LD-SAFE

Laser Dismantling Environmental and Safety Assessment

TECHNICAL VALIDATION REPORT

DELIVERABLE D5.5

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Laser Dismantling Environmental and Safety Assessment

1. INTRODUCTION

1.1. SUBJECT OF THE DOCUMENT

This document presents the results of the tests of both in-air (at HERA facility; CEA Marcoule) and underwater (at ONET Technocenter) demonstrators performed in the frame of LD-SAFE project.

It describes all tests carried out with laser cutting and presents:

- The experimental set-up
- The qualification tests
- The performance tests
- The representative tests

1.2. REFERENCE DOCUMENTS

N°	Reference	Version	Description
[R1]	CN-LD-SAFE-12584-DEL-146696-EN	A	D5.1 - Case study for the demonstrators
[R2]	CN-LD-SAFE-12584-DEL-146689-EN	D	D3.2 - Technology Qualification Plan
[R3]	CN-LD-SAFE-12584-DEL-146699-EN	A	D5.3 - Design, manufacturing and installation dossiers for the Mock-ups
[R4]	CN-LD-SAFE-12584-DEL-146697-EN	A	D5.2 - Integration and installation of the laser system
[R5]	CN-LD-SAFE-12584-DEL-146706-EN	A	D6.7 - Final exploitation plan and commercial roadmap

1.3. TERMINOLOGY

ACRONYM	DEFINITION
ALARA	As Low As Reasonably Achievable
BWR	Boiling Water Reactor
CEA	Commissariat à l'Energie Atomique et aux énergies alternatives
EC	European Commission
EG	Expert Group
EQ	EQUANS
FAT	Factory Acceptance Tests
HEPA	High-Efficiency Particulate Air
HMI	Human-Machine Interface
HSE	Health Safety Environment
I&C	Instrumentation & Control
IML	Integration Maturity Level
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
KPI	Key Performance Indicator
LD-SAFE	Laser Dismantling environmental and SAFEty Assessment
N/A	Not Applicable
NPP	Nuclear Power Plant
OT	Onet Technologies
P&ID	Piping & Instrumentation Diagram
PWR	Pressurized Water Reactor
RCF	Refractory Ceramic Fibres
RPV	Reactor Pressure Vessel
RVI	Reactor Vessel Internal
SAT	Site Acceptance Tests

ACRONYM	DEFINITION
TBD	To Be Defined
TE	TECNATOM
TML	Technology Maturity Level
TQ	Technical Qualification
TRL	Technology Readiness Level
TW	Technical Workshop
UW	UnderWater
VYSUS	Vysus Group

1.4. CONTEXT AND OBJECTIVES

1.4.1 GENERALITIES

The global objective of the LD-SAFE project is to validate the laser cutting technology in an operational environment in-air and underwater and prove that the technology is mature to address the dismantling of the most challenging components of nuclear power reactors (RPV / RVI), that means:

- Performances and benefits validated in operational environment, taking into account the specific associated constraints,
- Validation of the maturity of the laser system following mitigation actions indicated in the Technology Qualification Plan [R2],
- Compliance with the highest safety criteria as well as workers and environment protection standards and that the laser cutting technology can be included in the safety analyses of the decommissioning projects at the early stages of design,
- Reduction of the overall cost of the dismantling operations.

At the end of these tests, the suitability of the laser cutting technology to address the challenges of power nuclear reactor dismantling and its capability to improve these projects will be confirmed. The public version of this test report will facilitate the implementation of laser cutting technology in the European decommissioning market, as well as these other deliverables:

- Guidelines for the use of laser cutting in reactor dismantling environment which is a set of guidance notes that incorporates all LD-SAFE lessons learnt to provide to future end users and an overview of how to use laser safely for PWR and BWR RVI dismantling.
- A Generic Safety Assessment for the implementation and use of laser cutting technology (with the aim of being easily adaptable to the specific conditions of end users and reduce the associated licensing effort).
- A Technical validation report which highlights all demonstrator results and prove the maturity of in-air and underwater laser cutting technology (this deliverable).
- Online course on cutting technologies which integrates 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.

1.4.2 OBJECTIVES

The tests carried out as part of the two cutting campaigns (in air at CEA MARCOULE and underwater at Onet Technocenter) must comply with all these main KPI(s) indicated in the deliverable D5.1 [R1]:

- **Performance**
  - Cutting Speeds and maximum cutting thickness achieved
  - Reducing Secondary Waste
  - Improved Reliability / Robustness / Versatility
  - 30 % Reduced total Cost and Time
- **Ease of use**
  - Both in air and under water
  - Reduced maintenance
  - Reduce hands-on human activities.
- **Compliance and Safety**
  - Manage the generation of radioactive aerosols and gases
  - Increase visibility in underwater cutting
  - Reduce/Mitigate impact of the laser beam residual power
  - Compliance to Regulatory Requirements; and,
  - Safety Assessment Approval by Regulator.

To satisfy these objectives, the tests are divided into three phases:

- Qualification tests to validate the basic operation of the equipment
- Performance tests to demonstrate laser cutting performance under different conditions:
  - Variation of working conditions (speed cutting, laser power, etc.)
  - Variation of operating conditions (air, underwater, sample thickness, etc.)
- Representative tests to evaluate laser cutting efficiency in real operating conditions (cutting flexibility and operability on representative mock-ups)

2. LASER SYSTEM

The laser system is designed and implemented by Onet Technologies is an industrial one (with CE certificates provided by the manufacturers; machine directive compliance ensured).

The main laser utilities are implemented in two dedicated shelters:

- A shelter for the laser source
- A shelter for compressed air production

The shelters are positioned outside the building. Power and utilities are transmitted to the laser head installed in the cutting cell via dedicated fibers and pipes.

Figure 1: Implementation laser and compressed air Shelters at CEA MARCOULE

Figure 2: Implementation laser and compressed air Shelters at ONET Technocenter

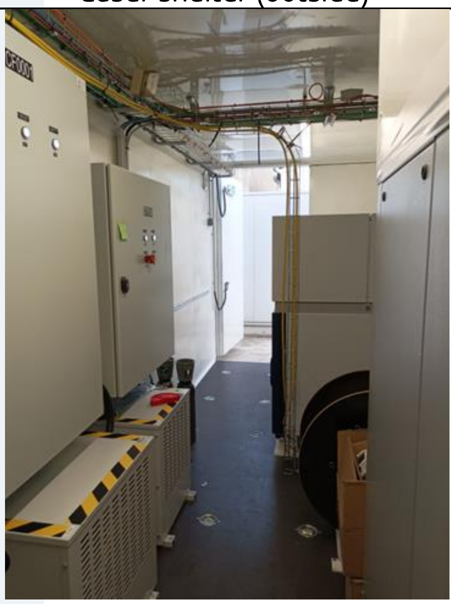
2.1. Laser shelter

A maximum of 16 kW laser power can be delivered to the laser heads. Laser source qualification tests have been done for in-air and underwater demonstrators to calibrate the laser power over its entire operating range (from 0 to 14 kW for the in-air laser head and from 0 to 16kW for the underwater laser head).

To make sure the laser system complies with manufacturer's recommendations, a calibration was carried out based on calorimeter measurements (to show that the power generated by the laser source over the entire range is in compliance with specifications).

The figure below shows the laser shelter composed of a laser source and a cooling unit.

Laser shelter (outside)



Laser shelter (inside)

Figure 3: Laser Shelter

2.2. Air compressed shelter

Air compressed shelter is associated to the laser shelter. It produces and supplies the compressed air required by the laser (head cooling and blowing). It is also located outside the HERA installation.

The figure below shows the compressed air shelter.

Compressed air shelter (outside)


Compressed air shelter (inside)

Figure 4: Compressed air shelter

2.3. In-air cutting device

(a) Laser head

The in-air laser head is designed by CEA for nuclear decommissioning activities.

Figure 5: In-air laser cutting head

The in-air laser head is mounted on the remote-controlled arm and connected to the various utilities:

- Laser fiber
- Compressed air (assist gas)
- Cooling water (fiber connector cooling)

(b) Collection device

An aerosol collection device has been developed by Onet Technologies. It can be mounted on the laser head to collect aerosols generated during laser cutting.

This device limits the dispersion of aerosols generated during cutting by extracting and filtering aerosols as close as possible to the cut.

The figure below shows the collection head mounted on the remote-controlled arm MAESTRO used for some configurations (where it was possible in terms of congestion to show that mitigation means can be implemented in the future to catch aerosols as close as possible to the cutting area).

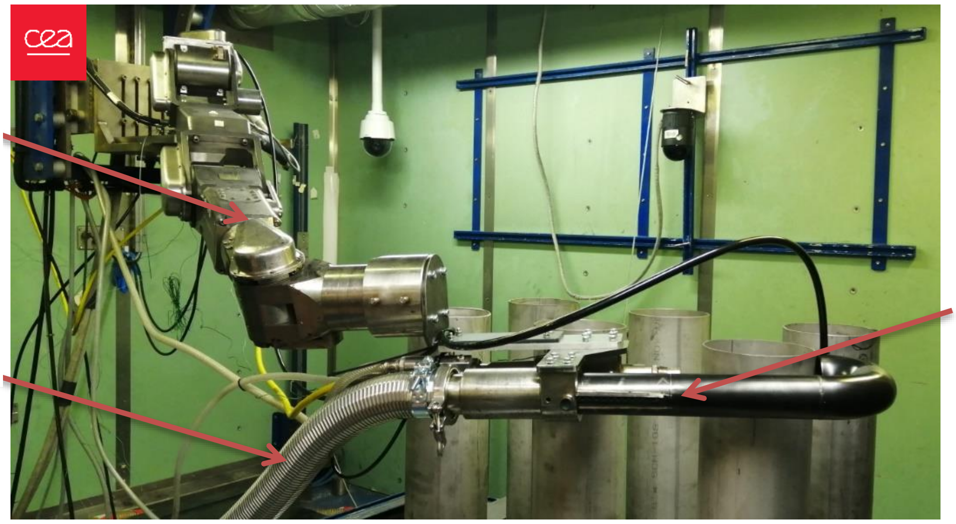


Figure 6: In-air laser head on MAESTRO arm (HERA Facility)

For aerosol collection, the collection head in air is connected to an aerosol transportation and filtration line, composed with 2 filtration stages:

- a first filtration stage with cyclonic filter
- a second stage of HEPA filtration by cartridge filter.

The cyclonic filter and flexible stainless steel hose are positioned in the cutting cell. All other components are located in the control area.

Figure 7: Cyclonic filter

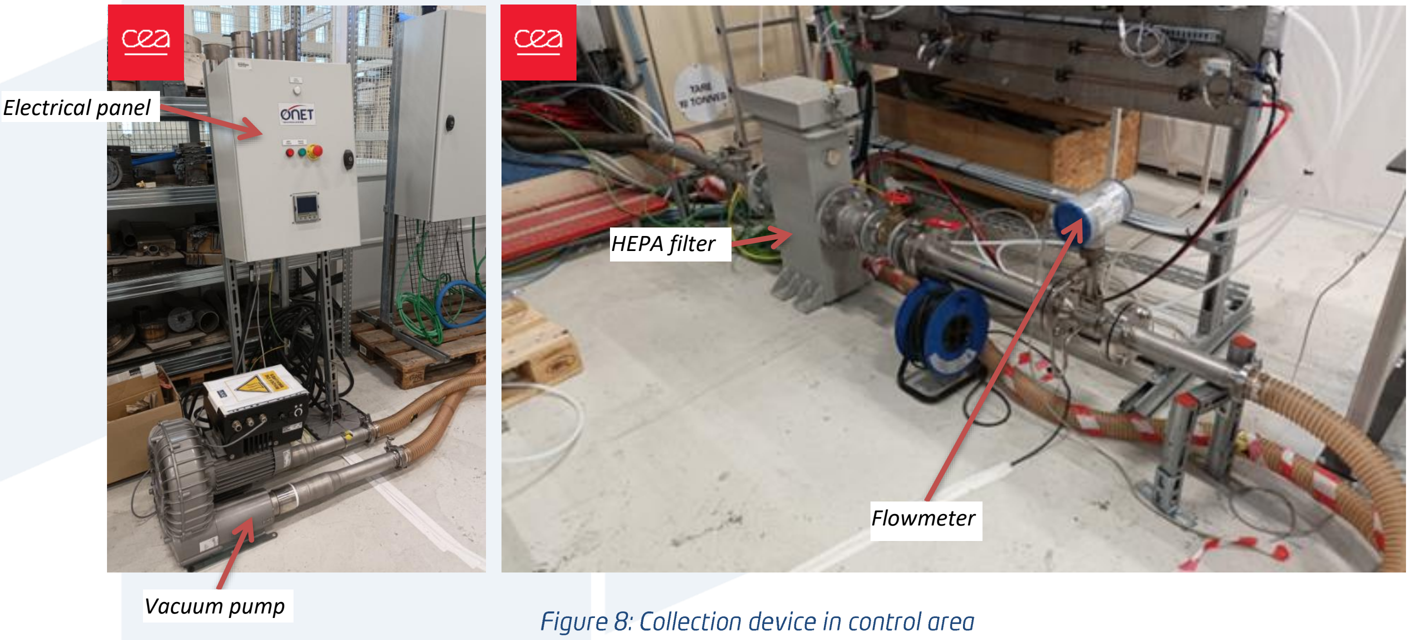


Figure 8: Collection device in control area

2.4. Underwater cutting tool

For underwater tests, a specific laser head was developed by CEA. The underwater laser head is a prototype with a power of 16 kW and a dual cooling (water for the optical unit and air for the nozzle).

To enable underwater cutting, the laser head must generate a dry cavity, as laser energy is quickly absorbed by water. To accomplish these functions, the laser head has 3 cavities (C1/C2/C3) to cool the nozzle and create the dry cavity.

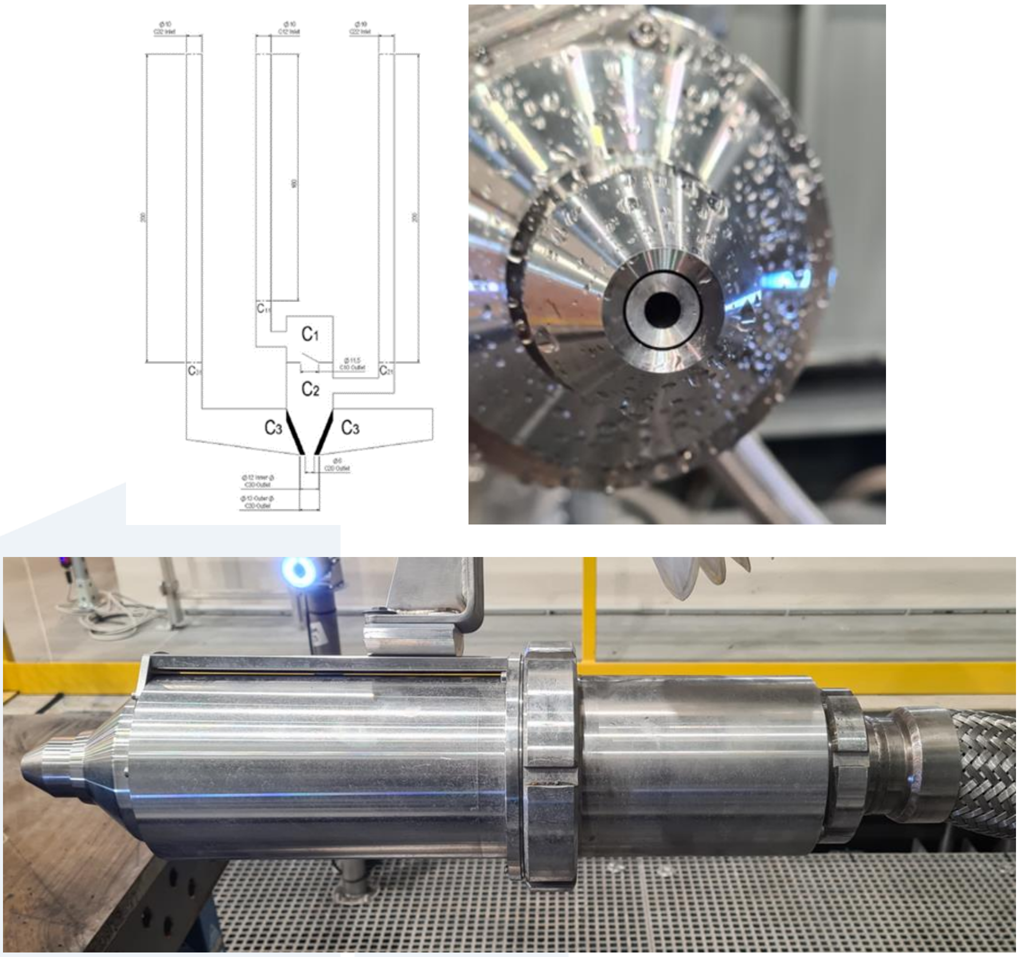


Figure 9: Underwater laser cutting head

The underwater laser head is mounted on the remote-controlled arm and connected to the various utilities:

- Laser fiber
- Compressed air (assist gas)
- Cooling water (fiber connector cooling)

3. SECONDARY WASTE MEASUREMENTS

3.1. Aerosols characterization

On several tests, the aerosols generated in the laser cutting cell are characterized using a PEGASOR©. The measurement device is positioned in a defined area representing the cell.

A PEGASOR© sensor is used to measure online the number concentration of airborne aerosols in the cutting cell generated at each instant. The PEGASOR© sensor can register aerosol concentrations ranging from 0 to 10^{10} #/m^3.

Note: aerosol measurement in a wet environment requires the use of a heated sampling line to avoid damage to the analyzer and incorrect results. The sampling line is heated to 200°C.

Figure 10: PEGASOR® Aerosols mass flow measurement

3.2. Sample weighing

An accurate balance has been used to weigh the cutting samples before and after laser cutting.

The balance is used to determine the amount of material removed by the laser.

4. MOCK-UPS

Two types of mock-ups are designed for each step:

- Simple mock-ups (samples) used for laser performance demonstration tests (metal plates)

- Representative mock-ups to evaluate laser cutting efficiency under real conditions (most representative PWR and BWR RVI configurations).

For the LD-SAFE project, representative mock-ups are defined on the basis of the dismantling of PWR and BWR nuclear power plants. Deliverable [R3] presents the representativeness of the models selected for these tests.

The table below shows all the mock-ups used for a test phase.

STEP	ITEM	REPRESENTATIVENESS	DIMENSION (mm)	MATERIAL	WEIGHT (kg)
Performance test	Plate with thickness 100mm	N/A	200x100x100	304SS	15,34
	Plate with thickness 40mm	N/A	200x100x40	304SS	6,10
	Plate with thickness 50mm	N/A	200x100x50	304SS	7,64
Representative test	Ferrule Upper plate	PWR: Upper plate ferrule	200x100x65	304SS	9,96
	Impact plates for laser beam residual power	PWR or BWR Reactor Pressure Vessel	500x500x50	Carbon steel	97,27
	Main model	PWR: Upper & lower plates (square grid & plates/tubes interfaces), Core shroud, Lower core support's grid Core support structure's ring BWR: Upper plate & lower plate	1000x375x360	304SS	471,70
	Model 1	PWR: Core shroud	685x374x258	304SS	39,58
	Model 2	BWR: core cover supporting rings (curved plates in steam dryer) PWR: Upper plate ferrule	685x374x200	304SS	35,38
	Model 3	BWR: Control rod guides, poisoning plates and control rods	1000x590x473	304SS	110,17
	Model 4	BWR: Steam dryer tubes (concentric tubes)	685x374x508	304SS	65,76

Table 1: List of test mock-ups

The figures below illustrate the respective mock-ups.

- Stainless steel plate and Ferrule Upper plate.

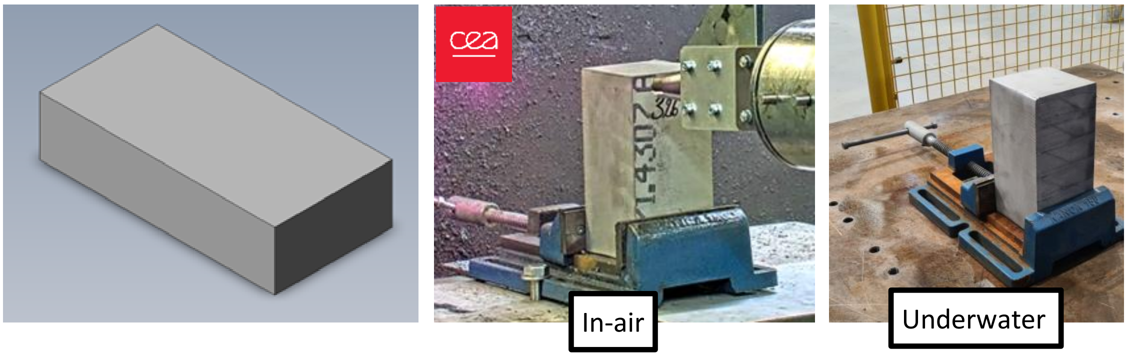


Figure 11: Stainless steel plate

- Main model representing the Upper Plate and control rods guide.

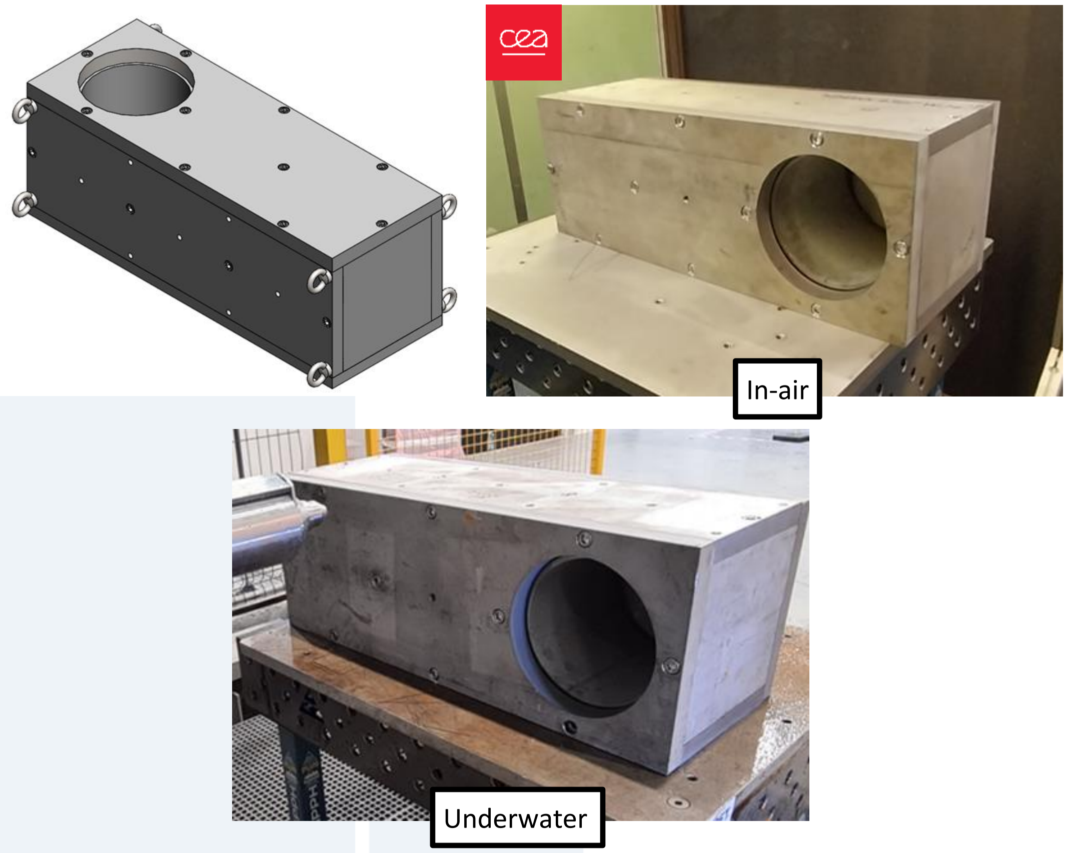


Figure 12: Main Model

- Model 1 representing the core shroud.

Figure 13: Model 1

- Model 2 / Model 4 representing steam dryer and core cover.

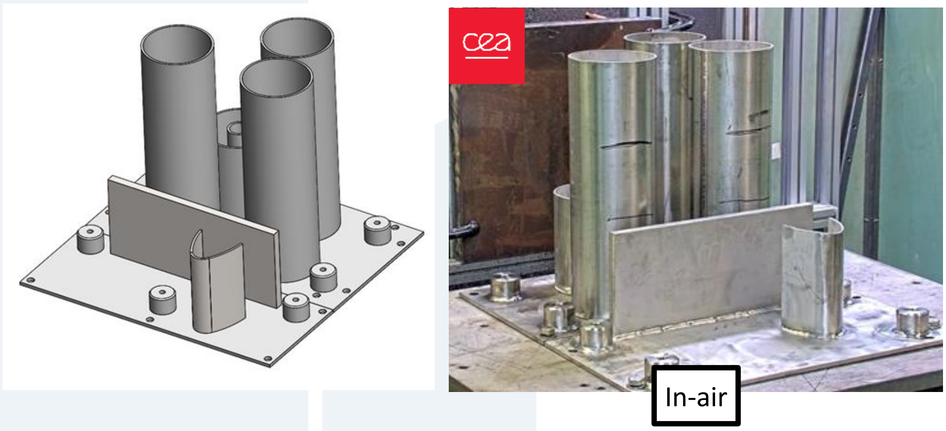


Figure 14: Model 2/Model4

- Model 3 representing control rods and control rods guide.

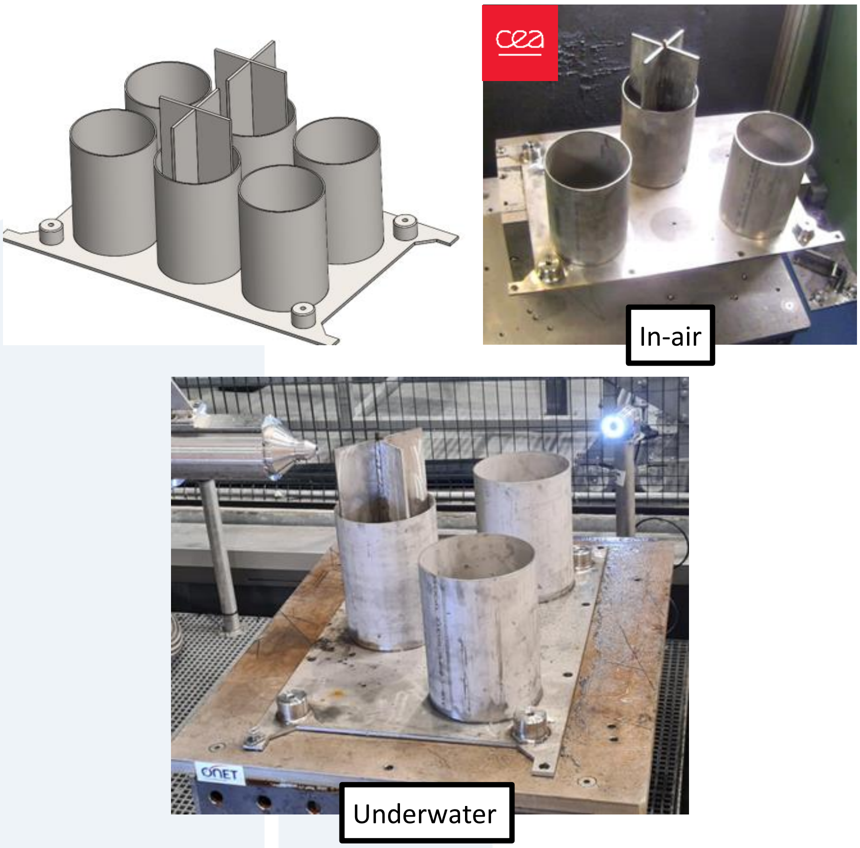


Figure 15: Model 3

Note: the mock-ups are identical for tests in air and underwater configurations.

5. CUTTING SCENARIO

The cutting scenarios in air and underwater conditions are identical, allowing the removal of all PWR and BWR reactor internals. Detailed cutting scenarios are presented in the deliverable [R1][R3].

	Original state	Final state
Reactor PWR		
Reactor BWR		

In-air and underwater demonstrators enable us to prove the feasibility of dismantling all the internals. The aim is to base these demonstrations on a removal scenario determined from 3D models of the reactors, and to carry out cutting tests on representative mock-ups (see §.4) under conditions identical to the scenario (dimensional constraints, cutting angle, etc.).

The main challenges for PWR and BWR reactors are presented below.

PWR REACTOR

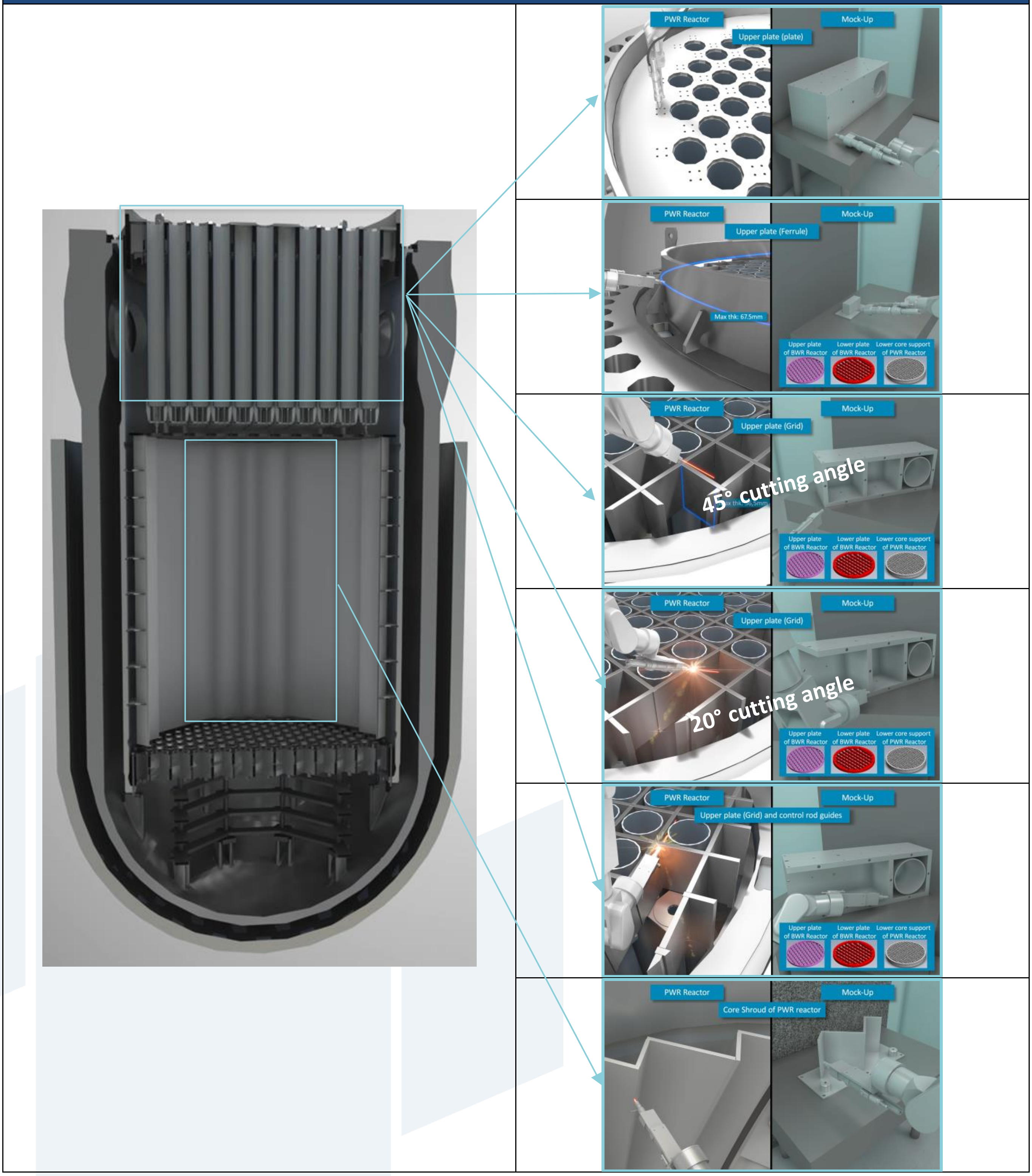


Table 2: Cutting scenario PWR reactor

BWR REACTOR

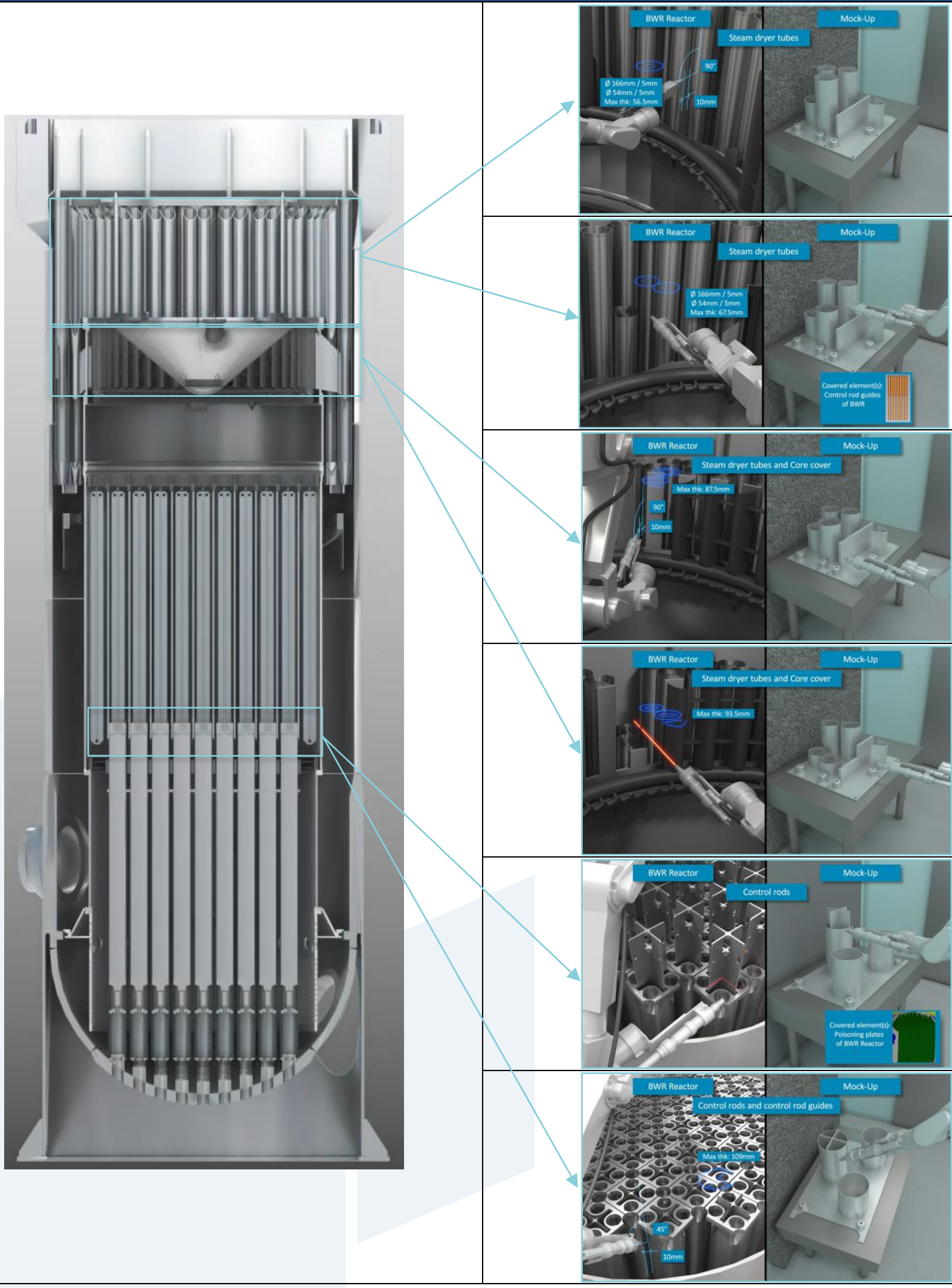


Table 3: Cutting scenario BWR reactor

6. IN AIR DEMONSTRATOR

6.1. EXPERIMENTAL SET UP

The in-air cutting tests have been carried out in the HERA facility of CEA MARCOULE.

