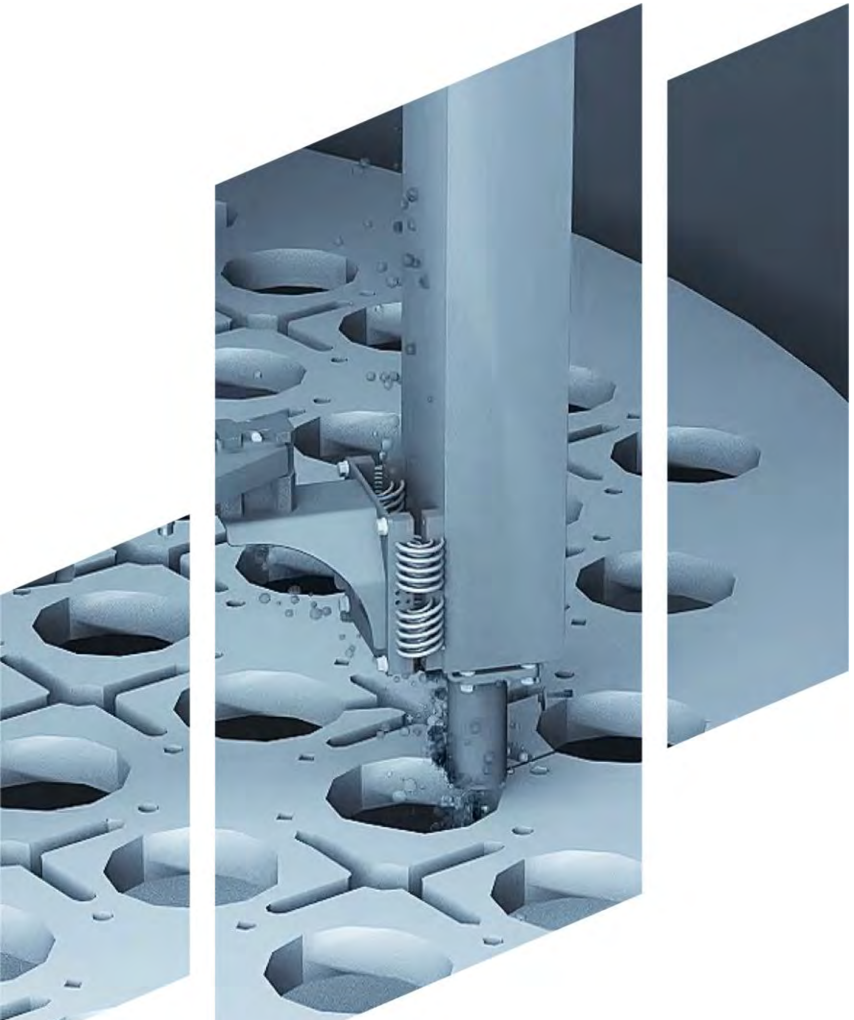
8.4. End Technical Workshop – Technical presentations



LD-SAFE

Decommissioning challenges with laser cutting technology

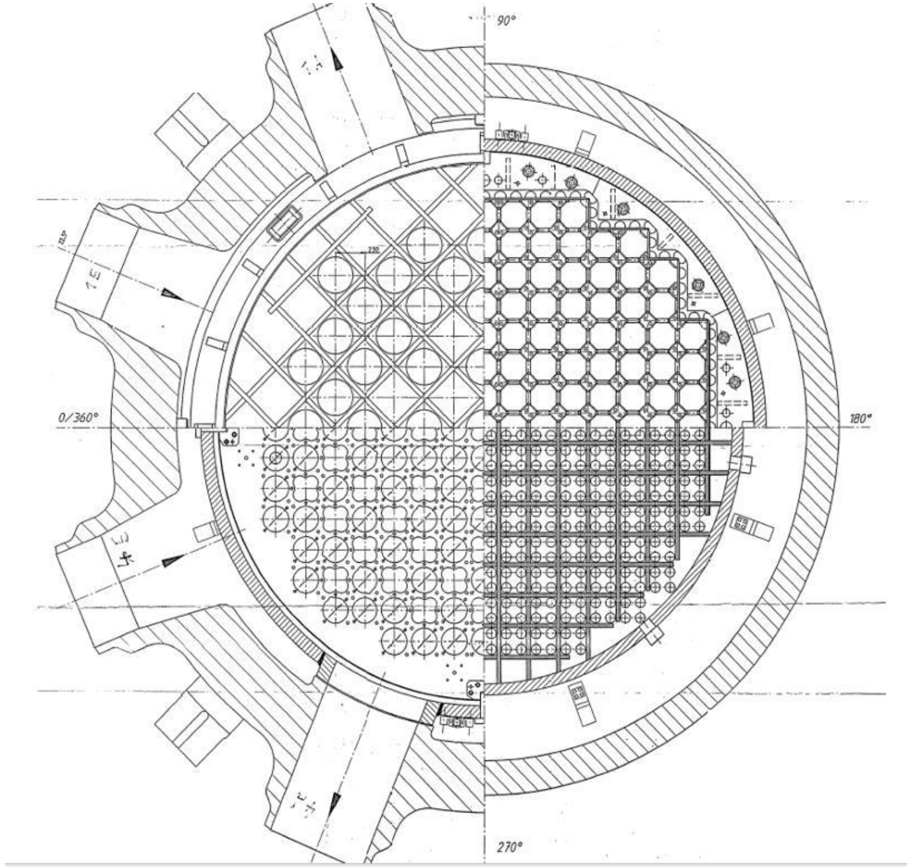
Author: Anton Nulens (EQUANS)
Date: 30/05/2024

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

Context

- Key figures
  - 177 PWR (most common) and 26 BWR among 22 countries in Western - Central - Eastern Europe)
  - 145 in operation and 58 in shutdown
  - Largest reactors fleet in France

- Challenges
  - Dismantling work to increase significantly throughout century
  - Immediate dismantling desirable
  - Time scales and costs must decrease

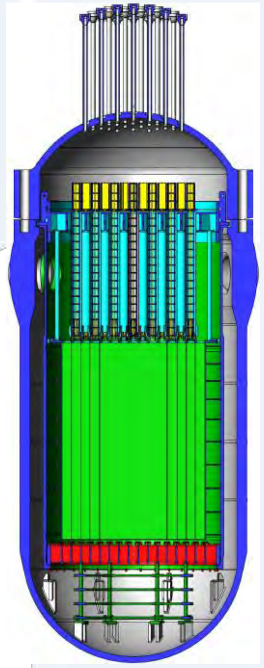


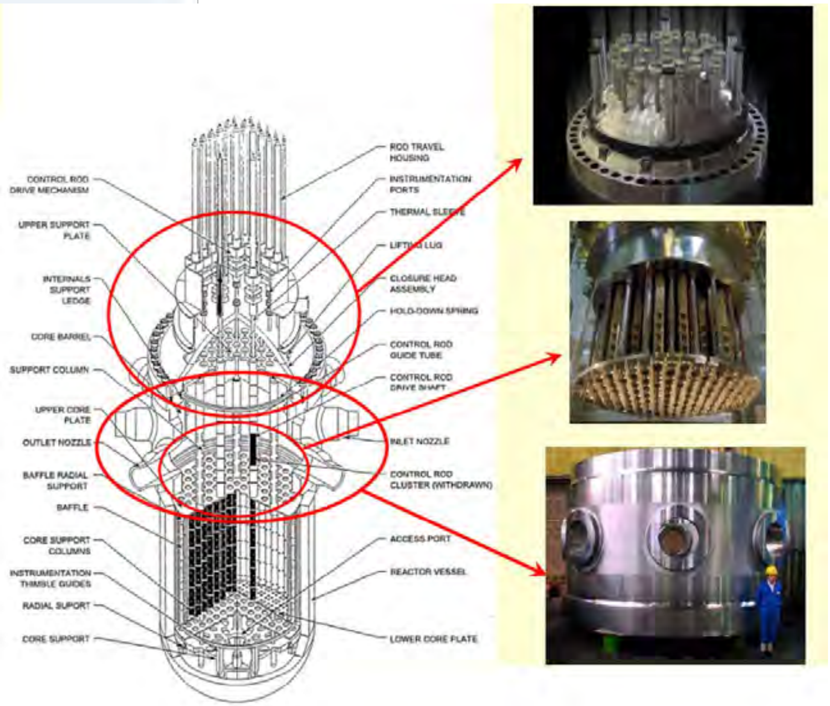
Top view of a PWR, showing the variety and complexity of their internals

Reactor components

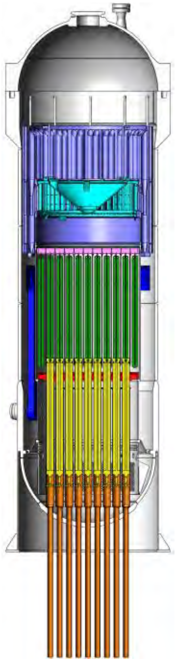
- Analysis of the dismantling of reactor components
  - RPV/RVI structure of metal assemblies, which vary considerably based on the type, size and design of reactors (i.e., BWR vs. PWR)

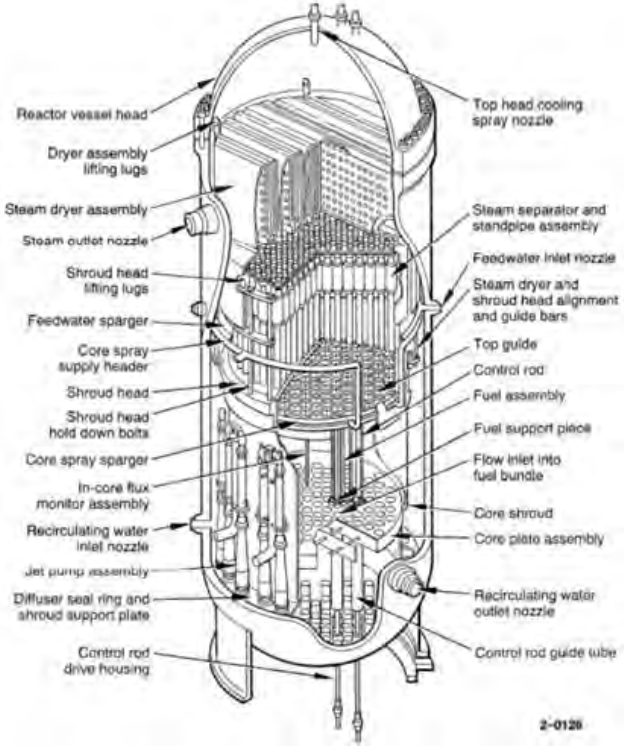
PWR





BWR

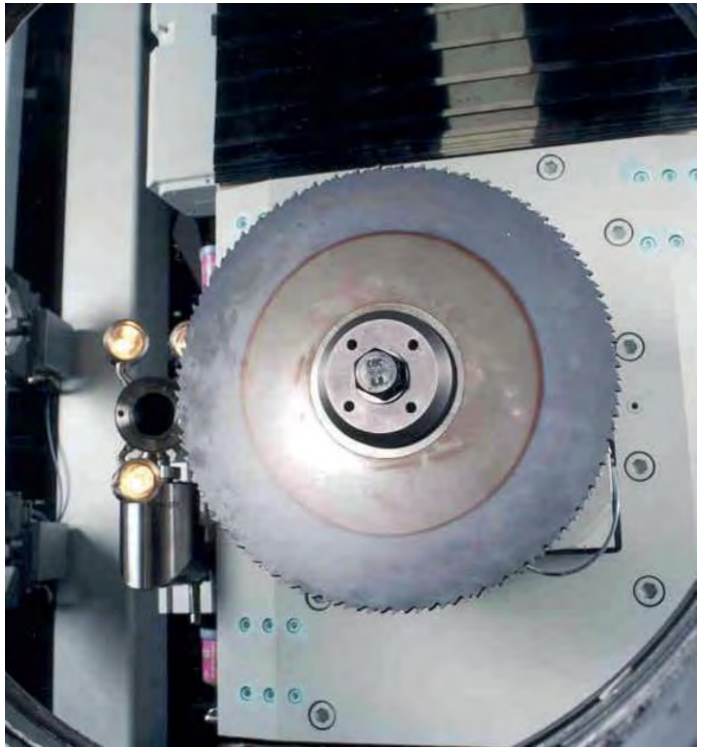




Dismantling today

- Types of tools

Mechanical	Thermal	Hydraulic
Band saw	**Plasma arc**	**Abrasive water injection jet**
Circular saw	Flame cutting	Abrasive water suspension jet
Milling cutters	Contact arc metal cutting	
Shearing	Oxygen cutting	
Grinding		



Circular saw for decommissioning

Most used cutting technique

- Mechanical tools are the most used
- Main drawbacks:
  - Multiplicity of methods (several methods used for different cuts)
  - Numerous dedicated tools (cranes, tables, …)
  - Technical risks
    - High number of spare and wear parts
    - Vibrations, torque, blockages due to mechanical tools

Band saw with dual column guide

Expectations for laser

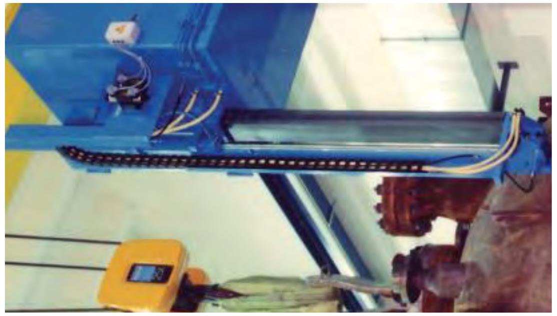
What must laser be capable of?

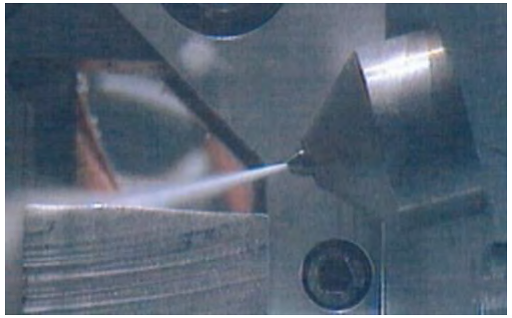
- Cutting efficiency (high thicknesses, complex geometries, speed)
- Low investment cost, low maintenance, ease of use
- Versatility
  - Few cutting tools
- Safety (including dose reduction)

Control room operator (right) controlling the Maestro robot arm in a Marcoule pilot unit (APM) cell (left).

- Environment
  - In-air, underwater
  - Ability to navigate inside reactor pressure vessel
  - Layout advantages (easy deployment, low surface use and circulation)
- Licensing process
  - Experience, expertise and evidence

Comparison with the main conventional cutting techniques





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

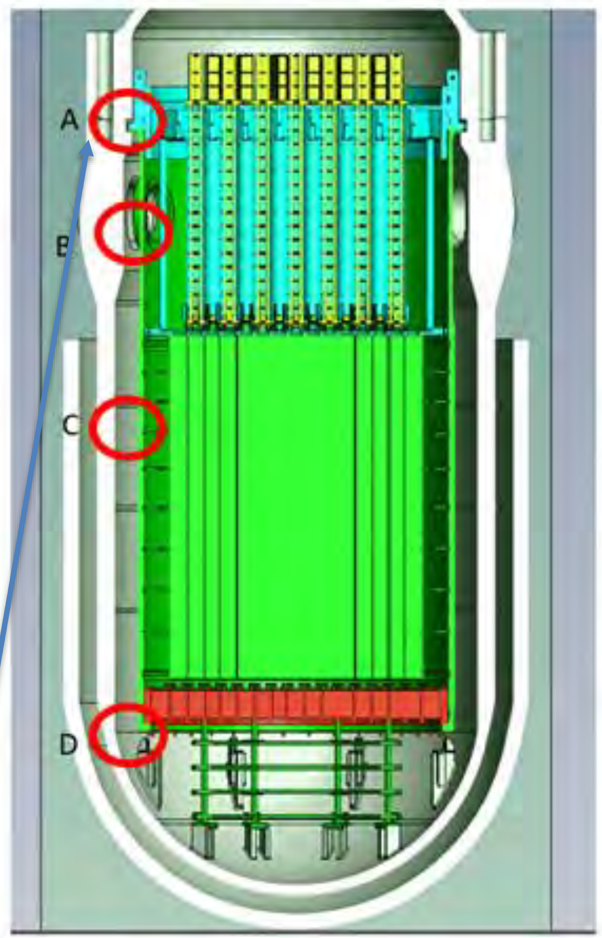
Conventional cutting techniques

Input data for laboratory tests

- Main specific risks for laser
  - Laser beam residual power
  - Hydrogen generation
  - Aerosol production

- Input data example (laser beam residual power)
  - The shortest distance between the vessel and the nearest internal component
  - The highest thickness of the internal component near the vessel

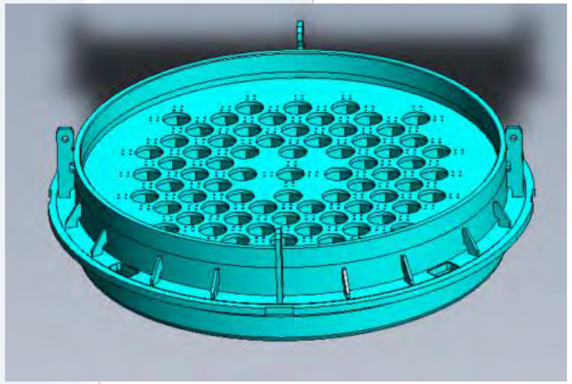
=> Most risky configuration for PWR vessel



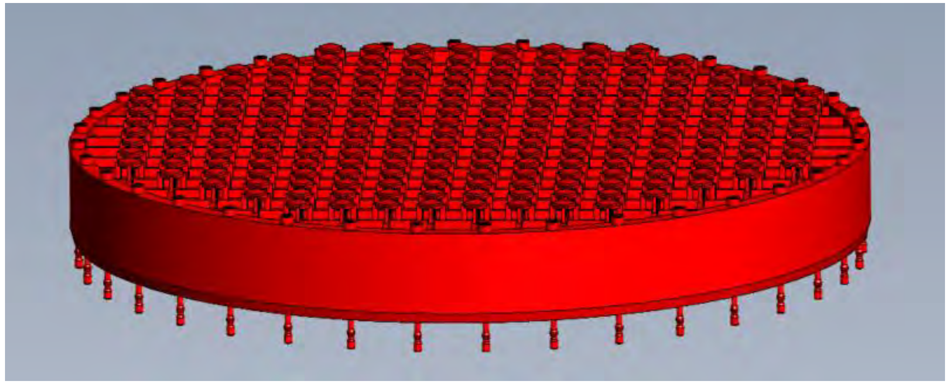
Shortest distances between vessel and internals

Most challenging configurations

- Some internals are more challenging than others
  - Identify the most challenging piece to be cut in the reactors (examples below)
  - All internals were listed and analyzed
  - Input for the mock-up design and cutting



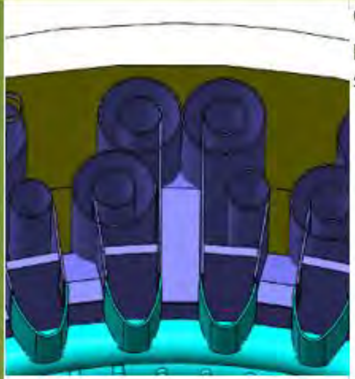
PWR's Upper plate

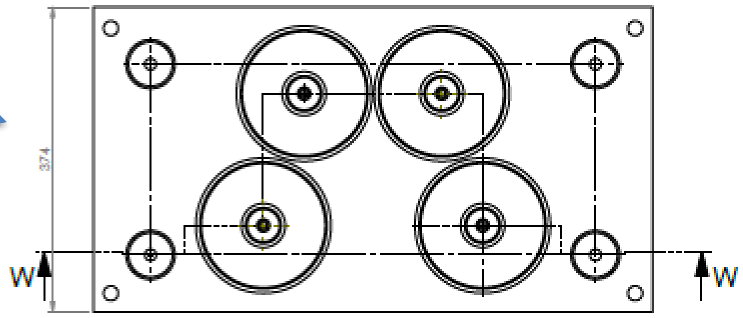


PWR's Bottom plate

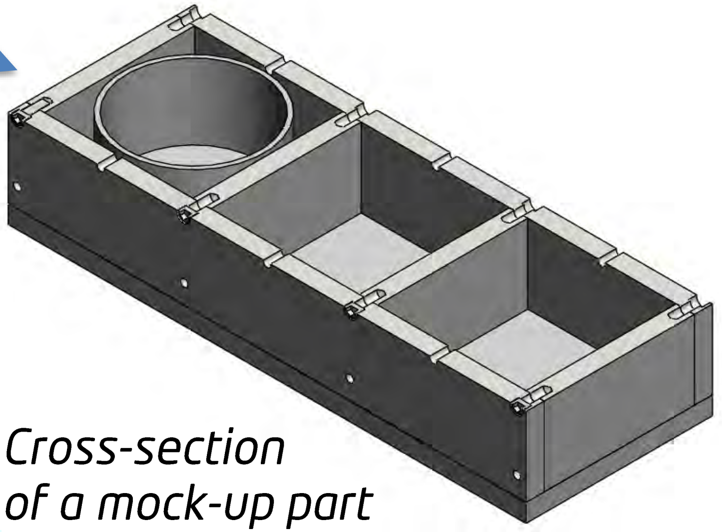
Most challenging configurations

- Example of internal inventory and implementation in modules

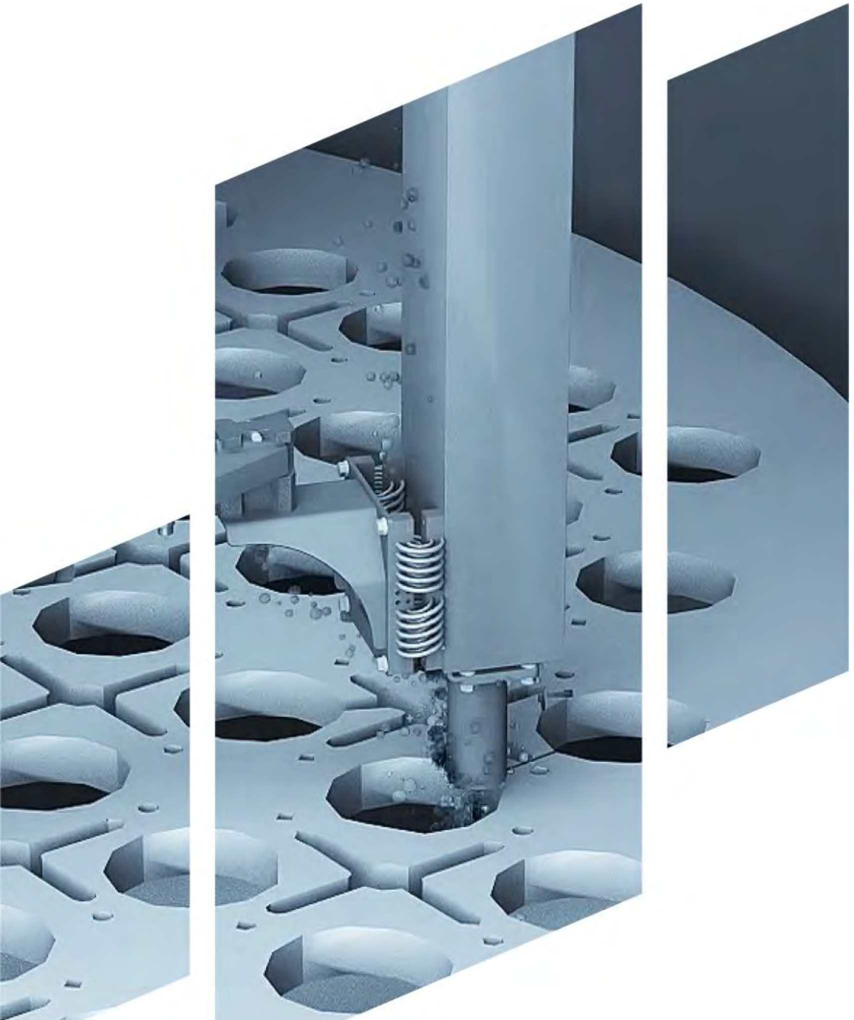
Subpart	Image	Description	Relevant characteristic	Real dimensions (mm)	Possible model	Representativity	Modul
Tube/plate interface		Hollow tubes encased in square grid	Square side (center to center) Thickness of grid Tubes: see dimensions above	325,2 35	Tubes encased in a grid, height 300, 1 represented	Represents the part between the bottom of the upper plate and the support. The dimensions should be conserved	Main
Curved shapes		Curved plates fixed perpendicular to a support ring	Profile shape and dimensions: see plan Thickness: 5				



