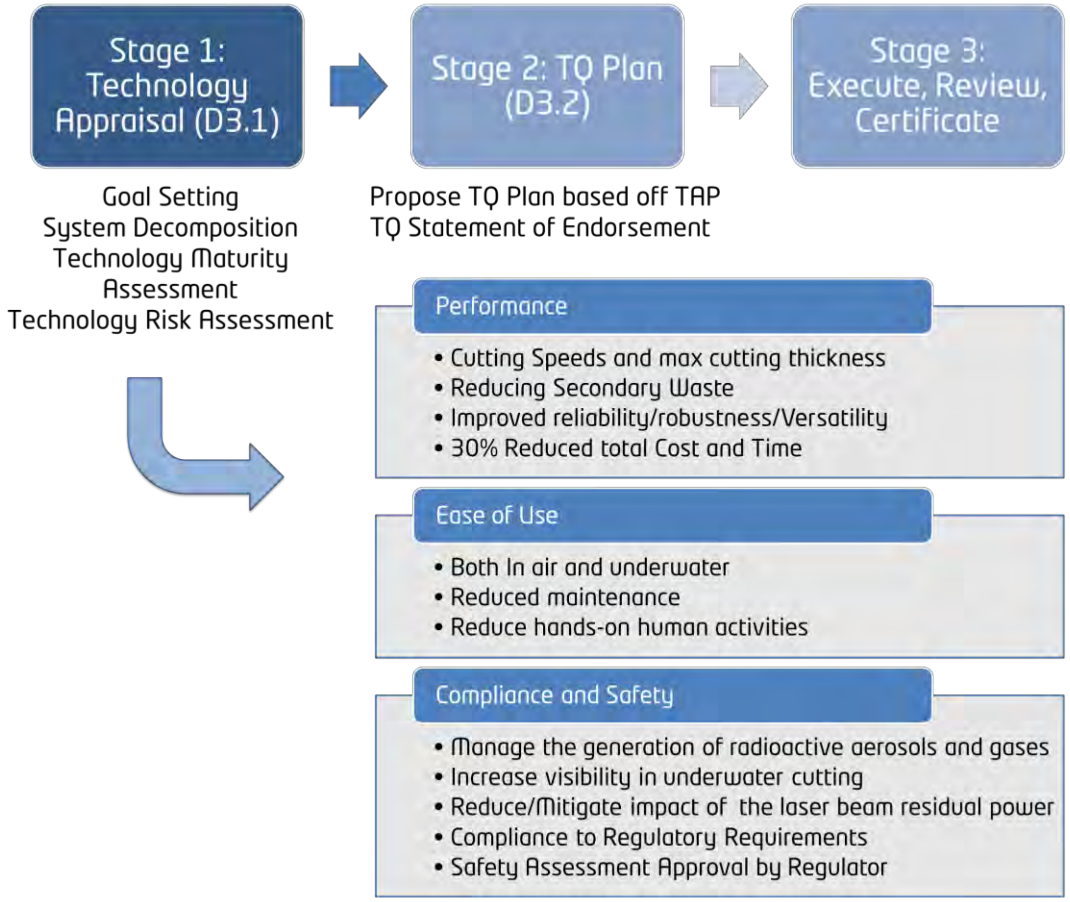


Technology Qualification and Demonstrators

Technology Qualification

The safety of the laser cutting technology for the workers and the environment is confirmed on the basis of a Technology Qualification Certificate (TQC), effectively approving the readiness of the technology for the next stage(s) of its development or for its application in the field.

Based on the feedback and experience of the project, guidelines for the industry for use of laser cutting technology in reactor dismantling environment are available at www.ldsafe.eu.



Technology Qualification and Demonstrators

In-air Demonstrator

In-air demonstrator at HERA Facility (CEA Marcoule)

Around 100 laser tests were carried out, acquiring great technical and safety feedback, and obtaining relevant results for qualification activities.

In-air demonstrator set-up:

- Maestro Pilot Station
- Laser Cutting Chamber
- Laser and compressed air shelters

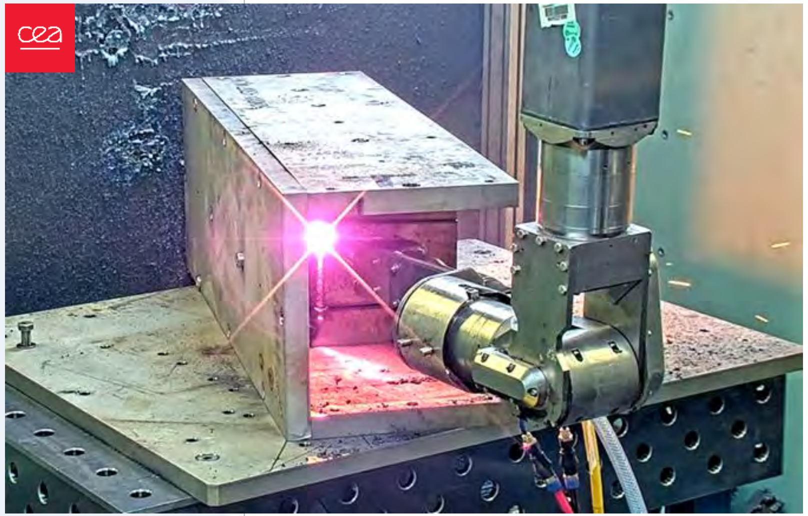
In-air laser cutting of mock-up (BWR Steam Dryer and Core Cover) at HERA Facility (CEA Marcoule). Source: CEA.