For each phase, the experimental set-up will be composed of the following main parts:

- The cutting cell;
- The cutting device (laser system, laser cutting head and collection head);
- The cutting samples and representative mock-ups;
- The analysis tools.

These elements are detailed in the following sections.

6.1.1 LASER FACILITIES

The test area is composed of the laser cutting cell and its external area including utilities distribution (Onet Technologies), laser and utilities control cabinets, and the MAESTRO remote arm pilot station (CEA).

With the exception of the MAESTRO arm control station, all other equipment is mobile.

For operating the laser head, the cell is equipped with a MAESTRO remote-controlled arm and with a part of the collection device (see §.2.3(b)).

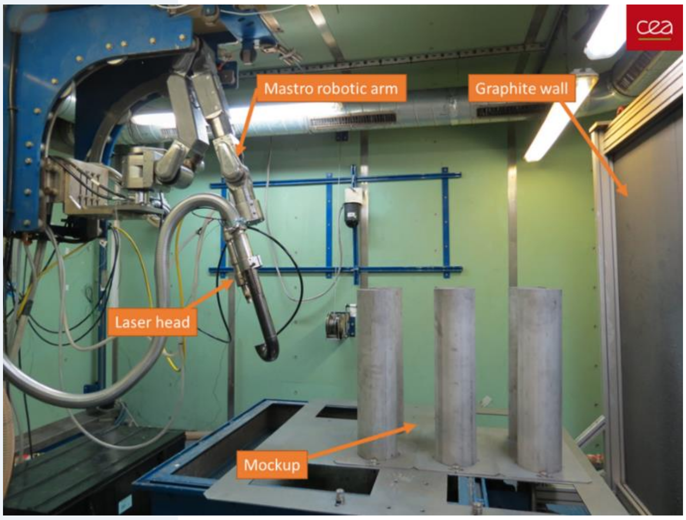


Figure 16: Laser cutting cell of CEA MARCOULE

The test area outside the cutting cell includes:

- MAESTRO remote arm pilot station

Figure 17: CEA Marcoule – HERA facility – MAESTRO Pilot station

- Utilities distribution manifold (compressed air and cooling water)

Figure 18: Utilities distribution manifold

- Electrical cabinets and cooling unit for coupler and connector

Figure 19: Electrical cabinets et cooling unit

- Laser and utilities control panel

Figure 20: Laser and utilities control panel

6.1.2 IMPLEMENTATION OF LASER SYSTEM AT HERA FACILITY

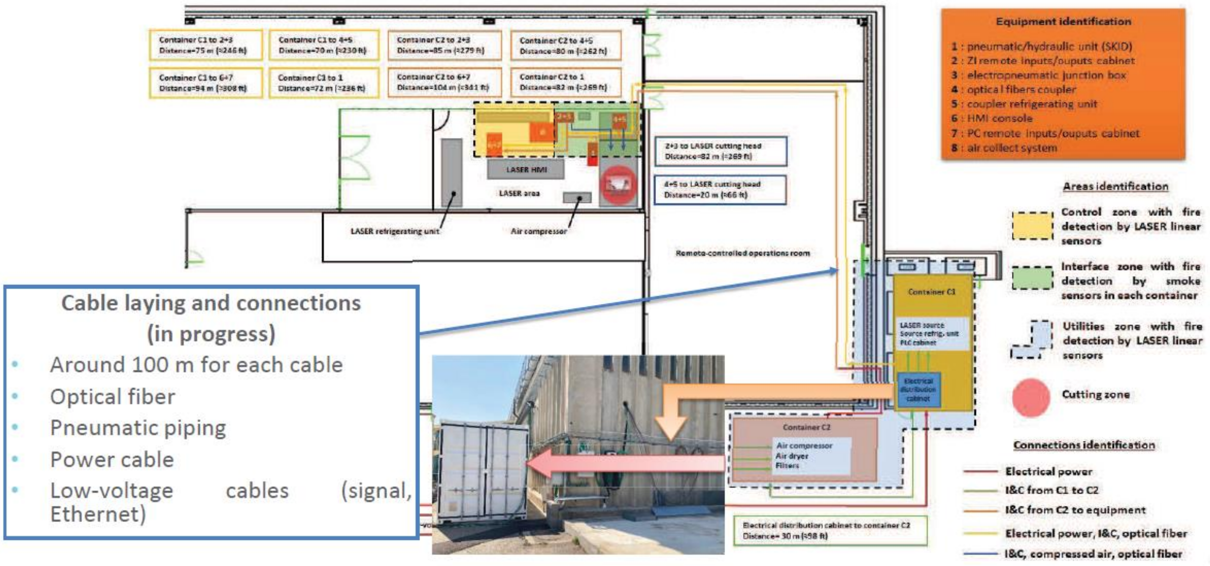


Figure 21: Implementation of the laser system at HERA facility (inside and outside)

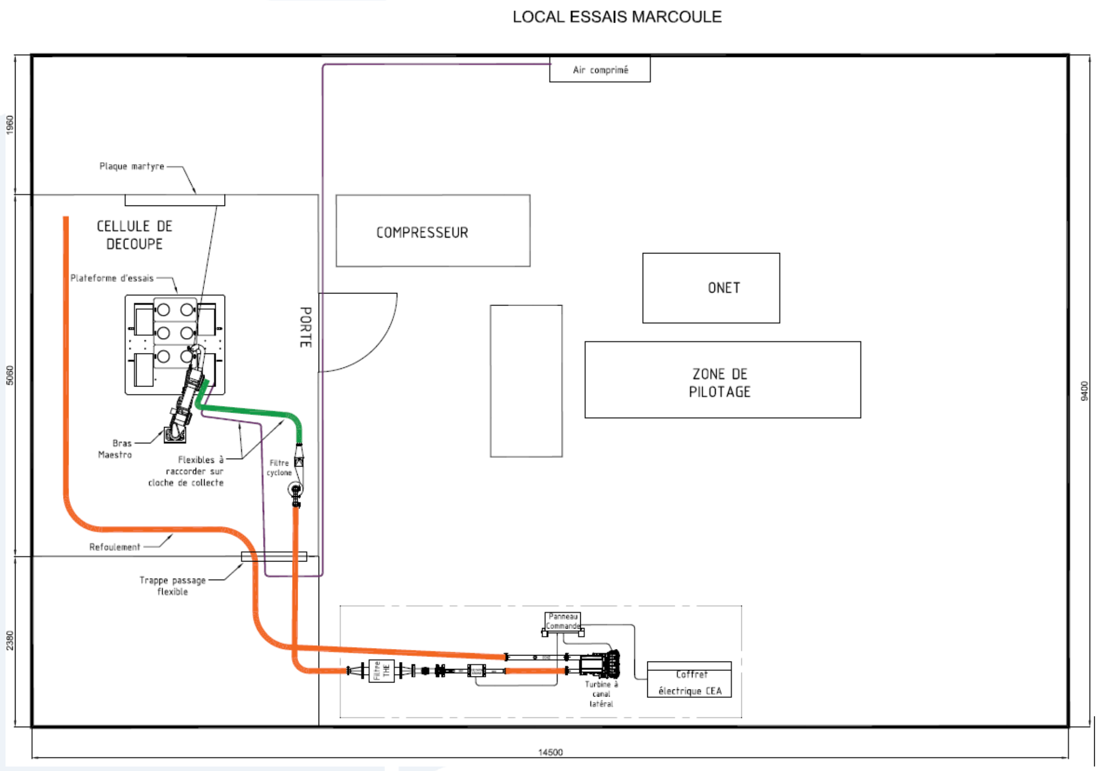


Figure 22: Implementation of equipment in the laser area

6.2. DETAILED RESULTS

6.2.1 STAGE 1 - QUALIFICATION TESTS

The qualification phase of the in-air demonstrator tests was expected to validate the following points (in accordance to the requirements of deliverable [R2]):

OBJECTIVE	TEST	VALIDATION
Check the suitability of links to the laser head (hydraulic, pneumatic and laser) to be used with a robotic arm during remote-controlled movements		
Umbilical (coupling robustness): no risks of damages on connectors during assembly or disassembly (with the laser head)	Perform multiple umbilical connections and disconnections on the laser head	**Robustness is compliant** Multiple connections revealed no deterioration of the connector
Umbilical: Capability to bend freely and within mechanical constraints as the robotic arm manoeuvres during cutting (strained cables could be subject to material fatigue at connections). Flexibility and its compatibility with the required movement of the manipulator uncertain	Perform all laser cutting tests (performance and representative tests) and check connector and umbilical integrity	**Lessons learned** A " pinching " defect has appeared on the fiber near the connector, causing laser defects when the stress on the fiber is too great.  **Solution:** - add a support or a balancer to hold the fiber in place - add a fiber guide at the connector
Ensure correct performance of compressed air distribution system		
Check flowrate of assist gas	400 to 800 Nl/min	Two nozzle diameters are available for the in-air laser head: **Flowrate is compliant with a 6 mm nozzle** **The maximum flow rate achieved with a 3 mm nozzle is 670 NL/min** The flowrate requirement for the laser head is 400 or 500 Nl/min at compressed air utilities are suitable.
Check flowrate of deflection airflow	500 Nl/min	**Flowrate is compliant**

OBJECTIVE	TEST	VALIDATION
Check that cameras are correctly positioned for arm and laser control (right visibility for operators)		
Check visibility of operations on control room monitors	Check that the cameras inside CEA's laser cell are correctly positioned for cutting the samples	In the first part of the tests, 3 cameras were installed in the cutting cell (see Figure 23). The cameras were well positioned to control the remote-controlled arm and the laser head. Note that to control the stand-off between the laser head and the sample, it is ideal to have a camera at 90° to the cut. This camera was added in the second part of the tests (see Figure 24).

Table 4: Qualification test results

The camera locations for the 2 test parts are shown below:

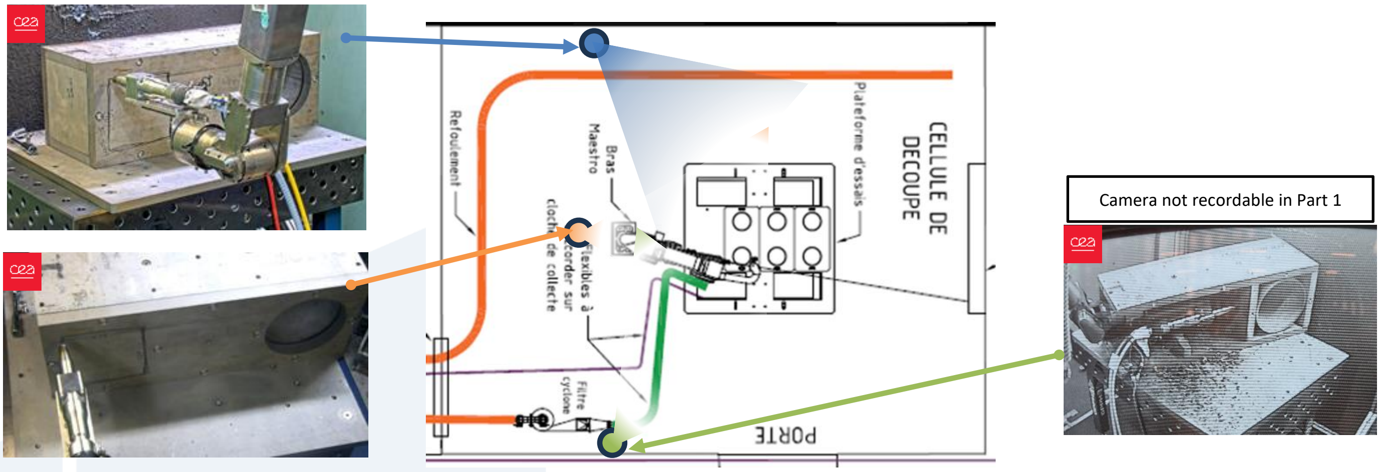


Figure 23: Camera positions in Part 1 of testing

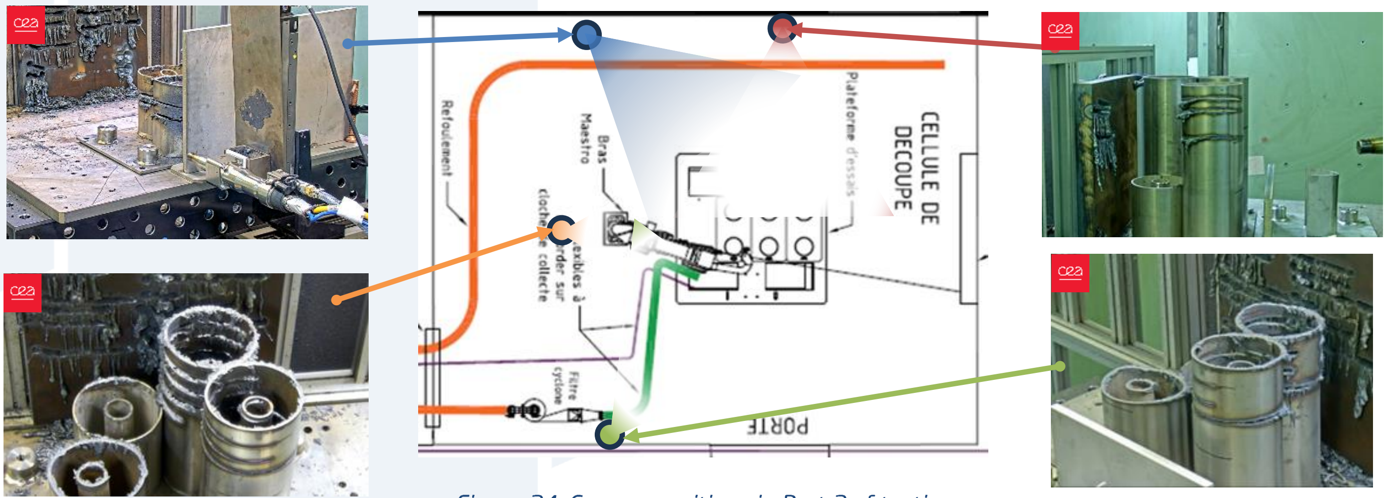


Figure 24: Camera positions in Part 2 of testing

6.2.2 STAGE 2 - PERFORMANCE TESTS

Performance tests correspond to laser cutting tests in basic configurations. They were carried out by laser cutting on stainless steel plates and satisfy the following requirements (KPIs):

<u>In air: 50 mm/min for a thickness of 100 mm of steel with a 14kW laser source</u>

Performance tests on stainless steel blocks with a thickness of 100 mm showed that cuts could be made at a speed < 50 mm/min and a power of 14 kW.

In this configuration, assist gas flow has no impact on cutting.

It can also be seen that the stand-off is an important parameter for cutting performance. If the stand-off is greater than 30 mm, laser cutting is more difficult.

The requirement to cut a 100 mm stainless steel block at a speed of 50 mm/min is not reachable.

<u>Strictly less than 800 g/m with laser cutting, without considering attached slag which further reduces the mass actually removed</u>

This requirement consists in carrying out several identical cuts on a 50 mm thick stainless steel sample.

For each cut, the sample is weighed before and after the test. The difference in mass is used to determine the amount of matter ejected and not fastened to the sample.

The criterion is 800 g of lost matter per meter of cut (**800 g/m**).

Tests have shown that all cuttings are achievable whatever the assist gas flow rate. Moreover, there was no difference in cutting performance as a function of gas flow rate.

For the mass loss requirement during laser cutting (800 g/m), we observed a significant difference depending on the assist gas flow rate:

- for an assist gas flow rate of 500 Nl/min: mass loss is high, at an average of 1077 g/m, and does not meet the requirement.
- for an assist gas flow rate of 400 Nl/min: mass loss is lower, at an average of 633 g/m, and complies with the requirement.

This difference is due to the greater evacuation of slag at higher assist gas flow rates. Slag does not adhere to the sample and mass loss is more significant.

To meet the requirement, the optimum assist gas flow rate is **400 Nl/min**.

6.2.3 STAGE 3 - REPRESENTATIVE TESTS

Representative tests correspond to laser cutting tests on scale 1:1 mock-ups representative of the various PWR and BWR reactor components. Representative mock-ups are shown in chapter 4.

The configurations summarized below (angle and stand-off) are determined from the realistic cutting scenario in the note [R1]. All cutting tests have been made at 14kW of laser power.

6.2.3.1. Upper plate

Cutting the Upper Plate consists in creating a square opening on the 40 mm thick stainless steel plate. The laser head is positioned at a 90° angle to the sample.

The in-situ cutting of the upper plate is considered to be the most challenging according to D5.1 [R1]. The cutting of the upper plate grants access to all the remaining internals inside the reactor vessel. The objective with this operation is to prove the ability of the laser cutting technology to perform the dismantling of the upper plate without relocating it in another place. This will allow to avoid a heavy handling operation in the reactor pool.

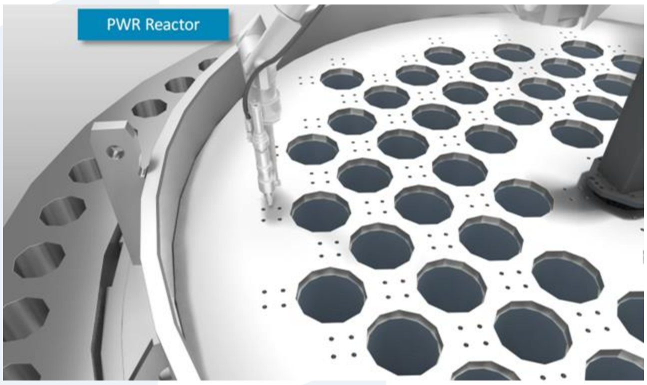


Figure 25: Upper plate of PWR reactor

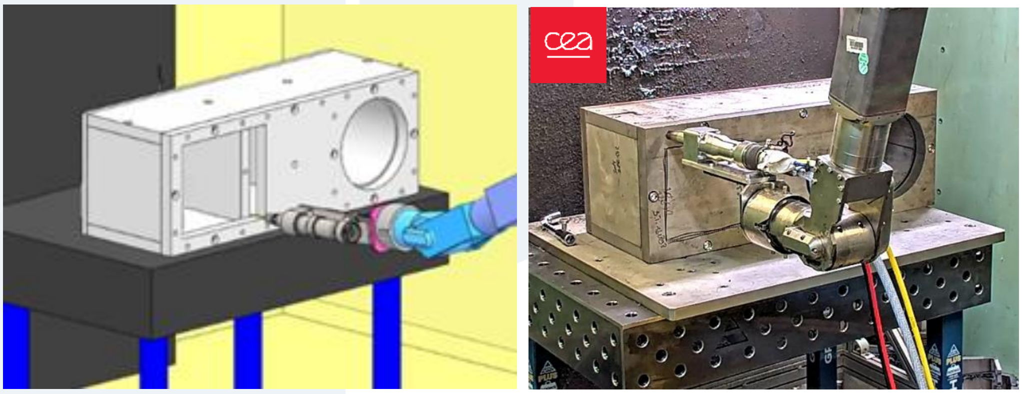


Figure 26: Upper plate (MainModule) Configuration before testing

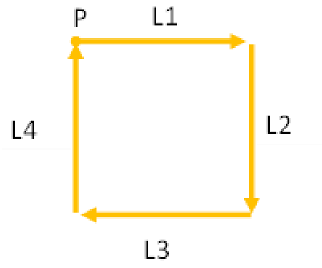
Two tests were carried out, each test consisting of cutting a square on the upper plate. The sequence for cutting the square is as follows:

SIDE 1: Initial piercing (P) → cutting line 1 (L1) → stop cutting

SIDE 2: Cutting line 2 (L2) → stop cutting

SIDE 3: Cutting line 3 (L3) → stop cutting

SIDE 4: Cutting line 4 (L4) → stop cutting



For all tests, cutting is achievable (see Figure 27).

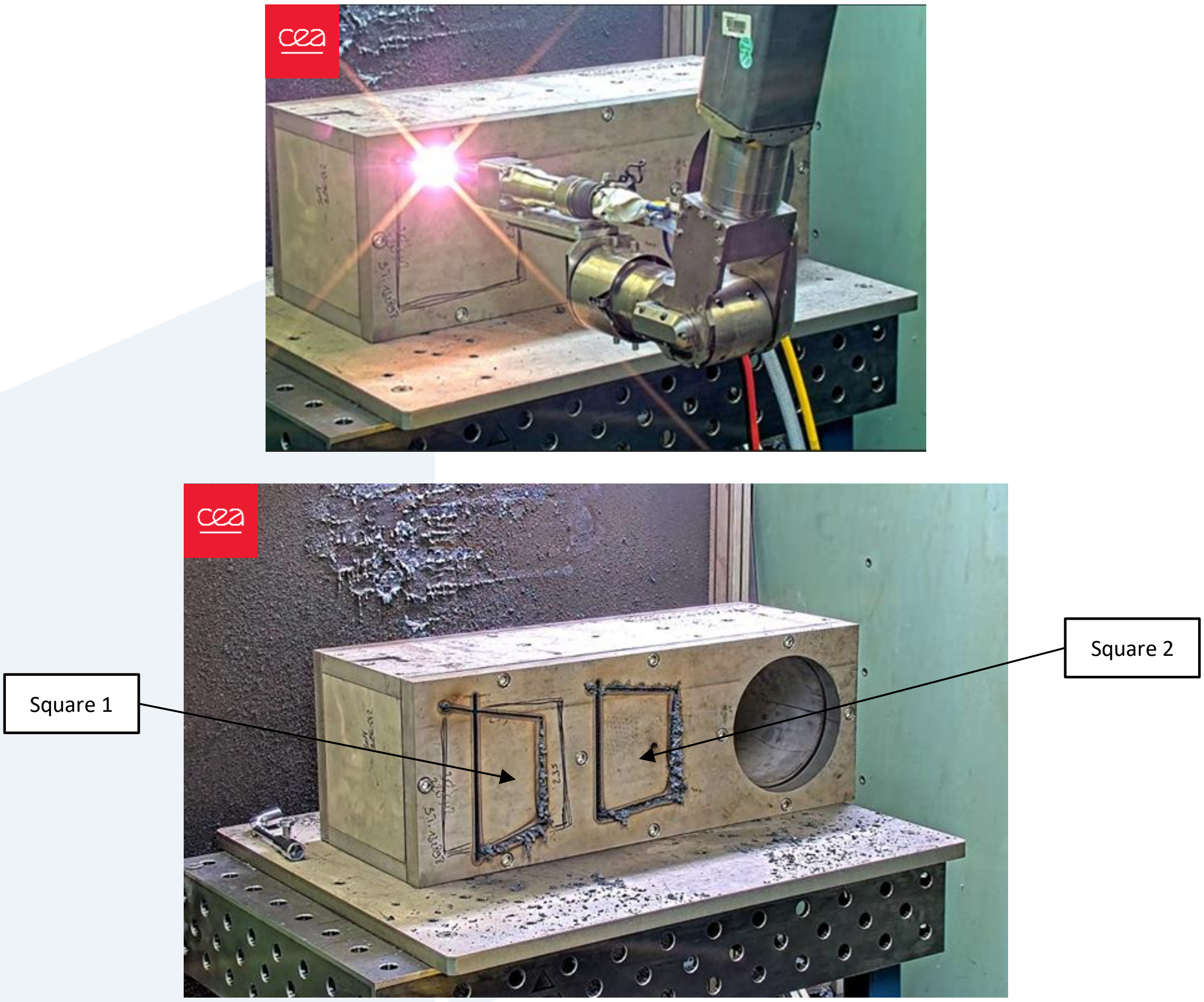


Figure 27: Result Upper plate tests (MainModule)

6.2.3.2. Ferrule

Cutting the Ferrule Plate consists in cutting a 65 mm thick stainless steel plate at an approach to the laser head of 15° angle. The effective thickness cut is then **67.5 mm**.

Note: effective thickness corresponds to the thickness penetrated by the laser beam, taking into account the thickness of the sample and the angle of approach of the laser.

The objective of this cutting is to simulate the congestion of this area and perform cutting of thick workpiece with a suboptimal cutting angle.

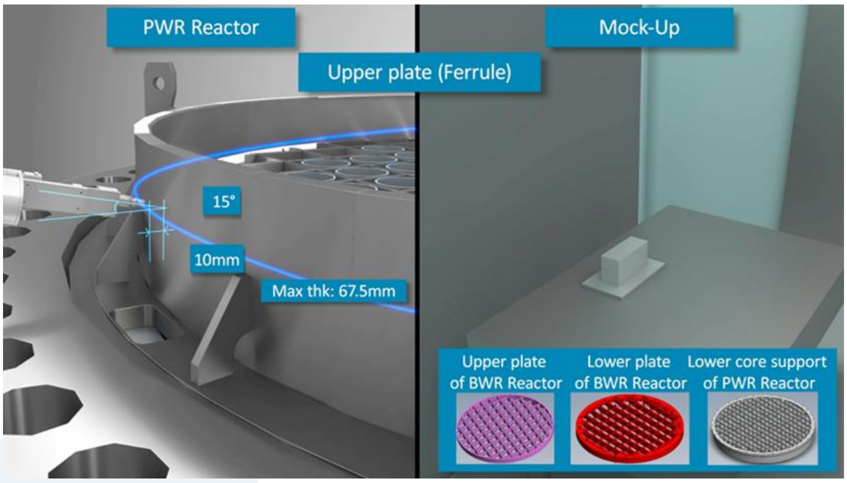


Figure 28: Ferrule of the Upper plate of PWR reactor

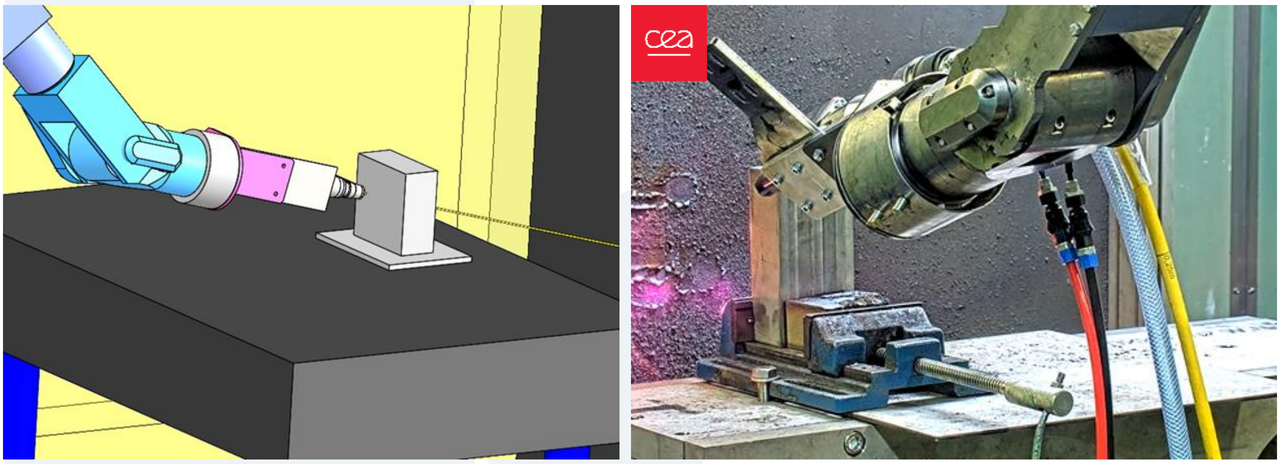


Figure 29: Ferrule plate configuration before testing

For all tests, cutting is achievable (see Figure 30).

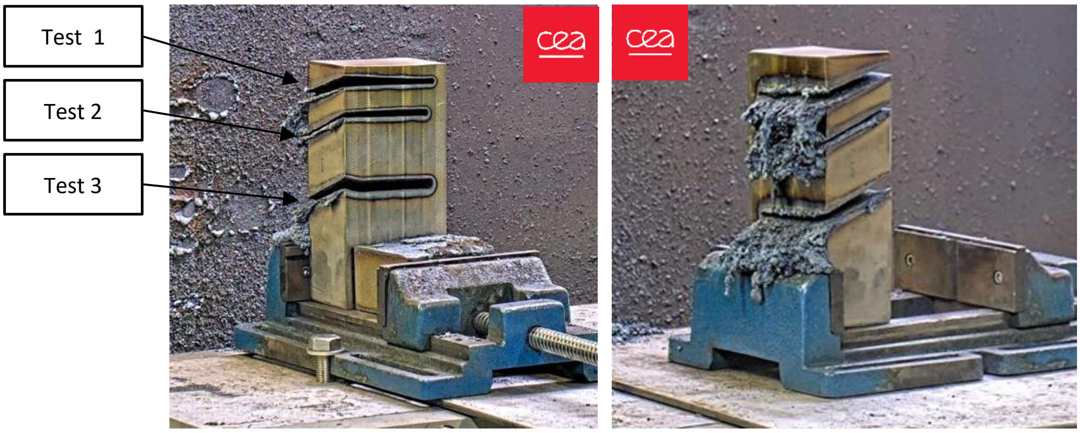


Figure 30: Result ferrule test (Front view left / rear view right)

6.2.3.3. Grid of the upper plate with 45° angle

This test consists in reproducing the cutting of a grid on the Upper Plate of the PWR reactor. The test is carried out on a 35 mm thick stainless steel plate with a 45° cutting angle. The effective thickness cut is then **56.5 mm**.

This 45° angle cutting simulates the first cutting of the grid of the upper plate. As there's no easy access to begin the cutting of the grid due to congestion of the area, the cutting must be performed with a 45° angle thus increasing the overall thickness to be cut. This cutting is the hardest one to perform on this reactor internal.