Top view of a mock-up part



Cross-section of a mock-up part



LD-SAFE

Laser beam residual power
End Technical Workshop

Mai 30, 2024

Lucas Brizzi, Ioana Doyen, François Simon, Timothy Picard, Laura Pereira
CEA

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

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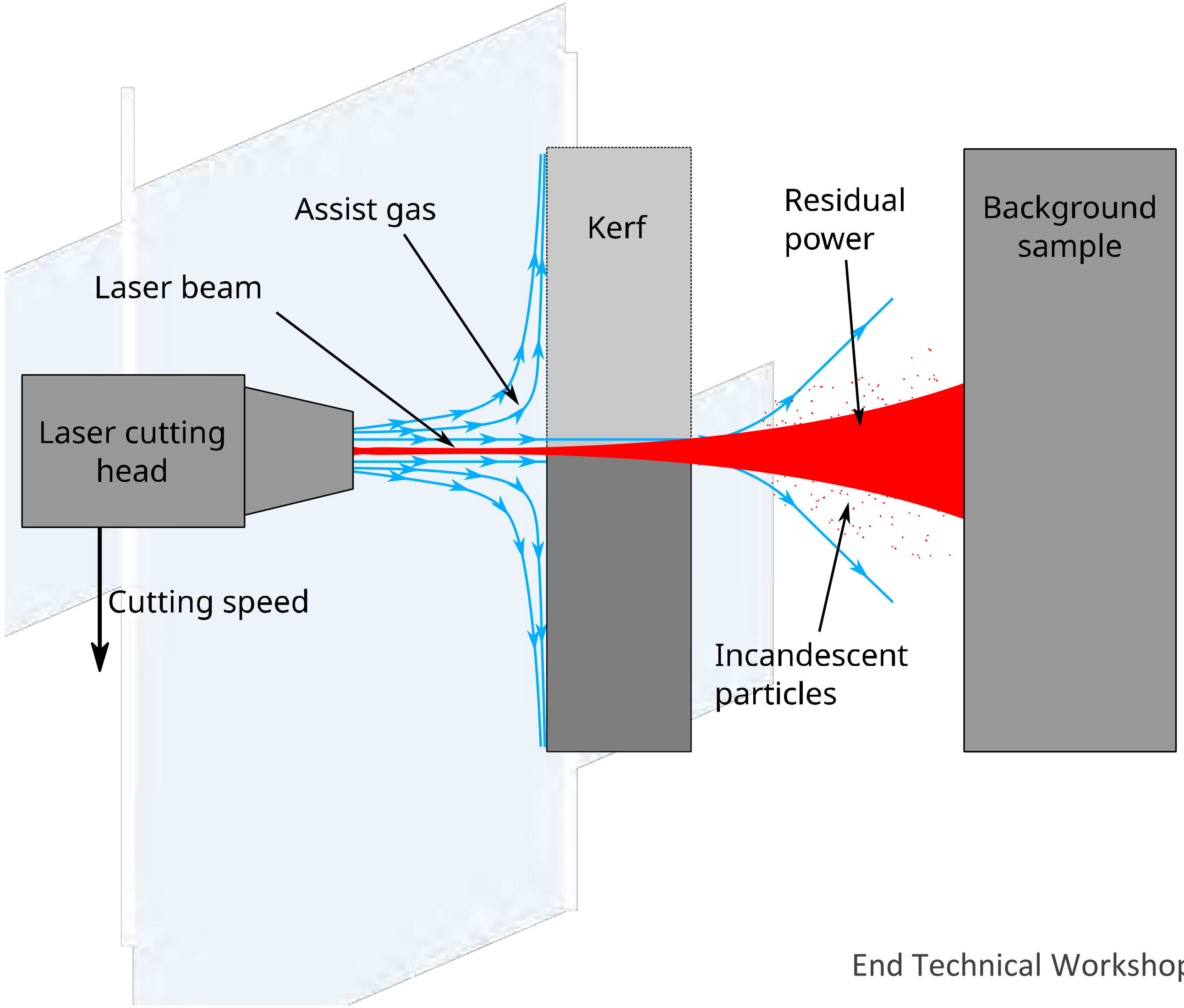
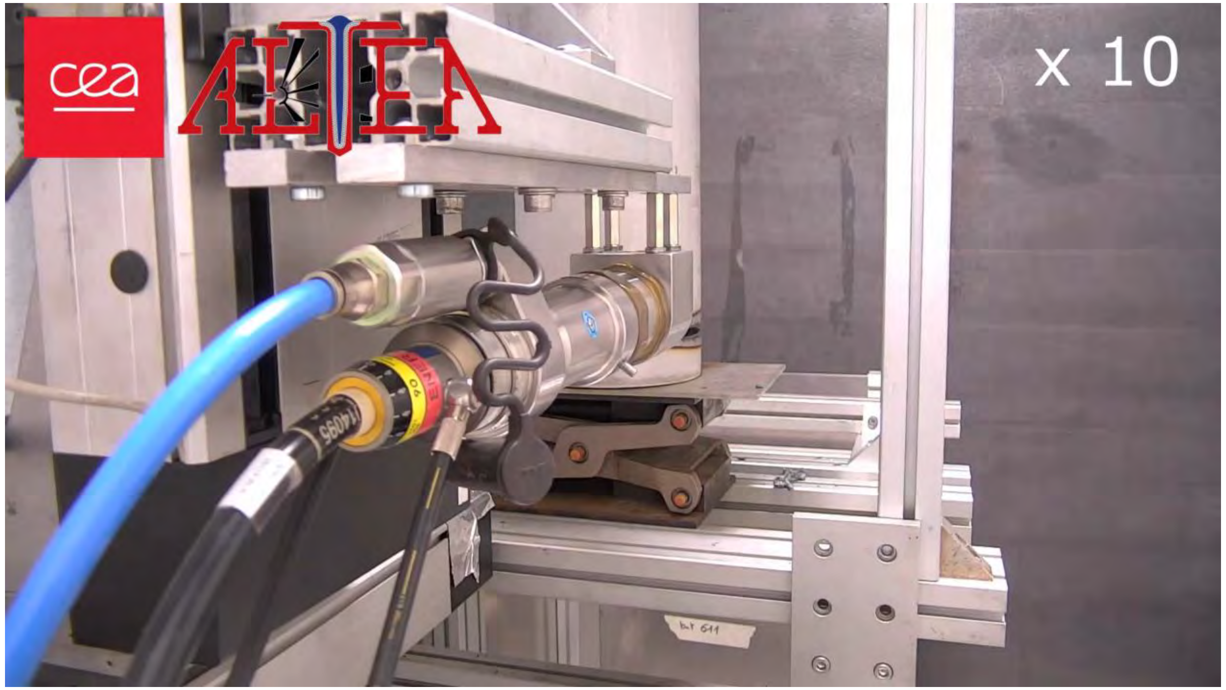
Introduction

Laser cutting process





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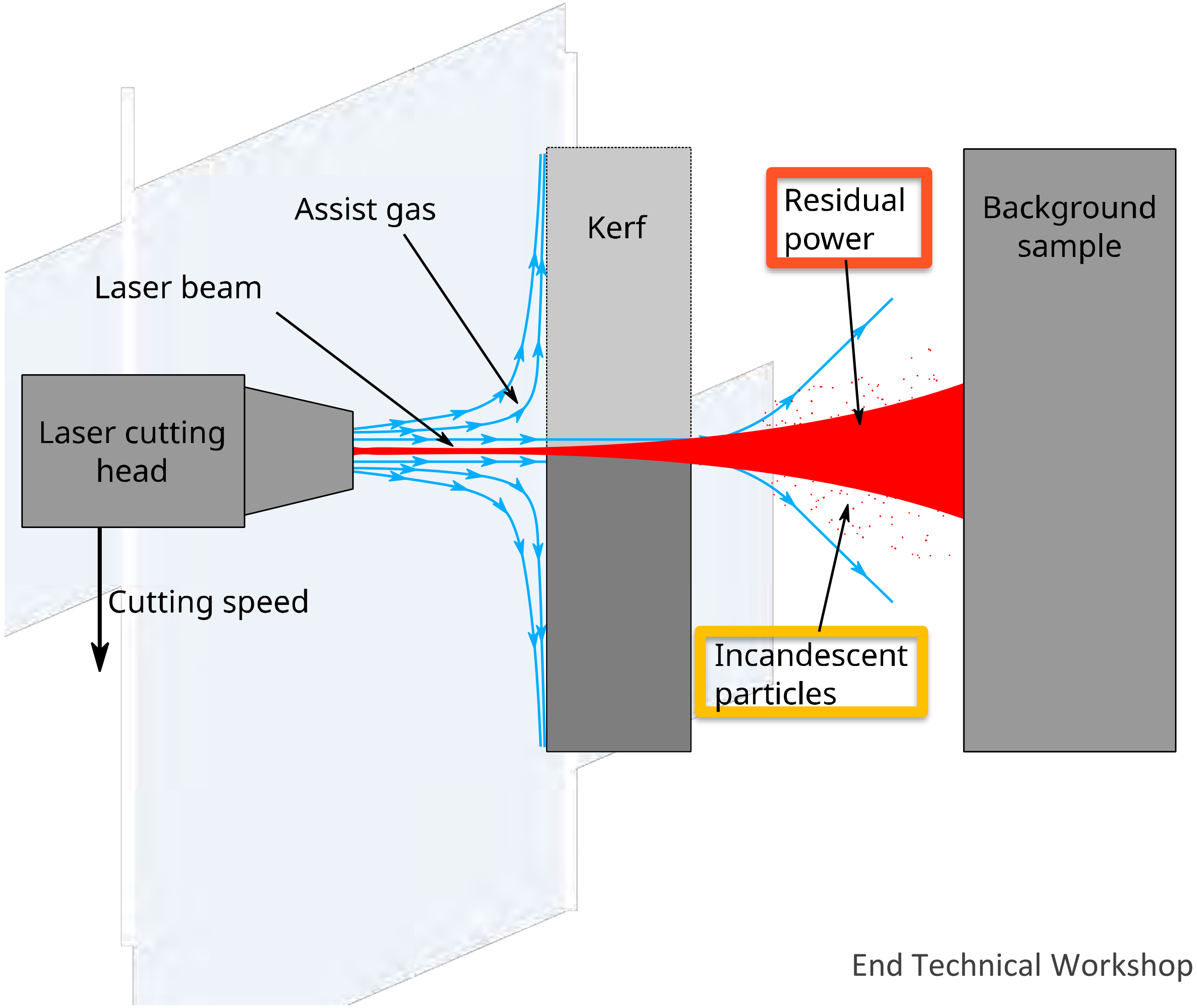
Introduction

Laser beam residual power



- **Impact on a background structure** = residual laser energy + thermal energy of incandescent particles
- A potential damage - may affect the mechanical integrity of components to be dismantled or the lost of confinement and radioactive particles release if the containment vessel is pierced.

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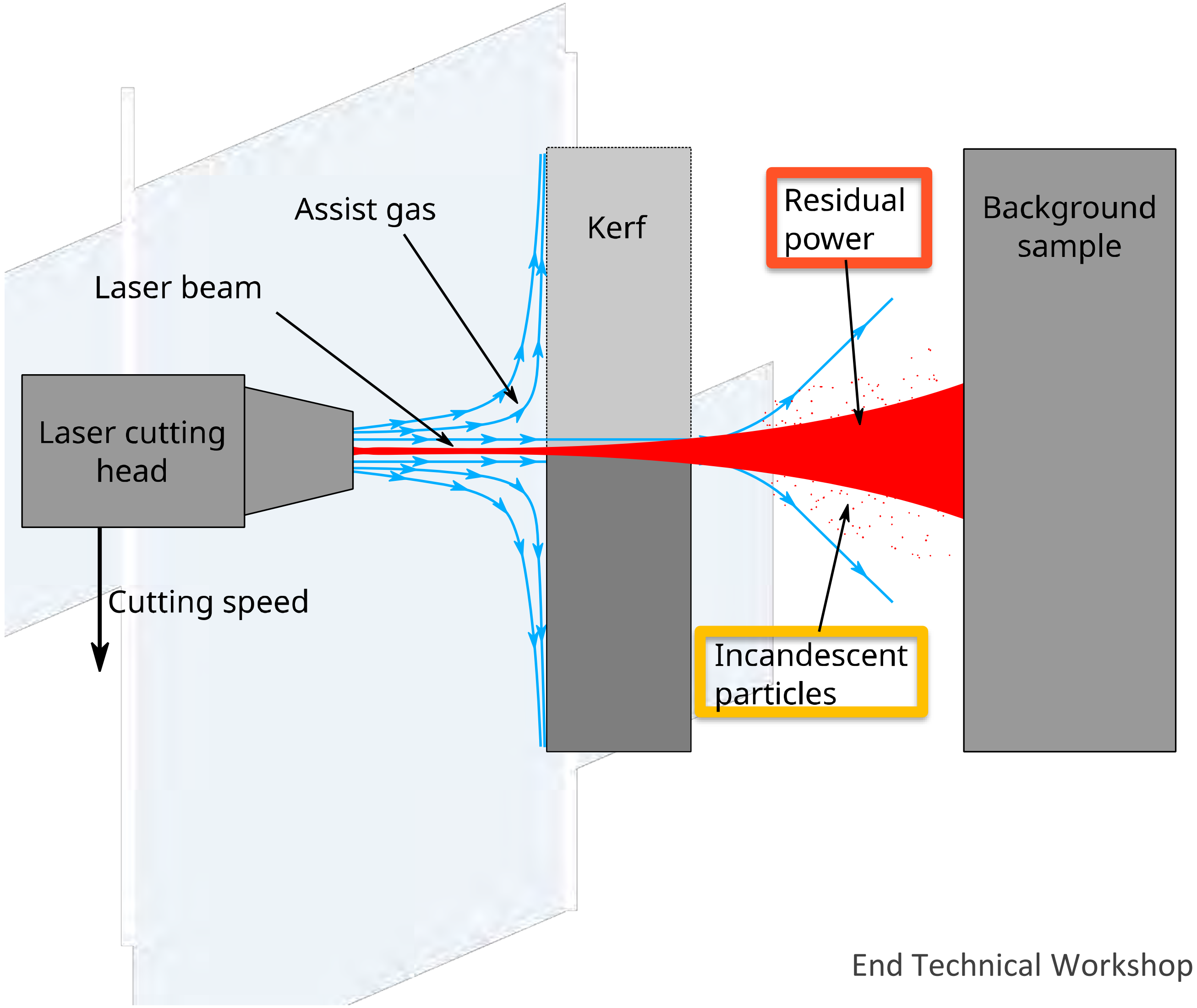
Introduction

Laser beam residual power



Main parameters:

- Laser power setpoint, cutting speed
- Workpiece (material and thickness)
- Background element (material and thickness)
- Distance between the cutting piece and the background

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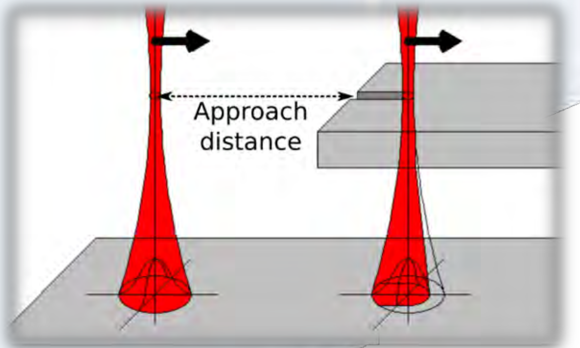
Introduction

Laser beam residual power

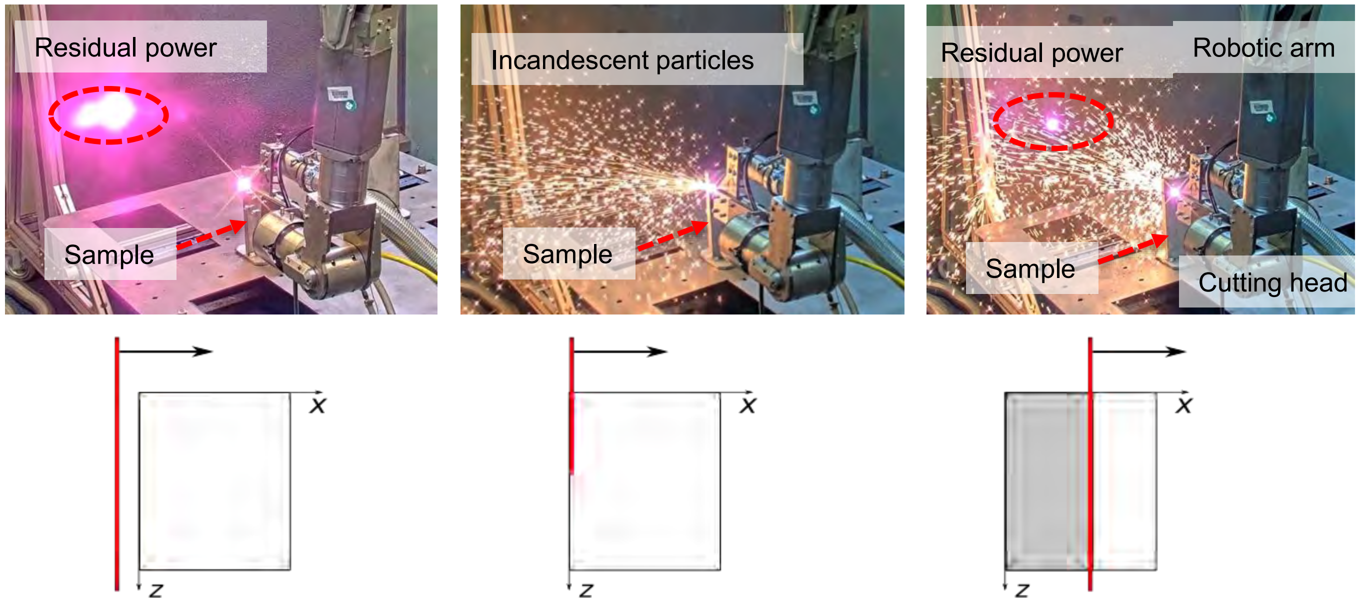
Cutting process comprises 4 phases :

- **Phase 1**: approaching phase 100% of the laser power reaches the background
- **Phase 2**: process initiation – almost 100% of laser power is absorbed
- **Phase 3**: cutting phase – a part of the laser power reaches the background
- **Phase 4** : end of the cutting process – 100% of the laser power reaches the background

Phase 1 Phase 3



Phase 1 **Phase 2** **Phase 3**



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Introduction

Objectives of the study

- Characterize laser residual power and asses its impact on metallic structures
- Gather data to support safety assessment for implementing laser cutting technology on-site
- Propose countermeasures to minimize the induced potential damage

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Introduction

Input data

Input data from WP1 regarding tests conditions

BWR

Vessel thickness: 380 mm
Thickness of component: 80 mm
Distance: 65 mm

Vessel thickness: 100 mm
Thickness of component: 80 mm
Distance: 30 mm

Vessel thickness: 100 mm
Thickness of component: 5 mm
Distance: 130 mm

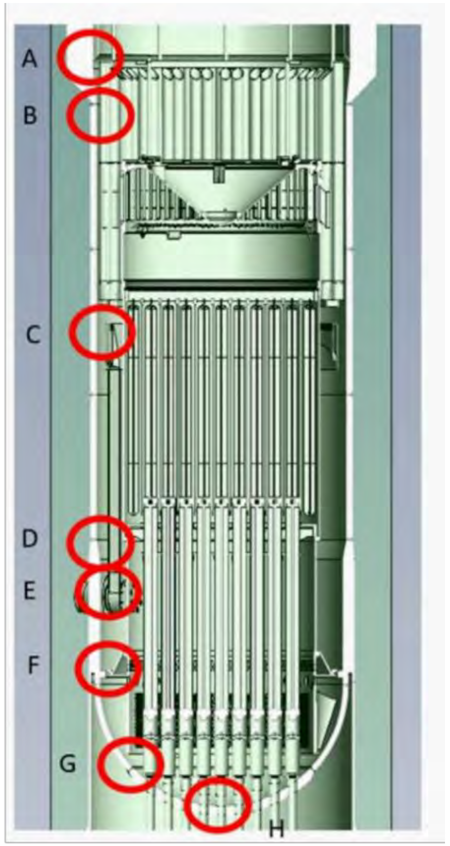
Vessel thickness: 100 mm
Thickness of component: 170 mm
Distance: 120 mm