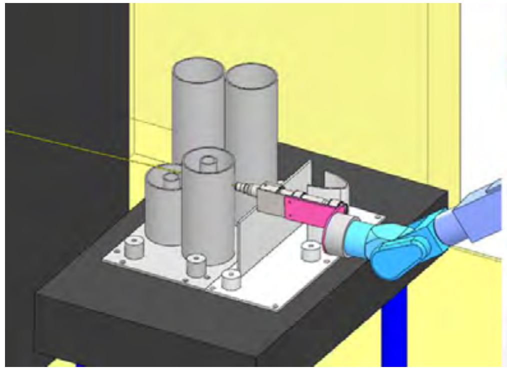
Technology Qualification and Demonstrators

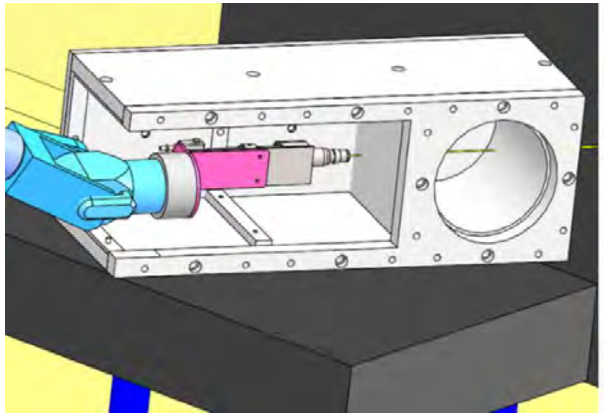
In-air Demonstrator

Feedback

Overall success during mock-up cutting tests, obtaining great feedback about cutting performances under different cutting configurations.
Multi-layers cutting for the configuration of modules 2&4 (BWR Steam dryer configuration)





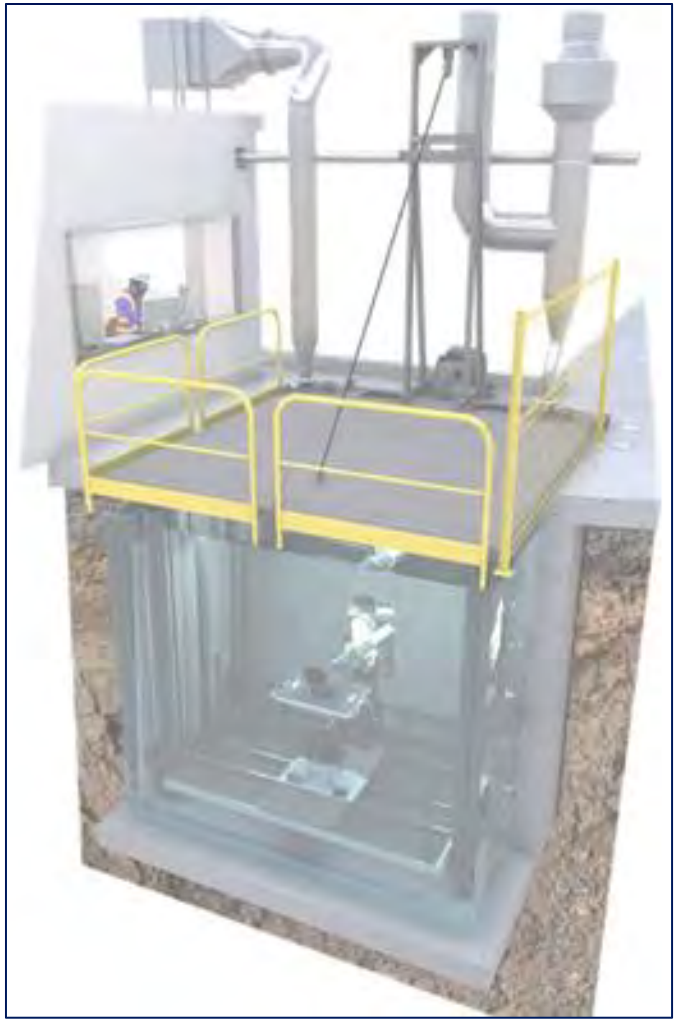


Technology Qualification and Demonstrators

Underwater Demonstrator

Underwater demonstrator at ONET Technocenter

Around 100 laser tests were carried out, acquiring great technical and safety feedback, and obtaining relevant results for qualification activities.



Technology Qualification and Demonstrators

Underwater Demonstrator

Main Feedback

- The laser system is robust and reliable.
- Cutting trajectories performed automatically (more reliable, ensuring adequate stand-off).
- Aerosols water scrubbing effect – Less significative generation.
- Underwater visibility ensured.
- Multi-thickness cutting was not achieved. This may modify in-air/underwater cutting scenarios.

Underwater cutting of mock-up (BWR Poisoning plate) at Onet Technocenter. Source: Onet.

7. Conclusions

Removal of the reactor pressure vessel and internals is one of the most challenging tasks in the decommissioning of nuclear power plants, due to, among others, mechanical and safety aspects.

There are key safety aspects to be managed for the implementation of the laser cutting technology for reactor segmentation. The risks can be reduced to ALARA with adequate safety measures.

There is need for improvement of processes, especially key dismantling activities. The laser cutting technology is presented as a promising alternative.

The LD-SAFE Project has made relevant steps forward to allow the future laser cutting of reactor pressure vessel and internals, which included among others, laboratory tests, Technology Qualification and Demonstrators.

Laser Cutting for Nuclear Reactor Dismantling

LD-SAFE Training Course

Advisory Board

End User Group

Expert Group

Support Group

¡Thank you!

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LD-SAFE Project

Online course at tecnatom.learningwithsoul.com/campus

https://tecnatom.learningwithsoul.com/campus/course/view.php?id=169

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