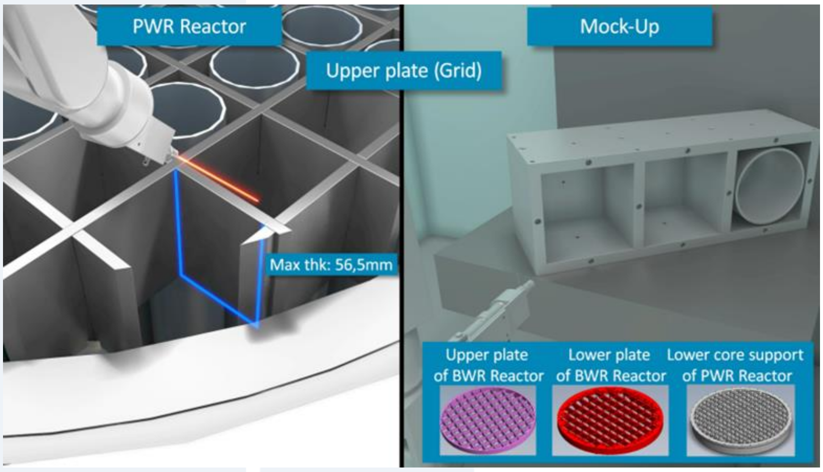


Figure 31: Grid of PWR reactor

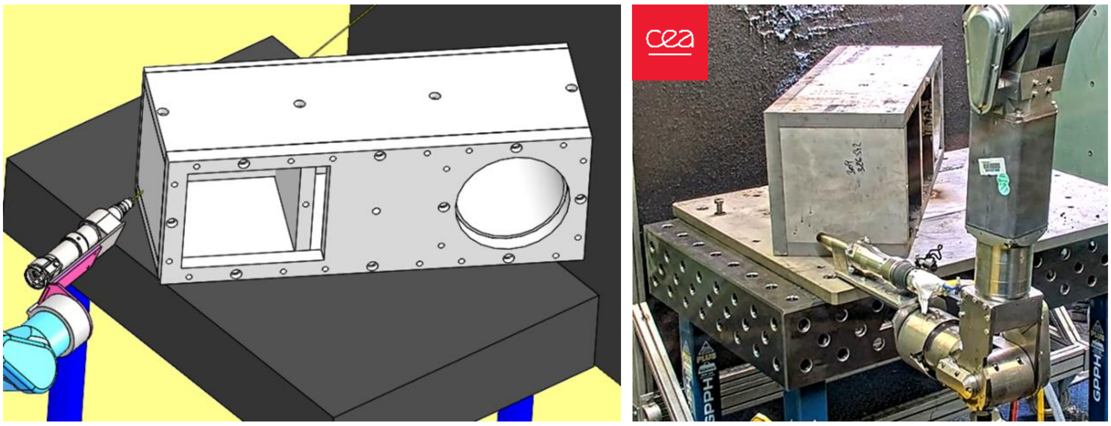


Figure 32: Grid configuration before testing

Five tests were carried out, each test consisting of cutting a line on the sample:

- Three vertical cuts
- Two horizontal cuts

For each test, cutting is carried out in the following sequence → piercing the sample with the laser in a stationary position, followed by linear cutting.

For all tests, cutting is achievable (see Figure 33).

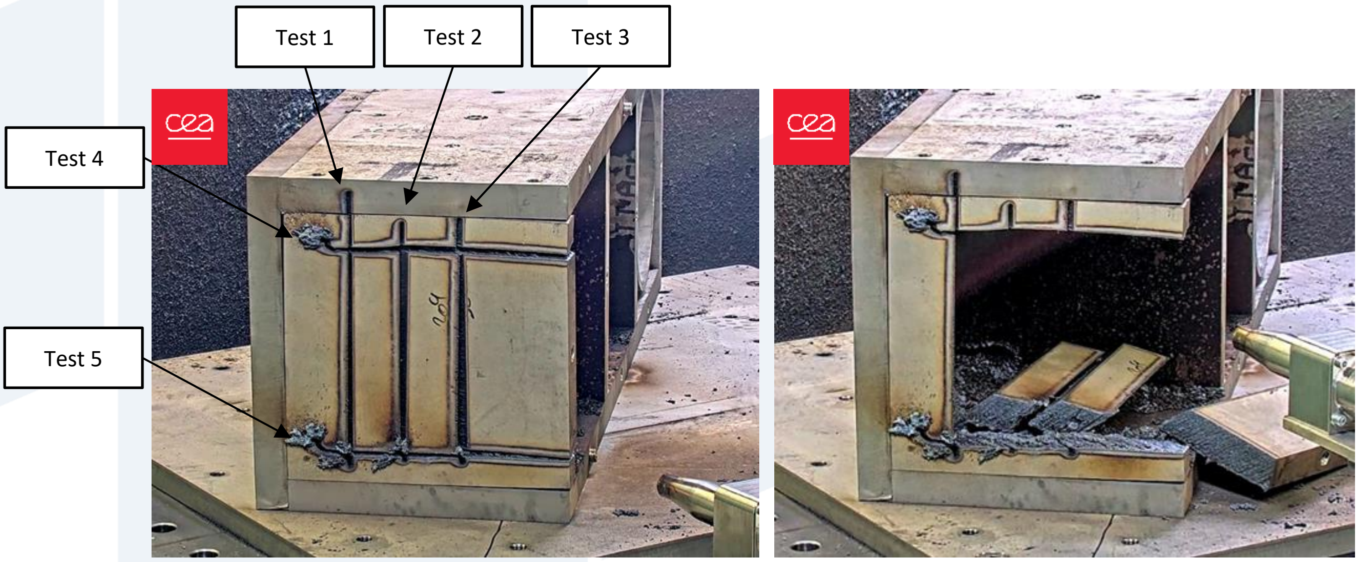


Figure 33: Result grid tests (MainModule)

6.2.3.4. Grid of the upper plate with 20° angle

This test consists in reproducing the cutting of a grid on the Upper Plate of the PWR reactor. The test is carried out on a 35 mm thick stainless steel plate with a 20° cutting angle. The effective thickness cut is then **37.5 mm**.

This 20° angle cutting simulates the second cutting of the grid of the upper plate. In addition to the possibility of cutting, this test also demonstrates the limitation of movement of the robotic arm inside the grid.

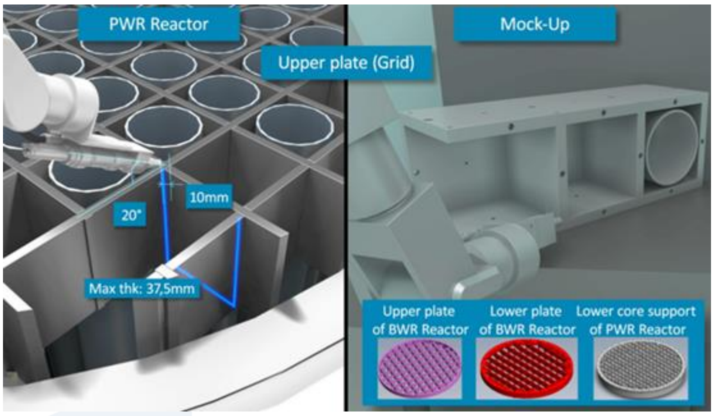


Figure 34: Grid of PWR reactor

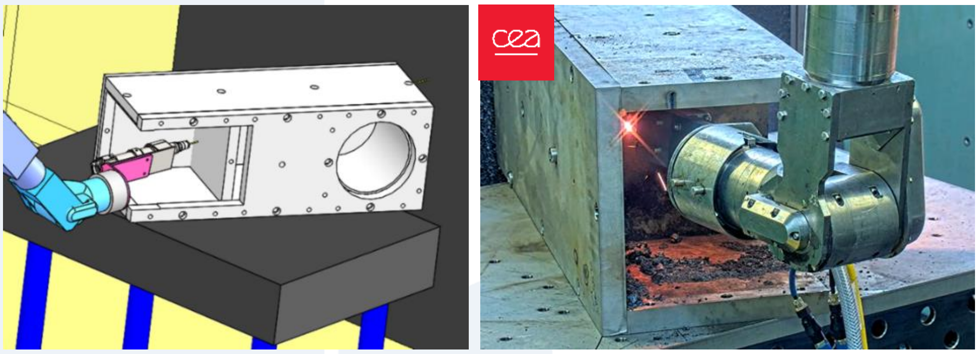


Figure 35: Grid configuration before testing

Five tests were carried out, each test consisting of cutting a line on the sample:

- Two vertical cuts
- Two horizontal cuts

For each test, cutting is carried out in the following sequence → piercing the sample with the laser in a stationary position, followed by linear cutting.

For all tests, cutting is achievable (see Figure 36).

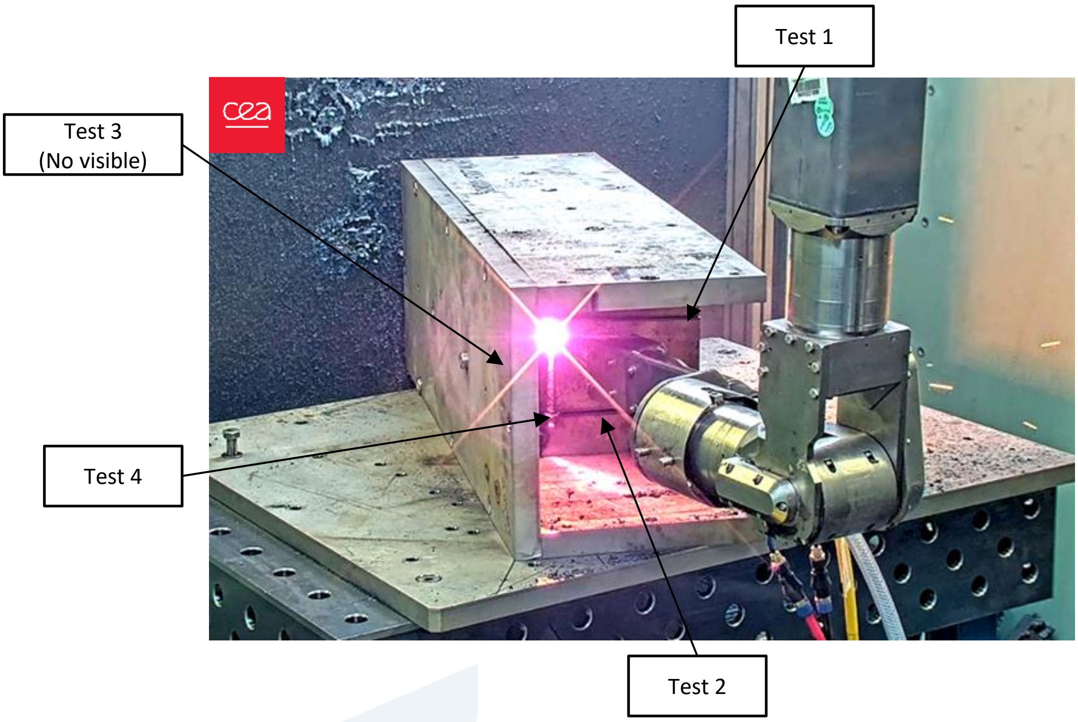


Figure 36: Result grid tests (MainModule)

6.2.3.5. Grid and control rod guides of the upper plate

This test consists in reproducing the cutting of grid and control rod guides on the Upper Plate of the PWR reactor. The test is performed on a combination of samples:

- 1 grid (35 mm thick stainless steel plate)
- 1 control rod guide (273.05 mm diameter, 9.27 mm thick stainless steel tube)
- 1 grid (35 mm thick stainless steel plate)

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **165 mm**.

If successful, this cutting test will highlight the possibility of cutting several layers at the same time and so, the time savings the laser cutting technology can provide.

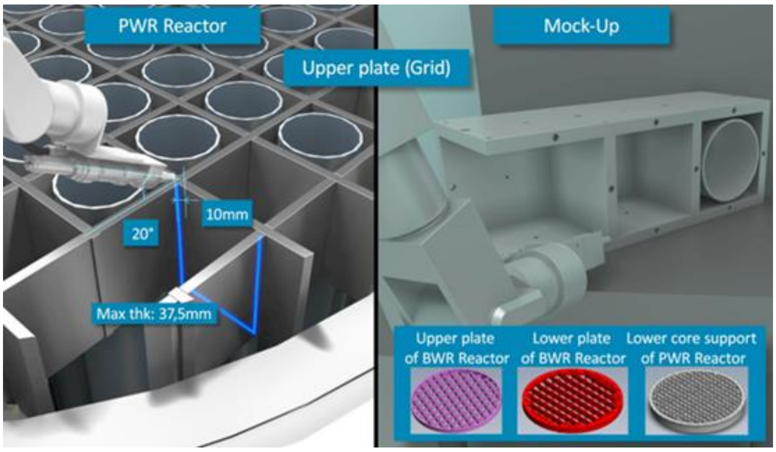


Figure 37: Grid and control rod guide of PWR reactor

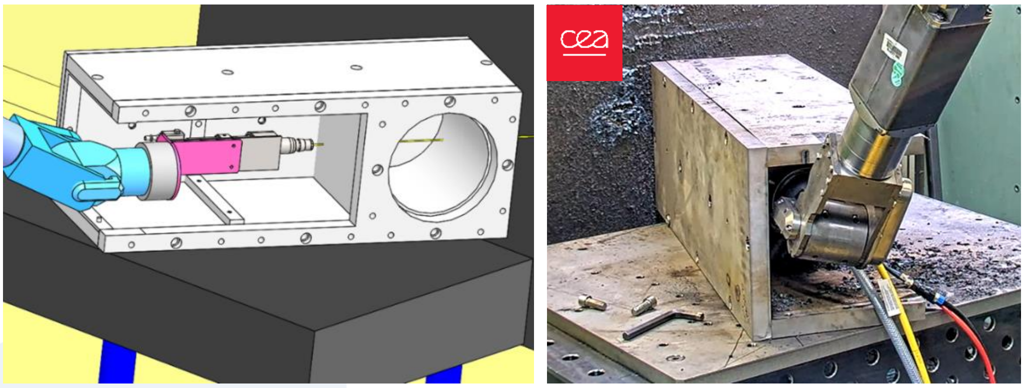


Figure 38: Grid and control rod guide configuration before testing

Two tests were carried out in horizontal position. For each test, cutting is carried out in the following sequence → piercing the sample with the laser in a stationary position, followed by linear cutting.

The cuttings are compliant except for test 2 on small segments which are not clear. Probably because the cutting speed is too high and the cutting thickness was greater than in test 1.

Test 1 is carried out in the center of the pipe, where the thickness is lowest for a 90° approach to the sample.

Test 2 is carried out at a lower level, and the thickness is therefore greater, taking into account the curvature of the pipe (see Figure 39).

Figure 39: Result Upper grid and control rod guides tests (MainModule)

6.2.3.6. Core shroud convex part

The tests consist in cutting a straight line in the convex part of the core shroud. The purpose is to completely remove the element. The laser head is positioned at a 90° angle to the sample.

This cutting test aims to assess the influence of geometry on the assist gas and the cutting performance.

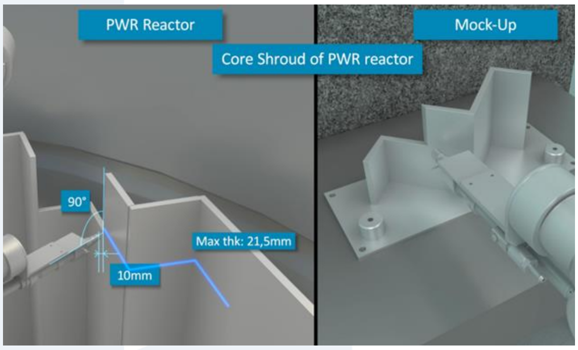


Figure 40: Core shroud of PWR reactor (convex part)

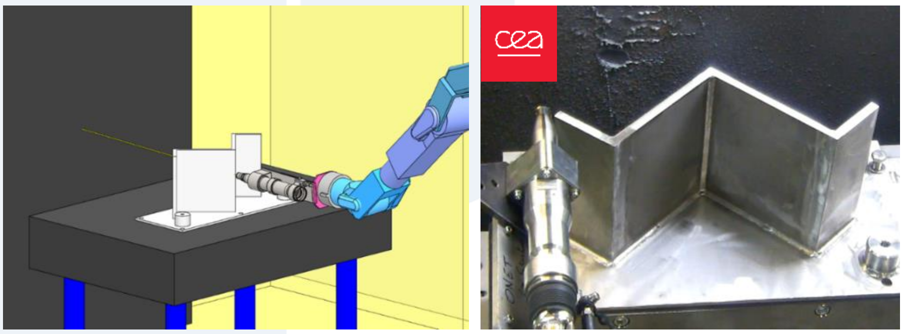


Figure 41: Core shroud configuration before testing

(a) Tests without collection device

For all tests, cutting is achievable (see Figure 42).

Figure 42: Result core shroud tests (convex part)

(b) Tests with collection device

The test configuration is identical to that of tests without collection devices. The addition of the collection head does not interfere with cutting operations.

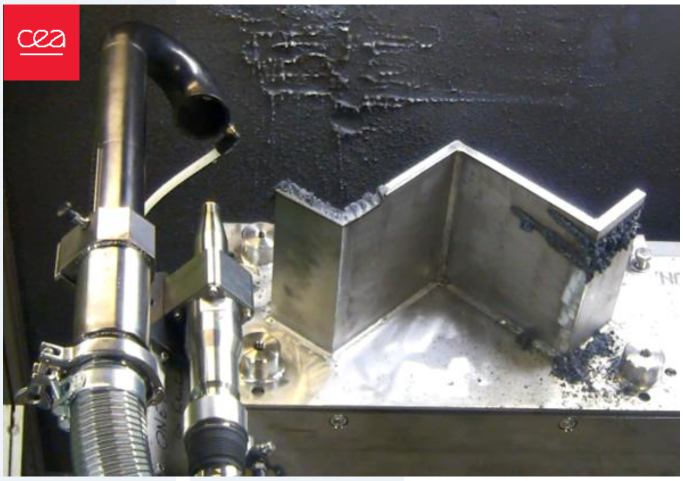


Figure 43: Core shroud configuration before testing with collection device

Test 1: Successful cutting but incorrect laser positioning (only a thin layer is cut)

Test 2: Successful cutting except at the beginning of the cut when the laser head is too far from the sample.

Test 3: Successful cutting but incorrect laser positioning → test stops because the collection head is in contact with the sample during cutting.

Test 4: Successful cutting.

Figure 44: Result core shroud tests (convex part with collection device)

For this configuration, the collection head allows aerosol dispersion to be decreased by 40%.

6.2.3.7. Core shroud concave part

(a) Tests without collection device

The tests consist in cutting a straight line in the concave part of the core shroud. The test is identical to the conditions in the convex part of the sample, but is carried out in the concave part.

This cutting test aims to assess the influence of geometry on the assist gas and the cutting performance.

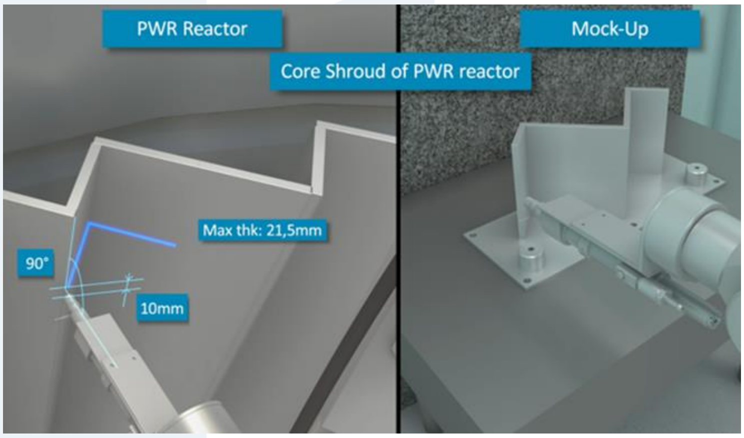


Figure 45: Core shroud of PWR reactor (concave part)

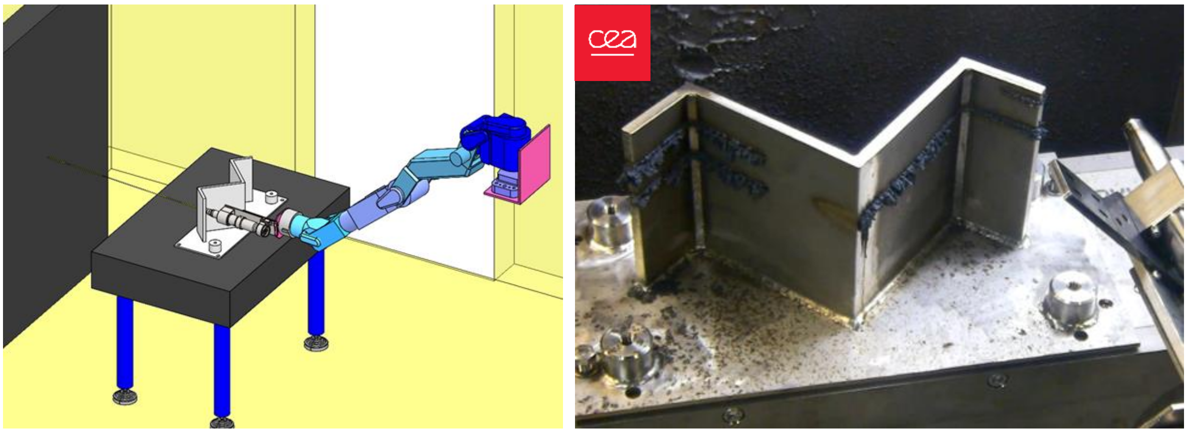


Figure 46: Core shroud configuration before testing

For all tests, cutting is achievable (see Figure 47).

Figure 47: Result core shroud tests (concave part)

(b) Tests with collection device

The test configuration is identical to that of tests without collection devices. The addition of the collection head does not interfere with cutting operations.

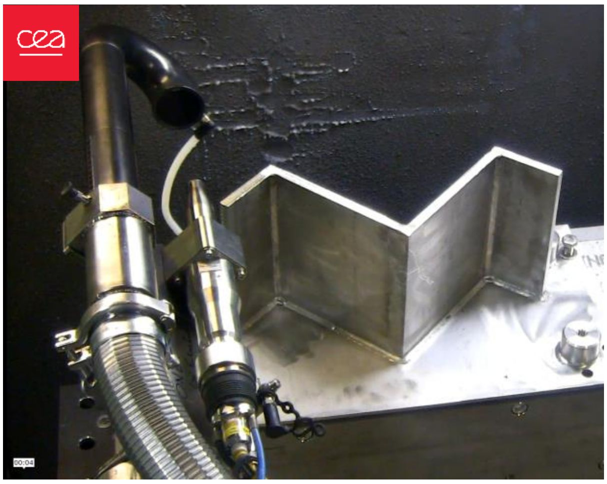


Figure 48: Core shroud configuration before testing with collection device

Results:

Test 1: Successful cutting except at the beginning of the cut when the laser head is too far from the sample.

Test 2: Successful cutting but close to test 1 line.

Test 3: Successful cutting.

Figure 49: Result core shroud tests (concave part with collection device)

For this configuration, the collection head allows aerosol dispersion to be decreased by 36%.

6.2.3.8. One pipe of BWR's steam dryer

The series of tests performed from §6.2.3.8 to §6.2.3.13 assess the ability of the laser cutting technology to dismantle several layers at the same time, which allows a great time reduction in dismantling operations.

This test consists in reproducing the cutting of one steam dryer of the BWR reactor. The test demonstrates the cutting of a steam dryer on the upper part, which consists only of a pipe with no internal parts (Model 4).

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **56.5 mm**.

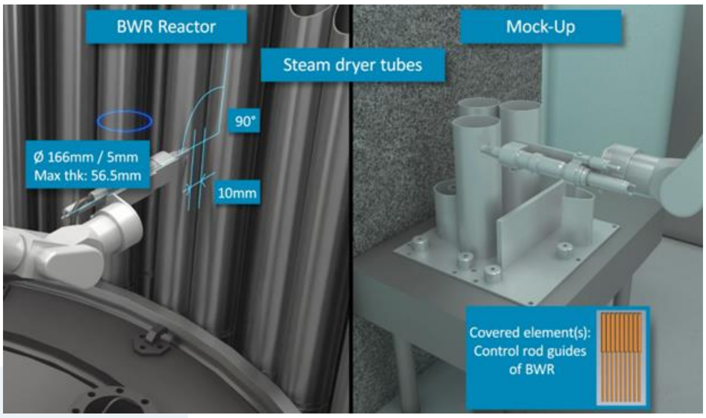


Figure 50: One pipe of BWR's steam dryer

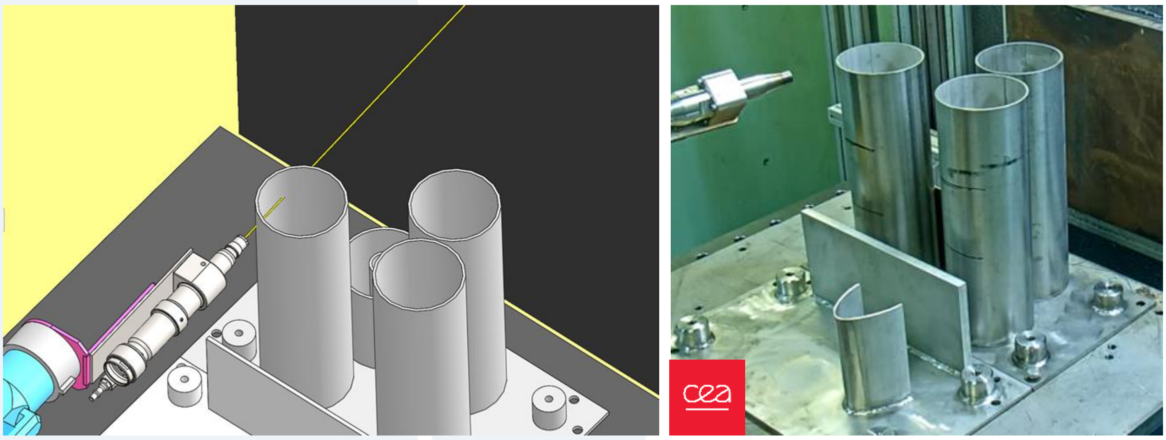


Figure 51: Steam dryer configuration before testing

For all tests, cutting is achievable (see Figure 52).

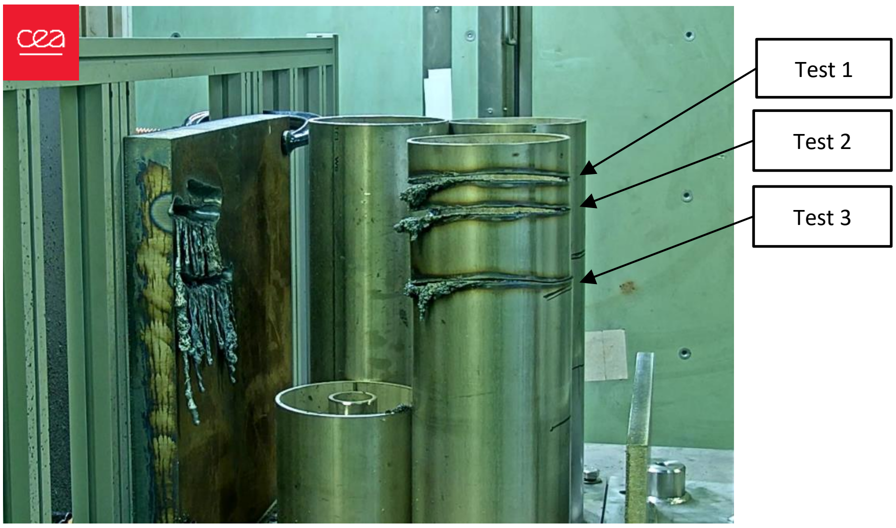


Figure 52: Result one steam dryer tests (side view)

6.2.3.9. Two pipes of BWR's steam dryer

This test consists in reproducing the cutting of two steam dryer of the BWR reactor. The test demonstrates the cutting of the steam dryer on the upper part, which consists of two pipes with no internal parts (Model 4).

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **67.5 mm**.

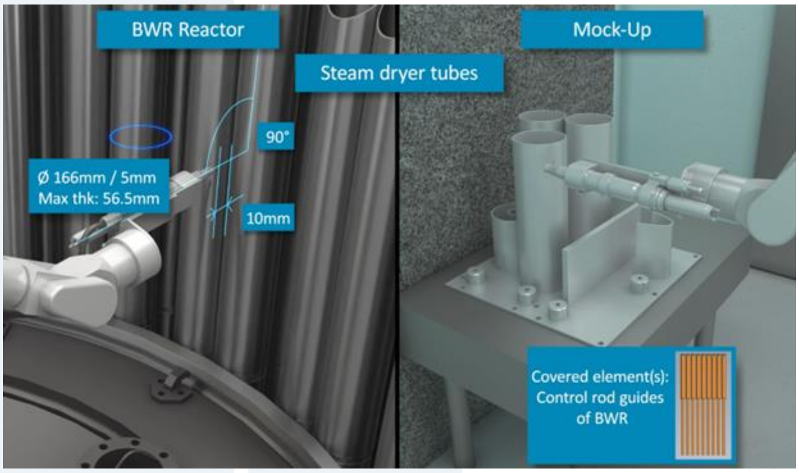


Figure 53: Two pipes of BWR's steam dryer

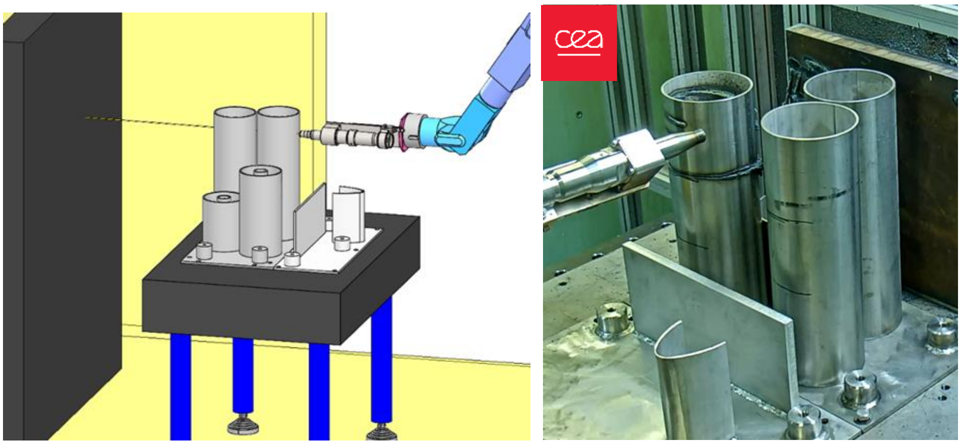


Figure 54: Steam dryers configuration before testing

For all tests, cutting is achievable (see Figure 55).

Figure 55: Results for two pipes of BWR's steam dryer (side view)

6.2.3.10. One pipe with internal of BWR's steam dryer

These tests are identical to those carried out for the steam dryers (see §.6.2.3.8), but with the addition of internals. The test demonstrates the cutting of a steam dryer on the middle part, which consists of a pipe with internal parts (Model 4).

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **56.5 mm**.

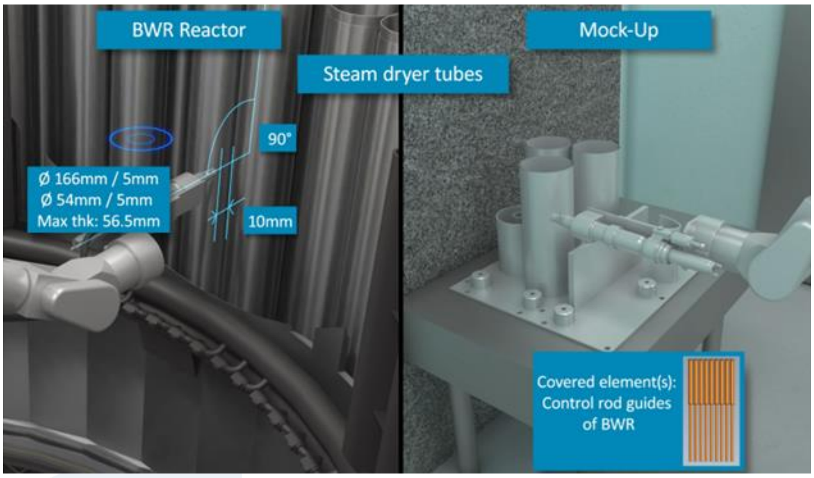


Figure 56: One pipe with internal of BWR's steam dryer

Figure 57: Steam dryer configuration before testing

For all tests, cutting is achievable (see Figure 58).