Vessel thickness: 100 mm
Thickness of component: 170 mm
Distance: 40 mm

Vessel thickness: 480 mm
Thickness of component: 100 mm
Distance: 0 mm

Vessel thickness: 125 mm
Thickness of component: 40 mm
Distance: 100 mm

Vessel thickness: 125 mm
Thickness of component: 51 mm
Distance: 80 mm



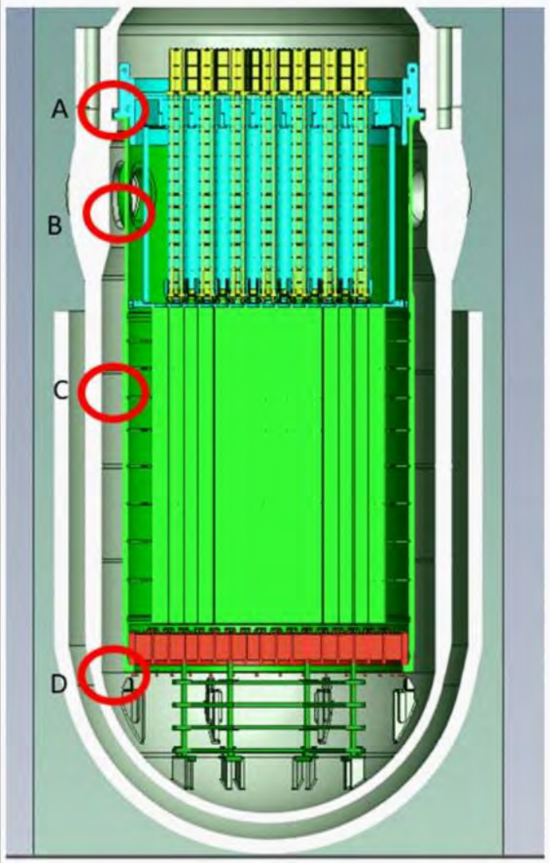
PWR

Vessel thickness: 495 mm
Thickness of component: 75 mm
Distance: 60 mm

Vessel thickness: 495 mm
Thickness of component: 45 mm
Distance: 90 mm

Vessel thickness: 243 mm
Thickness of component: 45 mm
Distance: 380 mm

Vessel thickness: 141 mm
Thickness of component: 30 mm
Distance: 380 mm



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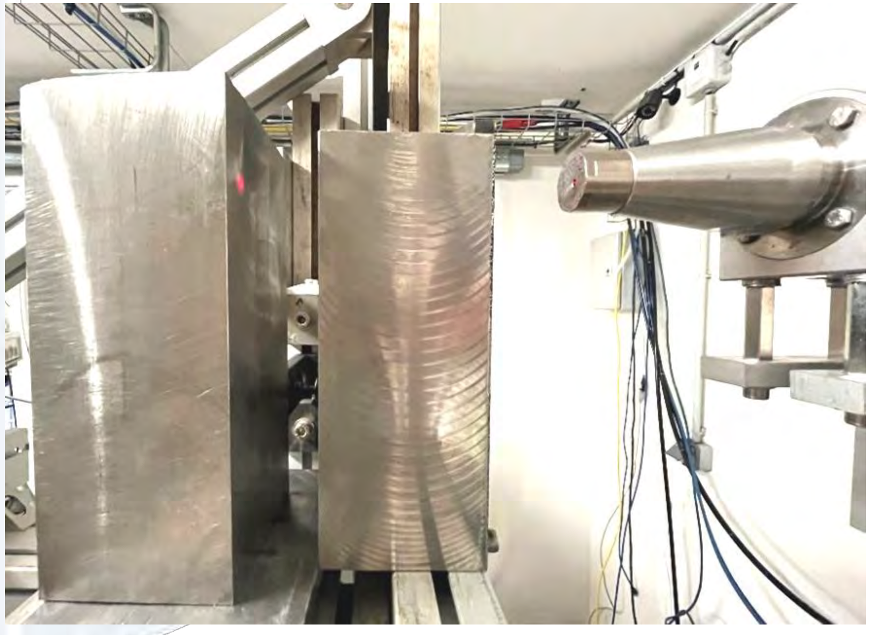
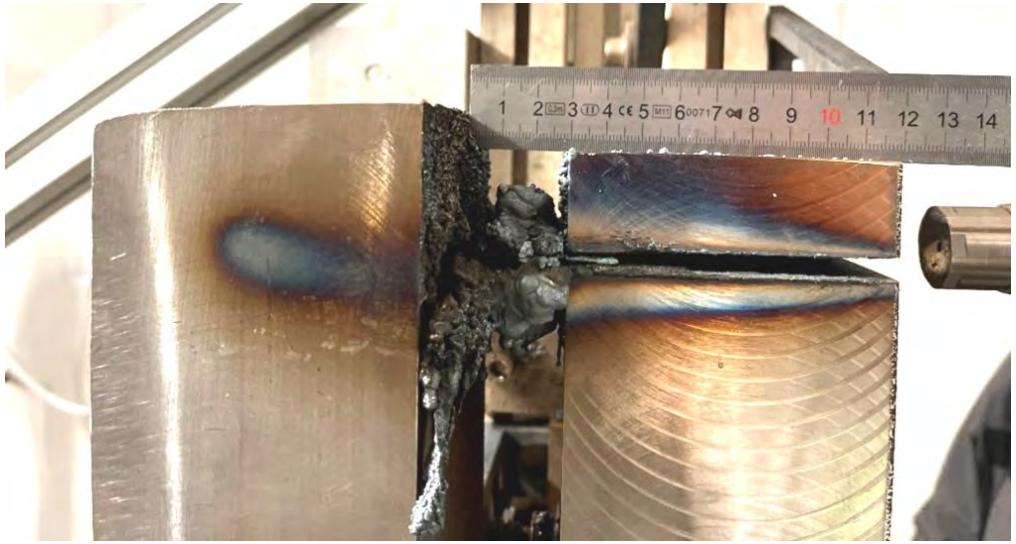
Impact of residual laser beam
Most challenging configuration

In-air laser cutting tests in CELENA facility – Assessment of background potential damage for the most challenging cases of pressurized water and boiling water reactors as defined by WP1.





Configuration BWR-B
- o P = 8 kW, 304L, **v = 1cm/min**
- o Background & workpiece thickness – 80 mm
- o Background distance – 30 mm

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Impact of residual laser beam

Most challenging configuration

In-air laser cutting tests in CELENA facility - Assessment of background potential damage for the most challenging cases of pressurized water and boiling water reactors as defined by WP1.

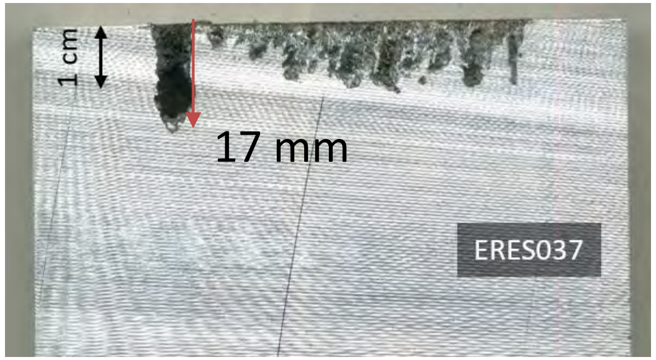
Approach distance impact

Configuration BWR-B (configuration with the smallest background distance)

- P = 8 kW, 304L, **v = 1cm/min**
- Background & workpiece thickness - 80 mm
- Background distance - 30 mm

Approach distance = 10 mm

Approach distance = tangent



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Impact of residual laser beam

Most challenging configuration

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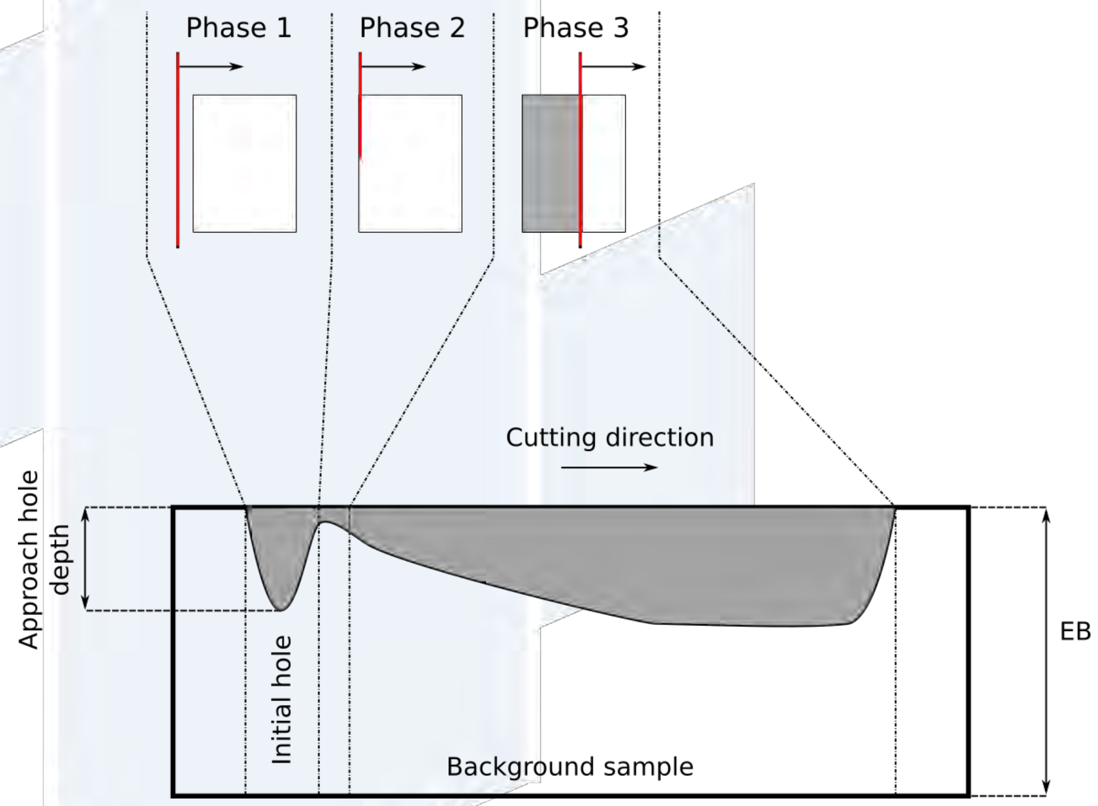
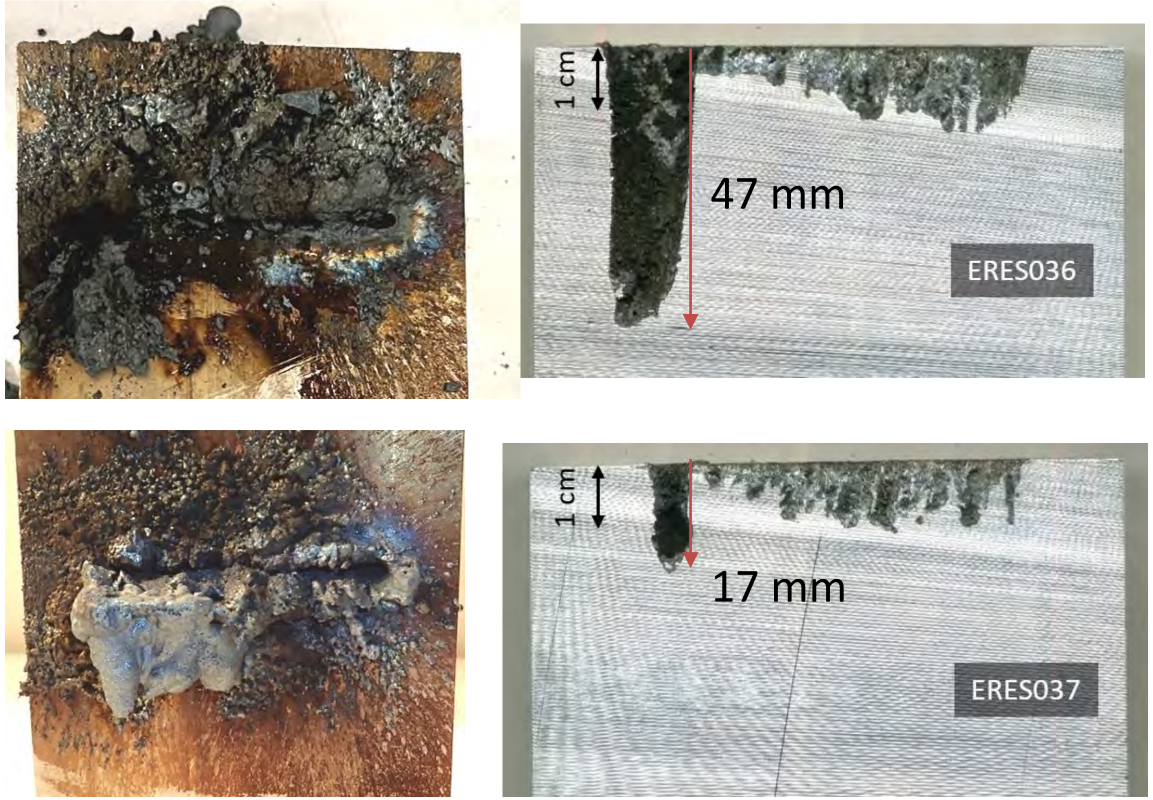
Approach distance impact





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Impact of residual laser beam

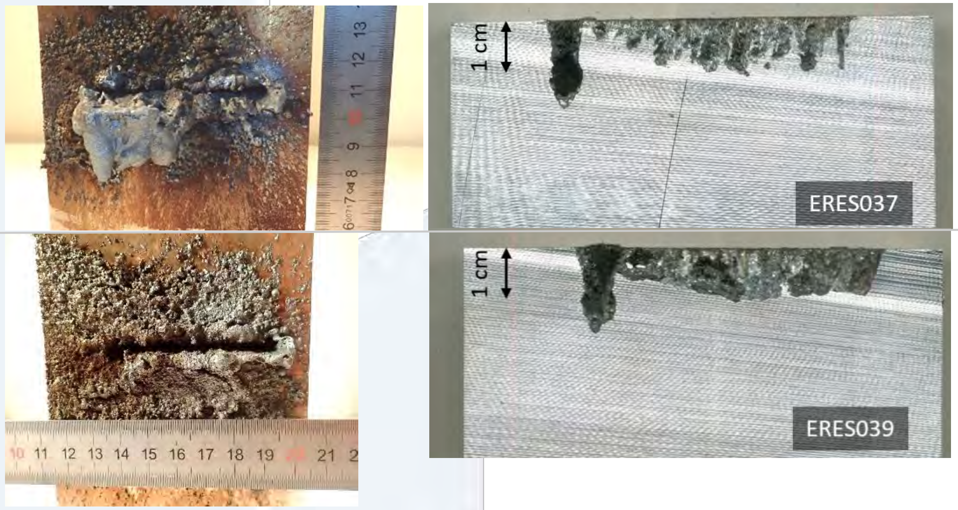
Most challenging configuration

In-air laser cutting tests in CELENA facility - Assessment of background potential damage for the most challenging cases of pressurized water and boiling water reactors as defined by WP1.

Cutting velocity & background distance influence

Background distance - 30 mm

Background distance - 60 mm



- P = 8 kW, 304L
- **V = 1 cm/min (50 % of cutting speed limit)**
- Background & workpiece thickness - 80 mm

- P = 8 kW, 304L,
- **V = 1,5 cm/min (75% cutting speed limit)**
- Background & workpiece thickness - 80 mm

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Impact of residual laser beam

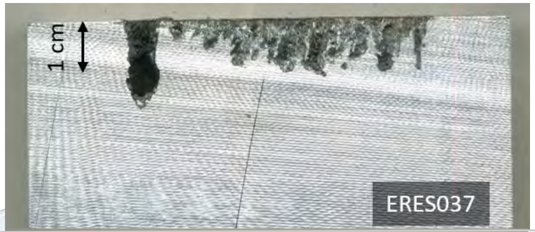
Most challenging configuration

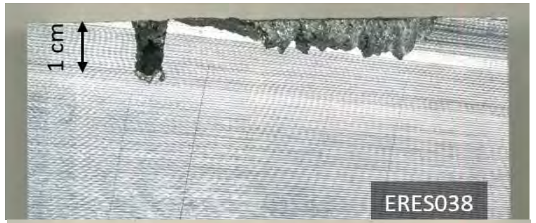
In-air laser cutting tests in CELENA facility – Assessment of background potential damage for the most challenging cases of pressurized water and boiling water reactors as defined by WP1.

Cutting velocity & background distance influence

Background distance – 30 mm

Max. depth kerf = 12 mm

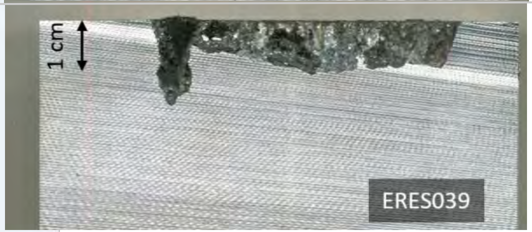




Max. depth kerf = 8 mm

Background distance – 60 mm

Max. depth kerf = 10.5 mm



Max. depth kerf = 6 mm

- P = 8 kW, 304L
- **V = 1 cm/min (50 % of cutting speed limit)**
- Background & workpiece thickness – 80 mm

- P = 8 kW, 304L,
- **V = 1,5 cm/min (75% cutting speed limit)**
- Background & workpiece thickness – 80 mm

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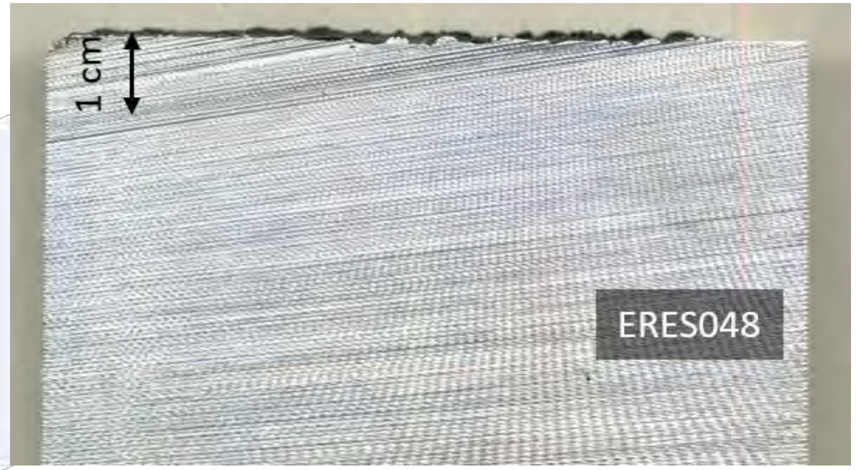
Impact of residual laser beam

Most challenging configuration

In-air laser cutting tests in CELENA facility - Assessment of background potential damage for the most challenging cases of pressurized water and boiling water reactors as defined by WP1.

Cutting velocity & background distance influence



Configuration PWR-C

- P = 8kW, 304L, v = 3.7 cm/min
- Workpiece thickness - 50 mm
- Background distance - 380 mm

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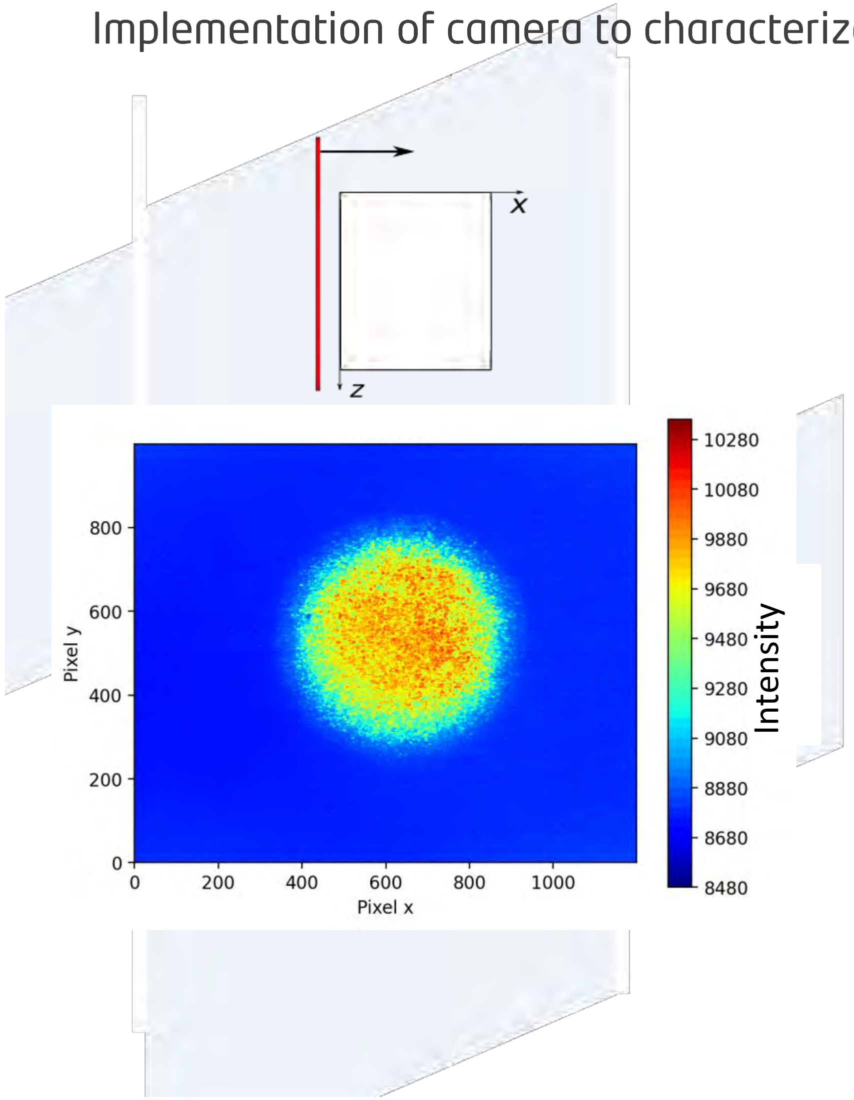
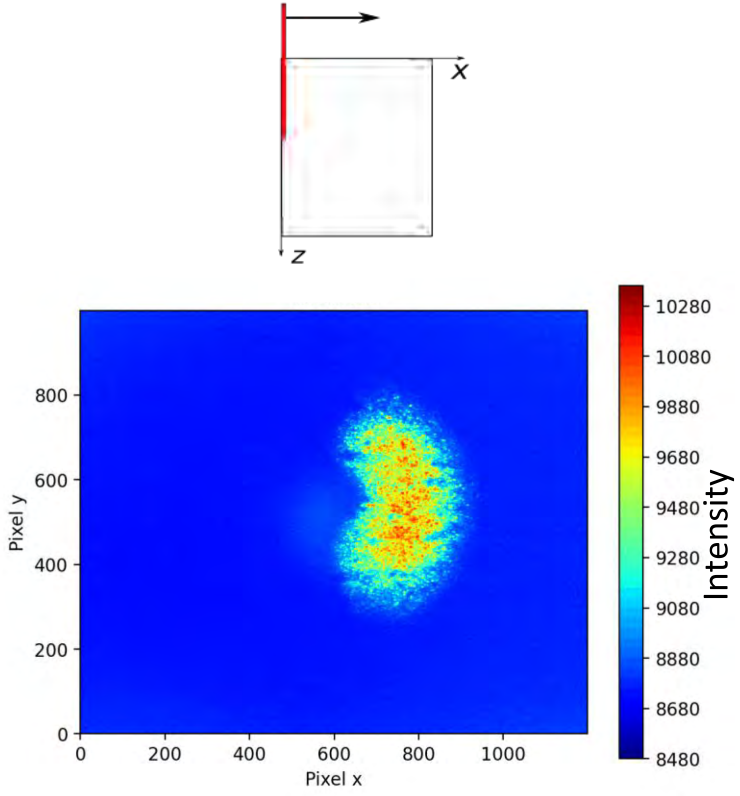
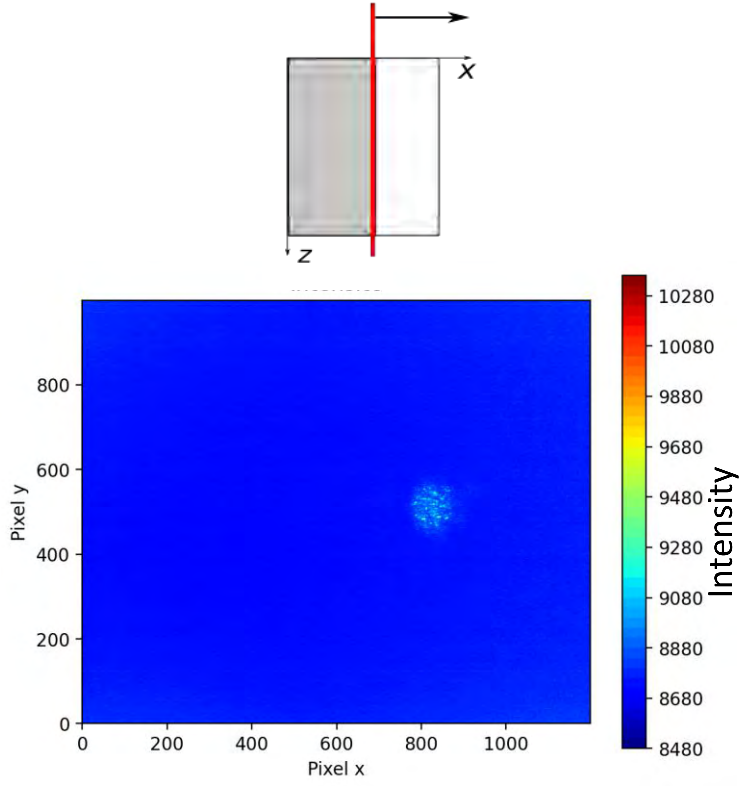
Residual laser beam

Characterization

Implementation of camera to characterize residual laser beam and measure power during cutting operation.