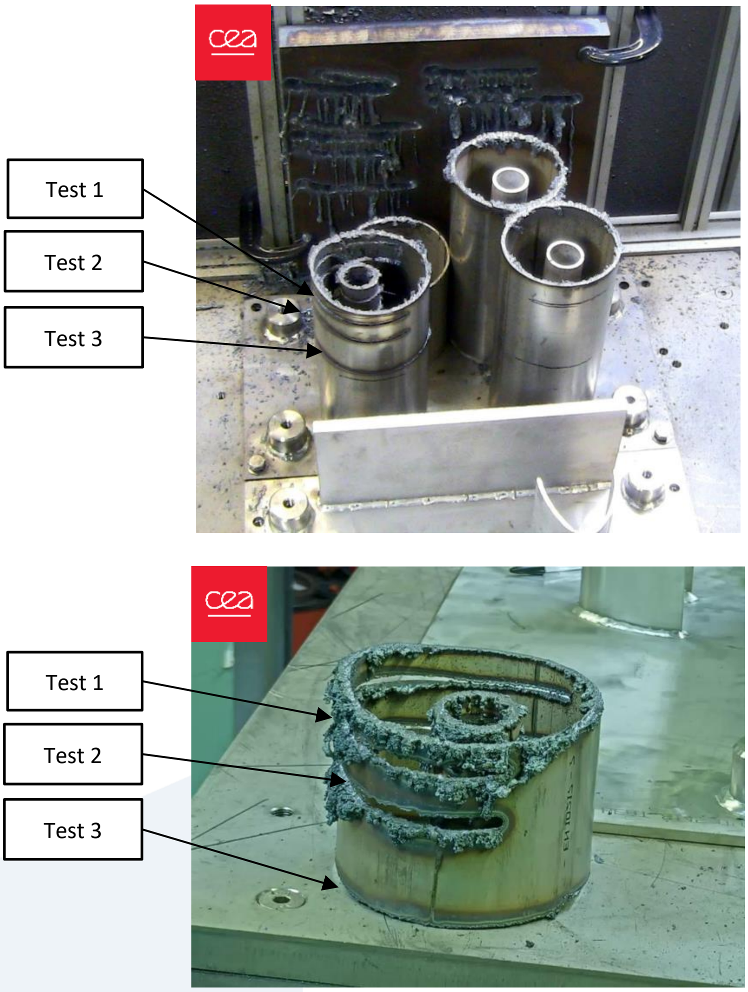


Figure 58: Results for one pipe with internal of BWR's steam dryer tests (Top view and Rear view)

6.2.3.11. Two pipes with internal of BWR's steam dryer

These tests are identical to those carried out for the steam dryers (see §.6.2.3.9), but with the addition of internals. The test demonstrates the cutting of the steam dryers on the middle part, which consists of two pipes with internal parts (Model 4).

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **98.7 mm**.

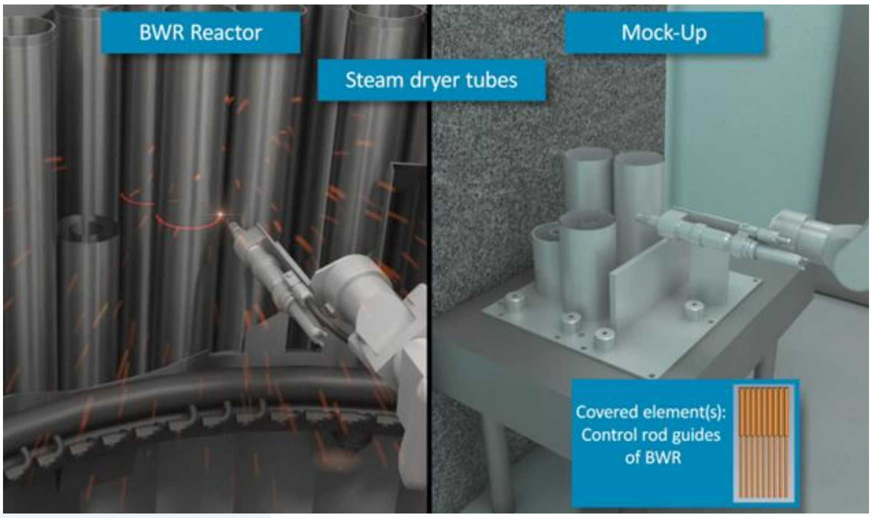


Figure 59: Two pipes with internal of BWR's steam dryer

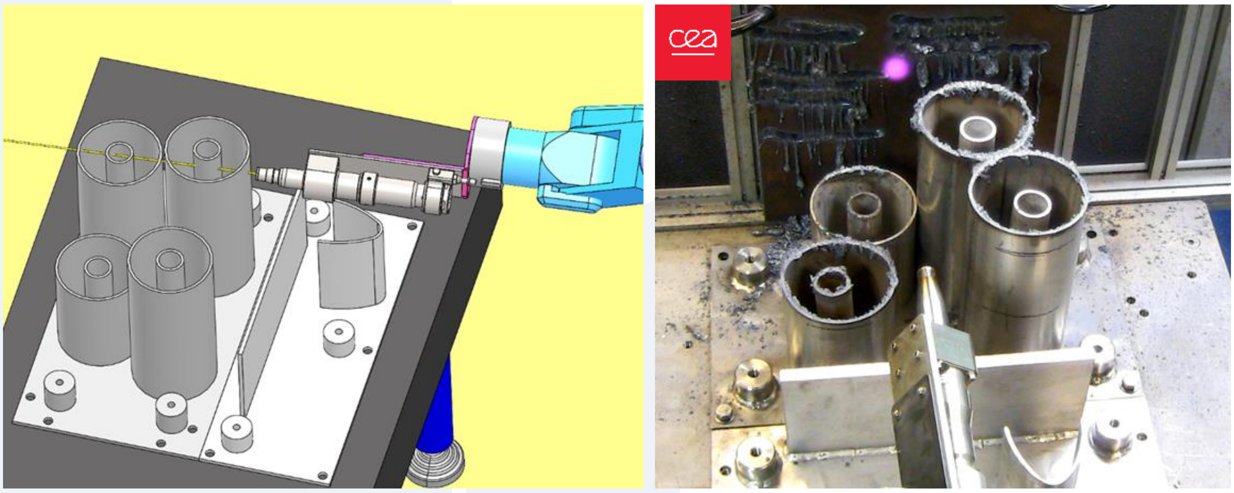
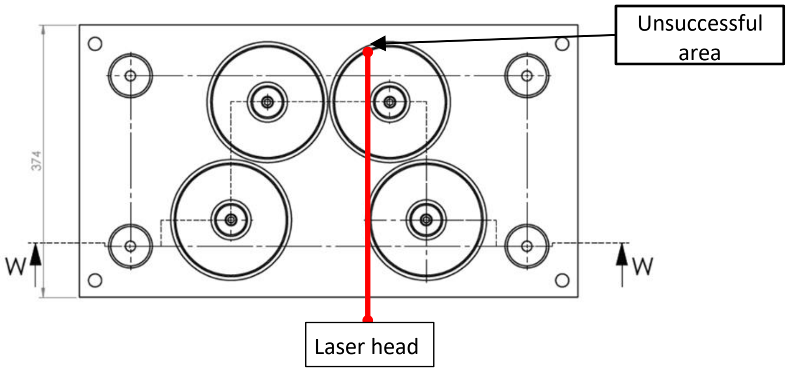


Figure 60: Steam dryers with internal configuration before testing

- Test 1: unsuccessful cutting in thickest part of sample (outside of pipe 1 + outside of inner pipe 2)



- Test 2: modification of the cutting speed to obtain total cutting of the sample → successful cutting
- Test 3: Increase speed to limit the impact of residual energy → successful cutting

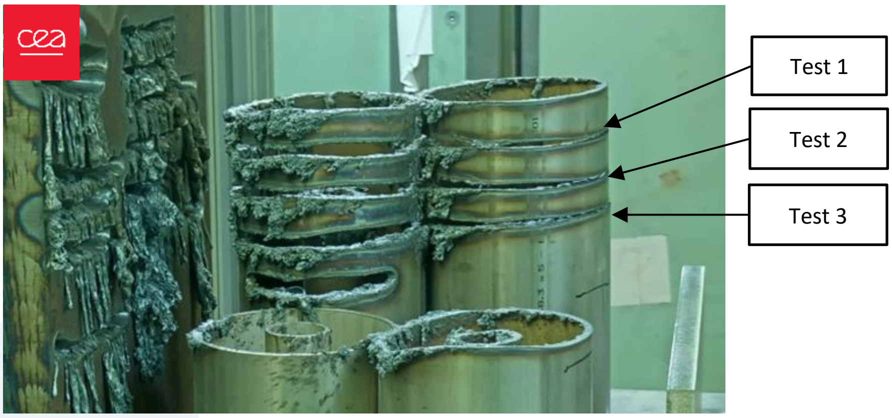


Figure 61: Results for two pipes with internal of BWR's steam (side view)

6.2.3.12. Two pipes with internal of BWR's steam dryer and support ring

These tests are identical to those carried out for the steam dryers with internal (see §.6.2.3.11), but with the addition of a wall representing the support ring. The test demonstrates the cutting of the steam dryers on the bottom part, which consists of two pipes with internal parts and a wall in front of the pipes. For these tests, the Model2 is positioned in front of the Model4.

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **118.7 mm**.

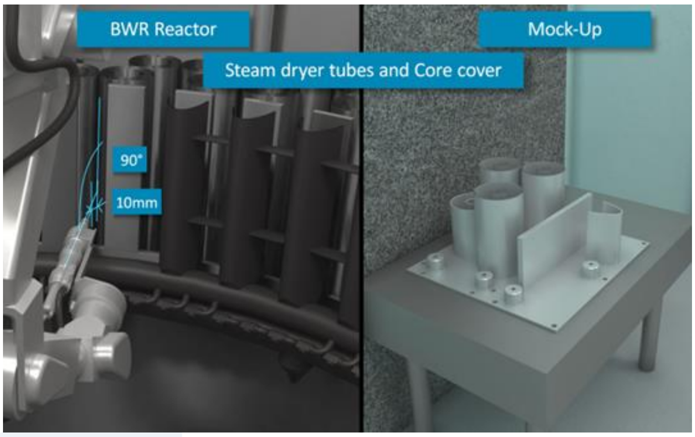


Figure 62: Two pipes with internal of BWR's steam dryer and support ring

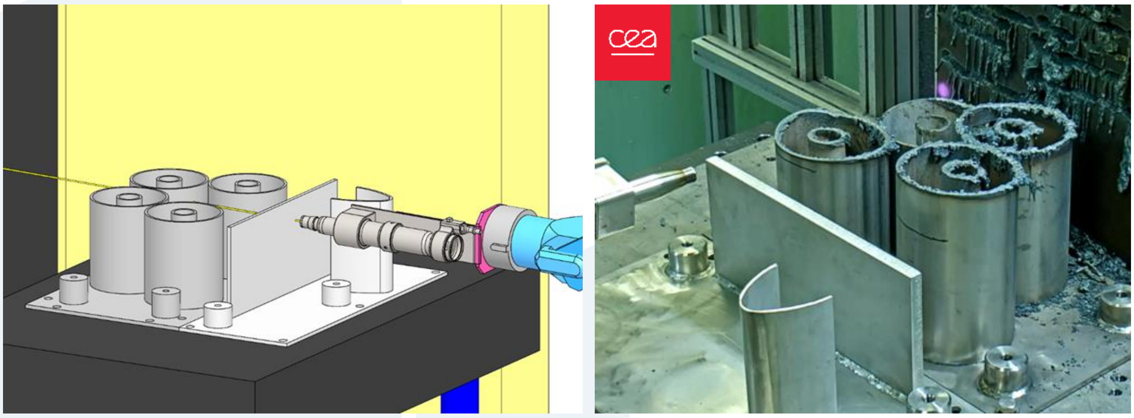


Figure 63: Steam dryers with internal and support ring configuration before testing

- Unsuccessful cutting in thickest part of sample (outside of pipe 1 + outside of inner pipe 2) even if applying low cutting speeds.

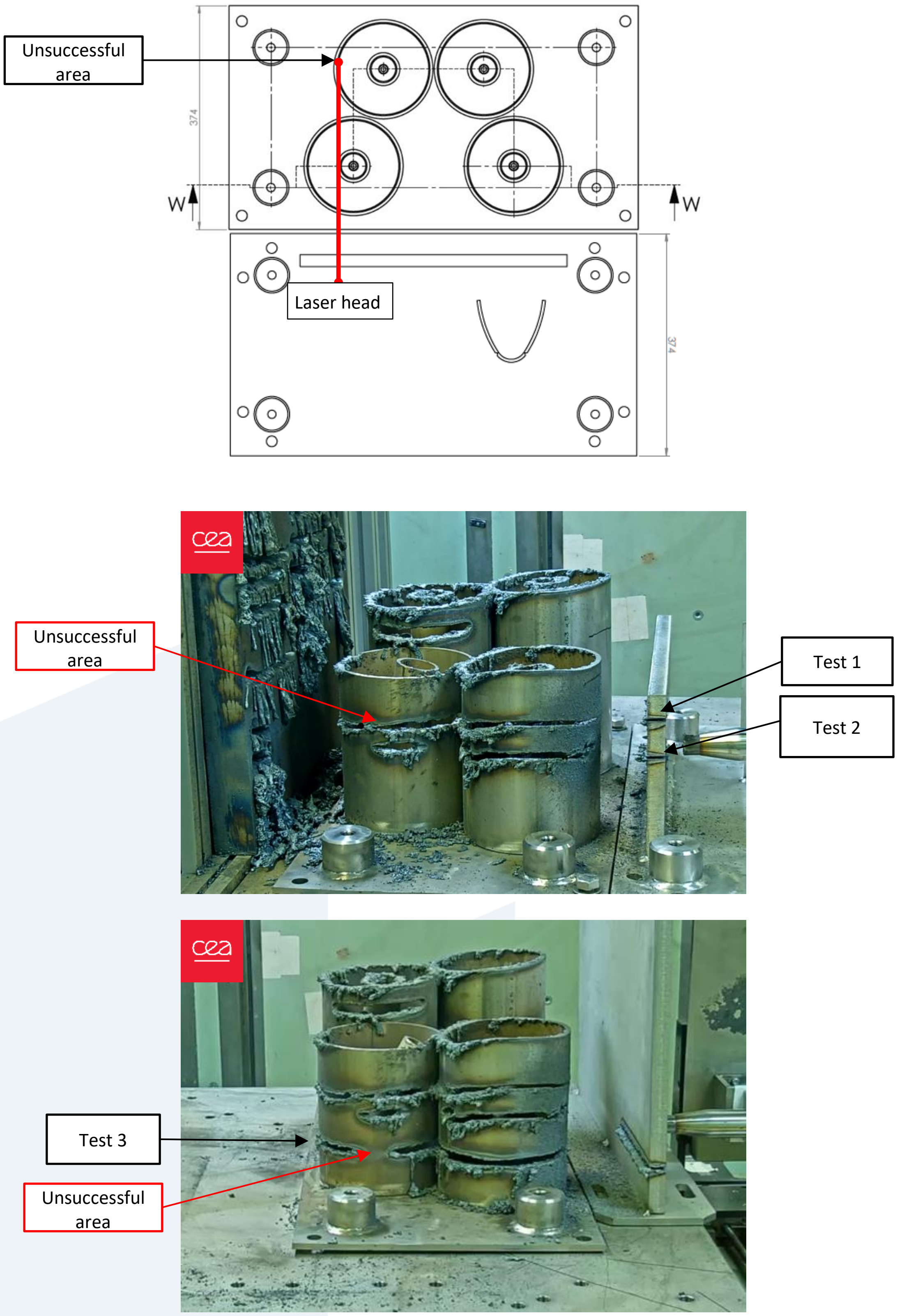


Figure 64: Results for two pipes with internal of BWR's steam dryer and support ring (side view)

6.2.3.13. Two pipes with internal of BWR's steam dryer, support ring and core cover

These tests are identical to those carried out for the steam dryers with internal and support ring (see §.6.2.3.11), but with the addition of a core cover. The test demonstrates the cutting of the steam dryers on the bottom part, which consists of two pipes with internal parts, a support ring and a core cover in front of the pipes. For these tests, the Model2 is positioned in front of the Model4.

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **124.7 mm**.

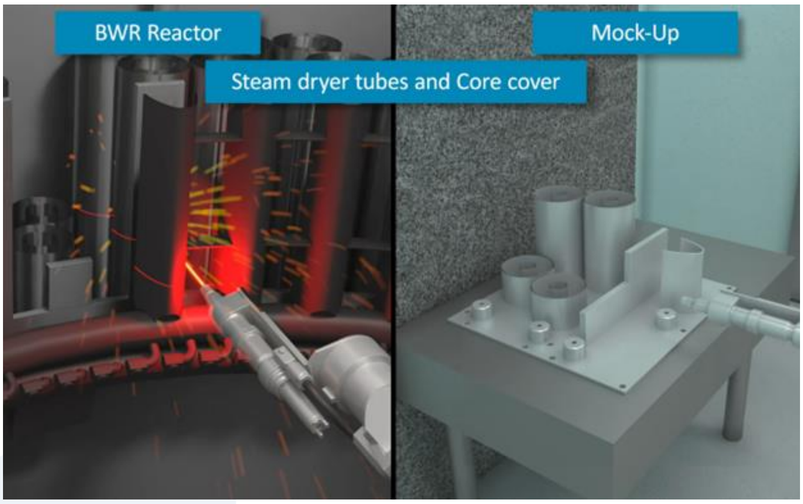


Figure 65: Two steam dryers with internal, support ring and core cover of BWR reactor

Figure 66: Steam dryers with internal, support ring and core cover configuration before testing

- Test 1: unsuccessful cutting in several parts of sample The cutting speed is too fast.
- Test 2: modification of the cutting speed to obtain total cutting of the sample → unsuccessful cutting in several parts of sample The cutting speed is too fast.
- Test 3: decrease cutting speed to obtain total cutting of the sample → unsuccessful cutting in thickest part of sample. The extensive stand-off (approx. 60 mm) is too pronounced to allow complete cutting of the sample with speeds defined by ONET database.

Figure 67: Result two steam dryers tests with internals, support ring and core cover (Front view)

Figure 68: Result two steam dryers tests with internals, support ring and core cover (Rear view)

6.2.3.14. Poisoning plates of BWR

This test consists in reproducing the cutting of poisoning plate of the control rods from the BWR reactor. The test demonstrates the cutting of a poisoning plate without control rod, the mock-up used is the upper part of the Model3. The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **87.5 mm**.

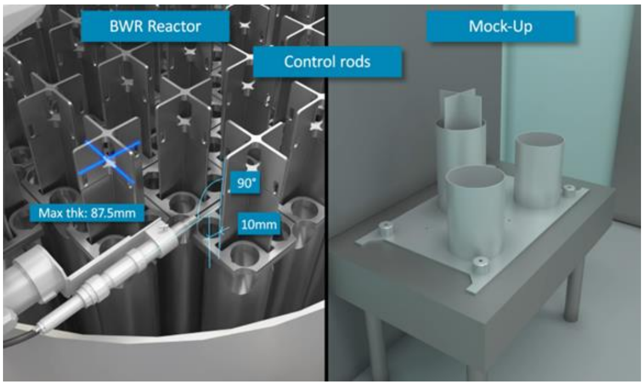


Figure 69: Poisoning plate of BWR reactor

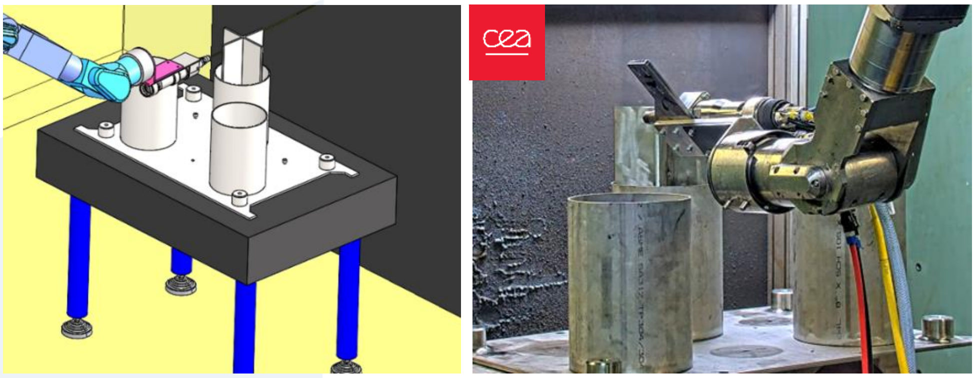


Figure 70: Poisoning plate configuration before testing

Tests 1 to 3 were carried out with an optimal stand-off 30 mm and successful cutting was achieved (see Figure 71). For test 4, the distance between the laser head and the sample is 130 mm. With the same cutting conditions (power, speed, gas assist), successful cutting was achieved (see Figure 72).

Note that as the stand-off increases, so does the thickness of the cut. This phenomenon is due to the expansion of the laser beam with distance.

Figure 71: Result poisoning plate tests (Front and rear view)

Figure 72: Result poisoning plate test 4 (side view)

6.2.3.15. Control rod with poisoning plate of BWR with 45° angle

These tests are identical to the previous ones, but the laser head is positioned at a 45° angle. Cutting is performed with a linear trajectory on the Model3. The test demonstrates the cutting of a poisoning plate with control rod when the reactor vessel is in close proximity.

The laser head is positioned at a 45° angle to the sample. The max effective thickness cut is then **109 mm**.

This 45° cutting angle simulates the congestion of the area at the beginning of the dismantling of these internals. If successful, this cutting will provide good indications of the ability of the laser cutting technology to clear a path to the several internals to be cut.

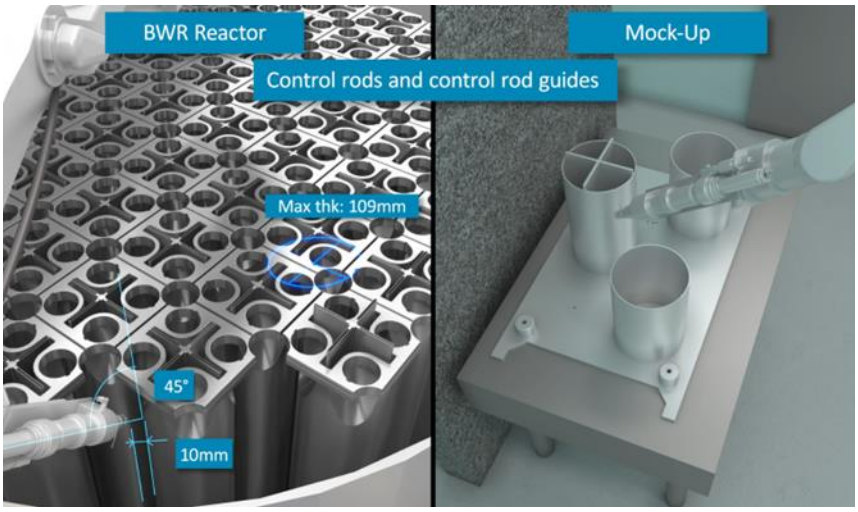


Figure 73: Control rod with poisoning plate of BWR reactor with 45° angle

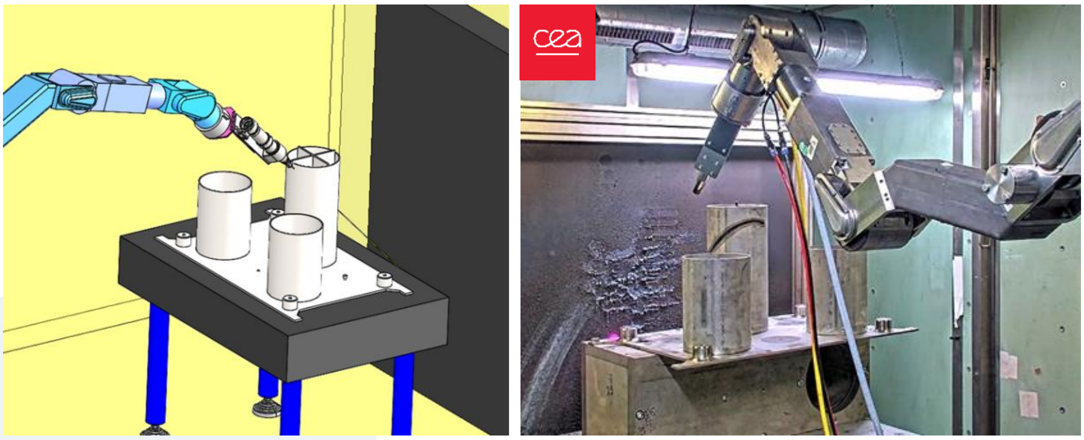


Figure 74: Control rod with poisoning plate configuration before testing (45° angle)

Cutting at an angle of 45° is achievable for several cutting speeds tested.

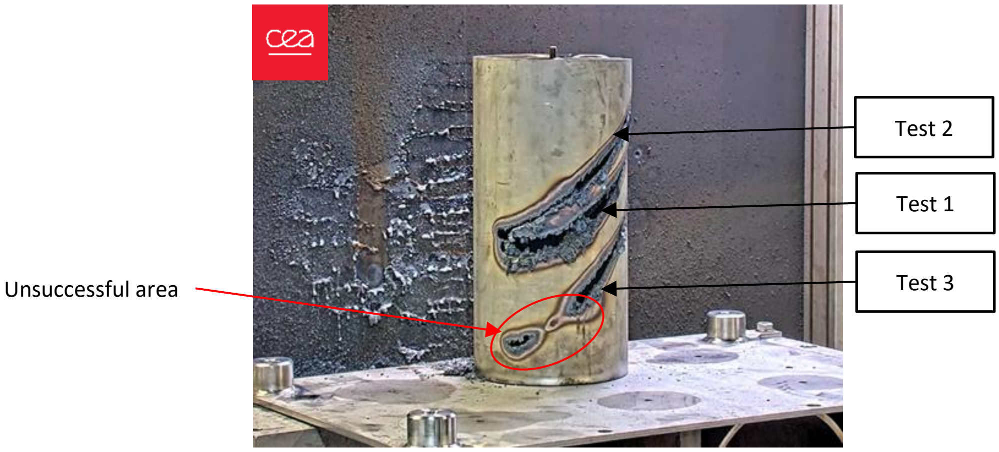


Figure 75: Result control rod with poisoning plate 45° angle tests (Front and rear view)

6.2.3.16. Control rod with poisoning plate of BWR

This 90° cutting angle is the optimal cutting angle. These tests will provide indications on the speed at which those elements can be dismantled.

This test consists in reproducing the cutting of control rod with poisoning plate from the BWR reactor. The test demonstrates the cutting of a poisoning plate with control rod, the mock-up used is the bottom part of the Model3.

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **92 mm**.

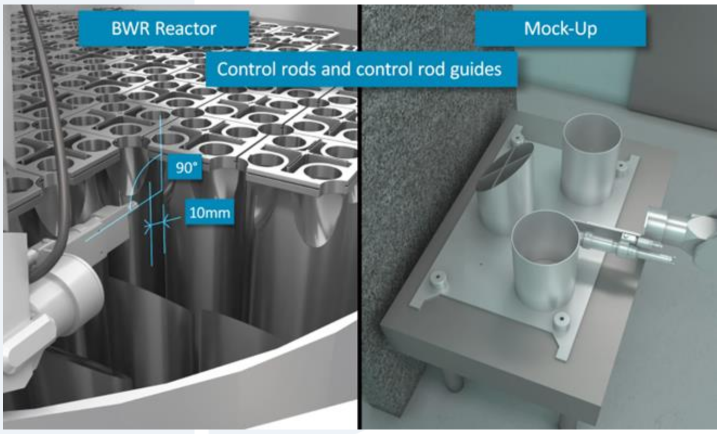


Figure 76: Control rod with poisoning plate of BWR reactor

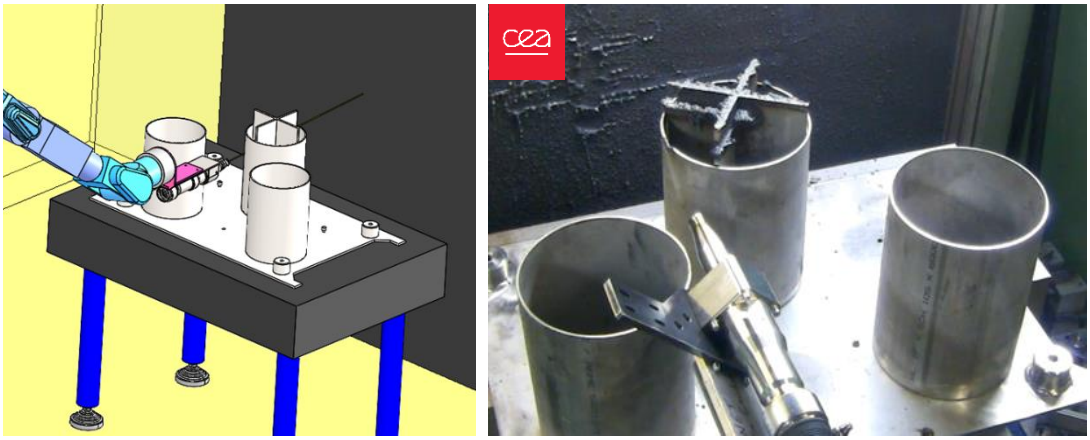
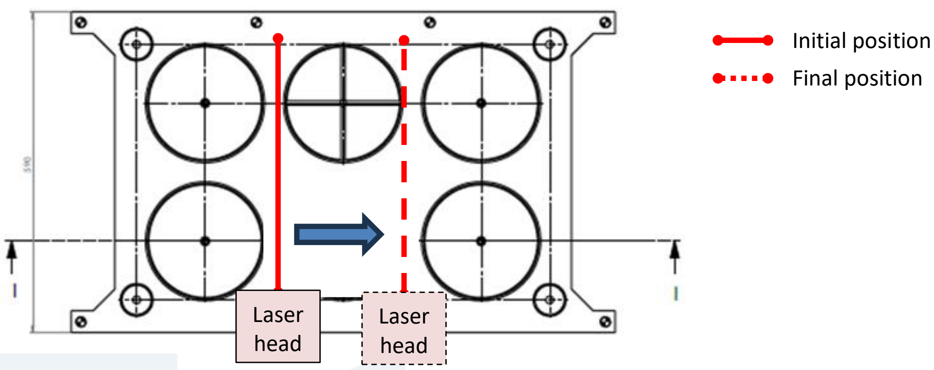


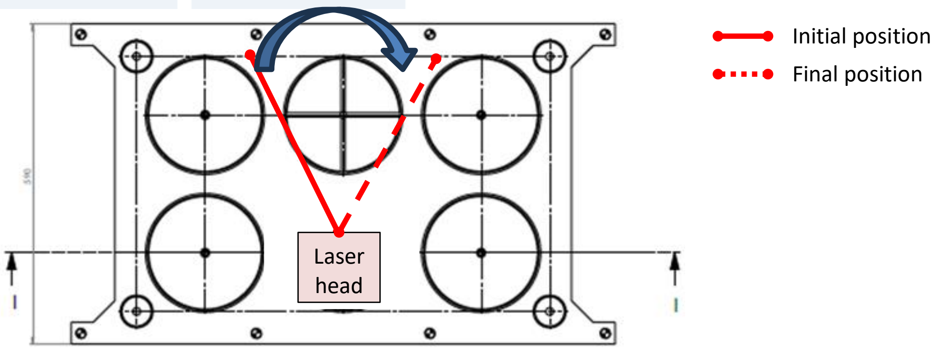
Figure 77: Control rod with poisoning plate configuration before testing

Because of the restricted space available on the control rods, cutting can be carried out in 2 ways:

- Linear cutting with a large stand-off to allow the laser head to be guided between the two front control rods.



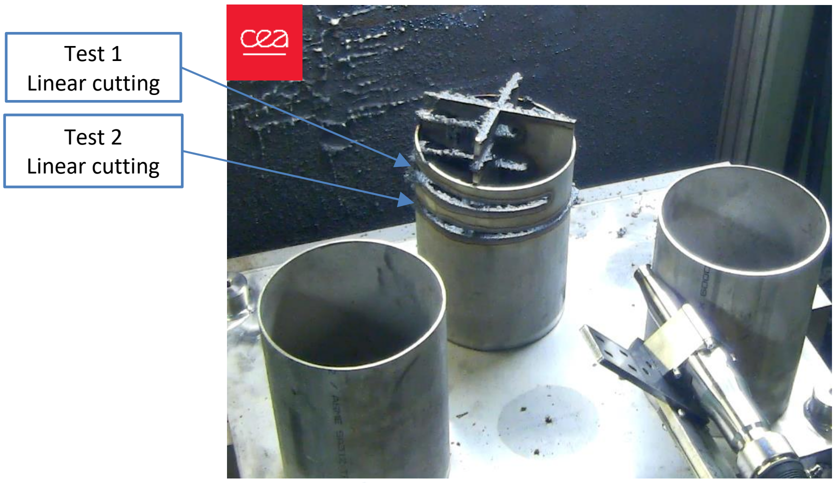
- Cutting with optimal stand-off (30 mm) but angular displacement of the laser head.