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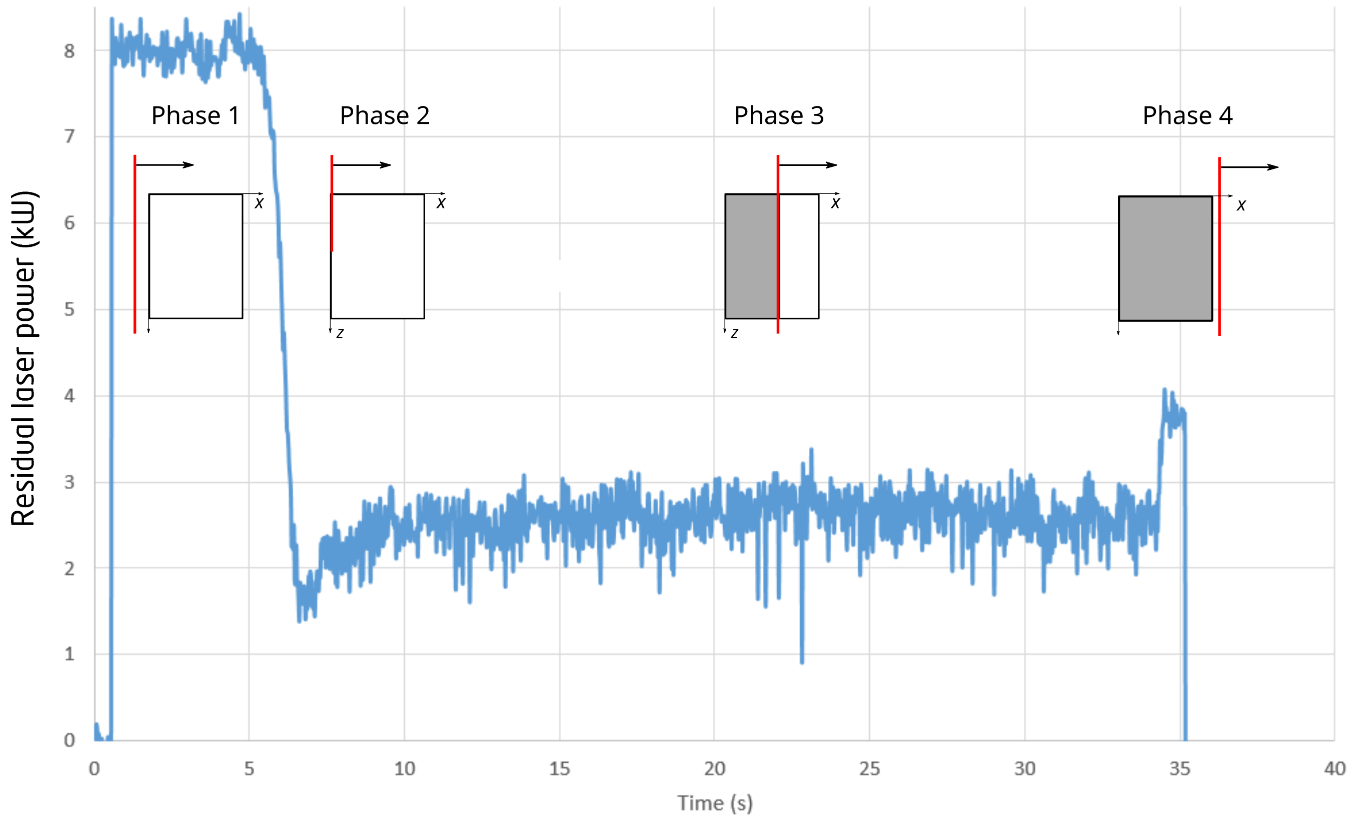
Residual laser beam

Characterization

Implementation of camera to characterize residual laser beam and measure power during cutting operation.

Cutting parameter

- o P = 8 kW
- o **V = 1,8 cm/min**
- o Workpiece (304L) - 80 mm
- o Background distance - 1500 mm



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Residual laser beam

Characterization

Design of experiment varying :

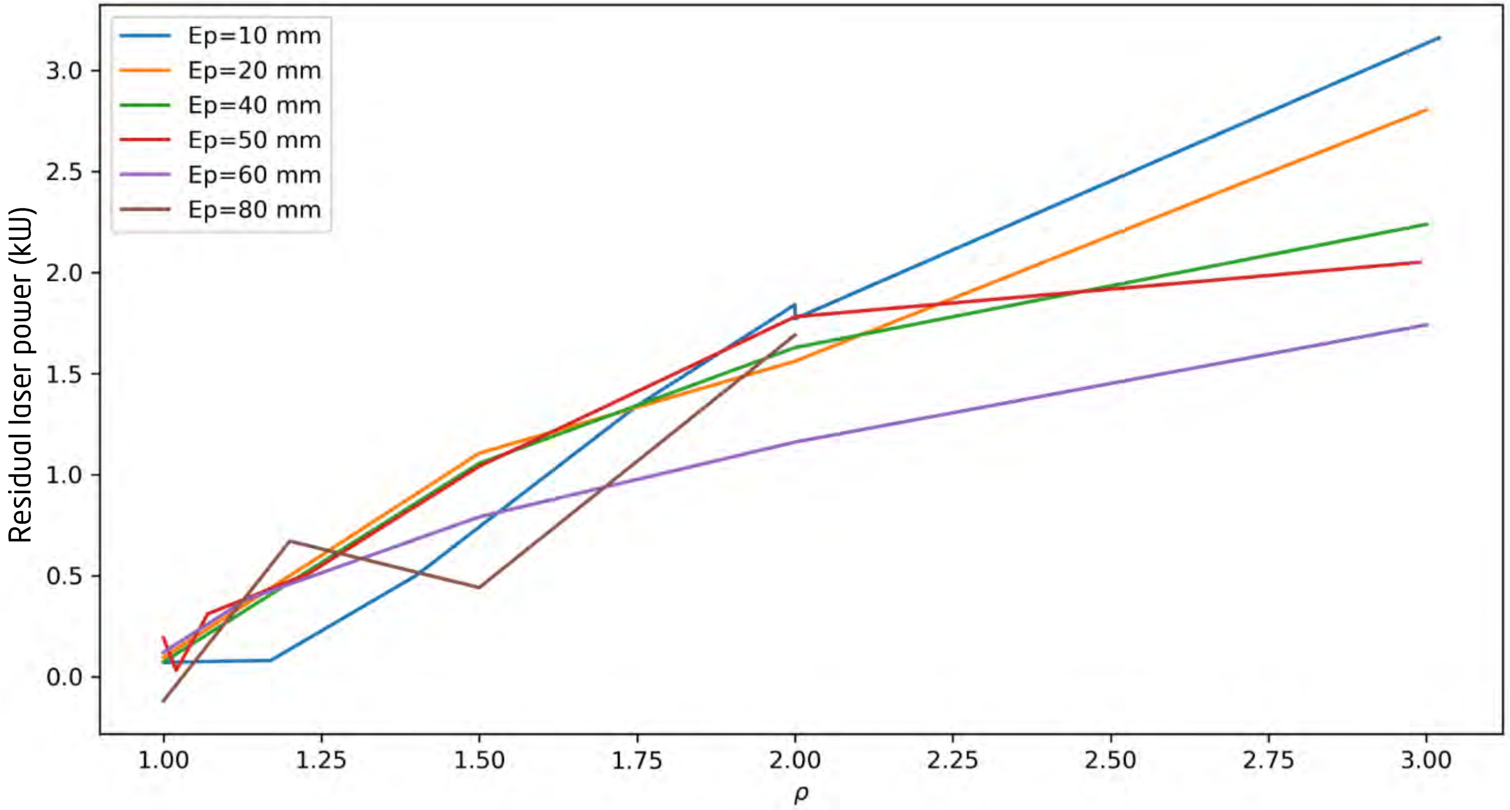
- Laser power: 6 and 8 kW
- Thickness cut: 10 to 80 mm
- Dimensionless cutting speed parameter 1 to 3

$$\rho = \frac{V_{lim}}{V}$$

Results

- High impact of the cutting : reducing cutting speed significantly increases residual laser power

Residual laser power (kW) as function of dimensionless cutting speed parameter ρ varying thickness cut



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Residual laser beam

Impact assessment

Objective: study impact of cutting parameters on impact of the residual laser power and acquiring experimental data.

Experimental setup with multiparametrics study

- Laser power: 8 to 16 kW
- Thickness to cut: 10 to 80 mm
- Background thickness: 10 & 20 mm
- Background distance: 0.5 & 1 m
- Dimensionless parameter: 1 to 2

$$\rho = \frac{V_{lim}}{V}$$

Measurement:

- Temperature
- Maximum depth impact
- Ordinal impact evaluation

Level	Level description
0	No visible impact
1	Thermal marking
2	Melting
3	Hole formed
4	Very deep hole formed
5	Through drilling

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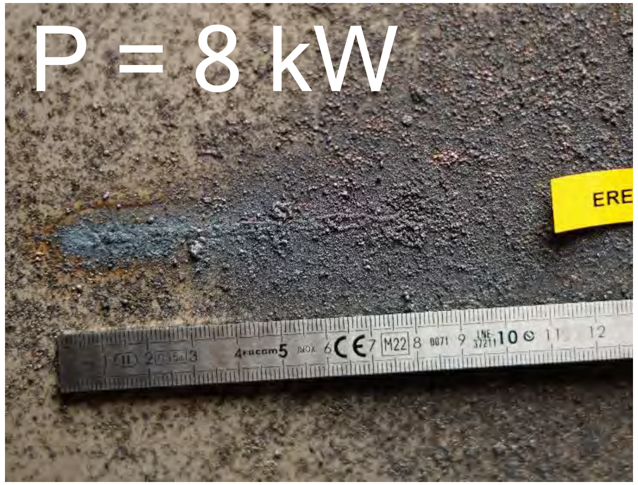
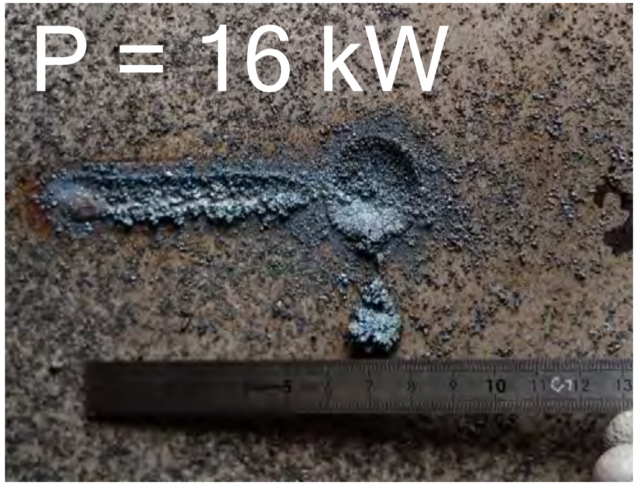
Residual laser beam

Impact assessment

Laser power = 12 kW
Cut thickness = 60 mm
Background thickness = 10 mm
Distance to background = 500 mm

ρ = 1,5
Cut thickness = 40 mm
Background thickness = 10 mm
Distance to the background = 500 mm





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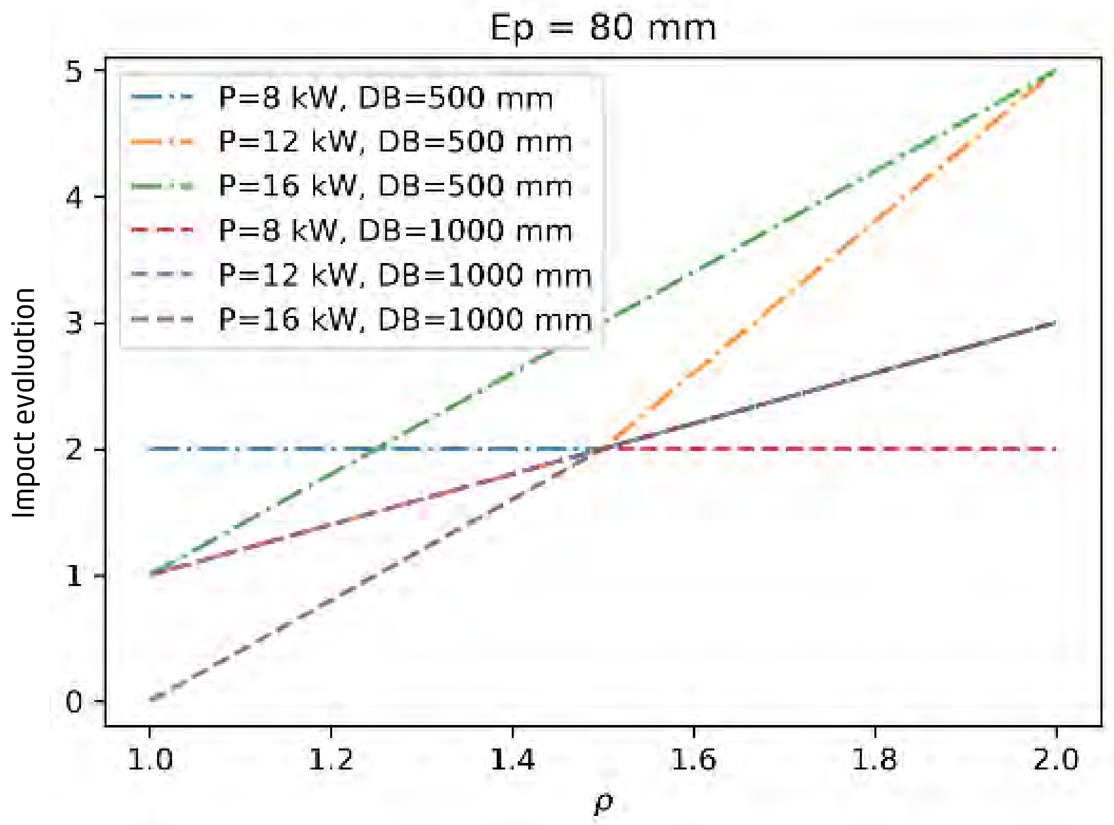
Residual laser beam

Ordinal impact evaluation

Ordinal impact evaluation of the damaged cause by the residual laser beam

Level	Level description
0	No visible impact
1	Thermal marking
2	Melting
3	Hole formed
4	Very deep hole formed
5	Through drilling

Background impact evaluation while cutting a 80 mm thick element



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Residual laser beam

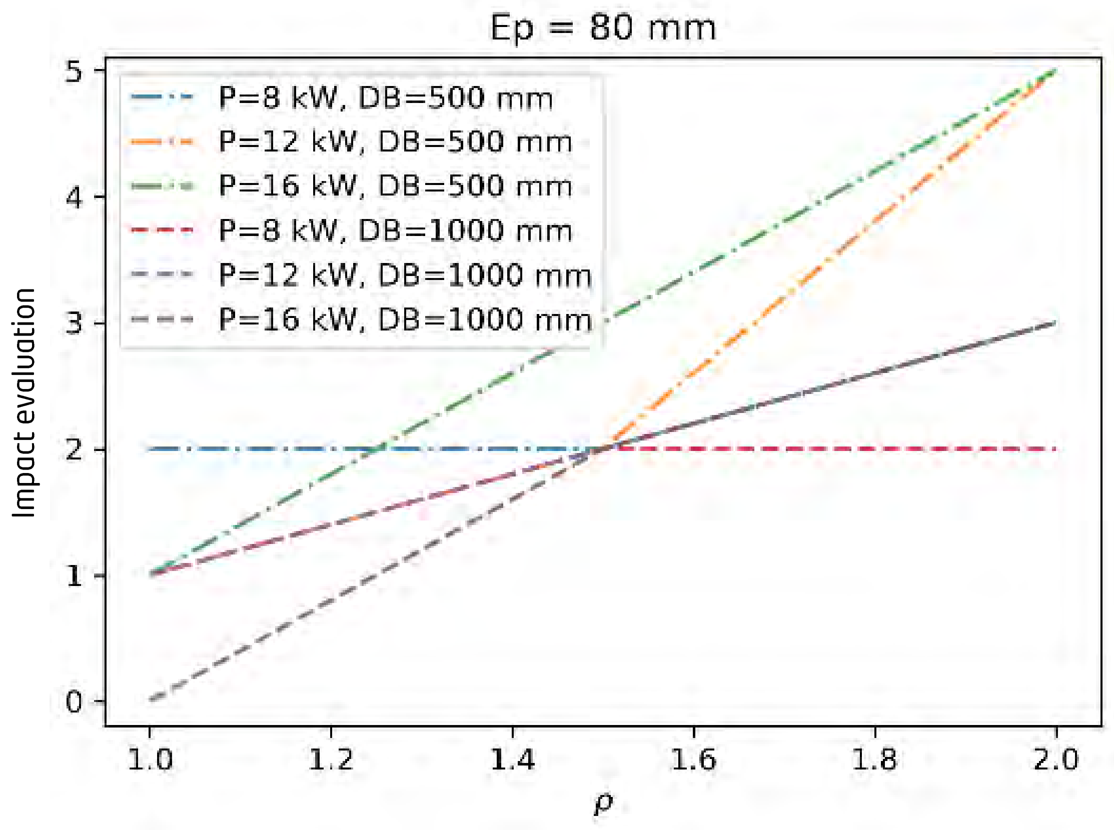
Ordinal impact evaluation

Ordinal logistic regression model to analyze all the data.

- Verifying the signification of this parameters
- The cutting speed is the most import parameter
- Following by the laser power

Variable	Coefficient value
Laser power	0.1163
ρ cutting speed parameter	3.6015
Distance to the background	-0.0030
Thickness cut	0.0411
Tickness of the background	-0.0686

Background impact evaluation while cutting a 80 mm thick element



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Conclusions

Conclusions

- Test on the most critical configurations for PWR and BWR configurations
- Test campaign to characterize the residual laser power and its impact on background structure as a function of process parameters
- Collecting experimental data to create an experimental database that can be used to predict impact

Main results / Countermeasures

- Reduce as much as possible the approach distance
- Optimizing the cutting parameters -> Adapted the cutting speed and the laser power to each case
- Initiation impact -> Uses less laser power during the approach distance

Perspective

- Technological countermeasures should be developed -> devices to be placed in the background
- Increase the range of values for which the parameters can be predicted -> Expand the database with new experiment by adopting a fractional experimental design strategy
- Adapted the operators training

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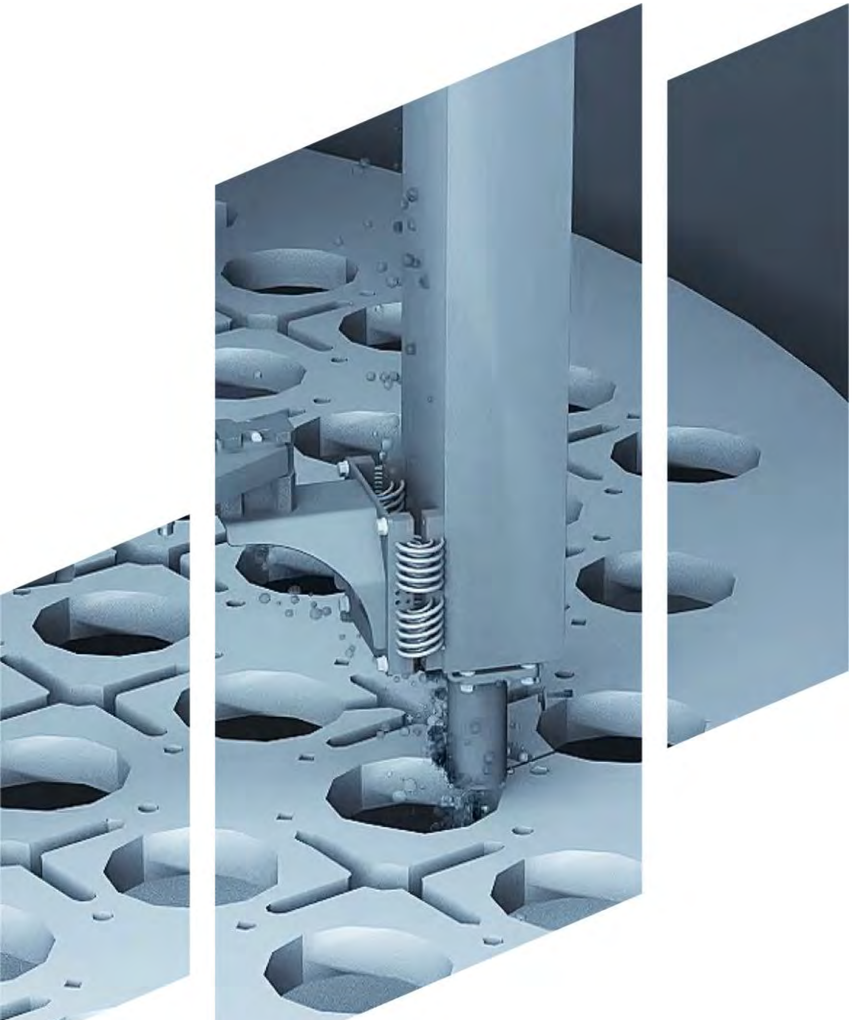

Aerosol characterization during laser cutting

Stéphanie ALAGE[1], Yohan LEBLOIS[1], Emmanuel PORCHERON[1], Célia GUEVAR[2], Véronique TESTUD[2], François SIMON[3], Ioana DOYEN[3], Christophe JOURNEAU[4]

Date: 30/05/2024

(1) IRSN, PSN-RES/SCA
(2) CEA MARCOULE, DES/ISEC/DMRC/SASP/LMAT
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(4) CEA IRESNE, DES/LEAG

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

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OBJECTIVES

LD-SAFE project

- Showcase the effective operation of laser cutting technologies underwater and in gas atmosphere, in addressing the challenges of dismantling nuclear reactor components
- Ensure the safety of the workers and the surrounding environment
  - ➢Assessing potential risks and safety issues
  - ➢Developing optimal measure to mitigate such risks

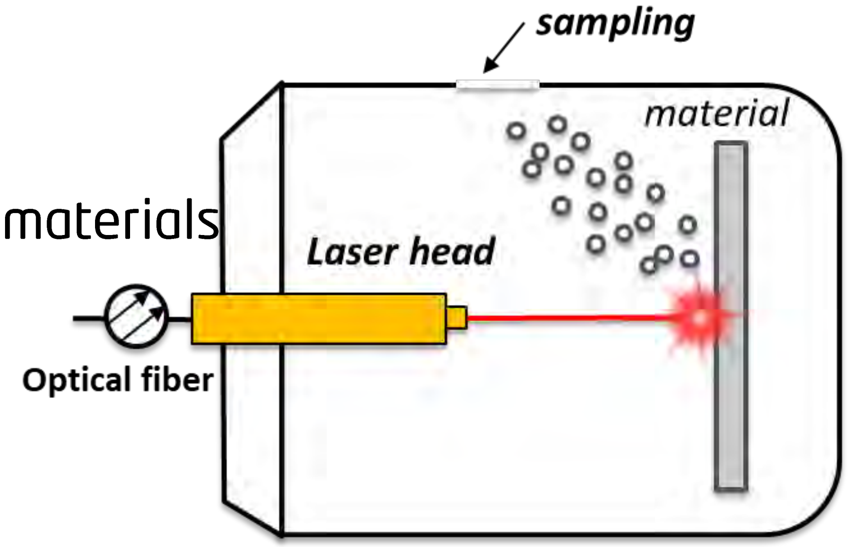
Task

Evaluate key parameters during laser cutting of representative materials

2.1- Laser beam residual power ;

2.2- Generation of aerosols ;

2.3- Hydrogen gas generation during underwater laser cutting ;



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CONTEXT

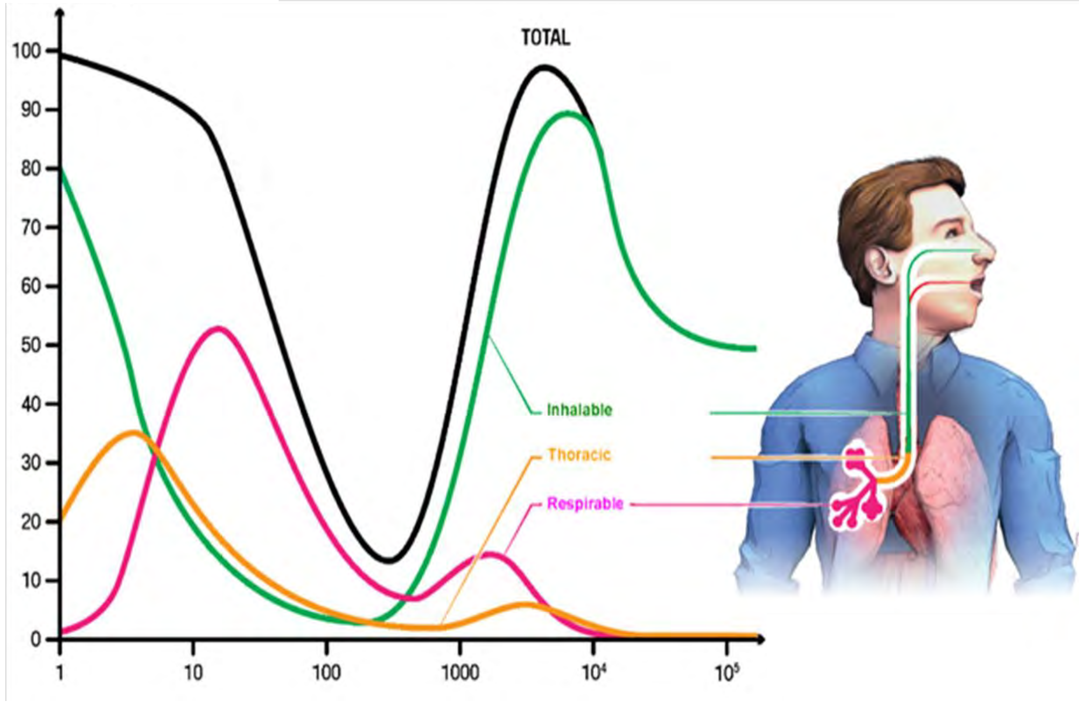
Airborne aerosols size < 10 µm

Aerosols = particles in suspension within a gaseous medium

- Dismantling activities of a nuclear power plant : generate **radioactive** and **non-radioactive** aerosols
- Key aerosol properties for exposure assessment :

- Aerosols size
- Mass and number concentrations
- Morphology
- Chemical composition

Deposited fraction (%)



Particle aerodynamic diameter (nm)

Source :©INRS -Jean-André Deledda/3zigs

Understand the behavior of aerosols and the risks associated with human inhalation and the surrounding environment

➔ *Define the most adapted strategies to mitigate the dispersion of particles*

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LASER CUTTING TRIALS CONDITIONS

- Material cutting: *Stainless-steel 304L / 316*

N 10027 (européenne)	Afnor NF A 35573 (France)	AISI (États-Unis)	Composition							
			% C	% Cr	% Ni	% Mo	% Si	% Mn	% P	% S
X2CrNi18-09 1.4307	Z3CN18-10	304 L	0,02	17 à 19	9 à 11	—	1	2	0,04	0,03
X5CrNiMo18-10 1.4401	Z6CND17-11	316	0,05	16 à 18	10 à 12,5	2 à 2,5	1	2	0,04	0,03

1- **Underwater** condition with air or nitrogen assist gases

2- **Gas atmosphere** condition with air or nitrogen assist gases; with/without humidity

PRINCIPLE OF AEROSOLS SAMPLING LOOP

- **Pegasor PPS-M sensor (P1)**

Time evolution of aerosol mass concentration

- **Low pressure impactor - DLPI (P2)**

Aerosol size distribution (aerodynamic diameter)

- **Sampling filter & sampling grid (P3)**

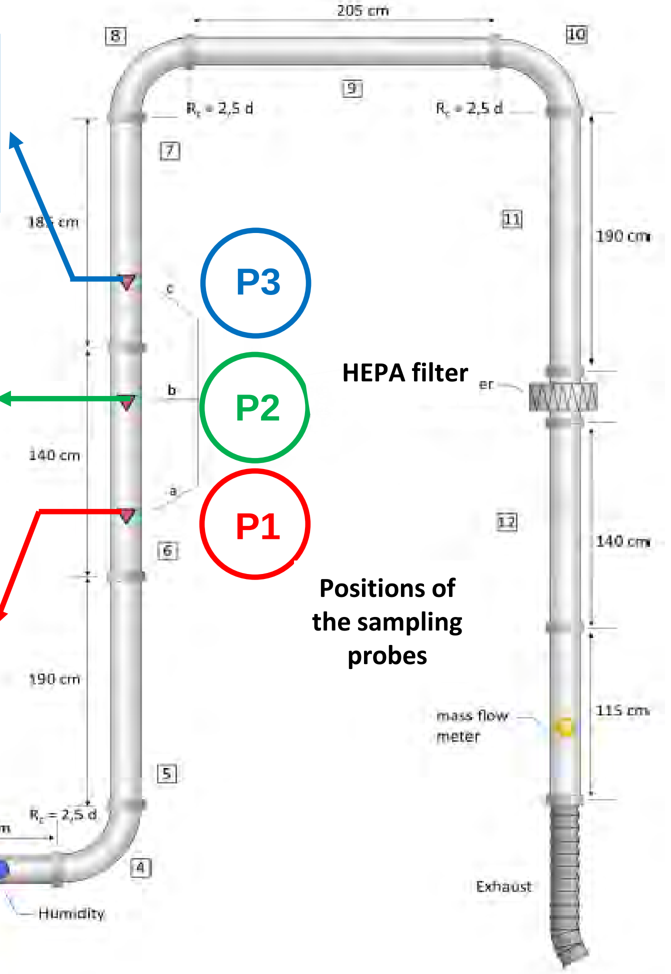
Integrated mass concentration, physico-chemical analysis, aerosol morphology

Particle sampling for TEM & EDS analysis

DELIA facility of CEA

Water collection for post chemical analysis

Sampling line



LD SAFE
Laser Dismantling Environmental and Safety Assessment

TEST GRID FOR UNDERWATER LASER CUTTING TRIALS

~~Failed trial~~

Reference	Test name	Steel	Cutting speed (cm.min^{-1})	Gas	Thickness of cutting (mm)	Length of cutting (estimated) (cm)	Flowrate DELIA (m^3.h^{-1})	Water level (m)
~~LD_W_1~~	~~LD_W_1_304L_Air~~	~~Steel 304L~~	~~2.6~~	~~Air~~	~~40~~	~~8.28~~	~~120~~	~~0.5~~
LD_W_2	LD_W_2_304L_Air	Steel 304L	2.6	Air	40	7.45	120	0.5
LD_W_3	LD_W_3_304L_Air	Steel 304L	2	Air	40	8.67	120	**1.0**
LD_W_4	LD_W_4_304L_Air	Steel 304L	2	Air	40	8.03	120	**1.0**
LD_W_5	**LD_W_5_316_Air**	**Steel 316**	**2**	**Air**	**40**	**8.00**	**120**	**1.0**
LD_W_6	LD_W_6_316_Air	Steel 316	2	Air	40	8.23	120	**1.0**
~~LD_W_7~~	~~LD_W_7_316_N2~~	~~Steel 316~~	~~2~~	~~N2~~	~~40~~	~~18.43~~	~~120~~	~~1.0~~
~~LD_W_8~~	~~LD_W_8_316_N2~~	~~Steel 316~~	~~2~~	~~N2~~	~~40~~	~~0.83~~	~~151~~	~~1.0~~
~~LD_W_9~~	~~LD_W_9_316_N2~~	~~Steel 316~~	~~2~~	~~N2~~	~~40~~	~~1.13~~	~~151~~	~~1.0~~
LD_W_10	LD_W_10_316_N2	Steel 316	0.9	N2	40	2.70	151	**1.0**
LD_W_11	LD_W_11_316_N2	Steel 316	0.9	N2	40	2.97	151	**1.0**
LD_W_12	LD_W_12_304L_N2	Steel 304L	0.9	N2	40	2.88	151	**1.0**
LD_W_13	LD_W_13_304L_N2	Steel 304L	0.9	N2	40	3.87	151	**1.0**

Repeatabilities

Cutting conditions kept constant for trials using one type of assist gas

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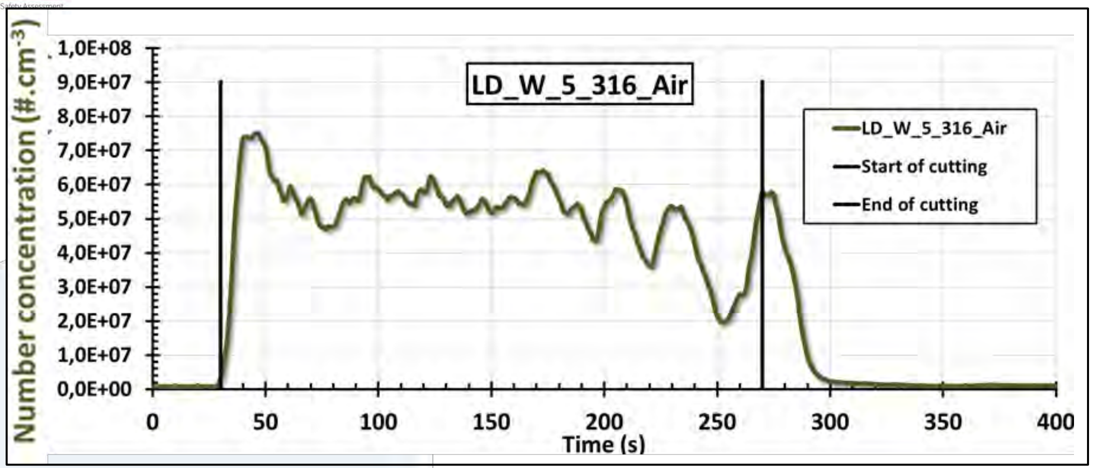
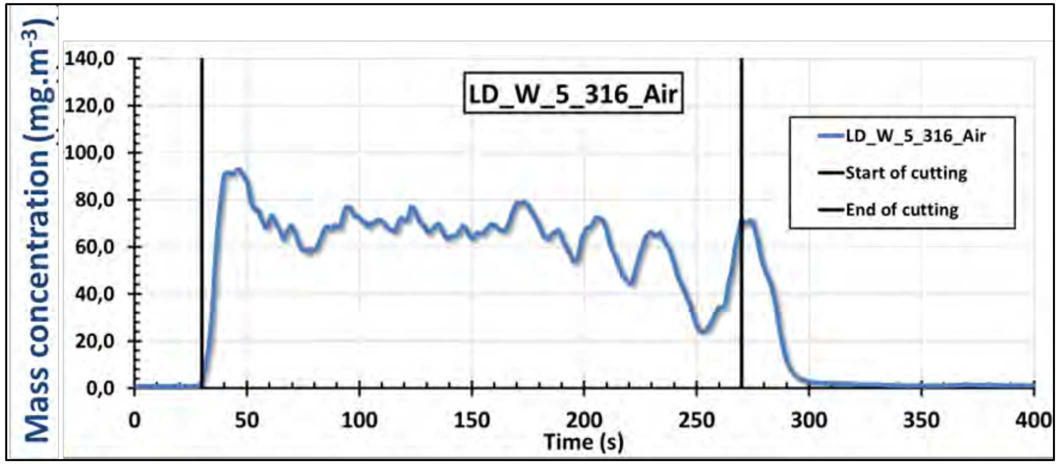
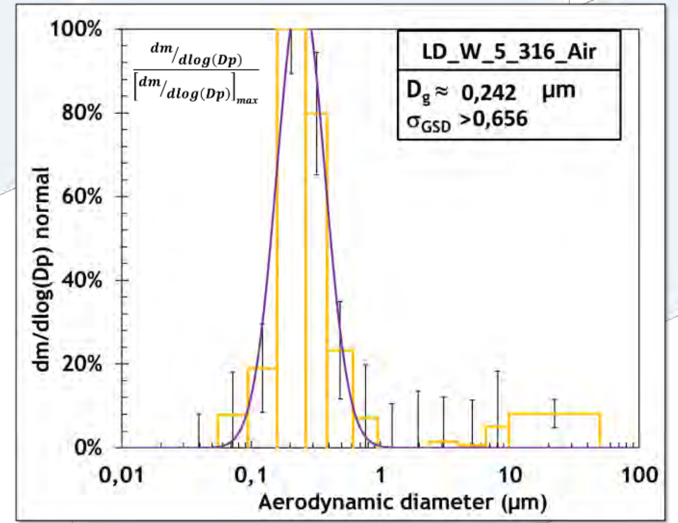
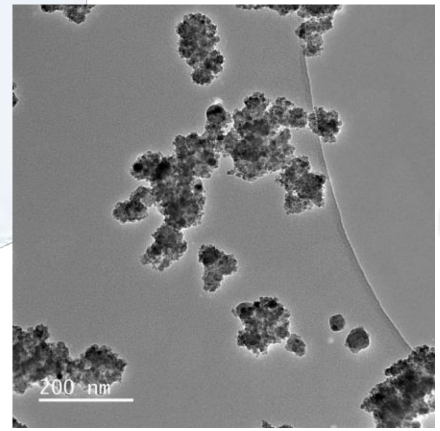
Example of results for underwater trial - LD_W_5_316_Air



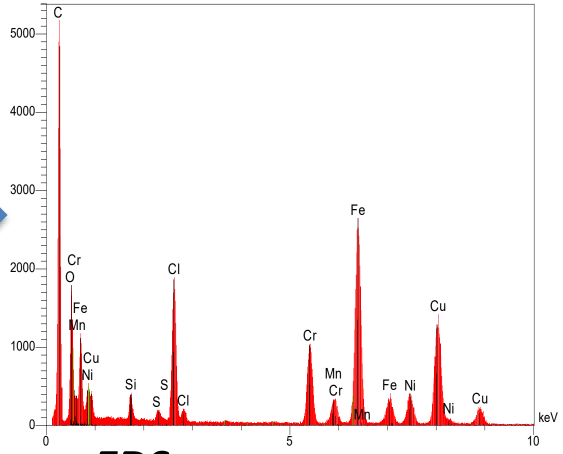




DLPI



TEM



EDS

Name of trial	Mass concentration ($mg.m^{-3}$)
LD_W_5_316_Air	63.14

- Submicronic particles
- Fractal morphology but without well identified structure for primary nano particles due to oxidation process

TEST GRID FOR GAS ATMOSPHERE LASER CUTTING TRIALS

~~Failed trial~~

Reference	Test name	Steel	Cutting speed (cm.min^{-1})	Gas	Humidity (>90%)	Thickness of cutting (mm)	Length of cutting (estimated) (cm)	Flowrate DELIA (m^3.h^{-1})
LD_A_1	LD_A_1_304L_AD	Steel 304L	2	Air	Without	40	10.00	125.4
LD_A_2	LD_A_2_304L_AD	Steel 304L	2	Air	Without	40	9.93	125.4
LD_A_3	LD_A_3_304L_ND	Steel 304L	2	N2	Without	40	8.60	127.0
LD_A_4	LD_A_4_304L_NH	Steel 304L	2	N2	With	40	7.93	127.8
LD_A_5	LD_A_5_304L_AH	Steel 304L	2	Air	With	40	9.00	123.8
LD_A_6	LD_A_6_316_AD	Steel 316	2	Air	Without	40	8.73	126.0
LD_A_7	LD_A_7_316_AD	Steel 316	2	Air	Without	40	9.27	125.4
LD_A_8	LD_A_8_316_AH	Steel 316	2	Air	With	40	9.00	125.4
~~LD_A_9~~	~~LD_A_9_316_ND~~	~~Steel 316~~	~~2~~	~~N2~~	~~Without~~	~~40~~	~~10.40~~	~~127,0~~
LD_A_10	LD_A_10_316_NH	Steel 316	2	N2	With	40	8.53	129.1
LD_A_11	LD_A_11_316_ND	Steel 316	2	N2	Without	40	9.10	129.6

Repeatabilities

Certain cutting conditions kept constant for all trials to study the influence of stainless-steel grade, the choice of the assist gas used, and the presence/absence of humidity.

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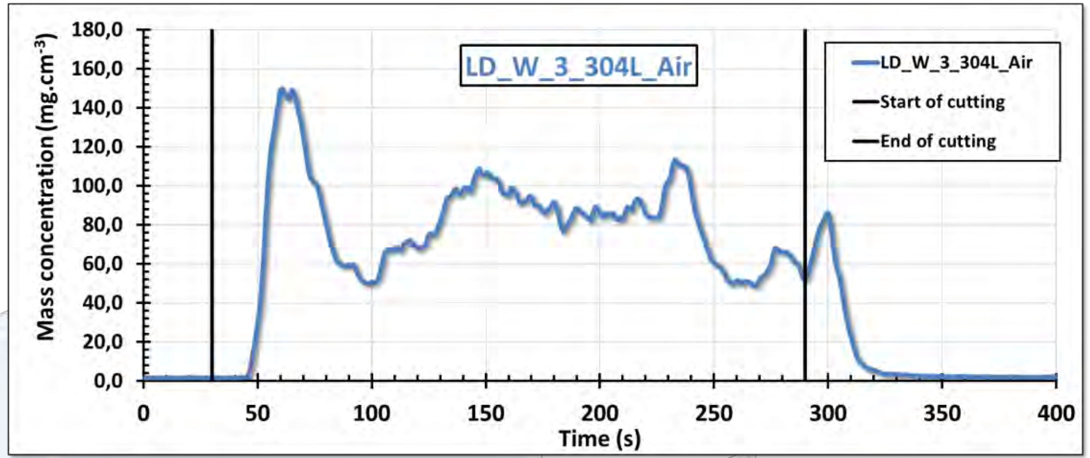
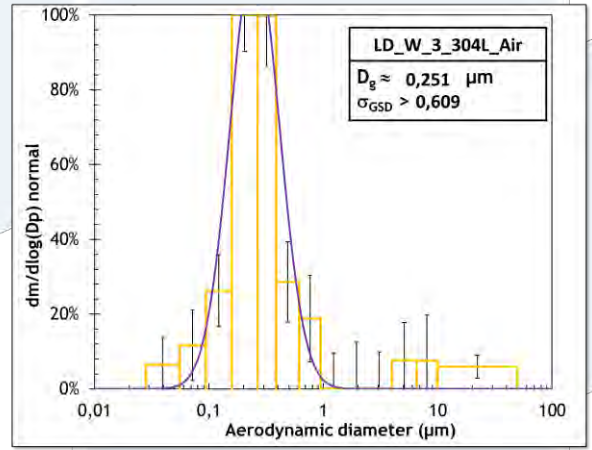
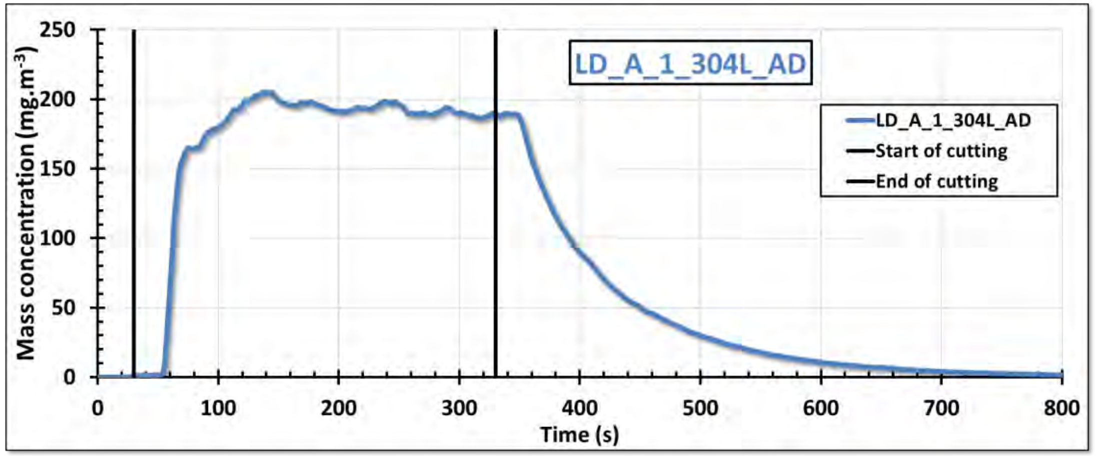
Underwater versus in gas atmosphere laser cutting – Air assist gas (Steel 304L)

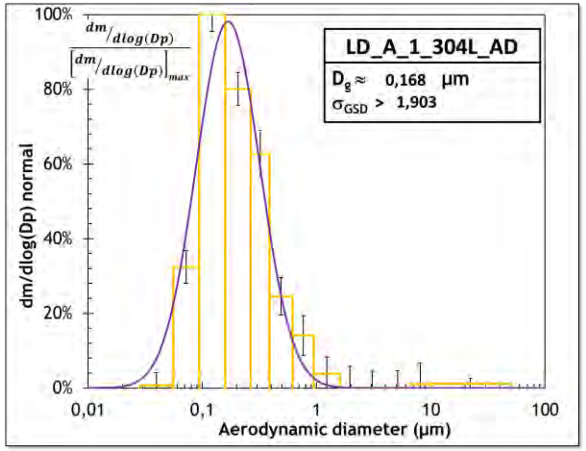
Underwater (1 meter)





Gas atmosphere (Dry condition)