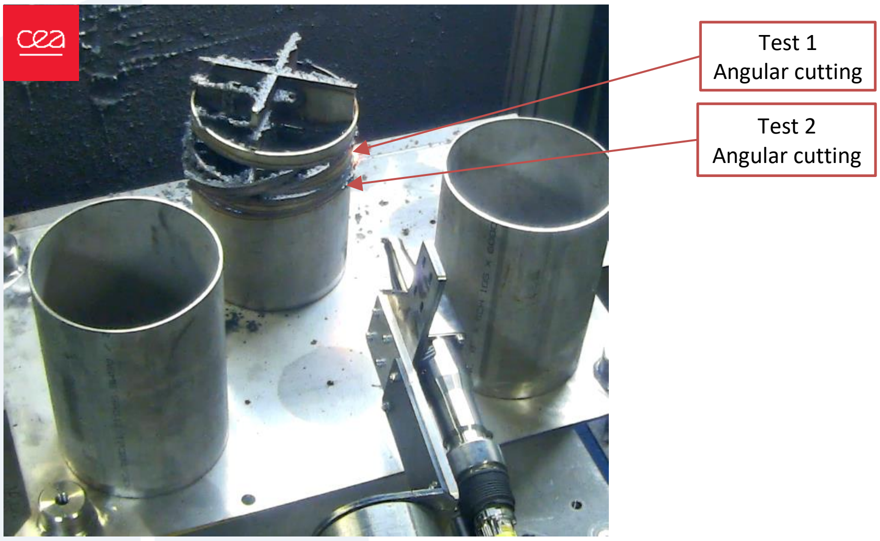


All cutting operations were successfully completed.

For linear cutting, we observed on the first tests that cutting was easily achievable, so we gradually increased the cutting speed. Cutting is achievable despite high speeds.

Note: Due to incorrect arm positioning, angular cutting test 1 is on the same trajectory as linear test 1.





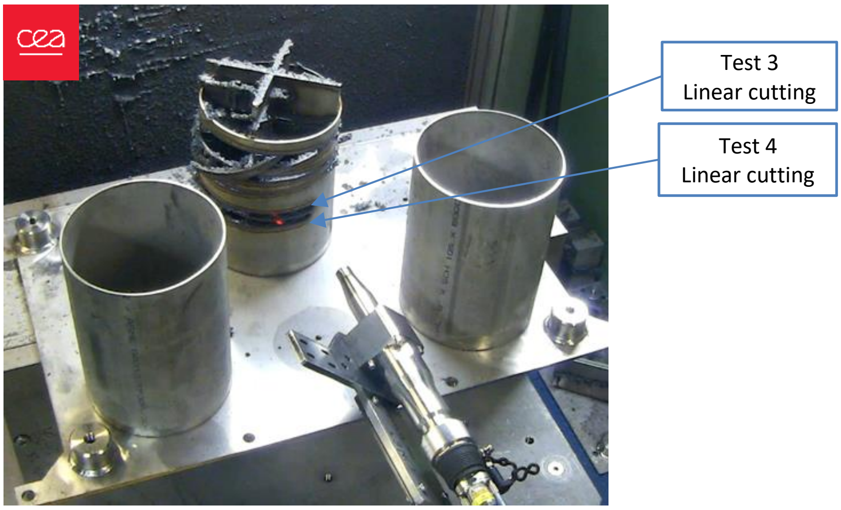


Figure 78: Result control rod with poisoning plate tests (Front view)

6.2.4 COMPLEMENTARY TESTS

6.2.4.1. Core shroud convex and concave part

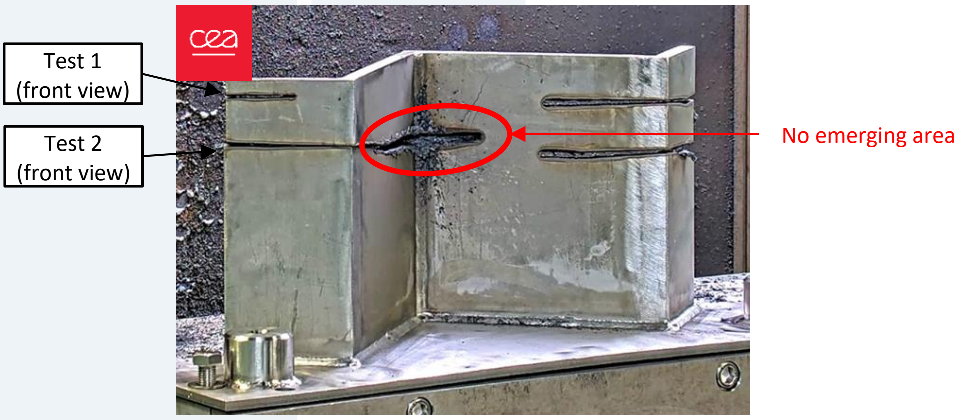
The tests consist in cutting a straight line on all core shrouds (convex and concave parts). The test is identical to the conditions in the convex and concave parts (see §.6.2.3.6 and §.6.2.3.7).

If successful, this cutting test will highlight the time savings the laser cutting technology can provide.

Test 1: cutting was quickly stopped because the laser head was in collision with the sample.

Test 2: cutting was completed, but on the most distant zone, cutting was not possible.

Test 3: the cutting speed was divided by 2 to allow the sample to be cut in all zones → successful cutting.



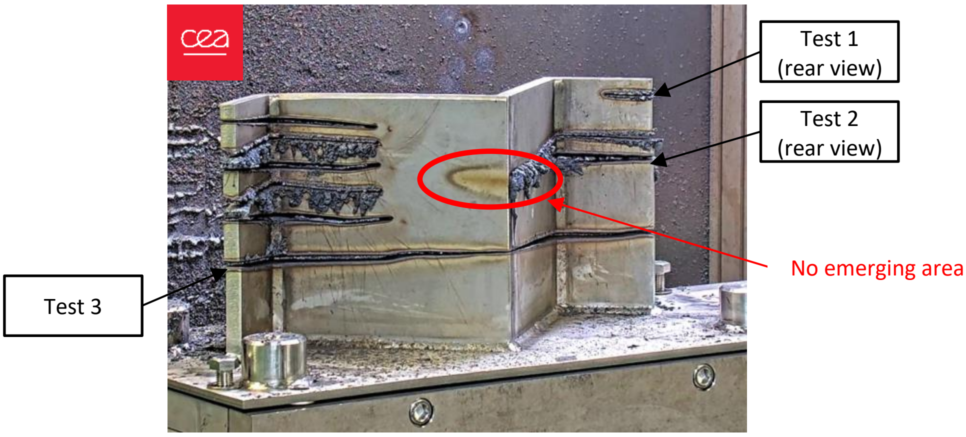


Figure 79: Result core shroud tests (convex and concave part)

6.2.4.2. Damages on impact plate

During the steam dryer cutting tests (see §.6.2.3.8 to 6.2.3.13), the impact of residual energy on a carbon steel plate was also tested. The purpose is to assess the potential damages due to laser beam residual power on the reactor vessel during the steam dryer's cutting operations.

Depending on the cutting elevation in the BWR, the distance between the reactor vessel and the steam dryer varies. On the upper part, the spacing is 77 mm and on the lower part 28 mm.

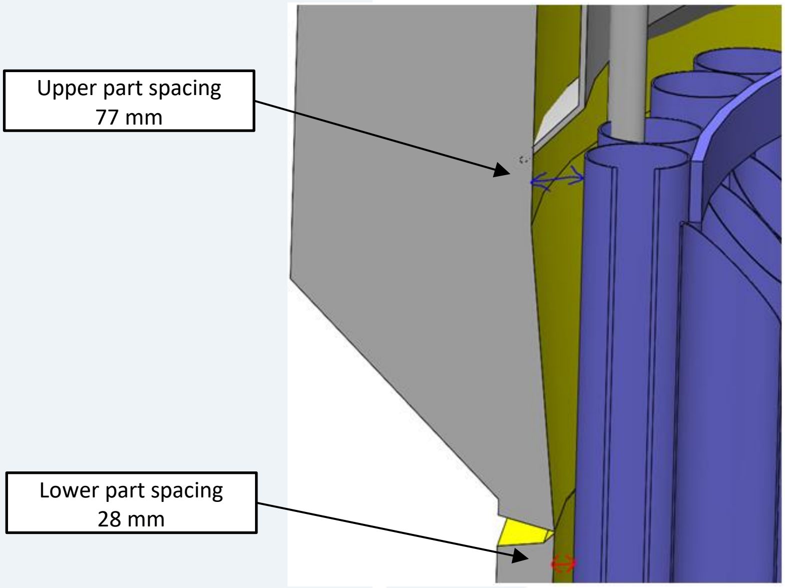


Figure 80: BWR configuration

For the tests, the configuration of the mock-ups and the cell only enabled us to perform cutting operations with the impact plate at around 70 mm, i.e. the configuration of the upper part of the BWR reactor.

Figure 81: Martyr plate test configuration

For basic configurations (1 pipe or 2 pipes without internals), the impact on the carbon steel impact plate is stable, as the variation in sample thickness is small. Impact on the impact plate is of the order of 20 to 25 mm in depth.

For more complex configurations (2 pipes with internals and obstacles), there are significant variations in the amount of material to be cut, from 10.8 mm to 124.7 mm.

However, laser power and cutting speed are fixed during a test session according to the maximum thickness to be cut. In areas of low thickness, the impact of residual energy on the martyr plate is therefore significant (until the carbon steel impact plate is drilled to a depth of over 50 mm).

For example, for tests with 2 pipes and internals, thicknesses can range from 98.7 mm maximum to 10.8 mm minimum. At the minimum cutting speed (25 mm/min), the impact of residual energy ranges from 20 mm to over 50 mm.

Two pipes with internal of BWR's steam dryer (Test Model4-A-NC-2P+I)	
Cutting thickness (mm)	**Impact plate Cutting depth (mm)**
98.7	20
10.8	>50

Figure 82: Impact plate results

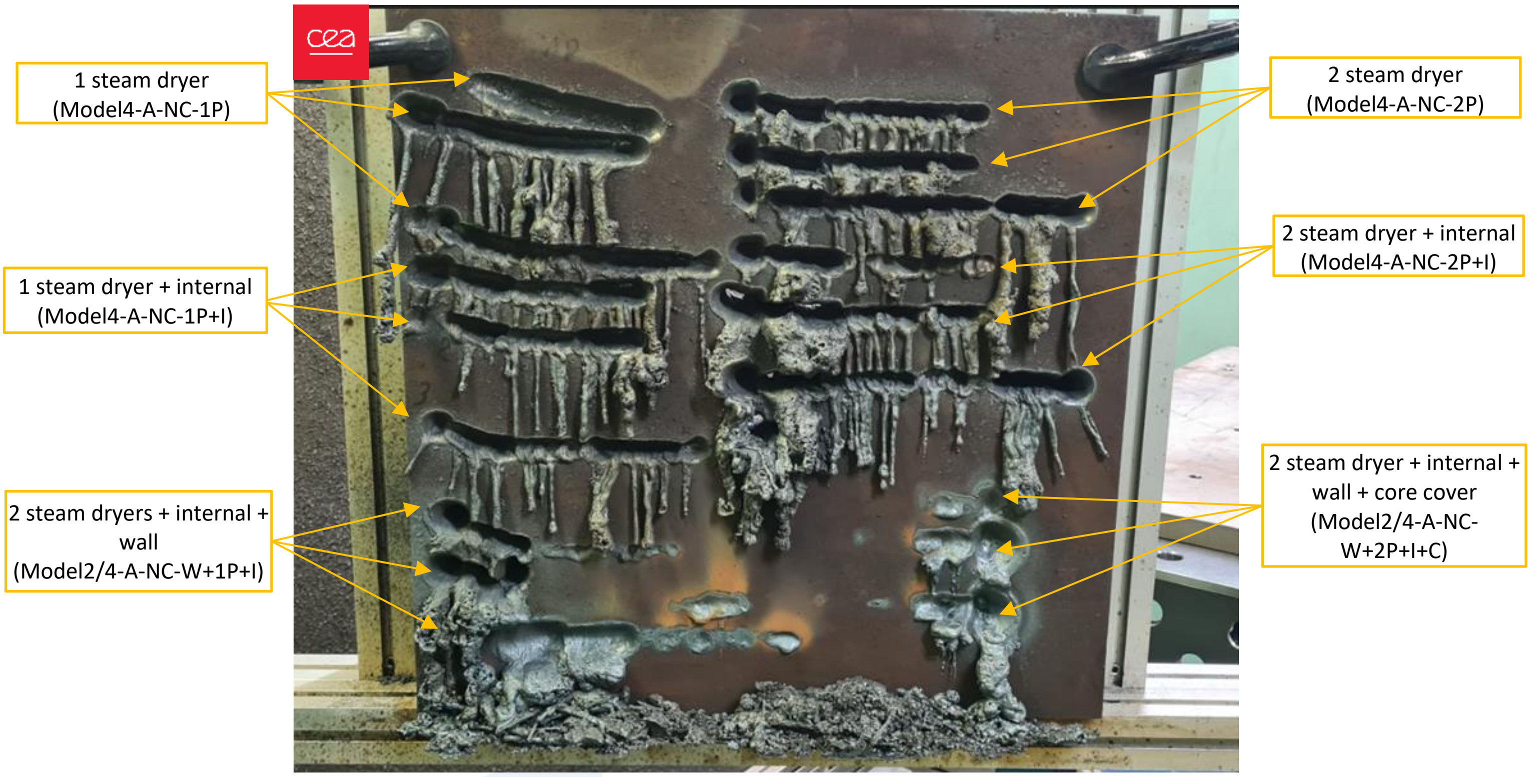


Figure 83: Residual energy on the carbon steel impact plate

Residual energy tests on the impact plate show that the laser has an impact on the elements located behind the cutting zone.

On the carbon steel plate placed 70 mm behind the sample, under normal conditions, the impact is of the order of 20 mm in depth.

For more complex components, the laser impact can be more than 50 mm deep.

Residual energy can be improved by setting certain cutting parameters:

- Start cutting the element as close as possible to limit laser impact before entering the material
- Adapting the cutting speed during the test according to sample thickness
- Adapting laser power during the test according to sample thickness

Note: The tests were carried out with a maximum power of 14 kW, i.e. the most severe damage.

6.3. FEEDBACK

6.3.1 Commissioning

Installation and commissioning of the laser system at CEA Marcoule was carried out in several steps:

- Delivery and reception of equipment
- Installation and connection of equipment: cable routing (electrical, hydraulic and pneumatic) and connection
- Laser system commissioning: laser and compressed air shelter commissioning
- Training: operator training for the remote-controlled arm and utilities console
- Disassembly and transport: disconnection, packaging and transport

The table below shows the operating times for the various steps.

STEP	ACTIVITIES	DURATION
Delivery and reception	Transport + discharge	1 day
Installation and connection	Equipment positioning + cable routing + connection	10 days
Laser system commissioning	Laser commissioning	3 days
	Compressed air commissioning	2 days
Training	Training for the MAESTRO remote-controlled arm	2 days + 2 days of arm handling
	Training for the utilities console	1 days
Disassembly and transport	Disconnection	2 days
	Cable routing	1 day
	Packaging + transport	3 days

Table 5: In-air demonstrator operating times

Note:

- 2 participants are considered for each step.
- Absence of PAC deployment duration to be compared with laser cutting. However, laser cutting technology is faster to deploy in comparison with mechanical tools.

6.3.2 Test

The tests carried out at CEA MARCOULE were on time.

Feedback from demonstrator tests in air is as follows:

- Laser system:
    - No malfunctions were observed during the underwater tests. Laser availability rate is 100%.
    - The fiber between the coupler and the laser device is mechanically damaged at the LLKD connector inlet of the cutting device:
        - The fiber is bent, probably due to excessive mechanical stress,
        - A guide to reinforce this portion of fiber would avoid this inconvenience.
- All mock-ups have been cut with the same manipulator (MAESTRO hydraulic robotic arm; no changes during the cutting campaign).
- MAESTRO robotic arm:
    - Good handling of the device by the EQUANS team.
- The ventilation of the airlock worked properly throughout the tests. 2 filter changes were carried out:
    - About halfway through the test campaign, when the airlock was changed. The filter was clogged.
    - At the end of the tests, the filter was not completely clogged.

7. UNDERWATER DEMONSTRATOR

7.1. EXPERIMENTAL SET UP

The tests will be carried out at Onet Technocenter in Chusclan (France).

For each phase, the experimental set-up will be composed of the following main parts:

- The underwater cutting pool;
- The cutting device (laser system and laser cutting head);
- The cutting samples and representative mock-ups;
- The analysis tools.

These elements are detailed in the following sections.

Onet facility has been specifically designed for laser cutting tests in air and underwater.

- Air tests are performed in a dedicated cell equipped with a remote-controlled arm and specific process ventilation,
- Underwater tests are carried out in a pool equipped with a remote-controlled arm.
- A control room enables all equipment to be monitored and controlled.

For operating the laser head, the laser cutting pool are equipped with a STAUBLI RX 160 HE remote-controlled arm with a specific sealing cover.

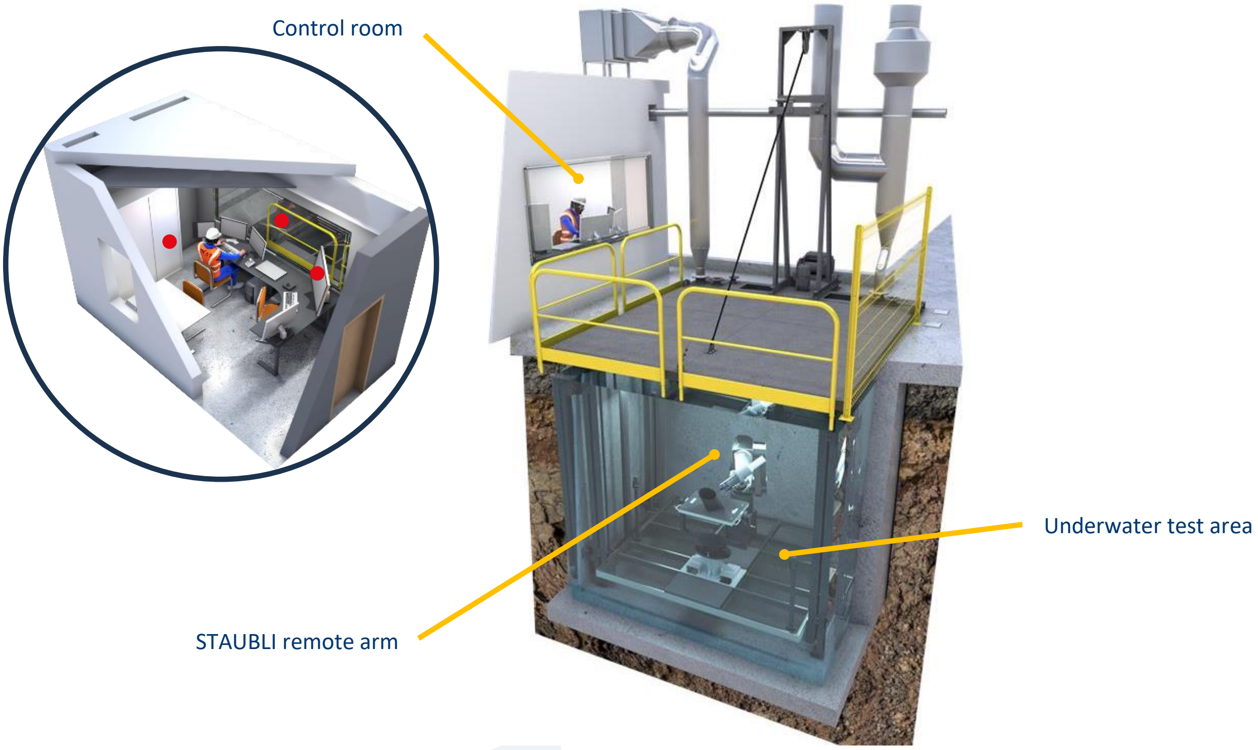


Figure 84: Laser cutting pool (TECHNOCENTRE)

The cutting pool is equipped with the following devices for equipment placement and containment:

- A sliding grating platform combined with a up and down mechanism
- A trap door with a winch for opening and closing
- A ventilation line equipped with a hydrogen sensor, a desiccator, a heater and a Krantz filtration skid (high-efficiency filtration)
- A water filtration and treatment line equipped with 2 filtration stages (25 µm and 1 µm) and a UV lamp

Note:

- Laser regulatory control performed about laser light tightness. Technical report provided by PYLA/ALPHANOV (laser safety organization) to provide recommendations before launching laser cutting tests in the water pit.

- In terms of safety, the laser cutting pool has been designed as static containment solution. However, dynamic containment solutions (and a combination of them) could be feasible in the future.

Figure 85: Trap door

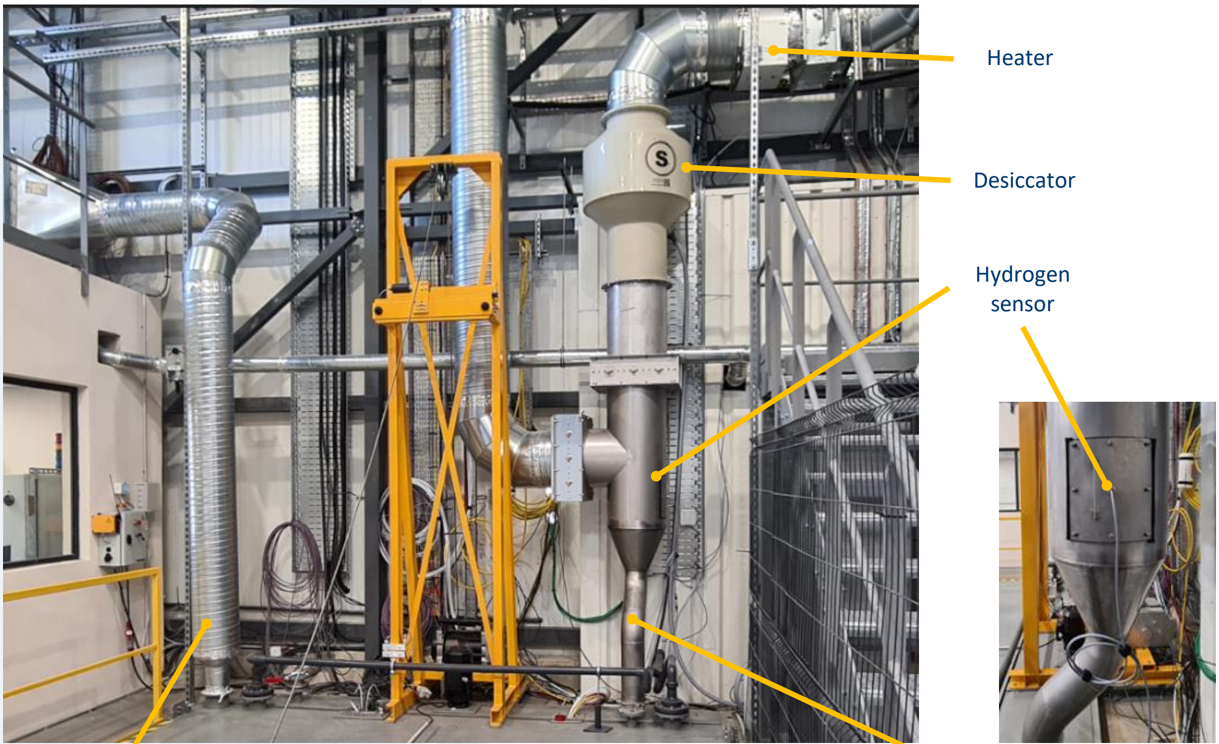


Figure 86: Ventilation line

Figure 87: Krantz filtration skid (HEPA filter)

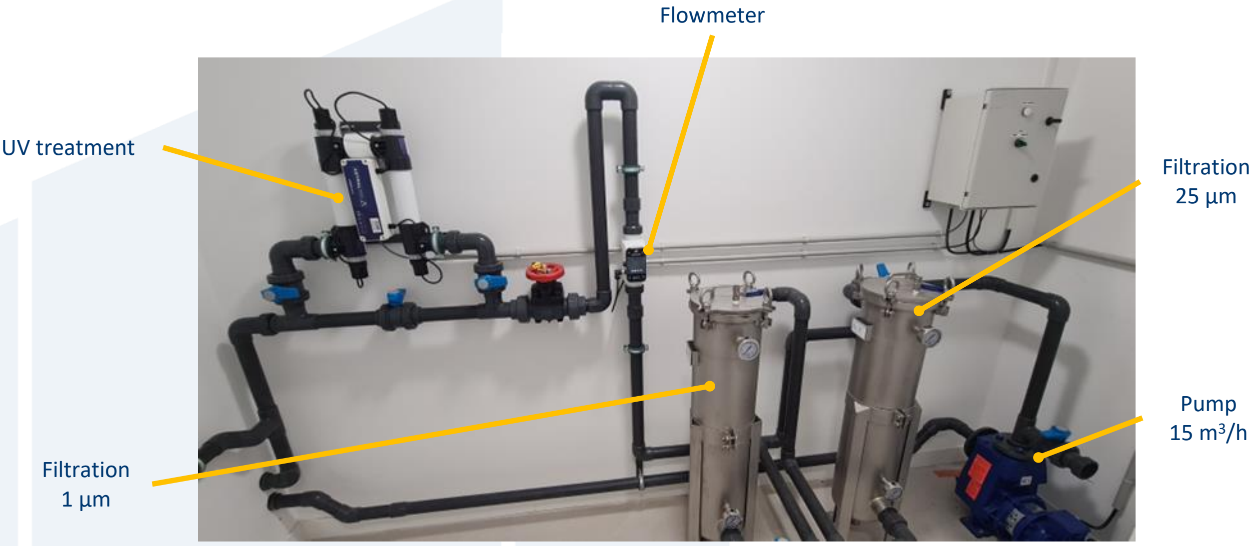


Figure 88: Water treatment

The control room is equipped with all the computers needed to control the laser, robot arm and cutting pool mechanisms (platform, trap door and ventilation).

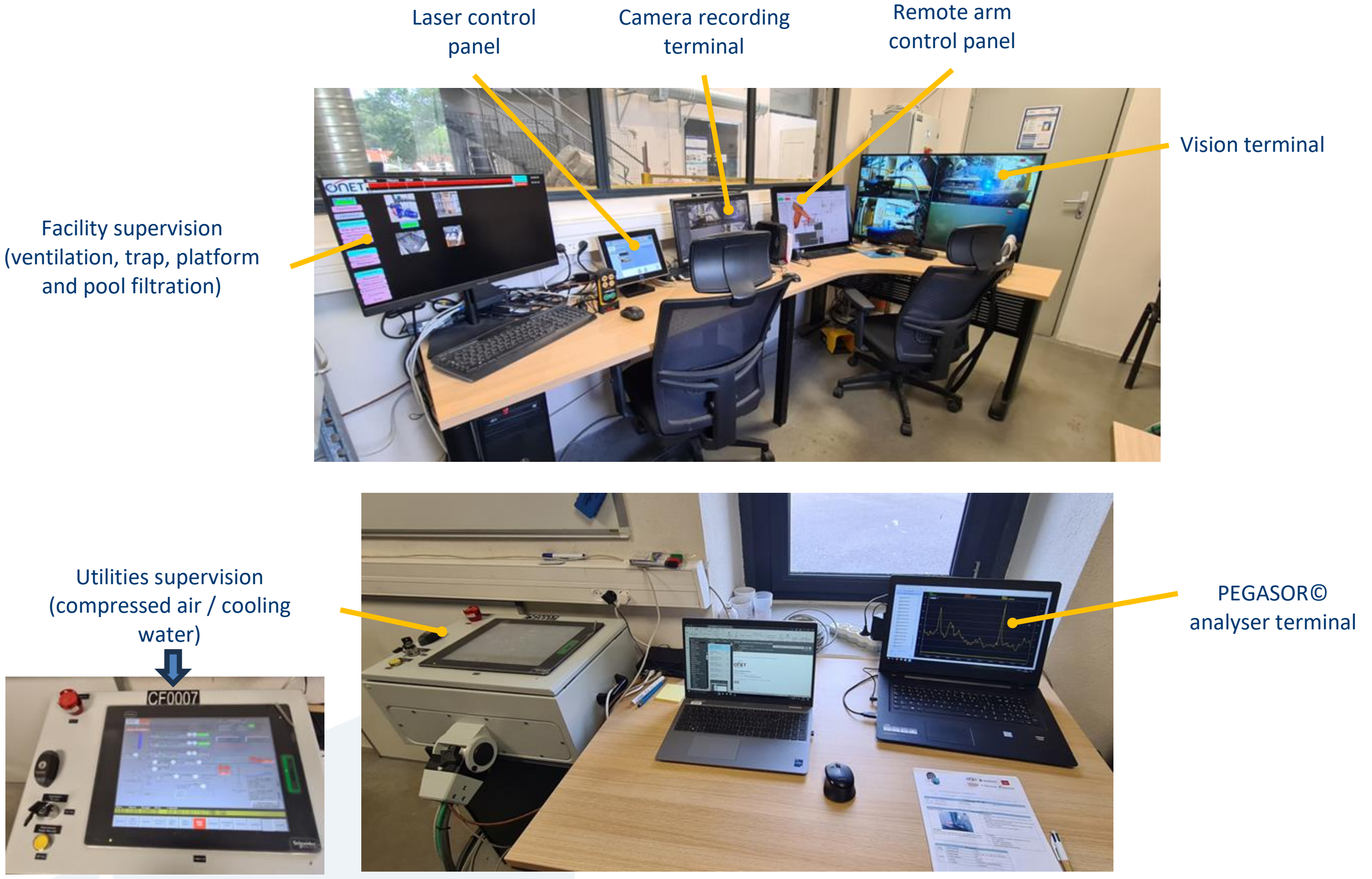


Figure 89: Control room

The ONET Technocenter's mezzanine floor houses the utilities distribution systems and control cabinets.

- Utilities distribution manifold (compressed air and cooling water), Electrical cabinets

Figure 90: Utilities distribution manifold

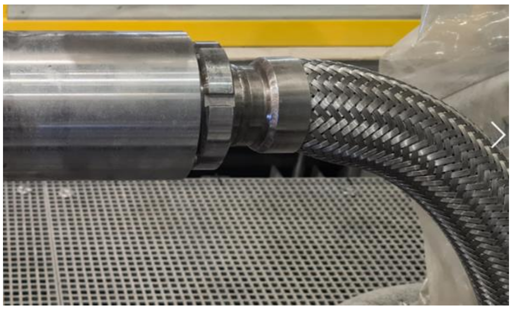
- Cooling unit for coupler and connector

Figure 91: Electrical cabinets et cooling unit

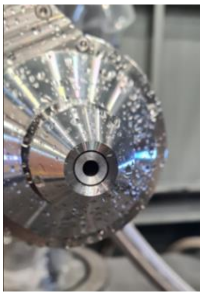
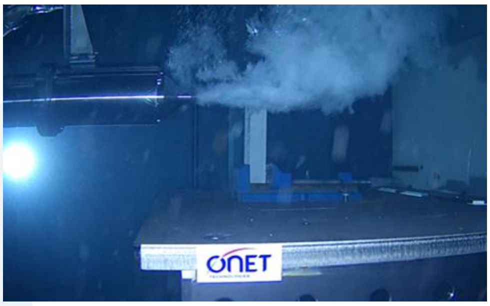
7.2. RESULTS

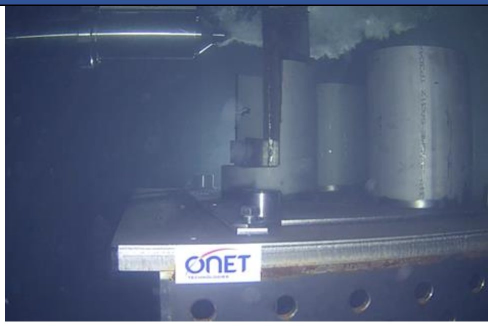
7.2.1 STAGE 1 - QUALIFICATION TESTS

The qualification phase of the underwater demonstrator tests was expected to validate the following points (in accordance to the requirements of deliverable [R2]):

OBJECTIVE	TEST	VALIDATION
Check the suitability of links to the laser head (hydraulic, pneumatic and laser) to be used with a robotic arm during remote-controlled movements		
Umbilical (coupling robustness): no risks of damages on connectors during assembly or disassembly (with the laser head)	Perform multiple umbilical connections and disconnections on the laser head	**Robustness is compliant** Multiple connections revealed no deterioration of the connector  
Umbilical: Capability to bend freely and within mechanical constraints as the robotic arm maneuvers during cutting (strained cables could be subject to material fatigue at connections). Flexibility and its compatibility with	Perform all laser cutting tests (performance and representative tests) and check connector and umbilical integrity	**Lesson learned** 115 laser cuttings were performed underwater **Good ability of robot arm with laser head and umbilical for most cuttings.** In specific cases (important angle or height), the umbilical had an impact on cutting → this phenomenon is explained by the limited capacity of the robot arm in terms of payload (20 kg nominal).