Standard deviation σ_{GSD} reduced by pool scrubbing

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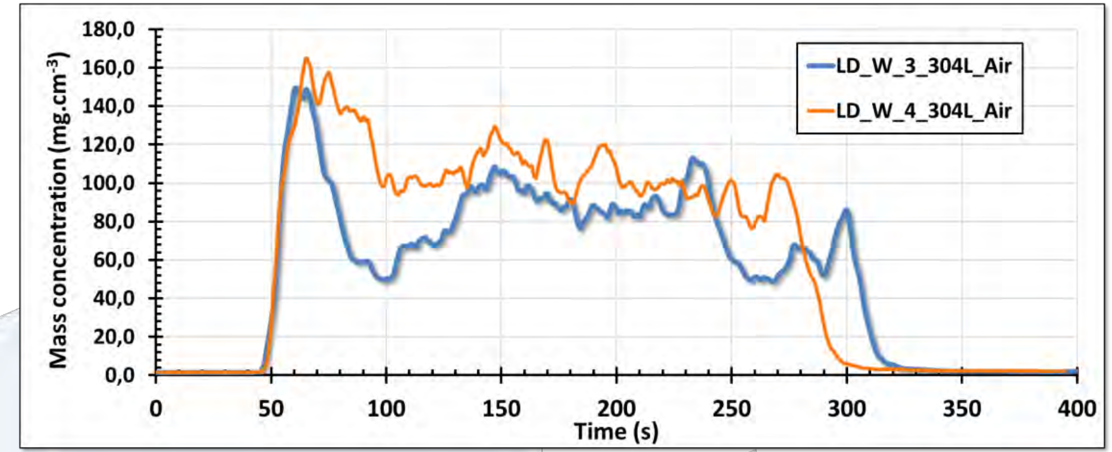
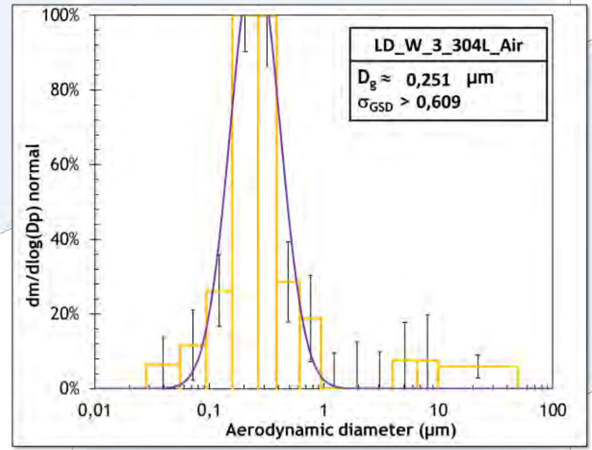
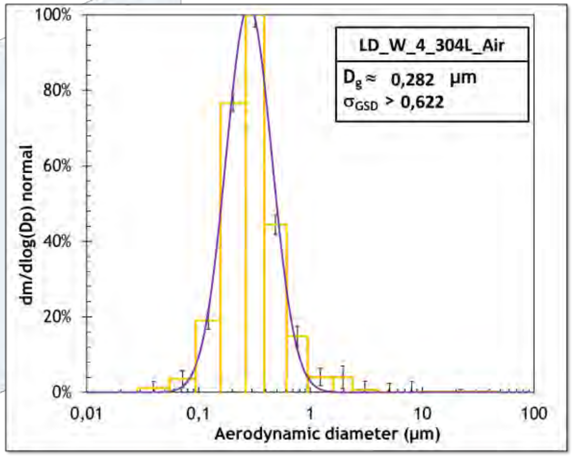
Underwater versus in gas atmosphere laser cutting – Air assist gas (Steel 304L)

Underwater (1 meter)

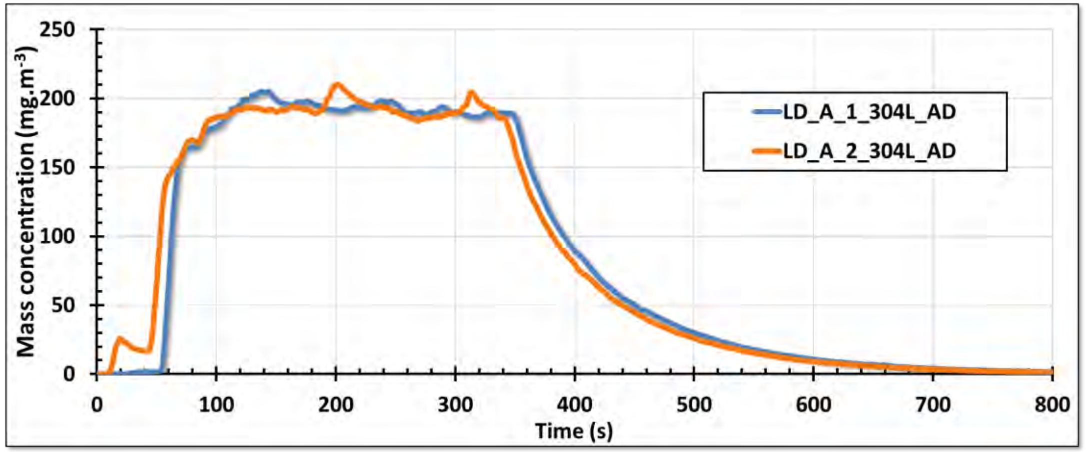


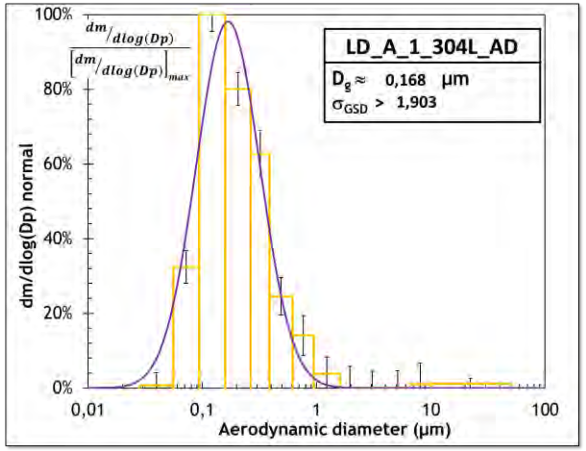


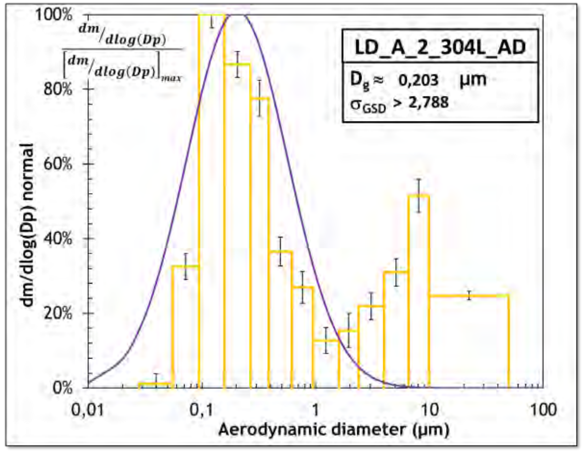


Good repeatabilty

Gas atmosphere (Dry condition)







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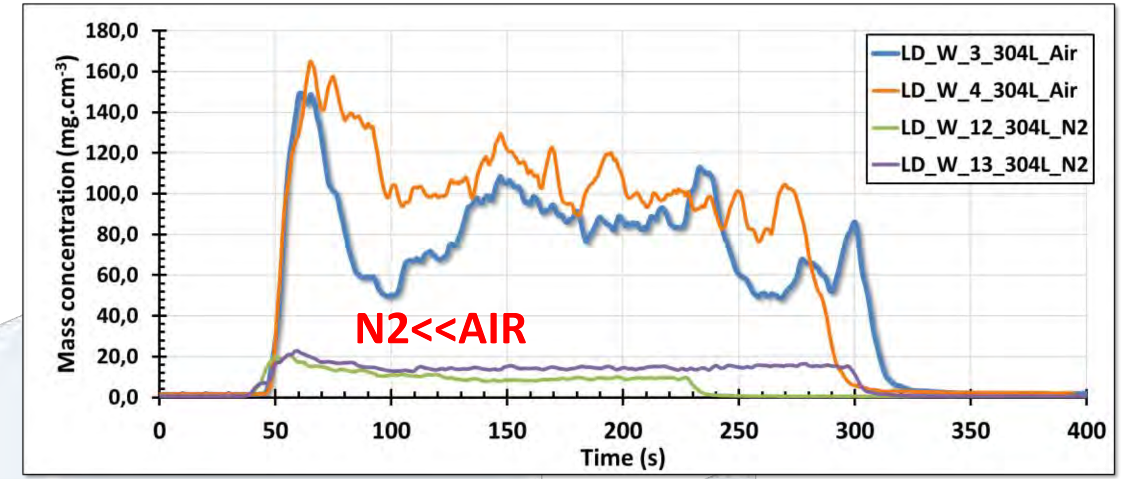
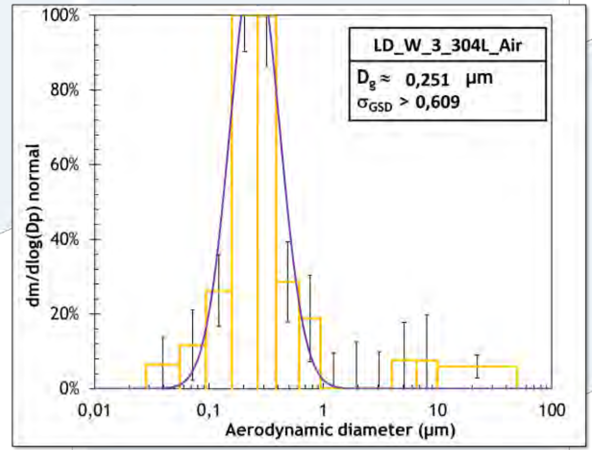
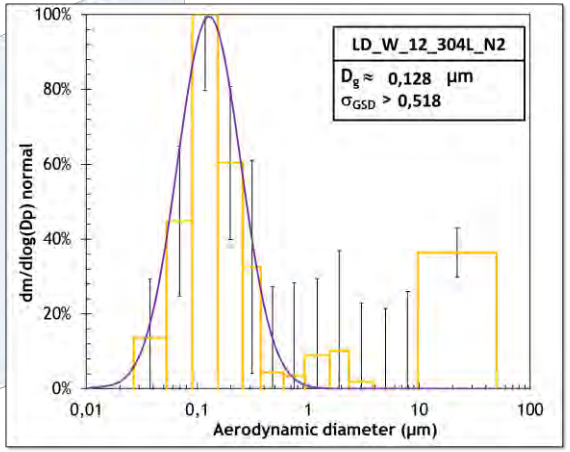
Underwater versus in gas atmosphere laser cutting – Air/N2 assist gas (Steel 304L)

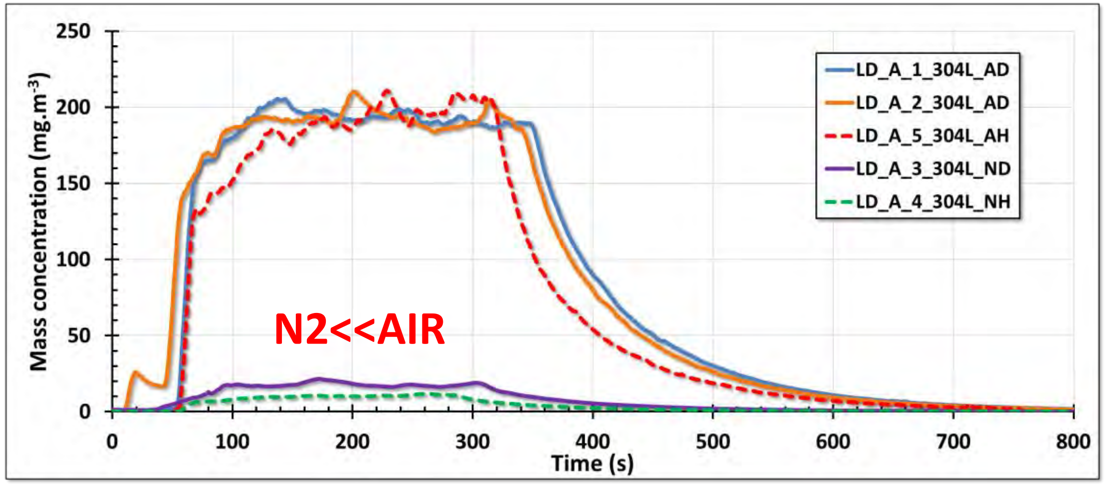
Underwater (1 meter)

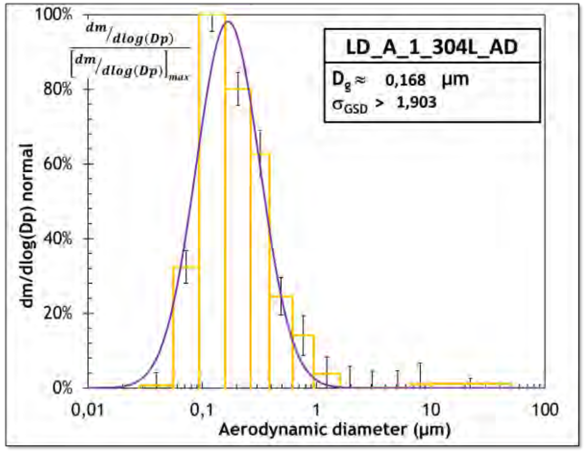


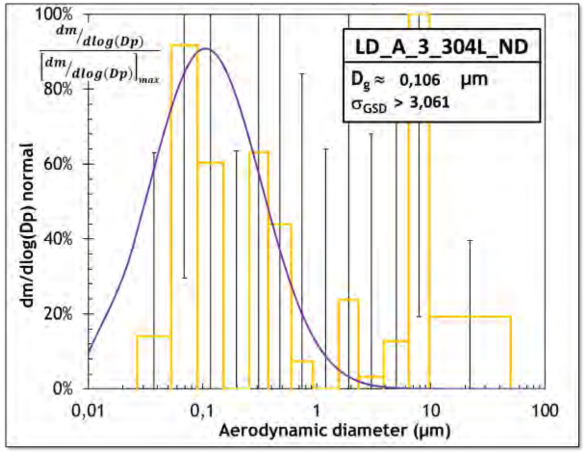




Gas atmosphere (Dry & Humid conditions)







Strong effect of N2 on particles mass concentrations emitted for stainless steel 316

Weak impact of humidity gas atmosphere trials

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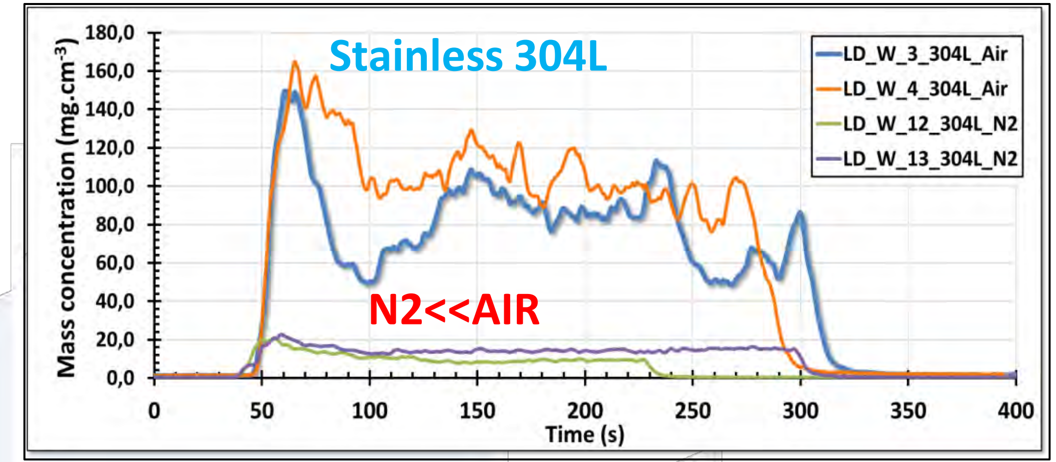
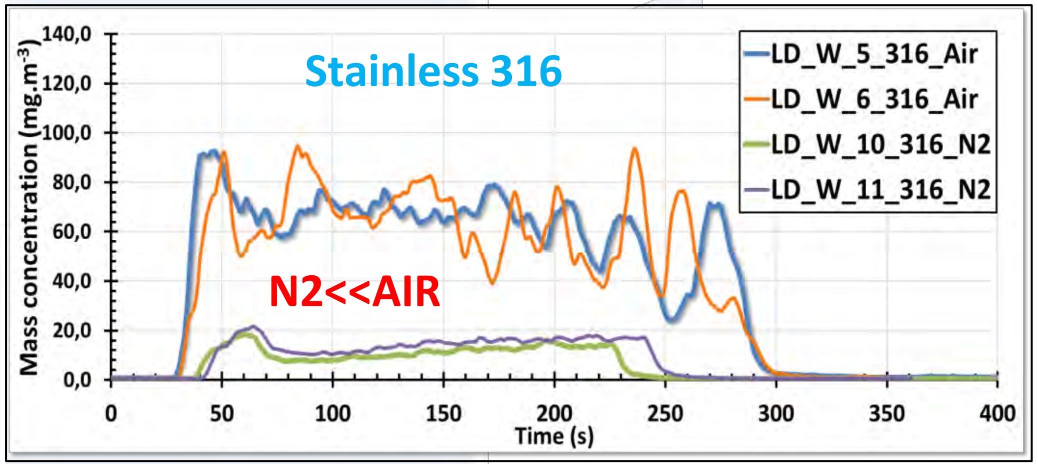
Underwater versus in gas atmosphere laser cutting – Air/N2 assist gases (304L & 316)

Underwater (1 meter)





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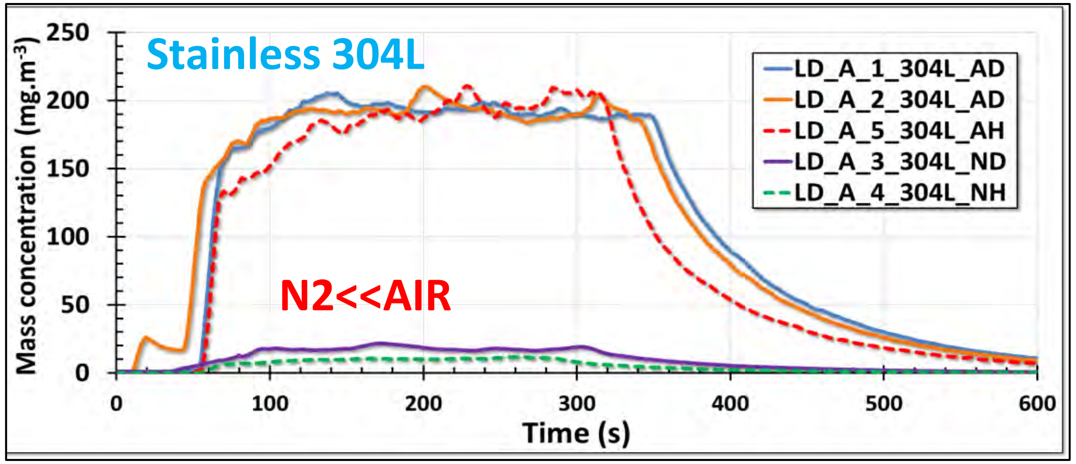

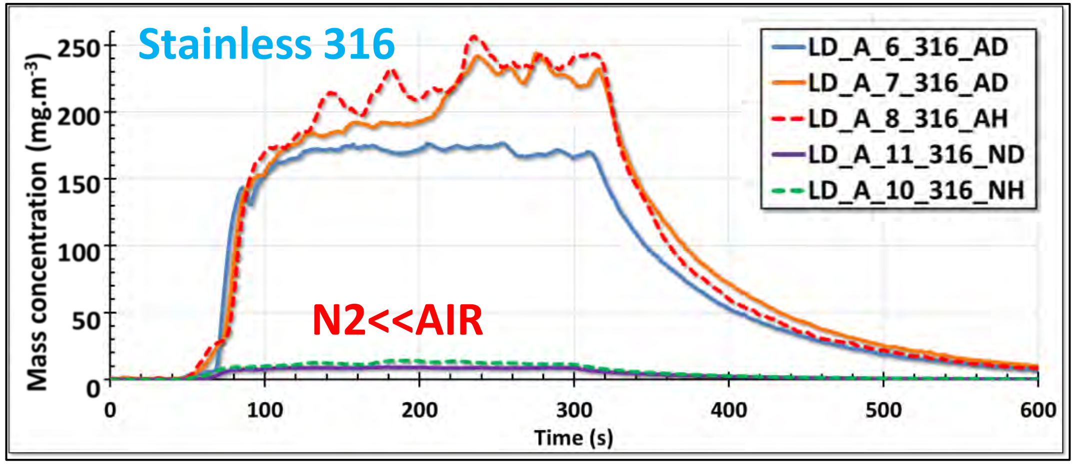

Strong effect of N2 on particles mass concentrations emitted for stainless steels 316 & 304L

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Gathered data for underwater and gas atmosphere laser cutting

Underwater

Trial name	Assist Gas	Particle diameter (nm) / GSD	Mass concentration ($mg.m^{-3}$)
LD_W_2_304L_Air	Air	294 / 1.5	88
LD_W_3_304L_Air	Air	251 / 1.6	93
LD_W_4_304L_Air	Air	282 / 1.6	104
LD_W_5_316_Air	Air	242 / 1.5	68
LD_W_6_316_Air	Air	228 / 1.7	65
LD_W_10_316_N2	N2	137 / 1.9	11
LD_W_11_316_N2	N2	-	14
LD_W_12_304L_N2	N2	128 / 1.9	11
LD_W_13_304L_N2	N2	130 / 1.7	15

Gas atmosphere

Trial name	Assist Gas	Humidity	Particle diameter (nm) / GSD	Mass concentration ($mg.m^{-3}$)
LD_A_1_304L_AD	Air	No	168 / 1.9	193.7
LD_A_2_304L_AD	Air	No	203 / 2.8	192.8
LD_A_3_304L_ND	N2	No	106 / 3.1	17.9
LD_A_4_304L_NH	N2	Yes	110 / 3.3	10.5
LD_A_5_304L_AH	Air	Yes	237 / 1.7	194.2
LD_A_6_316_AD	Air	No	172 / 1.6	171.1
LD_A_7_316_AD	Air	No	185 / 1.8	208.4
LD_A_8_316_AH	Air	Yes	264 / 1.6	173.4
LD_A_10_316_NH	N2	No	112 / 2.9	11.9
LD_A_11_316_ND	N2	No	82 / 3.1	8.8

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Pool scrubbing at 1 m depth reduces by a factor ~ 2 to 3 the mass generation of particles

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Pool scrubbing at 1 m depth reduces by a factor ~ 2 to 3 the mass generation of particles

Stainless-steel 304L yield higher **aerosol size & mass concentration** compared to **stainless-steel 316**

Weak influence of **Stainless-steel grade** on **aerosol size & mass concentration**

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Stainless-steel 304L yield higher **aerosol size & mass concentration** compared to **stainless-steel 316**

Weak influence of **Stainless-steel grade** on **aerosol size & mass concentration**

N2 assist gas reduces aerosol size to ~130nm compared to ~250 nm for **air assist gas** & reduces mass concentration by a factor >5

<->

N2 assist gas reduces aerosol size to ~100nm compared to ~200 nm for **air assist gas** & reduces mass concentration by a factor > 10

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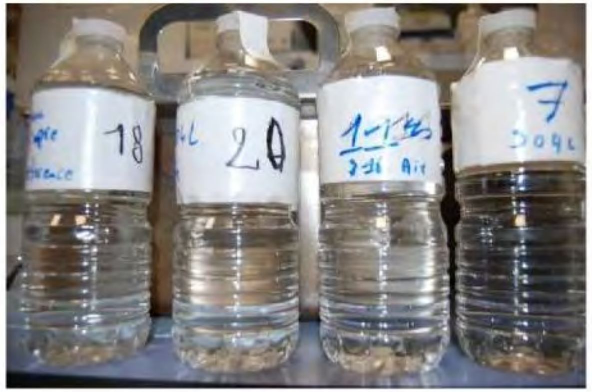
Chemical composition (CEA Marcoule)

Method : ICP-MS (Inductively Coupled Plasma - Mass Spectrometry)

Samples : 1 HEPA filters (all range of particle sizes), 2 DLPI impactor (by range of sizes) & 3 water.

HEPA filter

Aluminium plates (DLPI)



Water samples

Objective : quantifying Fe, Cr, Ni, Mn, Mo, Pb, and Co

Mineralization of aerosol deposits on the samples is conducted prior to ICP analysis

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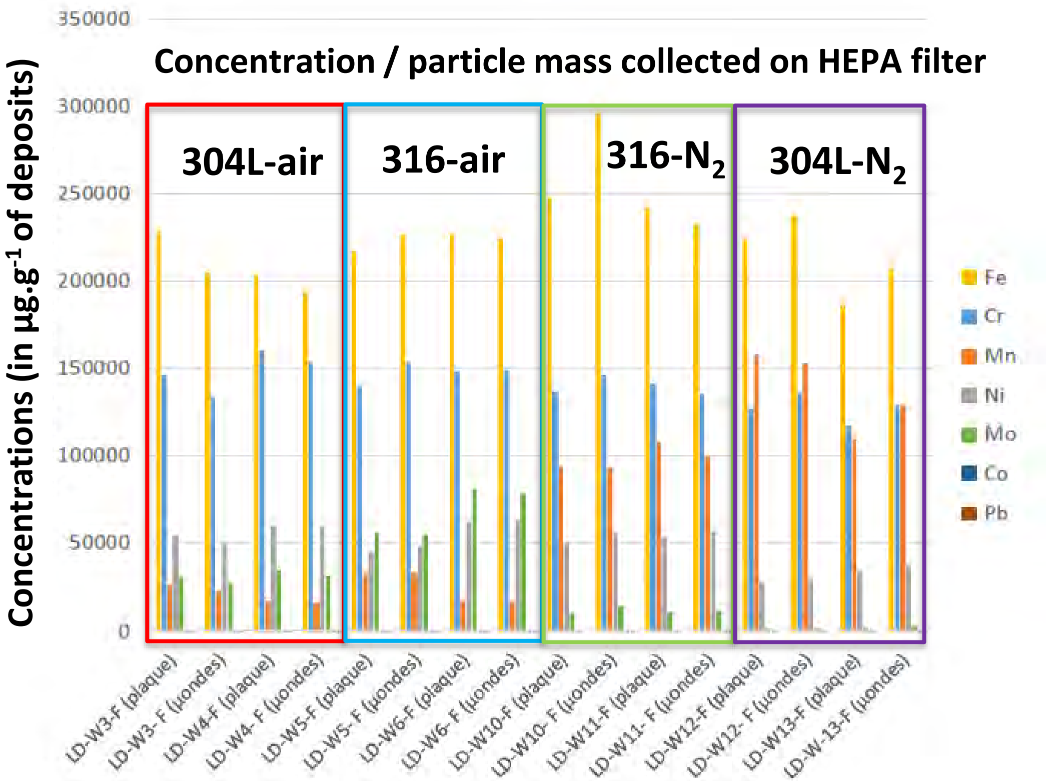
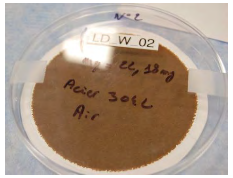
Chemical composition of aerosols collected by HEPA filter for <u>underwater</u> trials

1- Dissolution of the deposits on the filters by 2 methods : *heating plate and µwave reactor*



- Reproductible results (repeatability trials & dissolution methods)
- Main element: Fe & Cr
- **<u>N2 instead of air</u>** :Increase in Mn content & decrease Mo content
- **<u>Cutting of 316 steels</u>** : more Mo than the cutting of 304L
- Cobalt is between 60 to 500 µg/g of collected particles

Type	Reference	Test name	Fuel debris simulant	Gas	Water height (m)
Under water	LD_W_3	LD_W_3_304L_Air	Steel 304L	Air	1
	LD_W_4	LD_W_4_304L_Air			
	LD_W_5	LD_W_5_316_Air	Steel 316		
	LD_W_6	LD_W_6_316_Air			
	LD_W_10	LD_W_10_316_N2	Steel 316	Nitrogen	
	LD_W_11	LD_W_11_316_N2			
	LD_W_12	LD_W_12_304L_N2	Steel 304L		
	LD_W_13	LD_W_13_304L_N2			



HEPA filter

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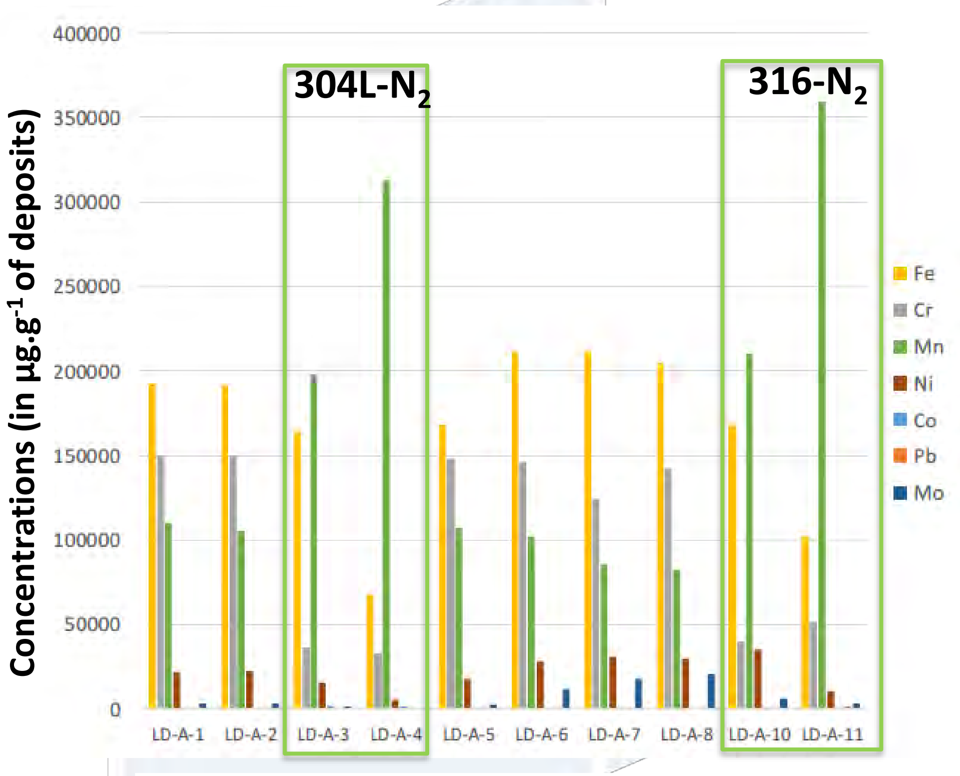
Chemical composition of aerosols collected by HEPA filter for gas atmosphere trials



Type	Reference	Test name	Fuel debris simulant	Gas	Humidity
In a gas atmosphere based on nitrogen or air	LD_A_1	LD_A_1_304L_AD	Steel 304L	Air	No
	LD_A_2	LD_A_2_304L_AD	Steel 304L	Air	No
	LD_A_3	LD_A_3_304L_ND	Steel 304L	Nitrogen	No
	LD_A_4	LD_A_4_304L_NH	Steel 304L	Nitrogen	Yes
	LD_A_5	LD_A_5_304L_AH	Steel 304L	Air	Yes
	LD_A_6	LD_A_6_316_AD	Steel 316	Air	No
	LD_A_7	LD_A_7_316_AD	Steel 316	Air	No
	LD_A_8	LD_A_8_316_AH	Steel 316	Air	Yes
	LD_A_10	LD_A_10_316_NH	Steel 316	Nitrogen	Yes
	LD_A_11	LD_A_11_316_ND	Steel 316	Nitrogen	No

- Reproductible results (repeatability trials)
- **N2 instead of air** : decrease in Cr content but increases in Mn contents
- **316 steels compared to 304L:** higher Mo content
- Cobalt is between 250 to 1600 µg/g of collected particles

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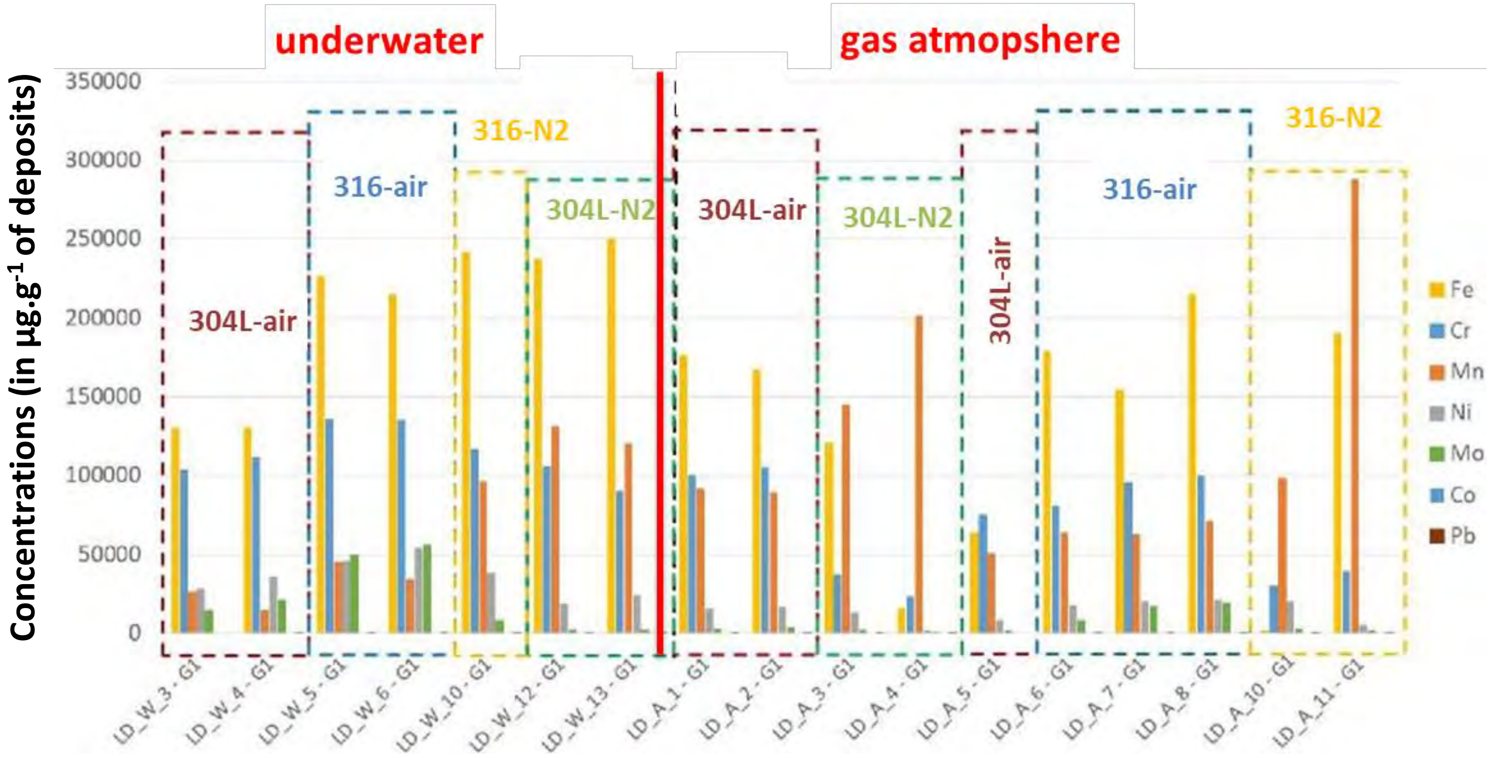
Chemical composition of aerosols collected by impactor plates from G1 for underwater and gas atmosphere trials

Impactor plates	Cut diameter	
1	0,028	Group 1
2	0,055	Group 1
3	0,094	Group 1
4	0,158	Group 1
5	0,265	Group 1
6	0,386	Group 2
7	0,616	Group 2
8	0,950	Group 2
9	1,597	Group 2
10	2,384	Group 2
11	3,979	Group 2
12	6,556	Group 2
13	9,899	Group 2



Mineralization of Aluminium plates

Influence of cutting under 1m of water (compared to cutting under gas atmosphere):

- Under air: decrease in the Mn content / increase in the Ni and Mo contents in the aerosols
- Under nitrogen: decrease in the Mn content / increase in the Fe, Cr and Ni contents in the aerosols

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Conclusion

- Characterization of aerosols emitted in the DELIA facility during laser cutting of two stainless steel grades (304L and 316)

Cutting conditions :

- Underwater or in a gas atmosphere (under dry or humid conditions);
- Air or nitrogen assist gases

Analysis of aerosol physical properties **:**

- The generated airborne particles are submicronic underwater and in gas atmosphere
- A slight increase of particle size for trials underwater compared to those in a gas atmosphere
- A reduction of particle size and particle mass concentration using nitrogen as an assist gas instead of air

Nitrogen as an assist gas presents a compelling interest due to its emission characteristics in terms of particle mass and number

Analysis of particles chemical composition : variation in elements concentrations depending on the cutting conditions

The overall data collected can be used to assess the safety of laser cutting

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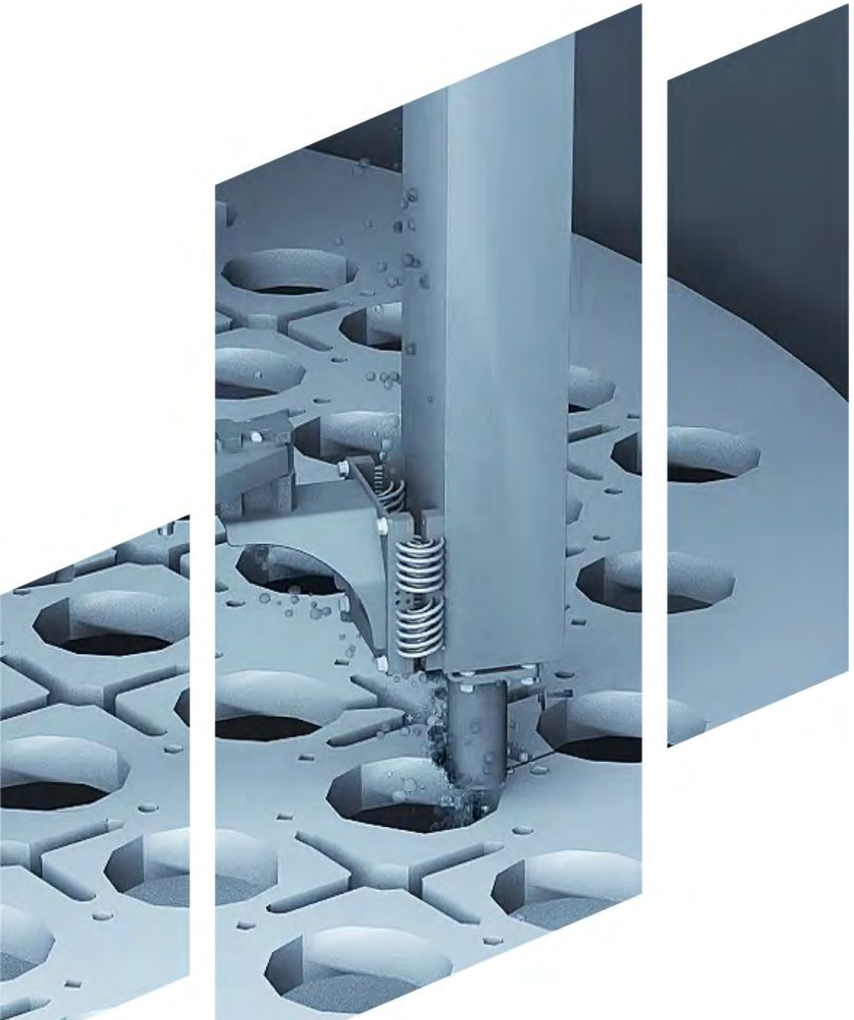


H_2 gas generation during laser underwater cutting

I. Doyen, F. Simon, C. Segarra, S. Pascal, C. Guevar, C. David, P. Piluso

CEA

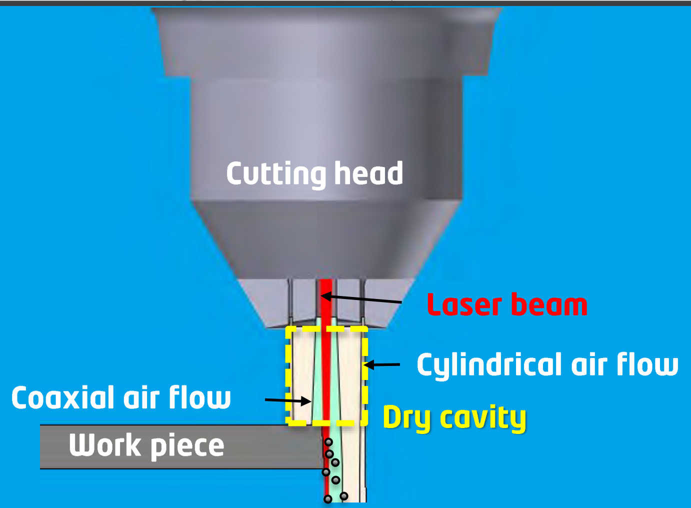
LD-SAFE End Technical Workshop

May 30-31, 2024, ONET Technocenter

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

Context

Laser underwater cutting of metallic structures for dismantling application

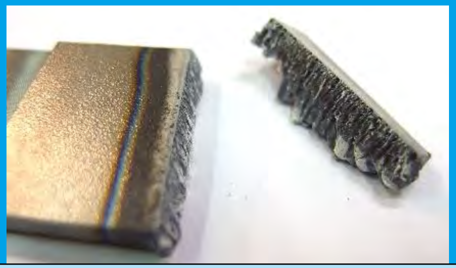


Principle is based on a **dry cavity concept**

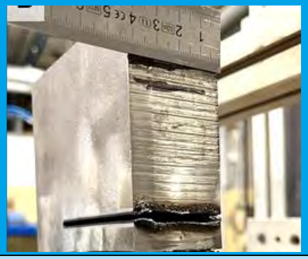
- Reduces interaction of water vapor with molten material & heat-affected zone
- Stability depends on water depth (hydrostatic pressure) and assist gas flow rate
- Generate oxides which tend to clutter the kerf & **dangerous gases : H_2**

Cutting underwater benefits:

- Biological shielding
- Aerosols trapping
- Low impact on background structures due to water absorption at λ_{laser}


30 mm Zr alloy - 8kW, 5.6m water depth

100 mm zirconia - 8kW, 5.6m water depth


316 L - 8kW, 5.6m water depth


304 L, 8kW, 5.6m water depth

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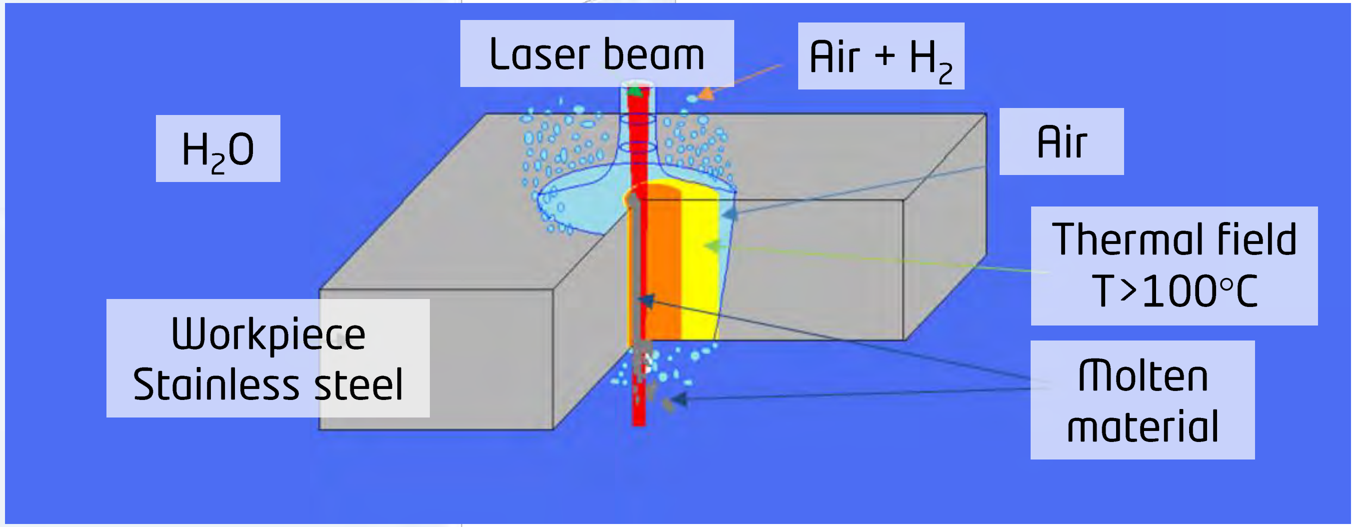
H_2 risk and laser underwater cutting

- Safety issue: Lower Explosive Limit H_2 in air is 4%
- H_2 risk widely study for the case of severe accidents in power nuclear reactor, mostly for the case of Zr at very high temperature and more recently for stainless steel especially for 304L (representative for RVIs)
- One of identified risks for laser cutting technology implementation when cutting metallic structures underwater.
- LD-SAFE consortium decided to focus on 304L stainless steel



$$xMe + y\,O_2 \rightarrow Me_xO_y,$$

$$xMe + y\,H_2O \rightarrow Me_xO_y + yH_2$$

$Me_x = Fe_{x'}Cr_{x''}\,(Si,Mn,Ni,Mo)_{x'''}$

$x = x'+x''+x'''$

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H2 gas generation during laser underwater cutting task

Objectives:

- Evaluate dihydrogen generation during laser underwater cutting of stainless steel
- Provide input data to support safety assessment for implementing laser cutting technology

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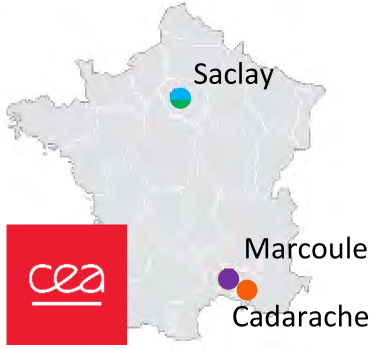
Main activities of the task

Collaborative work: 3 departments and 4 laboratories at CEA involved in this study



Laser underwater tests with real time H_2 monitoring in DELIA Facility

Numerical simulation of H_2 generation (Saclay)

Phisicochemical analyses of workpieces kerf walls after laser underwater cutting (Marcoule)

H_2 study

Design, implementation, operation and maintenance of the conditioning and sampling line for H_2 monitoring (Saclay)

Parametric laws for H_2 production when cutting 304L stainless steel (Cadarache)

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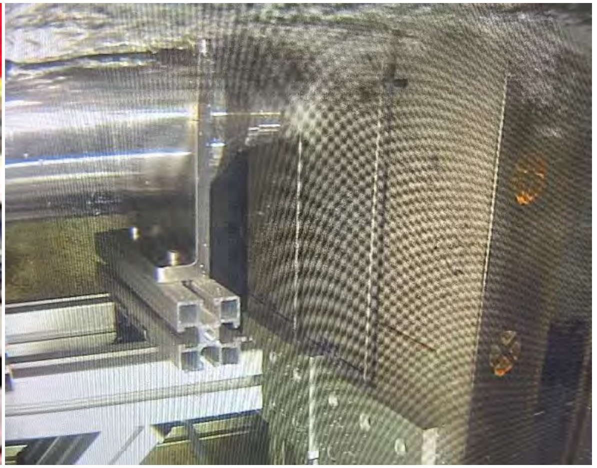
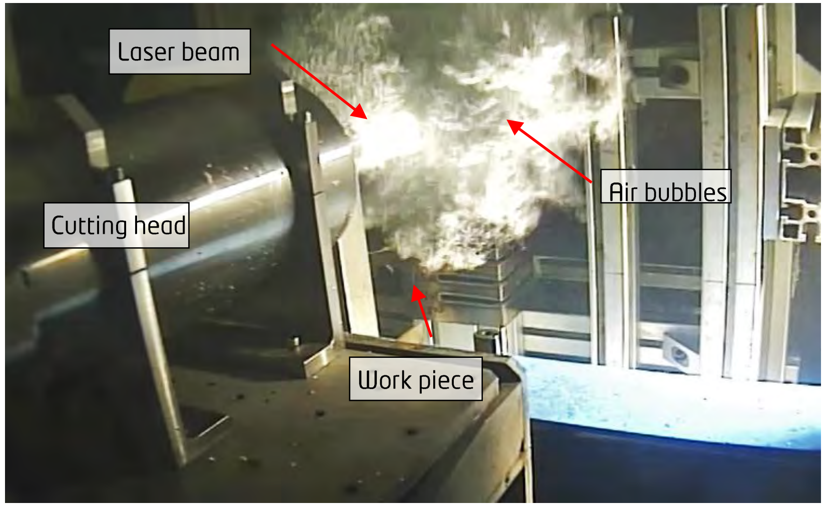
DELIA FACILITY

Laser underwater cutting facility 5 m³, up to 5.6 depth o water.