OBJECTIVE	TEST	VALIDATION
the required movement of the manipulator uncertain		
Umbilical: Blockages in air supply line don't cause ruptures or blow out of connectors (blockage possible through water rise in C2 and C3 air supply channels during visualization under water with a closed shutter). Hoses must resist >10bar pressure.	Perform all laser cutting tests (performance and representative tests) and check connector	**Robustness is compliant** Underwater tests did not reveal any ruptures or blockages in the air supply lines.
Ensure correct performance of compressed air distribution system		
Check flowrate of assist gas	2000Nl/min	**Flowrate is compliant** The sequence for pressurizing the laser head during underwater testing is as follows: - Pressurizing the laser head (shutter closed + cavity C1 pressurized) - Drop the laser head underwater - Cutting condition: • Purge cavities C2 and C3 • Pressure reduction in cavity C1 reduced and below pressure cavity C2 • Open shutter and adjust airflow in C1 - Laser cutting - Stop conditions: • Shutter closes • Cavity C1 pressurized • C2/C3 airflow reduced & cavity C1 still pressurized
Ensure correct performance of laser head		
Flexibility of the laser head to cut representative RVI models with minimum operator intervention (breakdowns, maintenance, adjustments, etc.).	Perform all laser cutting tests (performance and representative tests) and check laser head integrity	Following commissioning of the laser system, **no additional maintenance was required** until the end of the tests. The tests showed that underwater laser cutting has no impact on the underwater laser head (no heating and no adherent projections on the nozzle) (see photo). Note: however, on one test where the umbilical blocked the movement of the laser head (test at an angle of 20° and at height), the laser head

OBJECTIVE	TEST	VALIDATION
		came into contact with the sample and the nozzle was damaged (demonstrating its robustness as a dismantling head). **Initial status** **Final status**  
Check that cameras are correctly positioned for arm and laser control (right visibility for operators)		
Check visibility of operations on control room monitors	Check that the visibility with cameras inside the pool	A camera is positioned at an angle and high up in the pool. This camera is stationary and provides an overall view. 3 cameras are then positioned to provide a 3-axis view of the sample (front, rear and side) (see Figure 92). These cameras are mobile and can be moved to suit the sample. The water treatment enabled good visibility to be maintained during the 1st laser cutting tests (performance tests and representative tests on small scale models, around 80 cuts). **Initial view**  **View after 80 cuts**

OBJECTIVE	TEST	VALIDATION
		 However, during cutting tests on the Main Module, the high generation of aerosols over a short period of time meant that visibility was no longer sufficient. The filters in the filtration system were changed, but the accumulation of particles in the pool meant that visibility could not be restored.  **Final view**  Water samples were taken every day but did not allow us to really visualize the loss of visibility in the pool.  Note: - filtration flow rate with new filters is 11.5 m^3/h - filtration flow with fouled filters is 7.5 m^3/h

OBJECTIVE	TEST	VALIDATION
		Turbidity measurements were also taken at the end of the campaign to quantify water visibility (see below the table). Modifications can be made to the current system to improve performance: - recovery of dissolved particles in the water on resins, for example - filtering with a lower filtration threshold (currently installed with 2 filter cartridges in series of 25 µm and 1 µm) - turbidity in real conditions will be lower due to the dilution effect by a factor of 11 (BWR volume 485 m^3 compared with Technocenter pit volume 45 m^3)
Check humidity level in the umbilical/laser head		
Submerged umbilical for underwater cutting have not to be susceptible to water ingress	Perform all laser cutting tests (performance and representative tests) and check umbilical integrity	**Tightness compliant** The humidity sensor located in the umbilical at the connections area did not detect the presence of water in the umbilical.
Components which include fluid: implementation of a protection system to avoid water rise in the underwater laser head and its umbilical (operator mistake or other).	Perform all laser cutting tests (performance and representative tests) and check laser head and umbilical integrity	The laser head pressurization sequence (shown above) enables us to guarantee a tight seal between the laser head and the umbilical. • Valve tightness compliant • Compressed air flow rates and sequence compliance

Table 6: Qualification test results

Camera:

The camera locations for the test are shown below:

Figure 92: Camera positions

Turbidity:

Turbidity measurements at the end of the campaign (showed the evolution of turbidity at different levels of the pool.

Figure 93: Turbidity sensor

3 measurements were taken:

- at the surface (n=0m) = 6.2 FNU
- at mid- level (n=0.75m) = 6.2 FNU
- at low level (n=1.5m) = 5.5 FNU
- Clean water = 1.5 FNU

FNU = Formazin Nephelometric Unit

Analyses show that turbidity is equivalent throughout the pool at around 6 FNU, i.e. 4 times higher than the initial turbidity of the water.

Note: for information the conventional turbidity scale is given below.

- FTU < 5: clear water.
- 5 < FTU < 30: slightly turbid water.
- FTU > 50: turbid water.

Note: there is no information available in open access publications on turbidity in the case of plasma cutting. Comparison is not possible.

7.2.2 STAGE 2 - PERFORMANCE TESTS

Performance tests correspond to laser cutting tests in basic configurations. They were carried out by laser cutting on stainless steel plates and satisfy the following requirements (KPIs):

Underwater: 100 mm/min for a thickness of 40 mm of steel with a 16kW laser source

In the context of the tests carried out for this KPI specification, the aim was to determine the maximum speed limit for cutting of a 40 mm thick stainless steel block with a target to 100 mm/min.

The image below shows the test configuration for the cutting:

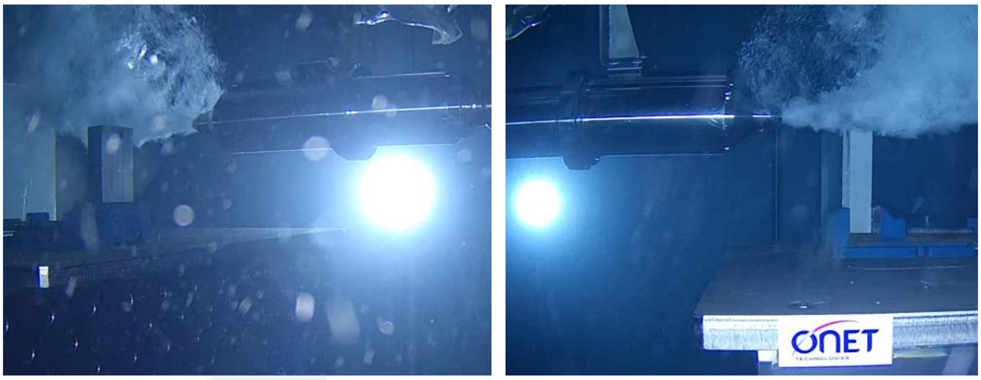


Figure 94: Cutting configuration

Performance tests on underwater cutting on a 40mm stainless steel block have shown that it is difficult to start cutting when the laser is outside the component.

In fact, despite multiple tests with different conditions (stand-off, slow starting speed, fixed point at the edge of the block), a small area remained uncut.

However, all the tests carried out with piercing in the sample were successful, with a cutting speed > **100 mm/min for 40 mm thickness**.

With the first 3 tests, the larger stand-off (20 mm) shows us the significant loss of efficiency as the stand-off increases.

For component piercing, the underwater condition presents no difficulties. Piercing is fast and similar to the air condition.

Maximum thickness for a cutting speed = 50mm/min

To determine the maximum thickness that can be cut at a speed of 50 mm/min, the sample used is a 100 mm stainless steel block. The laser power is fixed at 16 kW and the cutting speed is adjustable up to the point of cutting success.

The image below shows the test configuration for the cutting:

Figure 95: Cutting configuration

On the 100 mm thickness block, when approached from the face, the molten material is not drained off efficiently and emerges from the front of the block, risking damage to the laser head nozzle. Tests showed the emergence of slag from the front of the sample. To facilitate material evacuation, the laser head was positioned with a 10° approach.

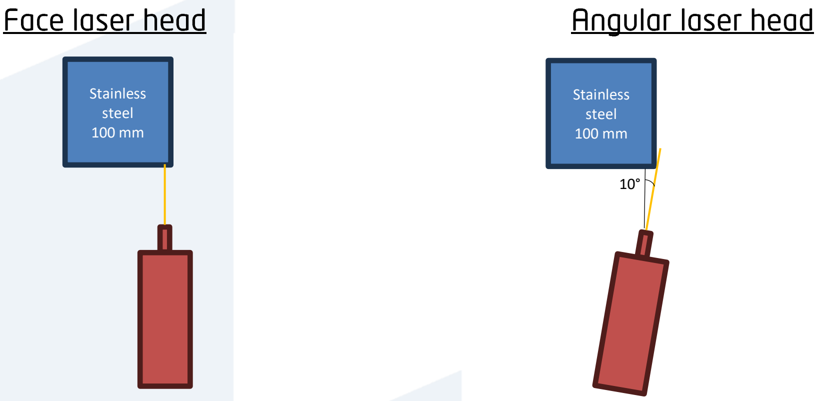


Figure 96: Laser head configuration to 100 mm cutting

Under these conditions, cutting the 100 mm thick block is a successful operation, and the optimum cutting speed is **< 50mm/min**.

On the same sample, underwater cutting (at a depth of around 1.5 m) reduces the presence of aerosols in the atmosphere by around 70%.

To see the laser capabilities on the thickest RVI of *a PWR/BWR*, results are presented on the "Ferrule" representative model in §. 7.2.3.2.

Underwater laser cutting system can be used for cutting in air environment

The aim of these tests is to perform cutting operations with the underwater laser head in an air environment.

The cutting tests are carried out on the steam dryer model (models 2 and 4). The test selected is the cutting of two pipes with internal of BWR's steam dryer, support ring and core cover identical to the air test configuration carried out at CEA Marcoule (6.2.3.13).

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **124.7 mm**. The test configuration is as follows:

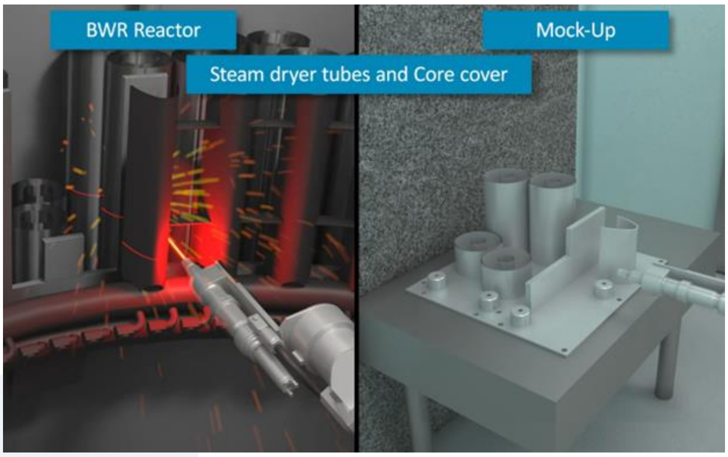


Figure 97: Two steam dryers with internal, support ring and core cover of BWR reactor

As a reminder, the air tests at CEA Marcoule (in this configuration) was not feasible to cut all the elements in 1 pass. In the areas of maximum thickness (at the tangential parts of the 2nd steam dryer), cutting was inconclusive (see chapter 6.2.3.13).

For underwater trials, the setup allows the laser head to be positioned at a stand-off of 10 mm, which improves cutting performance. The underwater laser head also has a higher power capacity, with a maximum output of 16 kW.

A cutting operation was carried out on the complete model, demonstrating that the underwater head is capable of cutting under air conditions. The test configuration (30 mm stand-off) enabled us to validate the laser cutting operation for all components in 1 pass, in contrast to the air tests carried out at CEA Marcoule.

The improved stand-off and the higher laser power of the underwater laser head (up to 16 kW) will enhance cutting performance.

Figure 98: Result two steam dryers tests with internals, support ring and core cover (Front view and rear view)

<u>Residual energy</u>:

This test also enabled us to test the impact of residual energy on the impact plate. The plate is positioned 28 mm behind the sample, representing the cutting configuration possible in the lower part of the BWR reactor. (see chapter 6.2.4.2).

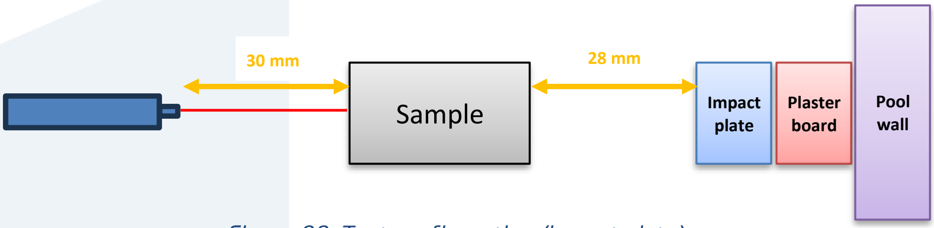


Figure 99: Test configuration (impact plate)

In the test conditions for cutting with the head underwater in air (16 kW power and 30 mm stand-off), a significant impact of residual energy was observed:

- Penetration of stainless steel impact plate (40 mm)
- Penetration of plasterboard (13 mm)

The impact of residual energy can be mitigated by adjusting the cutting parameters to the thickness of the sample.

As the sample thickness is not homogeneous, the laser power or cutting speed should be varied according to the thickness.

7.2.3 STAGE 3 - REPRESENTATIVE TESTS

Representative tests correspond to laser cutting tests on scale 1:1 mock-ups representative of the various PWR and BWR reactor components. Representative mock-ups are shown in chapter 4.

The configurations summarized below (angle and stand-off) are determined from the realistic cutting scenario in the note [R3]. All cutting tests have been made at 16kW of laser power.

7.2.3.1. Upper plate

The objectives of cutting in air or underwater conditions are identical. Cutting the Upper Plate consists in creating a square opening on the 40 mm thick stainless steel plate. The laser head is positioned at a 90° angle to the sample.

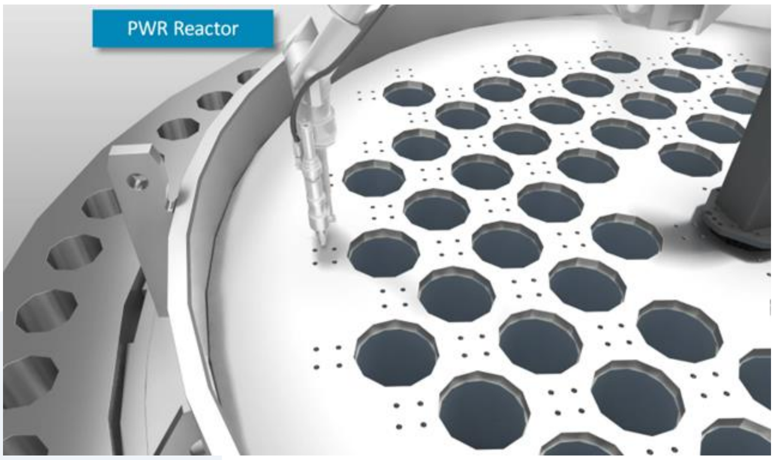


Figure 100: Upper plate of PWR reactor

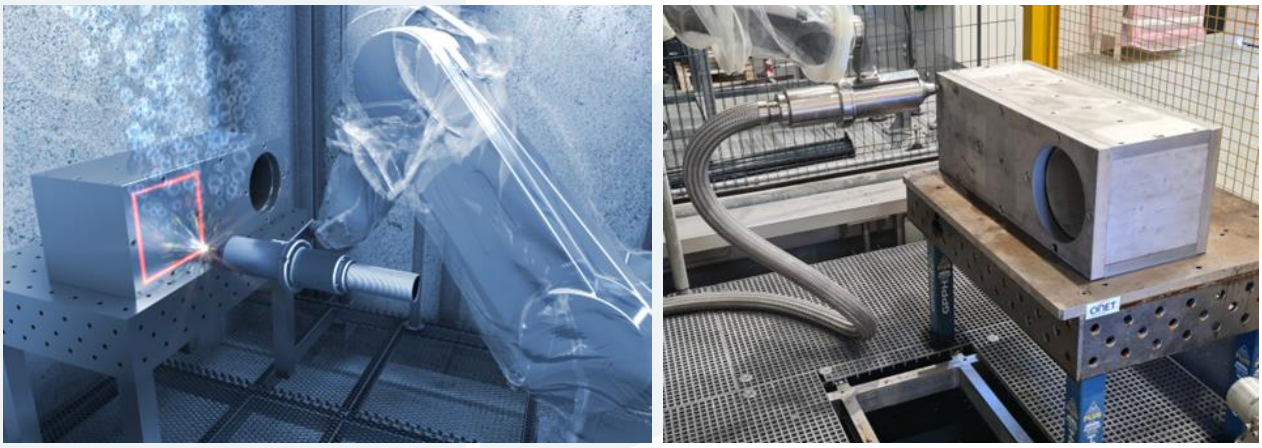


Figure 101: Upper plate (MainModule) configuration before testing

The sequence for cutting the upper plate is to drill the plate and then cut the square opening.

Various cutting speeds were tested.

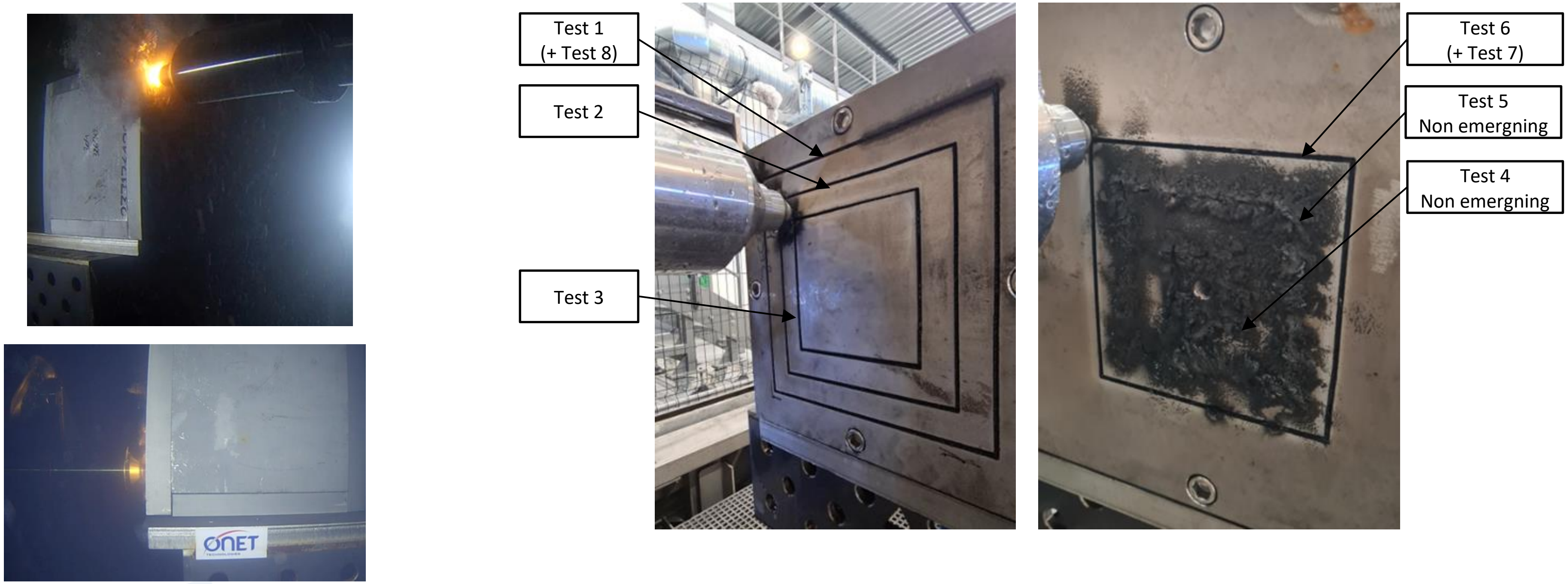


Figure 102: Result Upper plate tests (MainModule)

Tests carried out at 16 kW demonstrated the laser's ability to cut upper plate in underwater condition.

7.2.3.2. Ferrule

Cutting the Ferrule Plate consists in cutting a 65 mm thick stainless steel plate at an approach to the laser head of 15° angle. The effective thickness cut is then **67.5 mm**.

The objective of this cutting is to simulate the congestion of this area and perform cutting of thick workpiece with a suboptimal cutting angle.

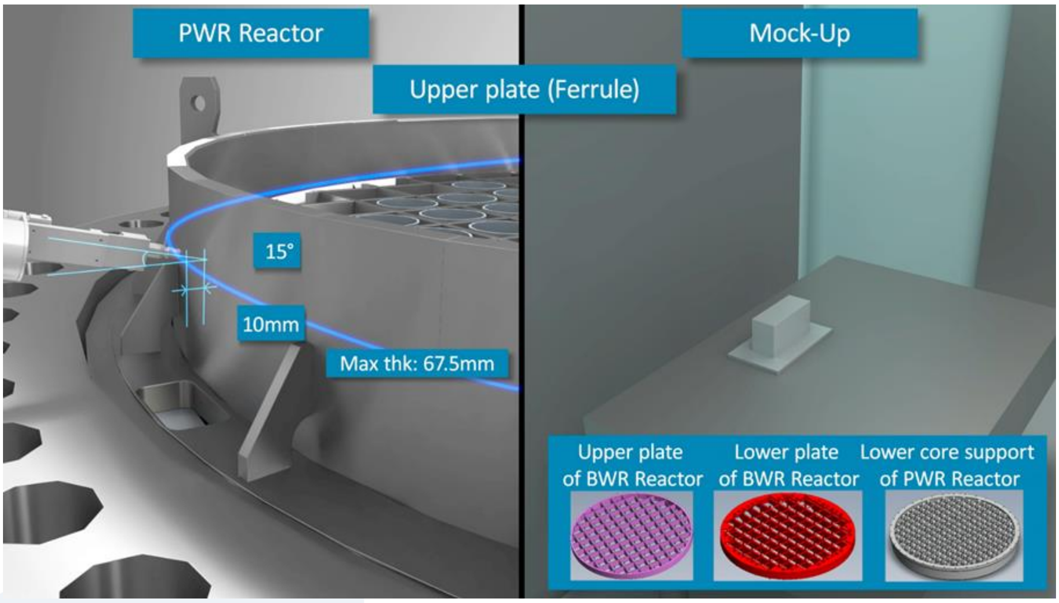


Figure 103: Ferrule of the Upper plate of PWR reactor

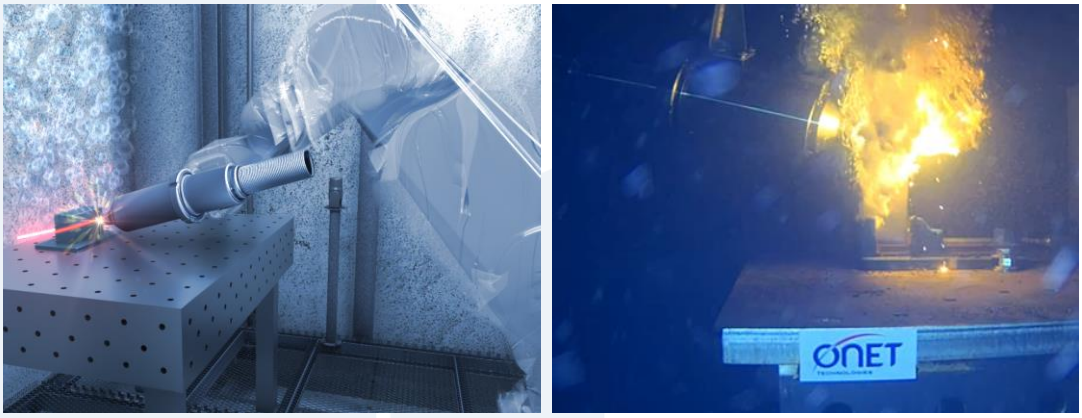


Figure 104: Ferrule plate configuration before testing

Speed variation tests showed that optimal stand-off is 10 mm.

In fact, test 4 shows slag on the front face at the end of the cut, indicating an unsuccessful cut.

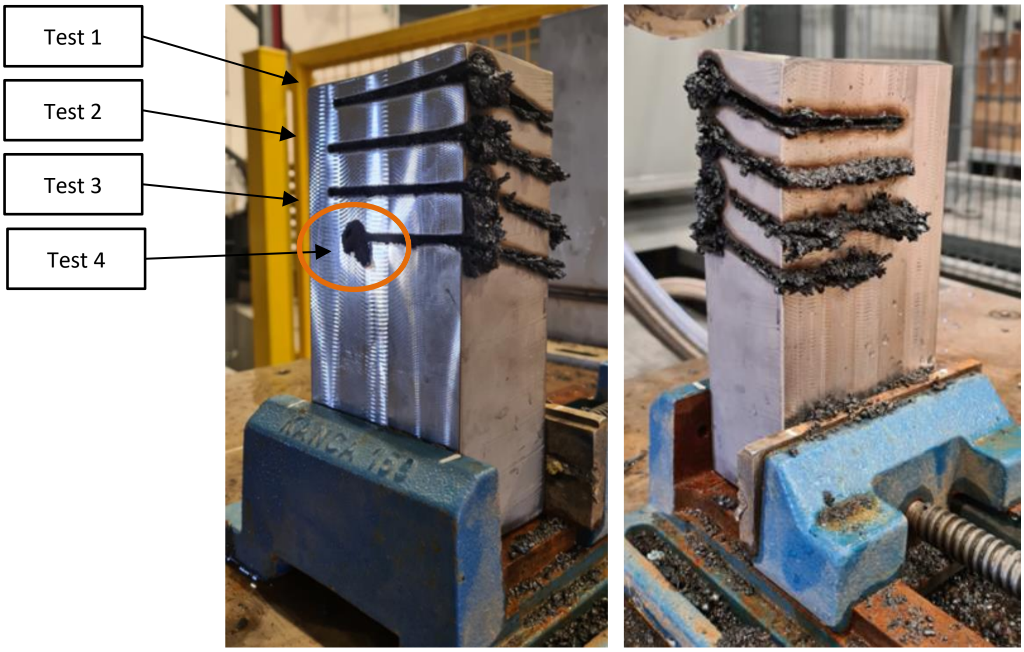


Figure 105: Result ferrule test (Front view left / rear view right)

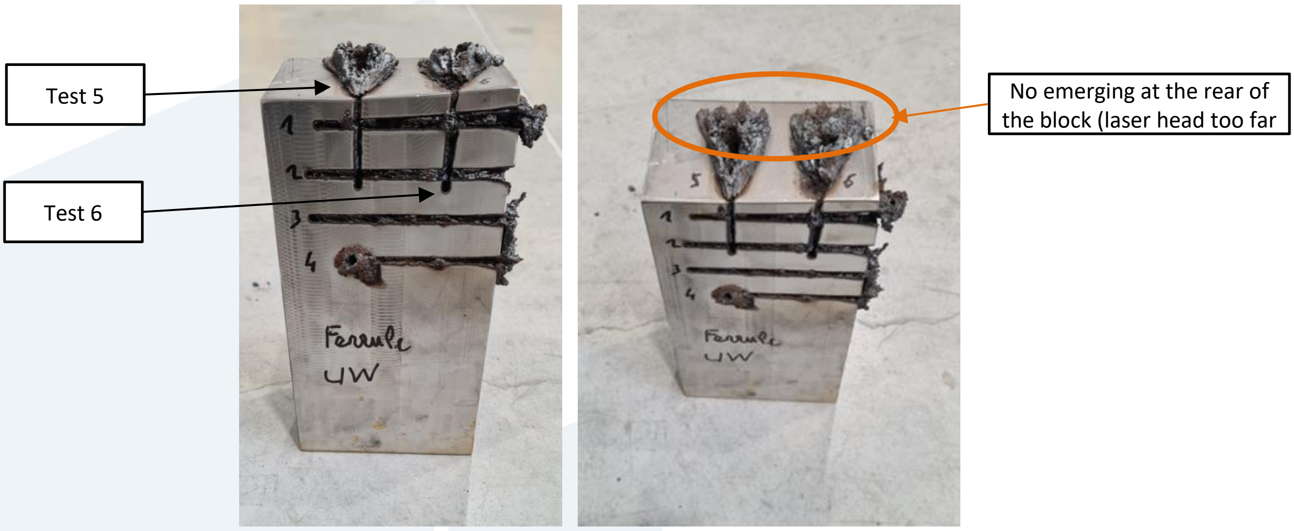


Figure 106: Result ferrule test (vertical cutting)

7.2.3.3. Grid of the upper plate with 45° angle

This test consists in reproducing the cutting of a grid on the Upper Plate of the PWR reactor. The test is carried out on a 35 mm thick stainless steel plate with a 45° cutting angle. The effective thickness cut is then **56.5 mm**.

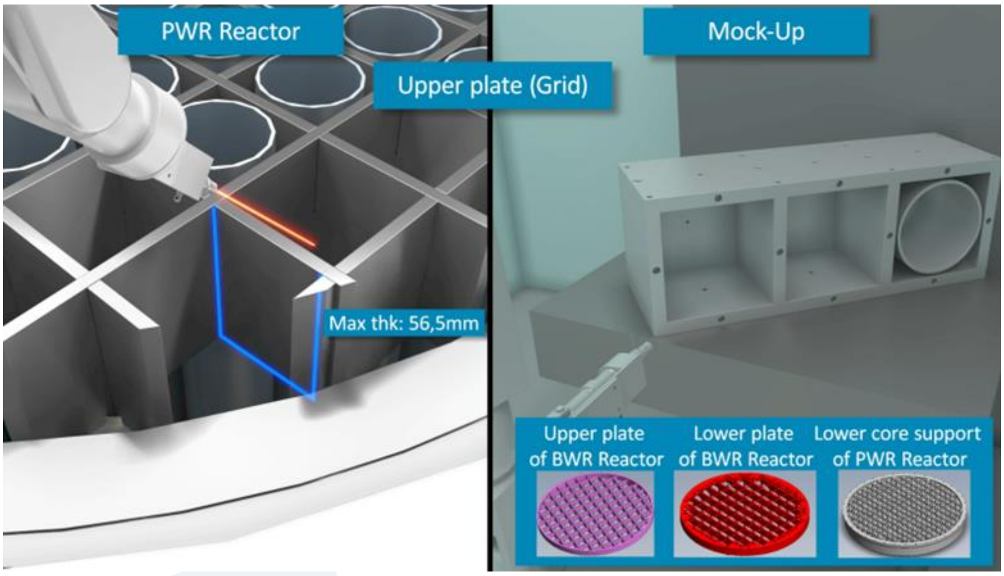


Figure 107: Grid of PWR reactor

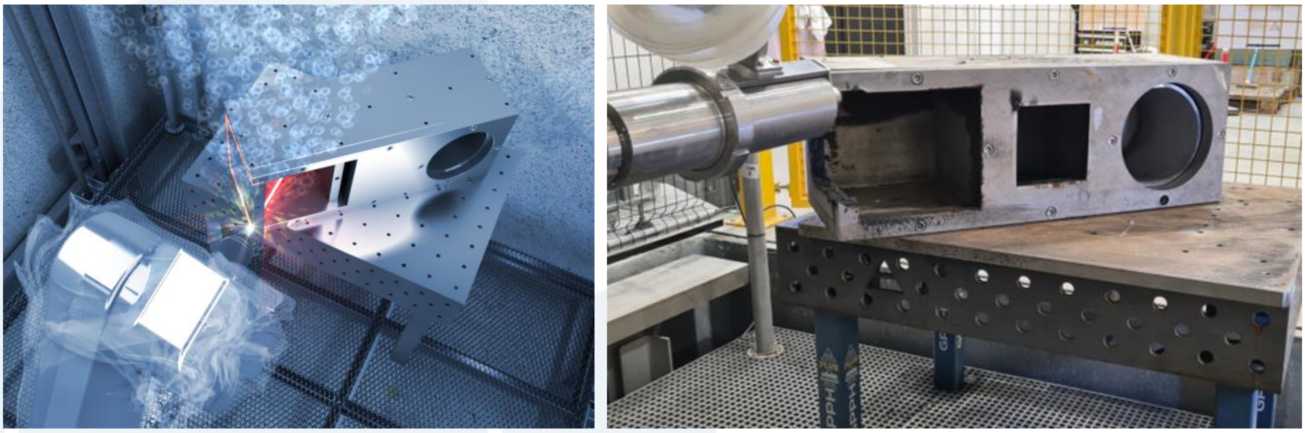


Figure 108: Grid configuration before testing

Five tests were carried out, each test consisting of cutting a line on the sample:

- Four vertical cuts to determine the optimal cutting speed
- A complete grid cutting (U shape)

Speed variation tests showed that optimal stand-off is 5 mm.

For the first 2 tests, the stand-off is too large and the cutting is dotted. For the following tests, the laser head is positioned at 5 mm from the sample.

In fact, with angular cutting, the stand-off is slightly different from cutting with the laser head pointing right. The shape of the nozzle does not allow the laser beam to keep a 10 mm stand-off when cutting at an angle. The edge of the nozzle respects the 10 mm distance, but in this case, the laser beam is at a distance of around 25 mm from the sample.

To limit this effect, the stand-off is set at 5 mm with angular cutting.

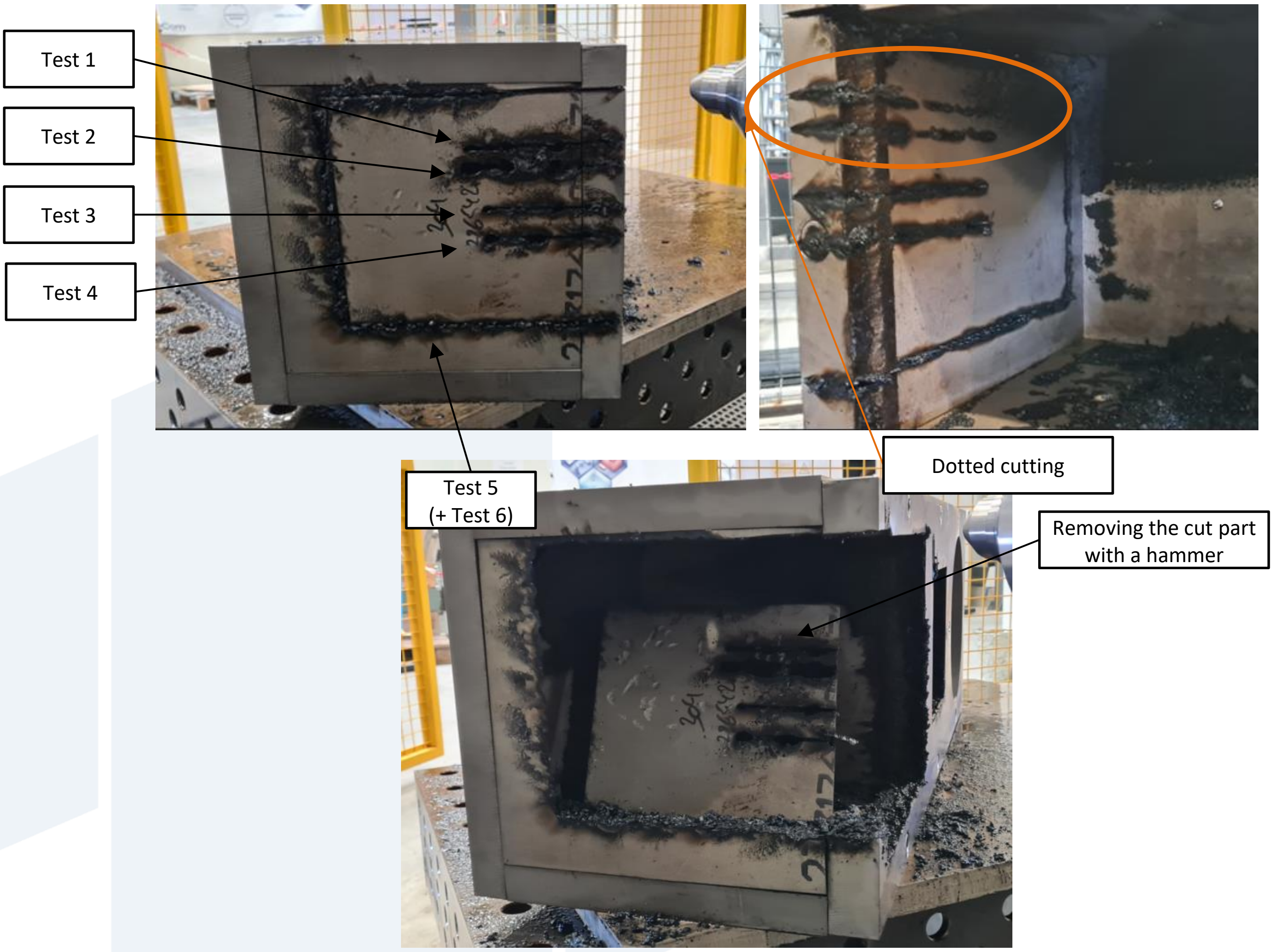


Figure 109: Result grid tests (Main Module)

7.2.3.4. Grid of the upper plate with 20° angle

This test consists in reproducing the cutting of a grid on the Upper Plate of the PWR reactor. The test is carried out on a 35 mm thick stainless steel plate with a 20° cutting angle. The effective thickness cut is then **37.5 mm**.

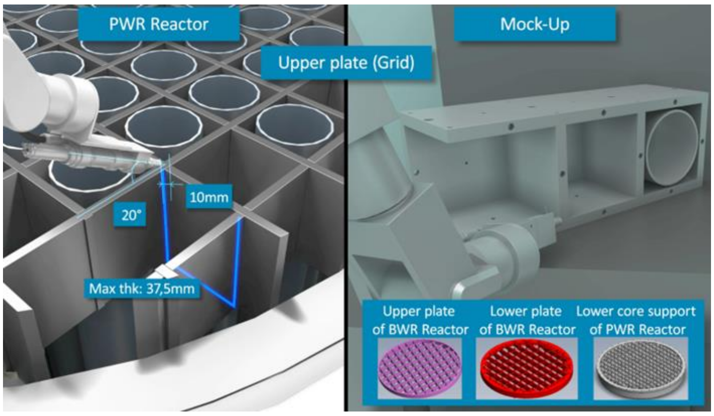


Figure 110: Grid of PWR reactor

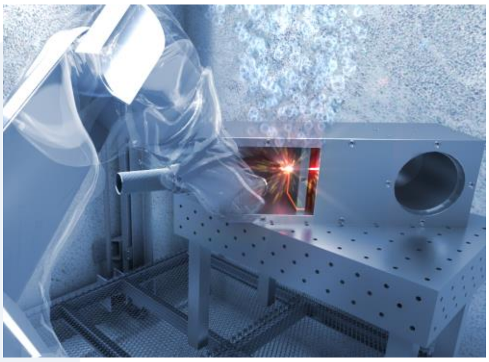


Figure 111: Grid configuration before testing

Three tests were carried out, each test consisting of cutting a line on the sample:

- Two horizontal cuts
- One vertical cut

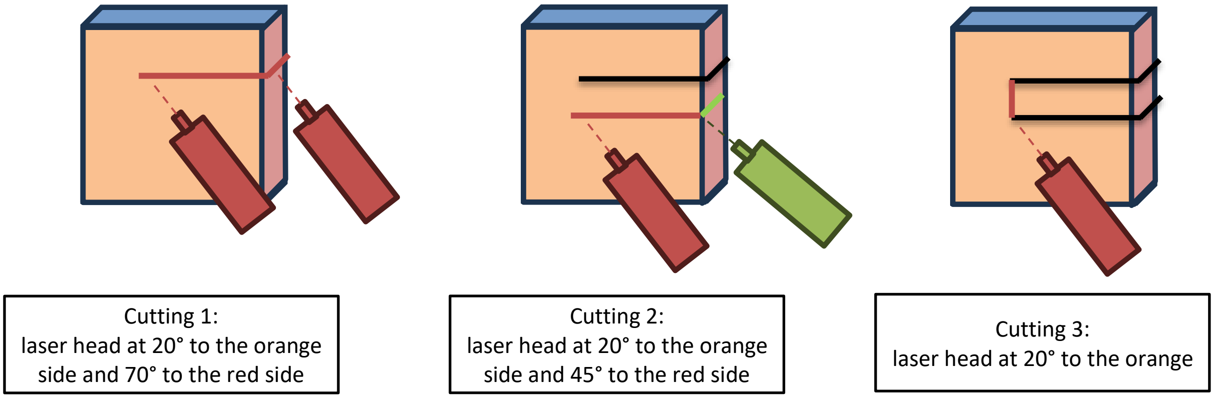


Figure 112: Test configuration (cutting orientation)

Note: for this configuration, the test consists of cutting the orange part at an angle of 20°.

In order to test the complete grid cutting, the red part is also cut with a change of angle of the laser head to facilitate cutting.

The optimal stand-off on the grid with 20° angle is 5 mm.

For all the tests, cutting is successful for the orange part at an angle of 20°.

For cutting the red part, the angle of approach is different to limit the thickness to be cut. On the 1st test, the angle of the laser head is constant throughout the cutting (orange and red), so the laser head has an angle of 70° on the red part. The thickness is too important and cutting is not possible.

On the 2nd test, the angle of the laser head on the red part is changed to 45° at a reduced speed of 30 mm/min. Cutting is a success.

As with the upper plate tests, the cutting part is removed with a hammer.

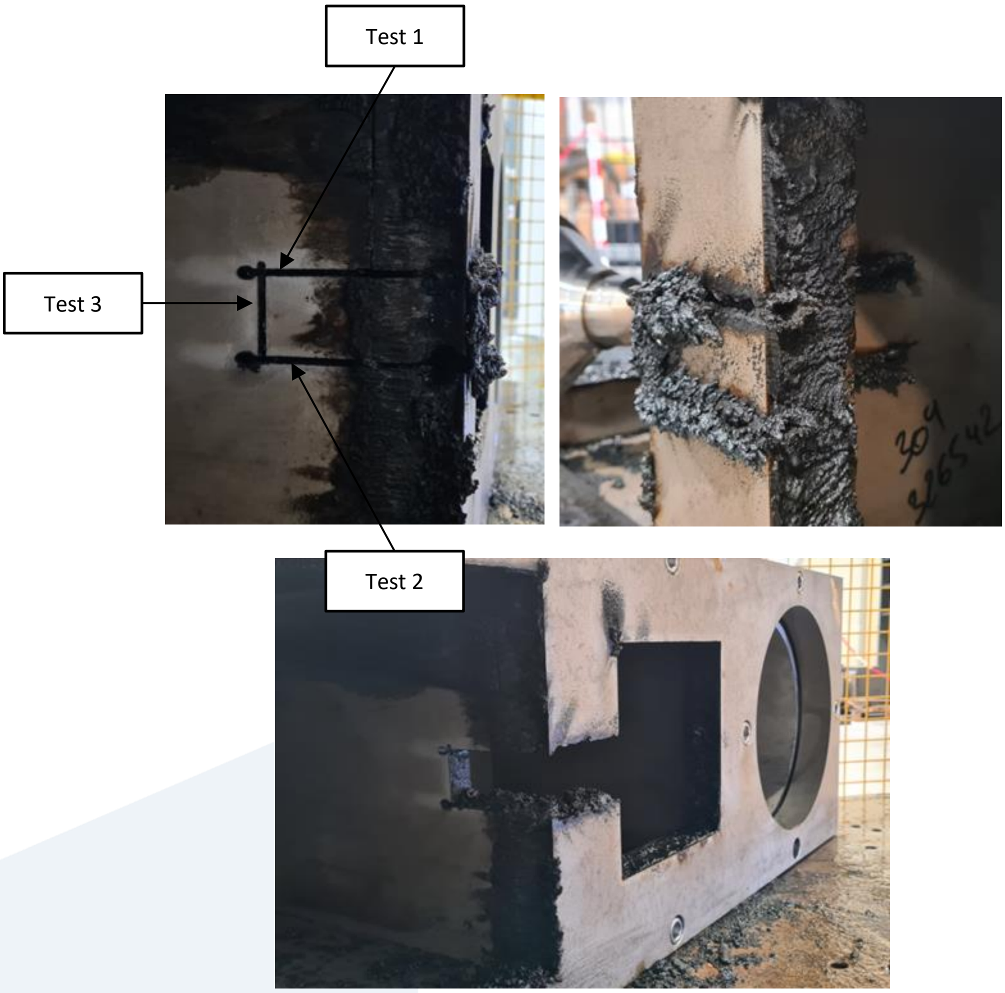


Figure 113: Result grid tests (MainModule)

7.2.3.5. Grid and control rod guides of the upper plate

This test consists in reproducing the cutting of grid and control rod guides on the Upper Plate of the PWR reactor. The test is performed on a combination of samples:

- 1 grid (35 mm thick stainless steel plate)
- 1 control rod guide (273.05 mm diameter, 9.27 mm thick stainless steel tube)
- 1 grid (35 mm thick stainless steel plate)

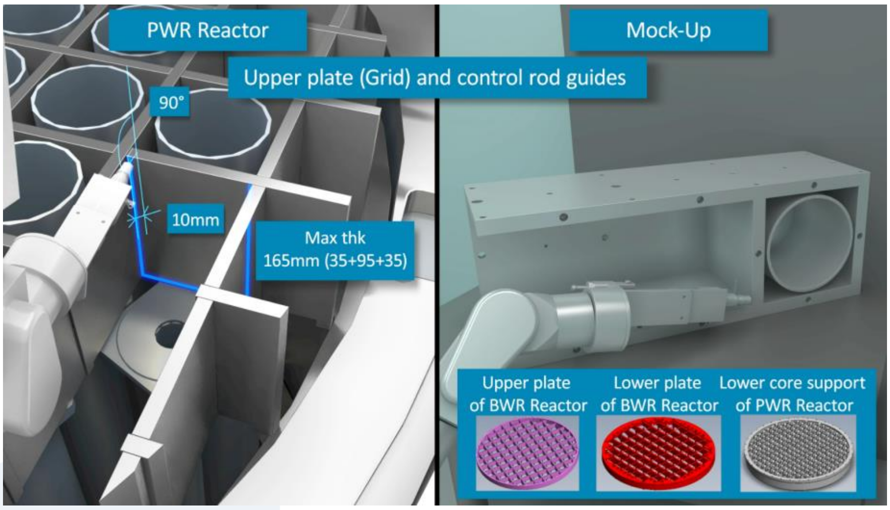


Figure 114: Grid and control rod guide of PWR reactor

These tests were not performed underwater, as it is not possible to cut a series of elements underwater.

In fact, water limits laser propagation and only allows cutting if the laser head is close to the sample and with the air jet.

7.2.3.6. Core shroud convex part

The tests consist in cutting a straight line in the convex part of the core shroud. The purpose is to completely remove the element. The laser head is positioned at a 90° angle to the sample.

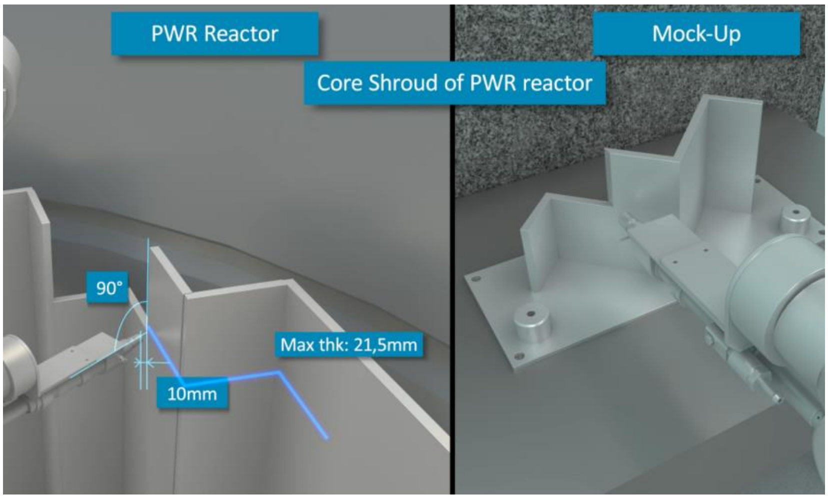


Figure 115: Core shroud of PWR reactor (convex part)

Figure 116: Core shroud configuration before testing

Speed variation tests on the core shroud in convex part showed that optimal is 10mm (Tests 4, 5, 8 and 9).

- Tests 1 and 2: unsuccessful cutting in the end of the part
    - Test 1: laser head too far from sample,
    - Test 2: cutting speed too high
- Test 3: unsuccessful cutting in the end of the part (cutting speed too high)
- Test 4: cutting ok

- Test 5: successful cutting on total sample length
- Tests 6 and 7:
  - Piercing during 5s
  - Unsuccessful at the end because the laser head moves too far away from the sample
- Tests 8 and 9:
  - Drill during 20s
  - Successful cutting

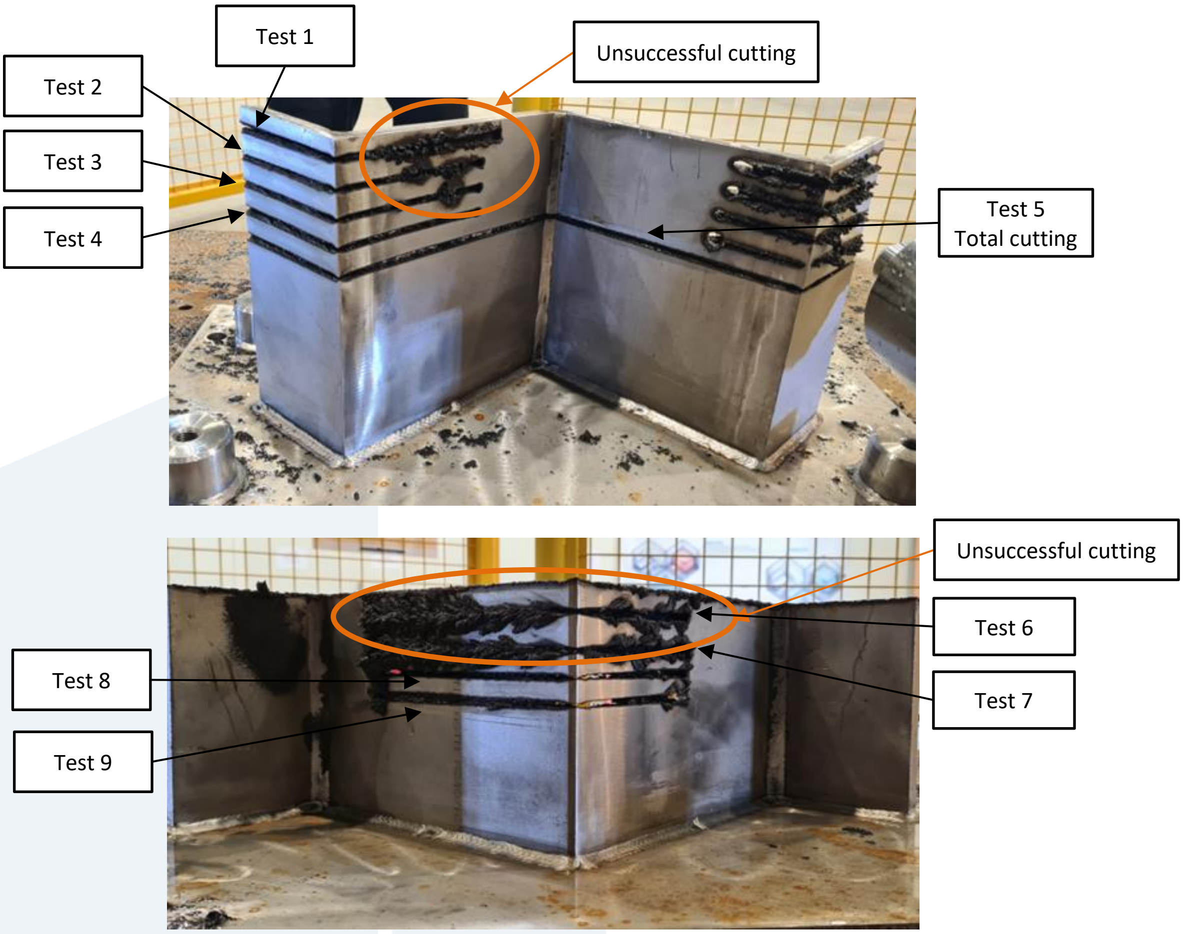


Figure 117: Result core shroud tests (convex part)

During tests 6 to 9, aerosol number concentration measurements were carried out in the pool atmosphere. In underwater condition, the evolution of aerosol concentration during cutting of the core shroud is similar to air condition.

Tests 6 and 7 are not included, as the cuttings are not representative (unsuccessful and incomplete cutting).

7.2.3.7. Core shroud concave part

The tests consist in cutting a straight line in the concave part of the core shroud. The test is identical to the conditions in the convex part of the sample but is carried out in the concave part.

This cutting test aims to assess the influence of geometry on the assist gas and the cutting performance.

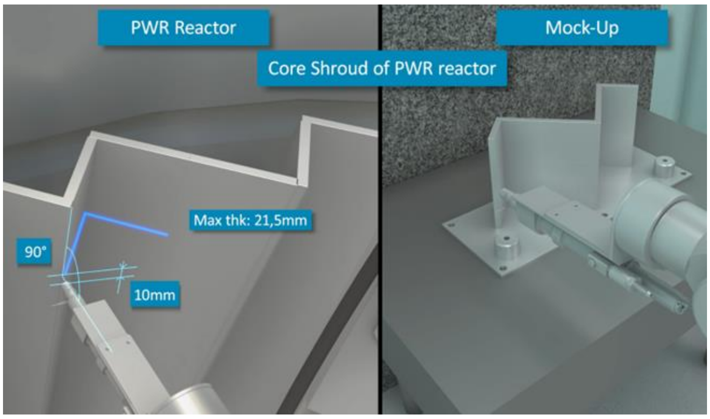


Figure 118: Core shroud of PWR reactor (concave part)

Figure 119: Core shroud configuration before testing

Speed variation tests on the core shroud in concave part showed that optimal stand-off is 10 mm (Test 2).

- Tests 1 and 2: successful cutting
- Tests 3 and 4: unsuccessful cutting in the center of the part (inside of the V) → due to the thickness of the weld and the larger stand-off in this area (around 20 mm).

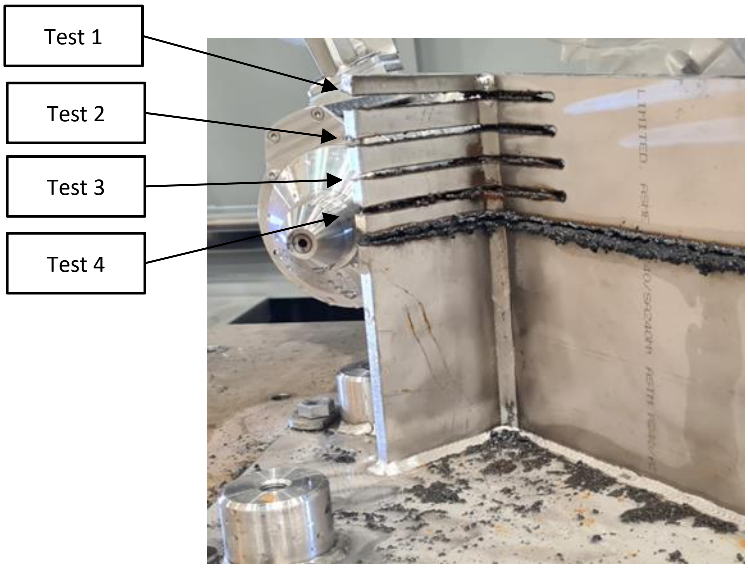


Figure 120: Result core shroud tests (concave part)

7.2.3.8. One pipe of BWR's steam dryer

Representative cutting tests on steam dryers should demonstrate the feasibility of dismantling these components under water.

Feedback from the underwater tests shows that it is not possible to cut several layers of components in a single pass. The following tests will demonstrate the removal of the various components.

This test consists in reproducing the cutting of one steam dryer of the BWR reactor. The test demonstrates the cutting of a steam dryer on the upper part, which consists only of a pipe with no internal parts (Model 4).

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **56.5 mm**.

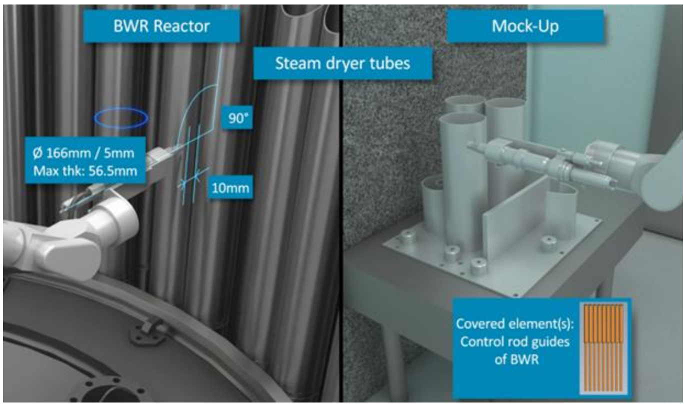


Figure 121: One pipe of BWR's steam dryer

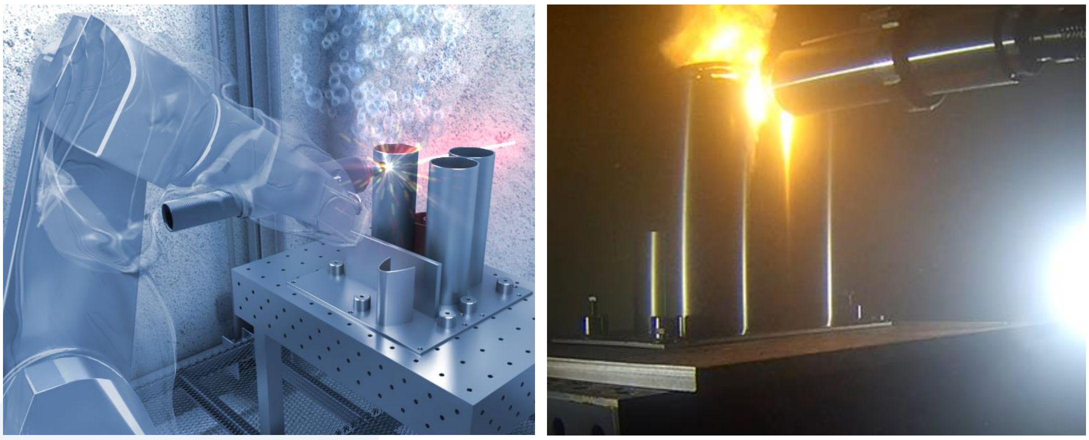


Figure 122: Steam dryer configuration before testing

The tests enabled different laser head positions to be tested in order to find the optimum position for component removal.

In all steam dryer tests, it was not possible to cut the pipe in 1 pass. The removal method is therefore as follows:

1. cutting the front of the hose
2. remove the front panel
3. cutting the rear panel

The cutting results below show the possibilities of cutting the front face of the pipe.

- Tests 1 and 2: linear cutting (stand-off between 10 and 50 mm) → unsuccessful cutting on pipe sides (stand-off too important)

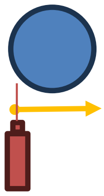


Figure 123: Pipe linear cutting

- Tests 3 and 4: circular cutting to follow the contour of the sample with the laser head at 90° (constant stand-off at 10 mm) → successful cutting

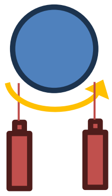


Figure 124: Pipe circular cutting

- Test 5: circular cutting to follow the contour of the sample with the laser head at 90°± 20° on the side (constant stand-off at 10 mm) → successful cutting

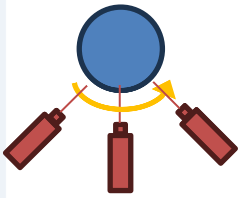


Figure 125: Pipe circular cutting with angular orientation

Figure 126: Result one steam dryer tests (side view)

7.2.3.9. Two pipes of BWR's steam dryer

The tests for cutting 2 pipes in one pass were not performed because cutting successive layers under water is not possible.

The steam dryers will have to be dismantled pipe by pipe, using the cutting sequence presented in the next chapter.

7.2.3.10. One pipe with internal of BWR's steam dryer

These tests are identical to those carried out for the steam dryers (see previous chapter), but with the addition of internals. The test demonstrates the cutting of a steam dryer on the middle part, which consists of a pipe with internal parts (Model 4).

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **56.5 mm**.

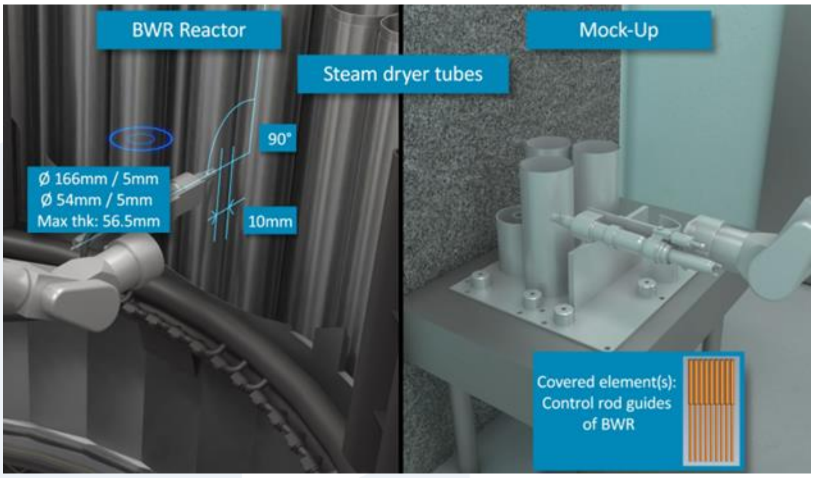


Figure 127: One pipe with internal of BWR's steam dryer

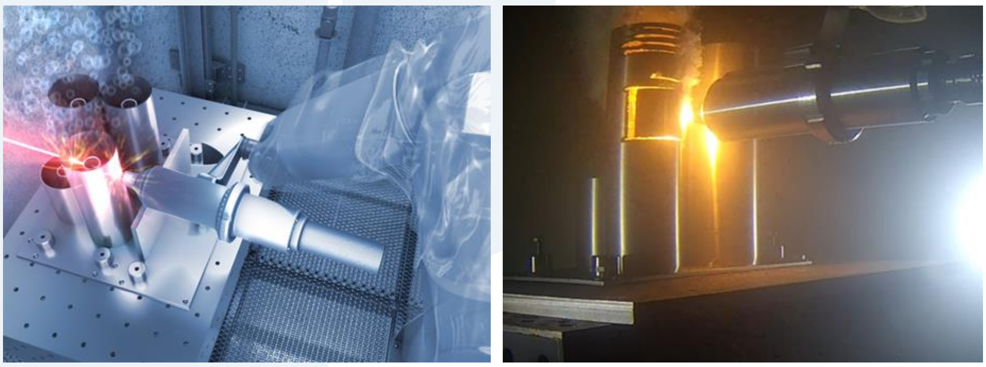


Figure 128: Steam dryer configuration

Two steps are performed to demonstrate the removal of a steam dryer with an internal. First, the front side of the steam dryer is opened, then the internal pipe is cut. The cutting parameters used for each pipe are as follows:

- **Steam dryer front side opening**

The cutting trajectory is identical to the tests Model4-UW-1P-3 and 4 → Circular cutting at 10 mm from pipe with straight head.

All tests showed that all configurations were a complete success. The tests also show that the inner tube is not impacted by cutting the front panel.

Figure 129: Results for front side of BWR's steam dryer tests

- **Steam dryer internal**

All the tests were not successful. Variations in trajectory type (linear or circular), speed cutting (down to 3 mm/min) and laser power (8 to 16 kW) were not sufficient to achieve cutting over the entire length of the cut.

The most difficult areas to cut were those far from the laser head, the tangential parts of the pipe (on the sides) and the center of the rear face.

For the internal pipe (diameter 54 mm), the dismantling procedure will be identical to that for the steam dryer (diameter 166 mm) → cutting the front face, then cutting the rear face.

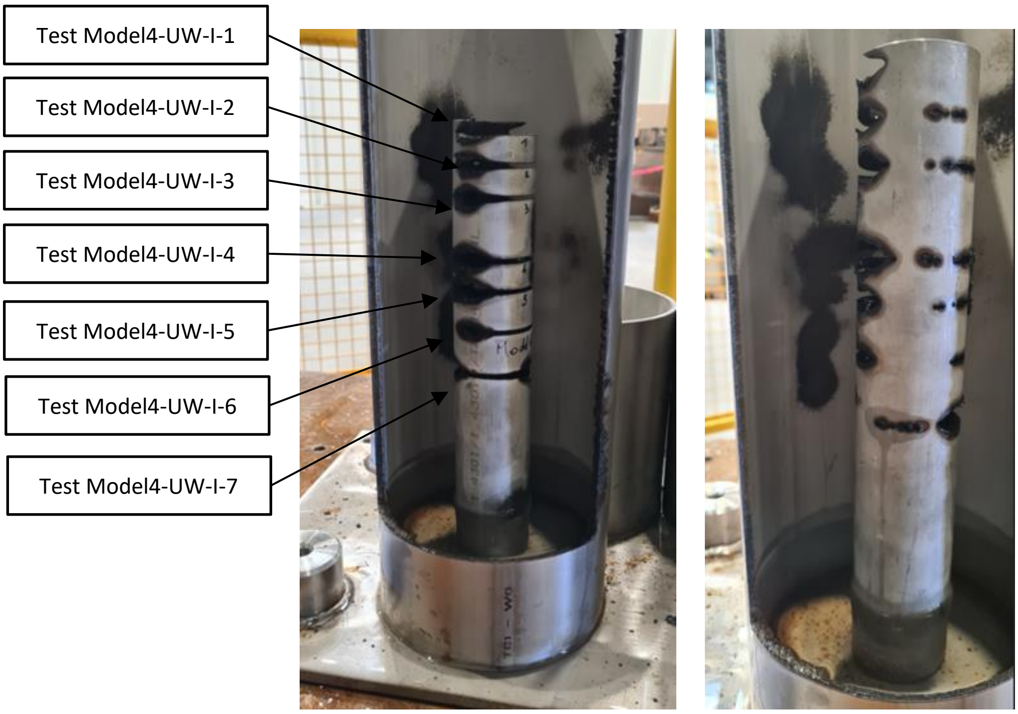


Figure 130: Results for internal pipe of BWR's steam dryer tests (Front and rear view)

7.2.3.11. Two pipes with internal of BWR's steam dryer

The tests for cutting 2 pipes with internal in one pass were not performed because cutting successive layers under water is not possible.

The steam dryers will have to be dismantled pipe by pipe, using the cutting sequence presented in §. 7.2.3.10.

7.2.3.12. Two pipes with internal of BWR's steam dryer and support ring

For underwater tests of these elements, only the laser cutting of the support ring is carried out. The steam dryers are cut in the same sequence as described above.

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **20 mm**.

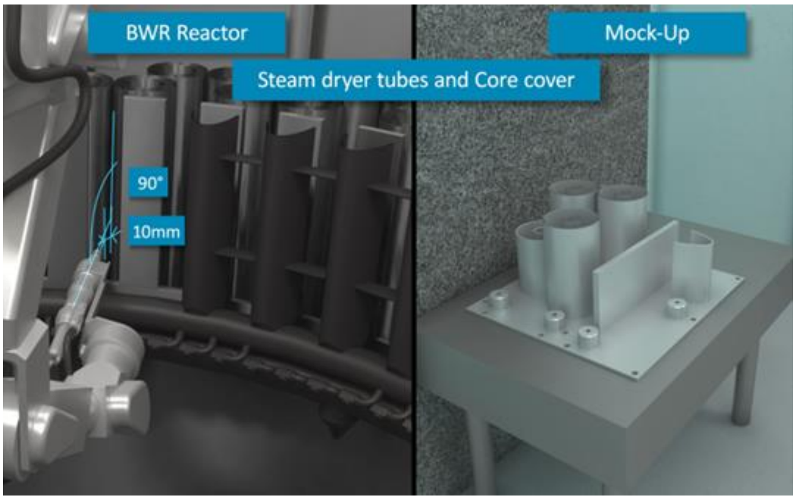


Figure 131: Support ring of BWR's steam dryer

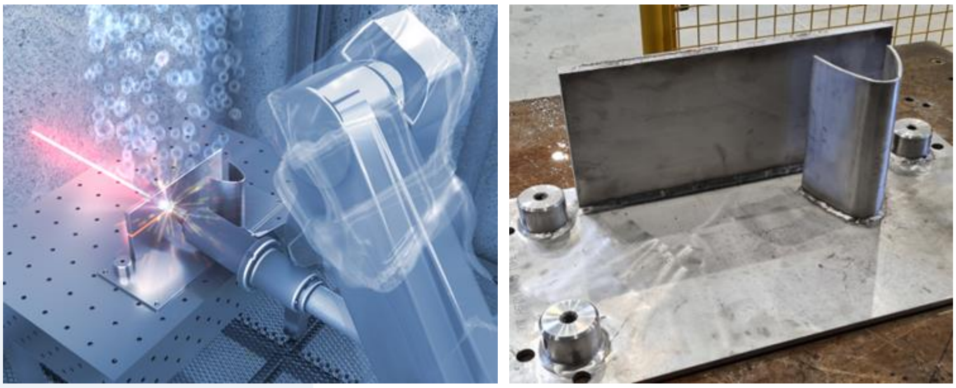


Figure 132: Support ring configuration before testing

All the tests were successful. Speed variation tests on the support ring sample showed that optimal stand-off is 10 mm (Tests 5 and 6).

Figure 133: Results for support ring

7.2.3.13. Two pipes with internal of BWR's steam dryer, support ring and core cover

The aim of these tests is the laser cutting of the core cover. The steam dryer and support ring will be removed following the procedures described previously.

The laser head is positioned at a 90° angle to the sample. The max effective thickness cut is then **6 mm**.

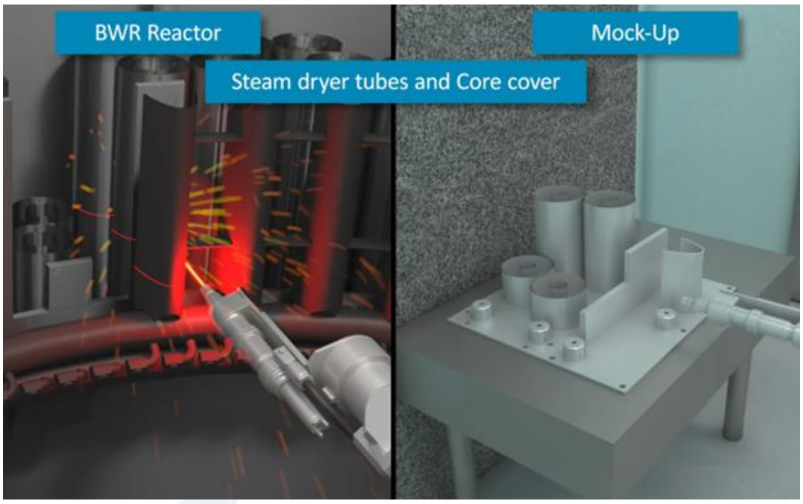


Figure 134: Core cover of BWR reactor

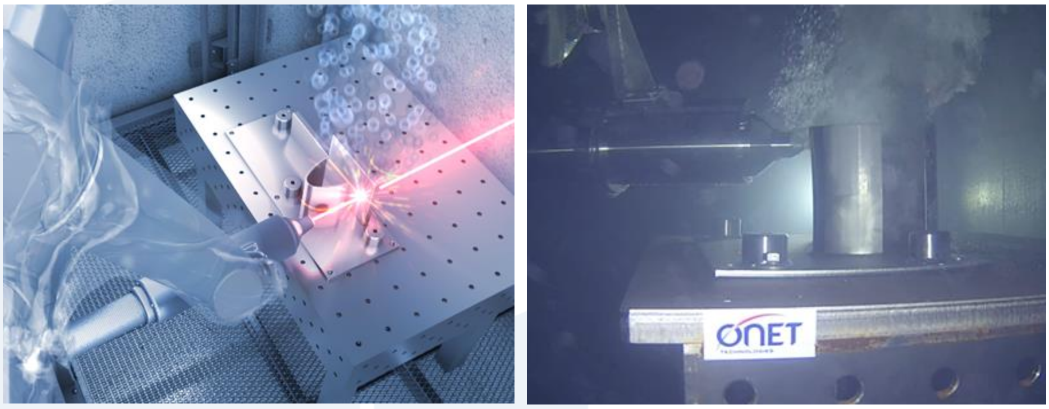


Figure 135: Core cover configuration before testing

Speed variation tests on the core cover sample showed that optimal stand-of is 10 mm with a 20°angle on the side parts (Test 2).

Figure 136: Result Core cover (Front view)

7.2.3.14. Poisoning plates of BWR

The test demonstrates the cutting of a poisoning plate without control rod, the mock-up used is the upper part of the Model3. The laser head is positioned at a 90° angle to the sample.

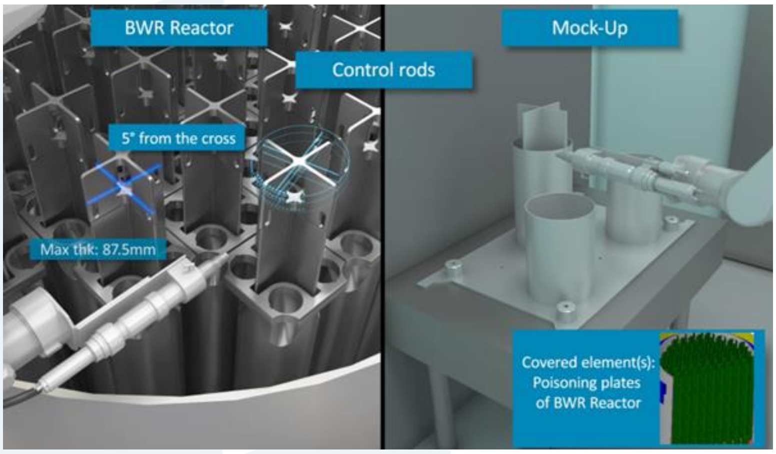


Figure 137: Poisoning plate of BWR reactor

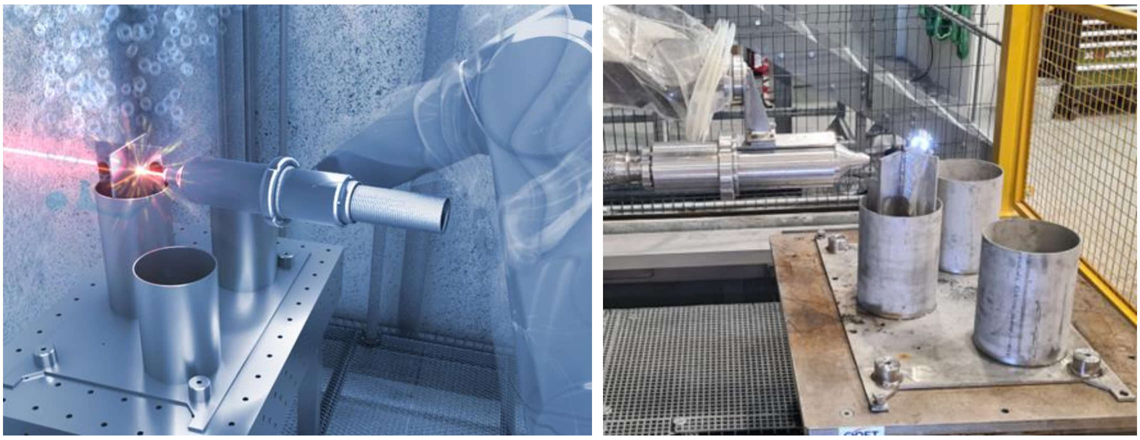
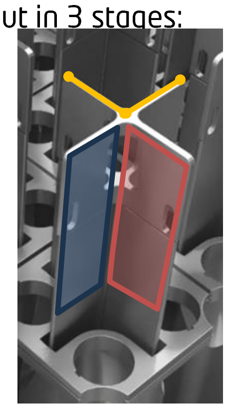


Figure 138: Poisoning plate configuration before testing

In the underwater configuration, cutting the sample is not allowed when a layer of water is present. For this purpose, the dismantling of the poisoning plate is carried out in 3 stages:

- cutting of a first front face (blue)
- cutting of a second front face (red)
- cutting of the last 2 rear faces (yellow)



Front face:

Tests 1 to 5 and 8 to 9 show that the front panel can be cut, a power of 16 kW and a stand-off of 10 mm.

Note: Tests 2 and 3 were carried out at a lower power level of 8 kW.

Cutting is achievable, but the kerf is less clean.

Figure 139: Result poisoning plate tests (front face)

<u>Rear face:</u>

Tests on cutting the rear panel (tests 6, 7, 10 and 11) showed how difficult it is to remove the reverse side of the poisoning plate.

In fact, in the central part of the component, the remaining roughness resulting from cutting the front faces increases the stand-off of the laser head in this area. To improve cutting, the laser cutting speed is limited in the central zone in comparison with the other zones.

On the first 3 tests, the increased stand-off did not enable the sample to be cut completely. In test 11, the head is rotated by 20° as it moves through the central part. This rotation enables the poisoning plate to be cut completely.

Total removal of the poisoning plate is achievable, but particular care must be taken with laser head positioning to limit stand-off at each stage.

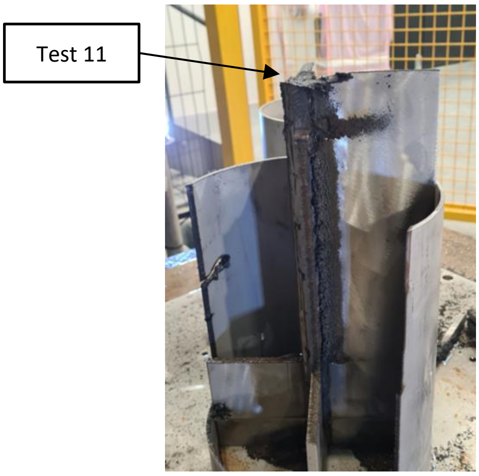


Figure 140: Result poisoning plate test (rear face)

7.2.3.15. Control rod with poisoning plate of BWR

This test consists in reproducing the cutting of control rod with poisoning plate from the BWR reactor. The test demonstrates the cutting of a poisoning plate with control rod, the mock-up used is the bottom part of the Model3. The laser head is positioned at a 90° angle to the sample.

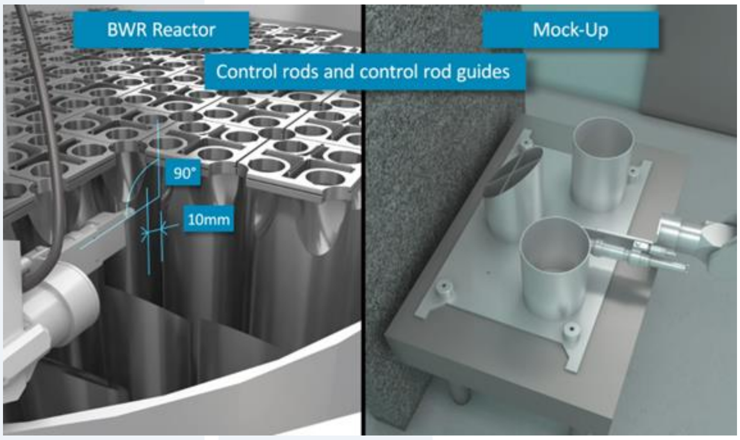


Figure 141: Control rod with poisoning plate of BWR reactor

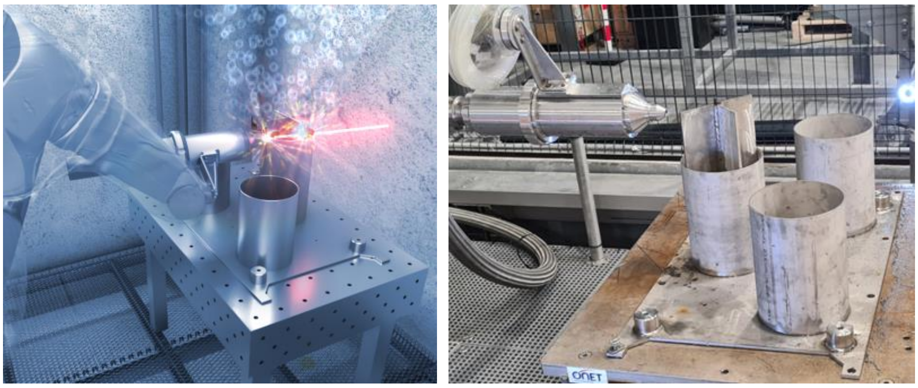


Figure 142: Control rod with poisoning plate configuration before testing

As underwater conditions do not allow the component to be cut totally, only the control rod cutting tests are presented in this chapter. For dismantling the poisoning plate, see the previous chapter.

All control rod cutting operations were successfully completed.

When cutting the control rod, impacts can be seen on the internal elements (poisoning plate). These impacts are due to the residual energy of the laser, which is low underwater and does not cause any significant damage to the internals.

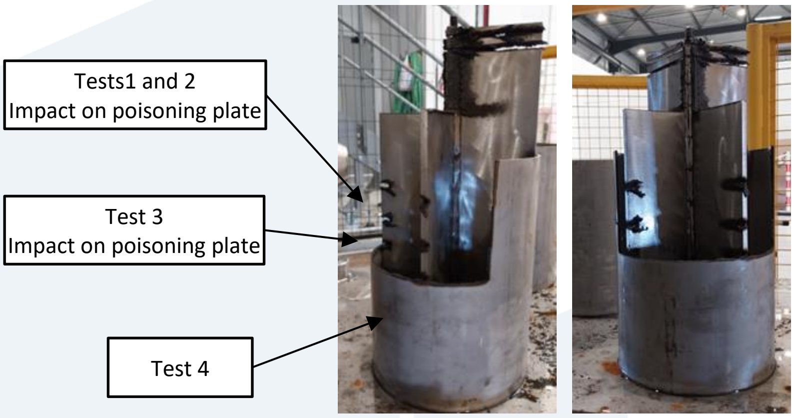


Figure 143: Result control rod tests

7.2.3.16. Control rod with poisoning plate of BWR with 45° angle

The present system configuration does not allow cutting of the poisoning plate at an angle of 45°.

We observed that the position of the laser head was close to the accessibility limits of the installation. The umbilical is too short to allow access to the side of the sample at an angle of 20°.

Positioning the laser head at 45° above the sample is not achievable.

In real-life conditions, dismantling at 45° will not present any cutting difficulties. Removal of the assembly must be carried out in accordance with the 90° laser head removal procedure:

- cutting the front face of the control rod
- cut the 2 front faces of the poisoning plate
- cut rear face of poisoning plate
- cut rear face of control rod

The difference with a 45° angle approach is the thickness to be cut, but in the underwater configuration, the cutting procedure is element-by-element, so there is no significant difference in thickness between the control rod and the poisoning plate. The capacity of the cutting laser is sufficient.

7.2.4 COMPLEMENTARY TESTS

7.2.4.1. Impact of stand-off

To determine the impact of laser head stand-off in underwater conditions, piercing tests were carried out on a 100 mm stainless steel block.

The conditions are identical for each test, except for the distance between the laser head and the sample.

Five stand-off were tested, the cutting depths obtained are as follows:

Stand-off (mm)	Depth (mm)
50	1
40	3
30	9
20	29
10	32

Table 7: Stand-off results

Figure 144: Stand-off results

These tests show that stand-off is an essential underwater parameter. There is a significant loss of cutting capacity when the laser head is 50 mm from the sample, with the impact barely perceptible.

In addition, model calculations were carried out to determine laser propagation in water and the risk to operators (calculation verified by PYLA ALPHANOV).

The risk of residual energy on operators is no longer present from a distance of 50 cm underwater. Tests will need to be carried out with light intensity measurements at different depths.

7.2.4.2. Impact of cutting trajectory

The aim of these tests is to demonstrate the cutting flexibility of laser tools. Flexibility can vary depending on the configuration of the installation:

- type of remote-controlled arm
- type of laser head (in air or underwater)

Cuttings are performed on stainless steel 304L plates of 5 mm thickness.

The cuttings obtained are shown below:

Figure 145: "Extended W" trajectory

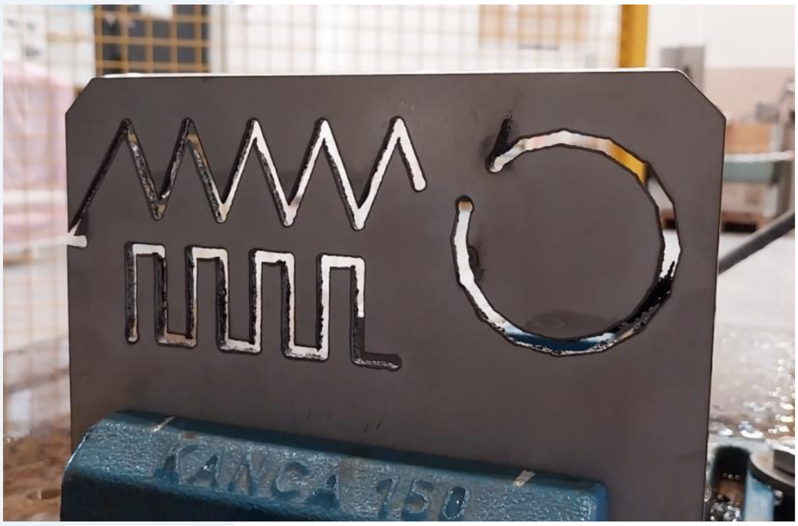


Figure 146: W / U / O trajectories

Laser tools can be used to produce a variety of cut types. This flexibility allows us to adapt to the configuration of installations (e.g. footprint) and also to adapt the cutting of components according to the characteristics of the waste packages. Optimization of waste package filling reduces dismantling costs.

7.3. FEEDBACK

7.3.1 Commissioning

Installation and commissioning of the laser system at Onet Technocenter was carried out in several steps:

- Delivery and reception of equipment
- Installation and connection of equipment: cable routing (electrical, hydraulic and pneumatic) and connection
- Laser system commissioning: laser and compressed air shelter commissioning
- Training: operator training for the remote-controlled arm and utilities console
- Disassembly and transport: disconnection, packaging and transport

The table below shows the operating times for the various steps.

STEP	ACTIVITIES	DURATION
Delivery and reception	Transport + discharge	1 day
Installation and connection	Equipment positioning + cable routing + connection	5 days
Laser system commissioning	Laser commissioning	2 days
Training	Training for the STAUBLI remote-controlled arm	3 days
	Training for the utilities console	0.5 day
Disassembly and transport (Not tested same as in air demonstrator)	Disconnection	2 days
	Cable routing	1 day
	Packaging + transport	3 days

Table 8: In-air demonstrator operating times

Note:

- 2 participants are considered for each step.
- No damages observed on the laser equipment during commissioning phase at Onet Technocenter following transport/lift of the laser system from CEA Marcoule (in-air demonstrator).
- Absence of PAC deployment duration to be compared with laser cutting. However, laser cutting technology is faster to deploy in comparison with mechanical tools.

7.3.2 Test

Feedback from demonstrator tests underwater is as follows:

- Laser system:
  - No malfunctions were observed during the underwater tests. Laser availability rate is 100%.
  - The laser system was successfully restarted by the laser manufacturer following the transfer of the laser shelter and the installation of the fiber at Onet Technocenter. No specific operations or component changes were required to restart the laser system.
  - Integration of the fiber into the watertight umbilical did not cause any malfunction or damage.
- All mock-ups have been cut with the same manipulator (Staubli electrical robotic arm; no changes during the cutting campaign).
- STAUBLI robotic arm:
  - Good handling of the device by the EQUANS team. All cutting was carried out with programmed trajectories.
  - Various issues have been reported with the STAUBLI robot arm:
    - 115 laser cuttings were performed underwater.
- 2 ventilation systems were used for the underwater demonstrator:
  - At the start of the tests, 25 cuts were made using the secondary ventilation system (ventilation turbine + very high efficiency HEPA filter). These cuts did not require filter replacement.
  - The remaining 90 cuts were made using a filtration system with 2 unclogging HEPA filters. This system is self-cleaning and did not require any filter changes during the test campaign. The pressure drops of the 2 filters evolved as follows:
    - 1st filter (RH13): initial dP 250 Pa / final dP 530 Pa
    - 2nd filter (H13): initial dP 235 Pa / final dP 235 Pa

    Note: filter replacement if dP = 1000 Pa
- Water analysis: At the end of the campaign, samples were taken from the pool. Analyses showed that COD, TSS and metal levels were in line with Technocenter discharge standards.

The most prevalent metal is chromium, particularly chromium VI, which comes from laser cutting of stainless steel.

8. CONCLUSION

8.1. Generalities

In-air and underwater demonstrator tests were carried out in 2 campaigns. All the tests were carried out using the same devices, which were packaged, transported and installed at the test sites (except the laser head and its umbilical).

The first series of tests took place at CEA Marcoule in October and November 2023 and enabled the demonstration tests to be carried out under air conditions.

Figure 147: In-air configuration test

The second tests were carried out at the ONET Technocenter in March and April 2024, and enabled representative underwater tests to be carried out.

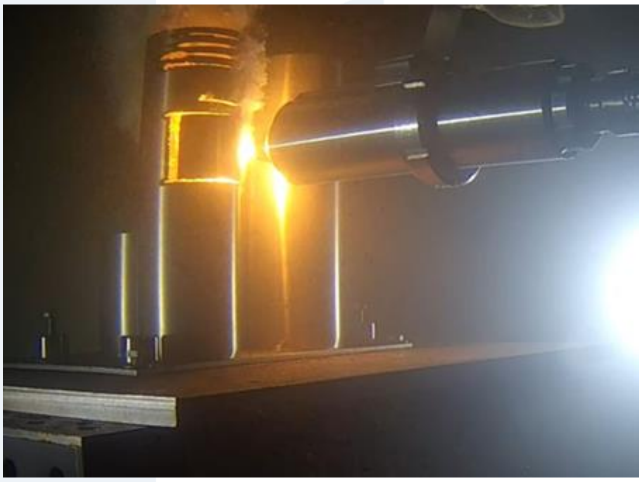


Figure 148: Underwater configuration test

These tests showed that dismantling RVI (Reactor Vessel Internals) is **feasible with laser technology**, both in air and underwater, but different conditions of use have been observed.

Condition	In-air	Underwater
Laser power	14 kW	16 kW
Max stand-off	150 mm	20 mm
Cutting multiple layers	Yes	No
Residual energy	Yes	No
Aerosols dispersion	Yes	Yes
Visibility	Yes	Yes

Table 9: Differences between In-air and underwater laser test

Different conditions of use in air and underwater provide advantages and disadvantages when implementing laser technologies.

<u>Laser power</u>:

The higher laser power of the underwater laser head (16 kW instead of 14 kW) enables similar cutting performance in terms of thickness cutting, despite the dissipation of underwater laser power. Indeed, a **100 mm stainless steel plate** was cut to assess the cutting speeds in both air and underwater conditions. Note: due to confidentiality of the cutting speeds, they are not presented in this public document.

<u>Stand-off</u> :

Underwater tests have shown the importance of stand-off to maintain cutting efficiency.

The **optimum underwater stand-off is 10 mm** with a maximum distance of 20 mm, whereas **in air the optimum stand-off is 30 mm** with a maximum distance of 150 mm.

In the air, remote operations are simplified because the laser head doesn't have to be very close to the component. Underwater, on the other hand, the laser head has to be close to the component and follow its shape.

<u>Multiple layer</u> :

Cutting components in air has the advantage of cutting multiple layers.

Underwater, with the laser beam absorption, only a single layer can be cut per pass. The removal operation can be performed under water, but will be divided into several separate cutting operations (e.g. 2 steam dryers + internals, support ring and core cover):

Cutting the core cover → Cutting the support ring → Cutting the front face of the 1st steam dryer → Cutting the front face of the inner tube → Cutting the back face of the inner tube → Cutting the back face of the 1st steam dryer → Cutting the front face of the 2nd steam dryer → Cutting the front face of the inner tube → Cutting the back face of the inner tube → Cutting the back face of the 2nd steam dryer

Residual energy:

Residual laser energy is inexistent in underwater conditions at a distance of 50 mm from the laser head. This is beneficial, as only the component to be cut is impacted by the laser.

In air, laser energy spreads over a greater distance. Impact tests on the carbon steel impact plate have shown that the impact depth is over 50 mm with the plate positioned 70 mm behind the component. Particular vigilance must be exercised with regard to residual energy, by adjusting cutting speeds and laser power according to component thickness, to limit the impact. It should be noted, however, that the residual energy of the laser in air does not degrade the total integrity of the reactor vessel, which guarantees containment.

Underwater, the laser risk to the operator is limited to 50 cm around the laser head. Calculations have shown that beyond 50 cm in water, direct laser light is no longer dangerous for the operator. Real-life tests will have to be carried out to confirm the calculations.

Dispersion aerosol:

Underwater cutting is the best condition for reducing aerosol dispersion. For example, when cutting a 100 mm stainless steel block, underwater cutting reduces the number of aerosols released into the atmosphere by 70%. Mitigation devices can be implemented in the air to limit aerosol dispersion. Tests with a collection head show a 35% (as average, few tests are shown is this document) reduction in aerosol concentration under similar conditions.

Visibility:

Visibility is an important parameter for remote operations.

In air laser cutting, laser does not present any difficulties for operator visibility. Cameras need to be positioned before cutting operations, to visualize the front and rear areas of components, as also the stand-off between the laser head and the component.

For most of the underwater tests, **visibility was satisfying** to allow remote operation of laser cutting. For cutting the thickest components (Main module), visibility was not sufficient. The generation of a large quantity of particles in a short period of time prevented the facility's water treatment system from maintaining good visibility.

However, a combination of measures can be taken to ensure good underwater visibility:

- increased the flow rate (Test condition: renewal rate of 0.25 → 11 m^3/h for a volume of 45 m^3)
- reduced filtering thresholds (Test condition: 2 filtration levels 25 µm and 1 µm)
- improved pool agitation (Test condition: non agitation)

Note: A laser pointer can be part of future development to precisely determine the stand-off between the laser head and the component, as this parameter is an important element in cutting efficiency.

The laser system has demonstrated its versatility by successfully testing laser cutting in air and underwater conditions using a unique tool (underwater laser head). The results of cutting tests with the underwater laser head in air conditions are similar to those achieved with the laser head in air at CEA Marcoule.

The test campaign, which included 2 test phases with transport, installation and cutting tests on 2 facilities, demonstrated the robustness of the laser system. No maintenance or parts replacement was required on the laser system. Only a commissioning of the laser source by the laser manufacturer is recommended after moving the device.

During demonstration phase, nuclear safety aspects have been considered (and confirmed H2 risk is negligible) and it has been proved dismantling with laser technology is feasible.

8.2. TRL assessment

Following NASA scale of evaluation of technology maturity, TRL of the laser system has been assessed.

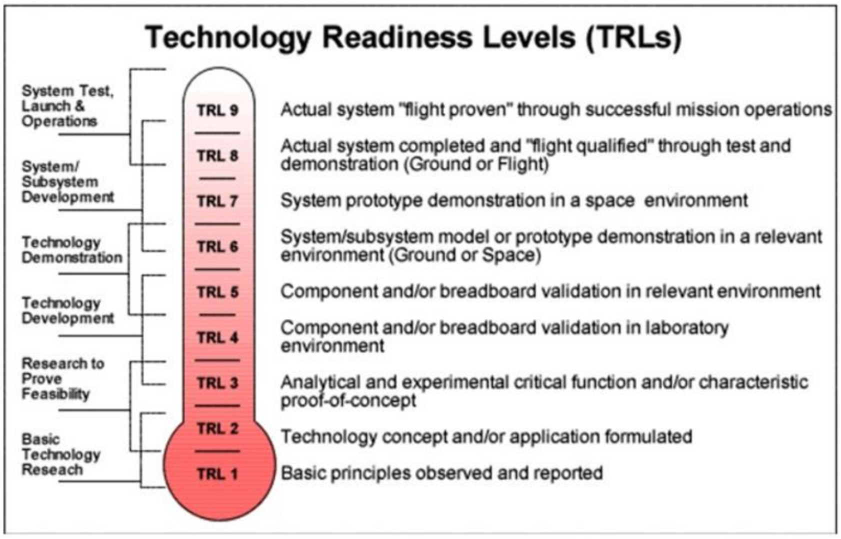


Figure 149: Technology Readiness Levels

Based on the following feedback from both demonstrators, TRL 7 is confirmed.

The laser system by itself has all the features of the final product:

- Representative spatial breakdown of the system has been deployed (separation between nuclear and non-nuclear area): junctions have been managed with the interface zone
- Representative length of connections has been tested
- Transportation of the laser system from one site to another have been performed
- All the safety features have been tested
- Each RVI's mock-up has been successfully cut in both environments (in air and under water)

The laser system has been deployed in an environment representative of dismantling project:

- It has been tested in a similar environment to a NPP: CEA Marcoule nuclear research center
- Design and behavior of the laser head, its sleeve and connections have been validated under water

8.3. Cost and time reduction

In the deliverable [R5], a economical comparative analysis between laser and mechanical tools have been done (Mechanical technique is the most used in Europe today).

Indeed, **CAPEX** and **cutting time duration** comparison have been assessed on the basis of LD-SAFE outcomes (including demonstrator's results) and partner's experience in decommissioning.

<u>CAPEX:</u>

- Since 1st unit to be dismantled, Laser CAPEX is already less expensive than Mechanical tools (almost 50% of cost reduction). For a second unit, even if the cost investment is less important, the cost reduction represents almost 65%.
- After 10 units dismantled, Laser represents almost 70% of cost reduction in comparison with mechanical tools.

<u>Time reduction (cutting operation and waste removal to the waste package):</u>

- Based on the laser-cutting times for each component obtained during demonstrator tests, it is possible to give an estimate of the laser cutting duration for all the RVI of a PWR reactor (the most known reactor technology in Europe).
- Hypothesis:
  - 10 effective hours per day (2x8 shift)
  - 202.25 days worked per year (feedback from ONET)
  - Duration of the individual steps for each cut

	Duration (min)
Operator cutting environment analysis	5
Arm movement	5
Choice of cutting parameters (laser / trajectory)	2
Cutting time	Defined by component
Waste removal	30
Hazards	50%

- Time reduction by using laser is 30% in comparison with mechanical tools for RVI dismantling (for a PWR)
- This time reduction is given for information only, and a more detailed scenario will have to be determined to refine laser cutting durations and to be confirmed in real RVI PWR dismantling project.