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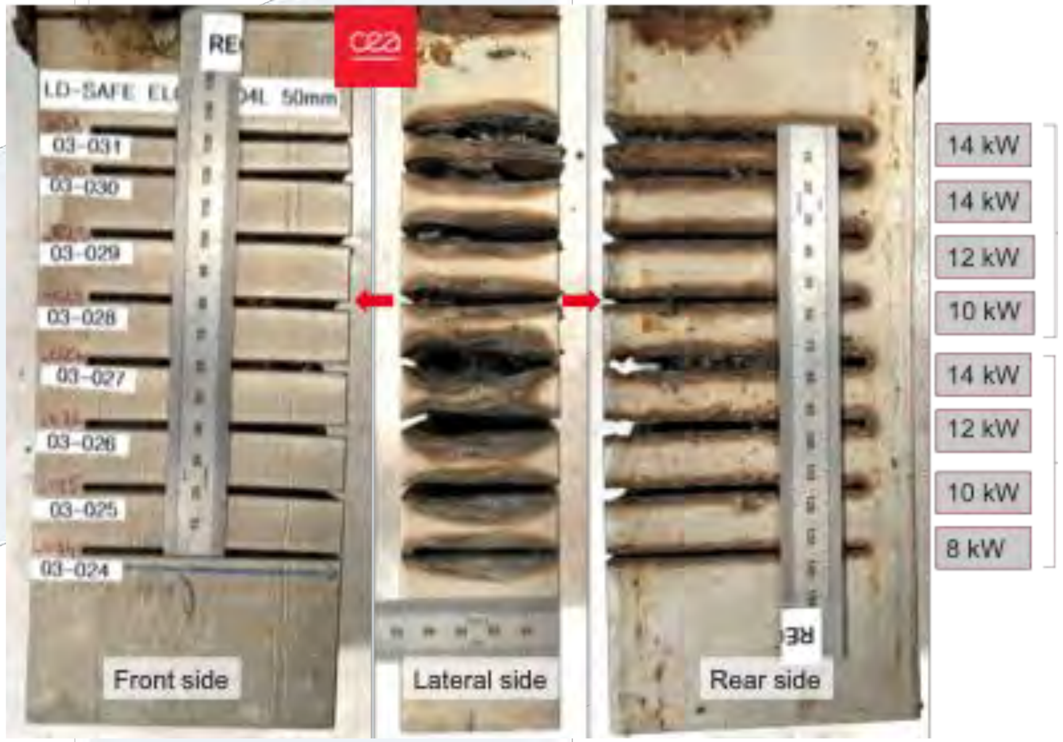
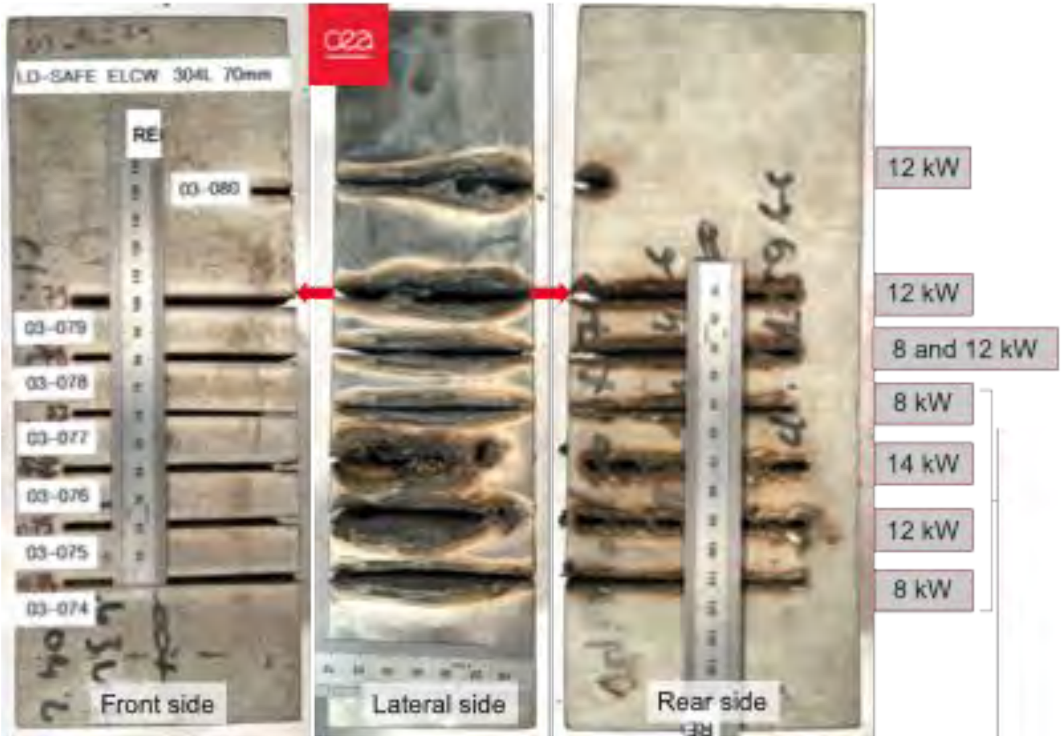
Laser underwater cutting tests

50 mm thickness



70 mm thickness



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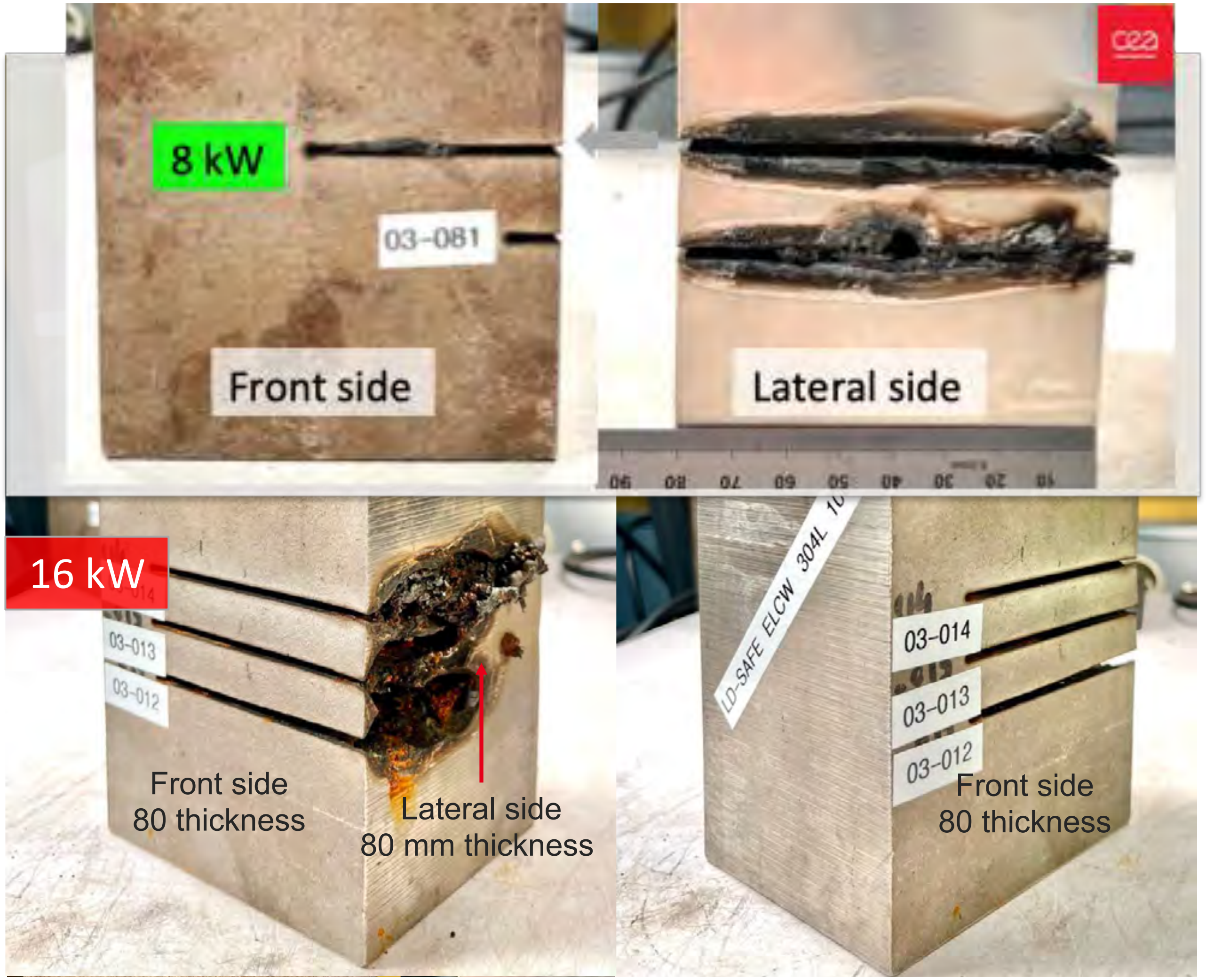
Laser underwater cutting tests

Cutting high thickness 304L SS

- 60 mm
- 70 mm
- 80 mm
- 100 mm



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Laser underwater cutting tests

- No notable influence of water level on cutting performances observed (40 mm thick 304L SS cut at 1,3 and 5.6 m of water depth)
- Nature of gas: Air vs 100% N_2 - very poor cutting performances achieved (10 times slower cutting speeds)
- Slight impact on cutting performances when air flow rate increases
- Cleaner cuts obtained for lower laser power (8kW)
- Process instabilities observed at high power (P>10KW)
- Successful cuts up to 80 mm

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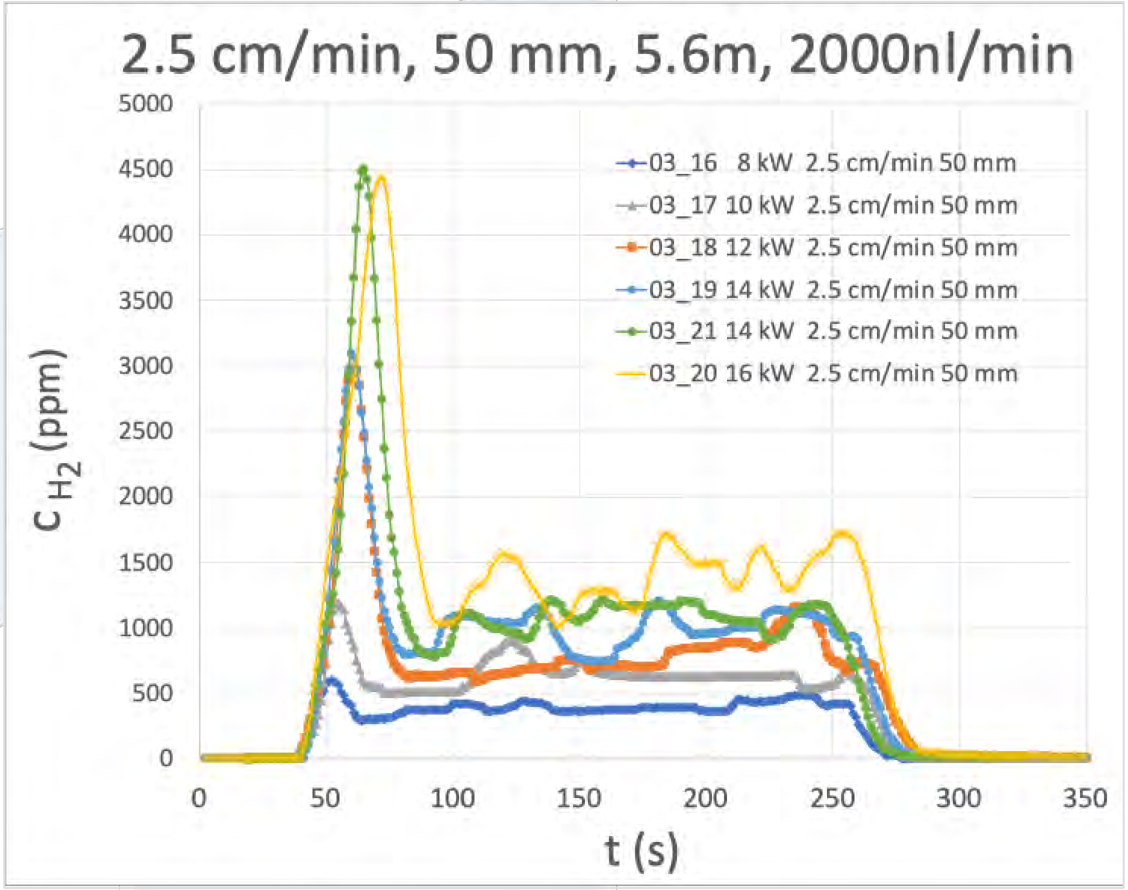
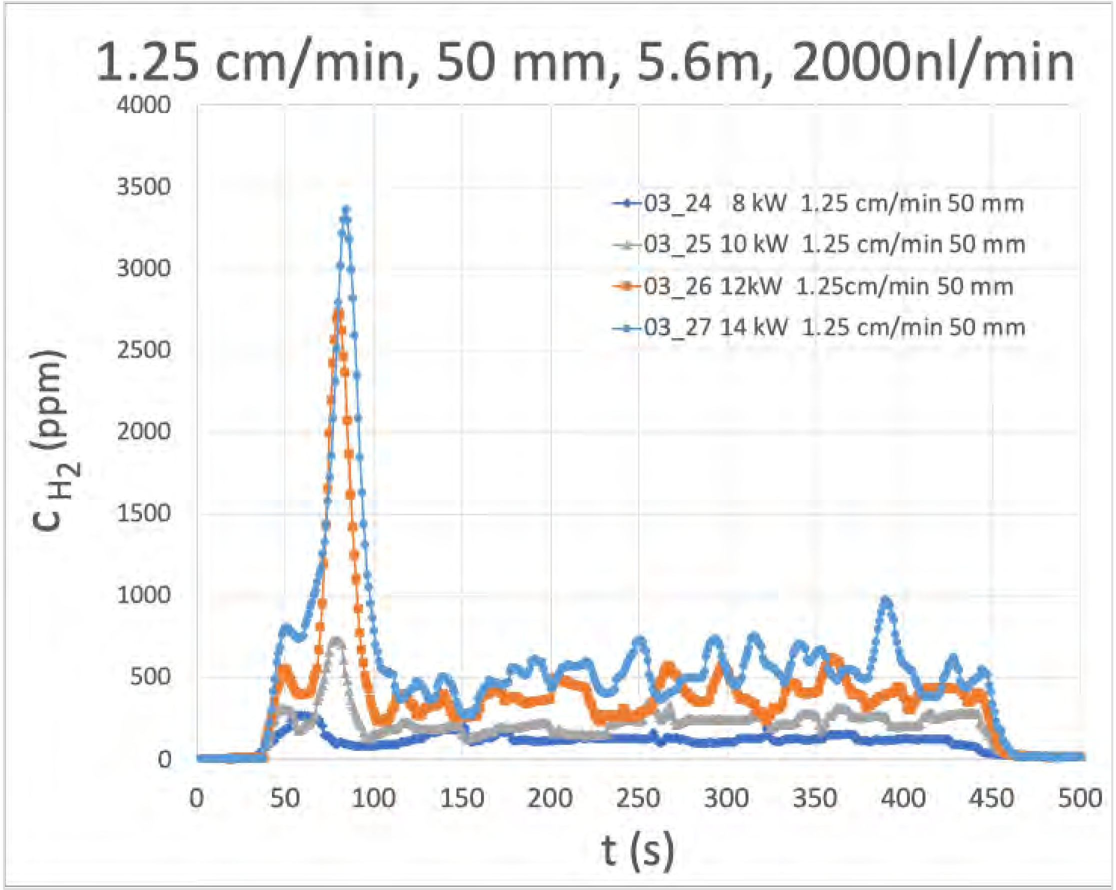
H_2 tests results

Ex: H_2 generation during cutting of a 304L SS workpiece





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Physicochemical analyses

Provide insights to understand the mechanism of generating H2 during laser cutting of 304L stainless steel

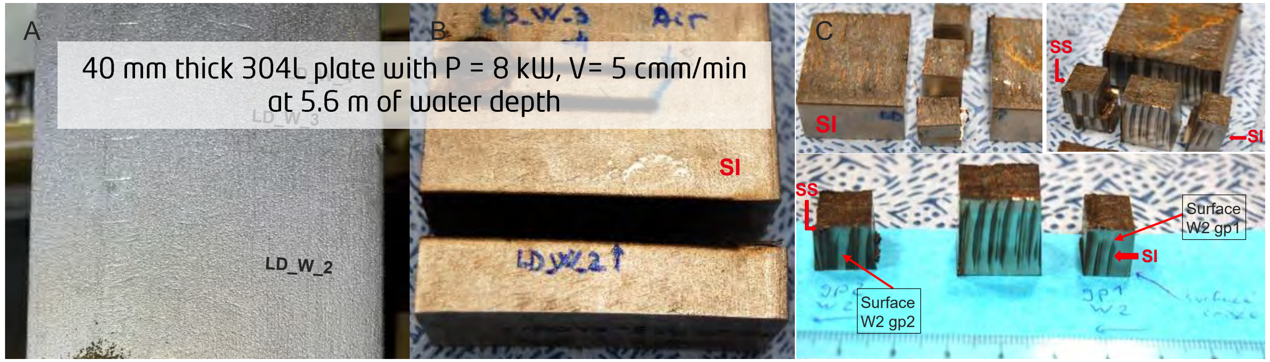
SEM, EDS and WDS analyses

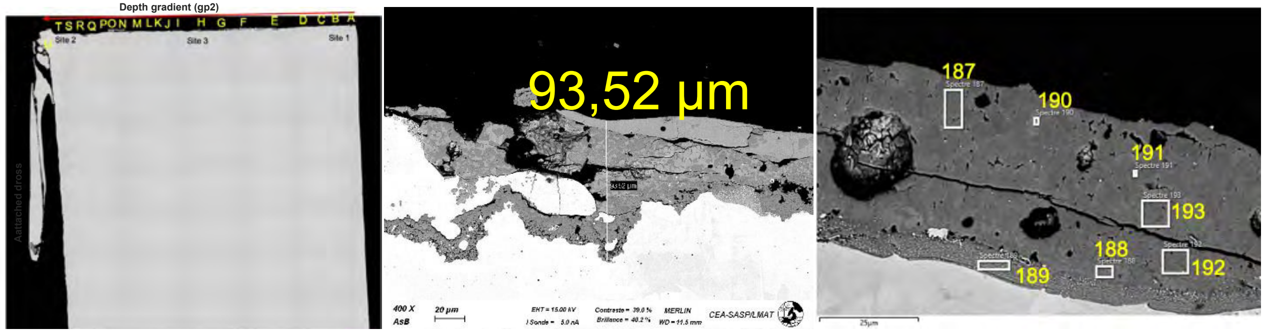
↳ Oxide layer thickness and composition

↳ Quantity of produced H_2

Element	Analysis	Atomic % (1)	Atomic % (2)
O	WDS	60.00	55.72
Si	EDS	0.38	1.11
Cr	EDS	6.69	7.55
Mn	EDS	0.75	0.77
Fe	EDS	31.16	33.01
Ni	EDS	1.01	1.62
Mo	EDS		0.22

⇨ 40% Metal (min) & 60% Oxygen (max)





$Fe_2(Cr_{0,4}Mn_{0,1}Ni_{0,1})O_4 = Me_3O_4$ ➡ $2\,Me + 3\,H_2O \rightarrow Me_2O_3 + 3\,H_2$ Ratio O/Me=1.5

$Fe_{2,4}(Cr_{0,5}Mn_{0,1}Ni_{0,1})O_4 = Me_2O_3$ ➡ $3\,Me + 4\,H_2O \rightarrow Me_3O_4 + 4\,H_2$ Ratio O/Me = 1.3

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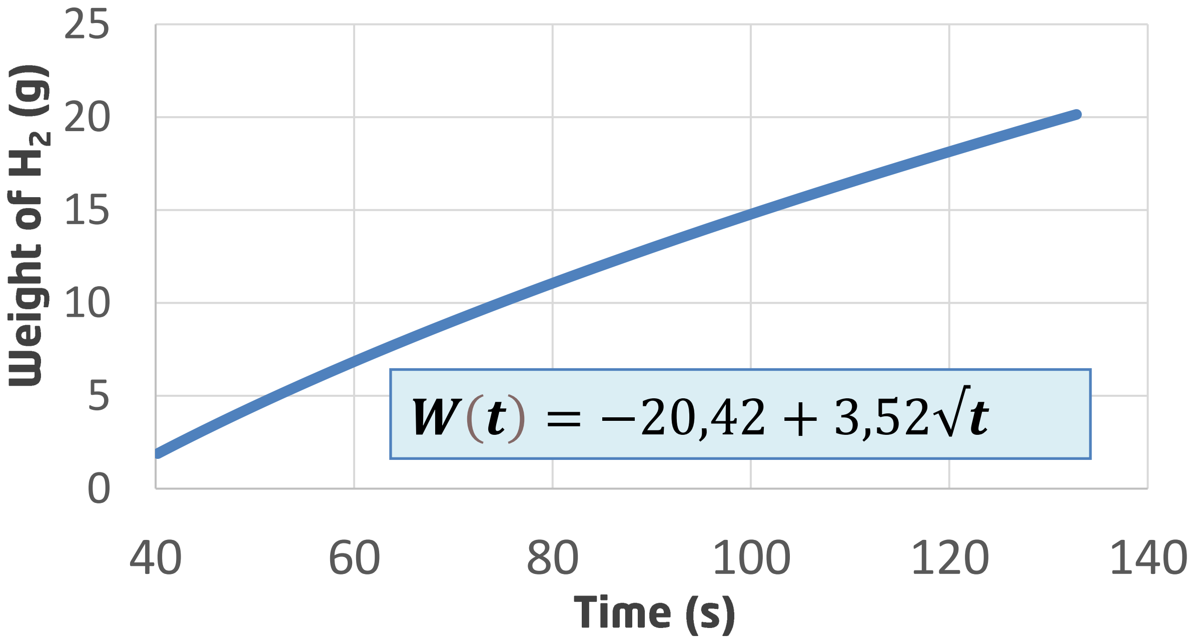
H_2 Parametric laws

Cumulative hydrogen production throughout the duration of the laser cutting process

$$W(t) = k \times \int_0^t [H_2](u).du \quad ; \quad k = \frac{m_{t_f} - m_i}{\int_0^{t_f} [H_2](u).du}$$

Hypotheses:

- Complete oxidation of ejected scoria and dross
- Uniform oxide composition of ejected debris
- Oxide layer thickness: 100 µm.
- Uniform composition of oxide layer formed on the surface
- Oxide layer formed on the surface ejected debris have the same composition
- Two type of oxides: $\mathbf{Fe_2O_3}$ & $\mathbf{Fe_3O_4}$



$$W(t) = -20{,}42 + 3{,}52\sqrt{t}$$

- Case of $\mathbf{Fe_3O_4}$: 20.15 g of H_2 produced in 133 s. (85 mm long cut, 40 mm thick 304L, 5 cm/min & 8 kW)
- 10% less H_2 for the case of $\mathbf{Fe_2O_3}$

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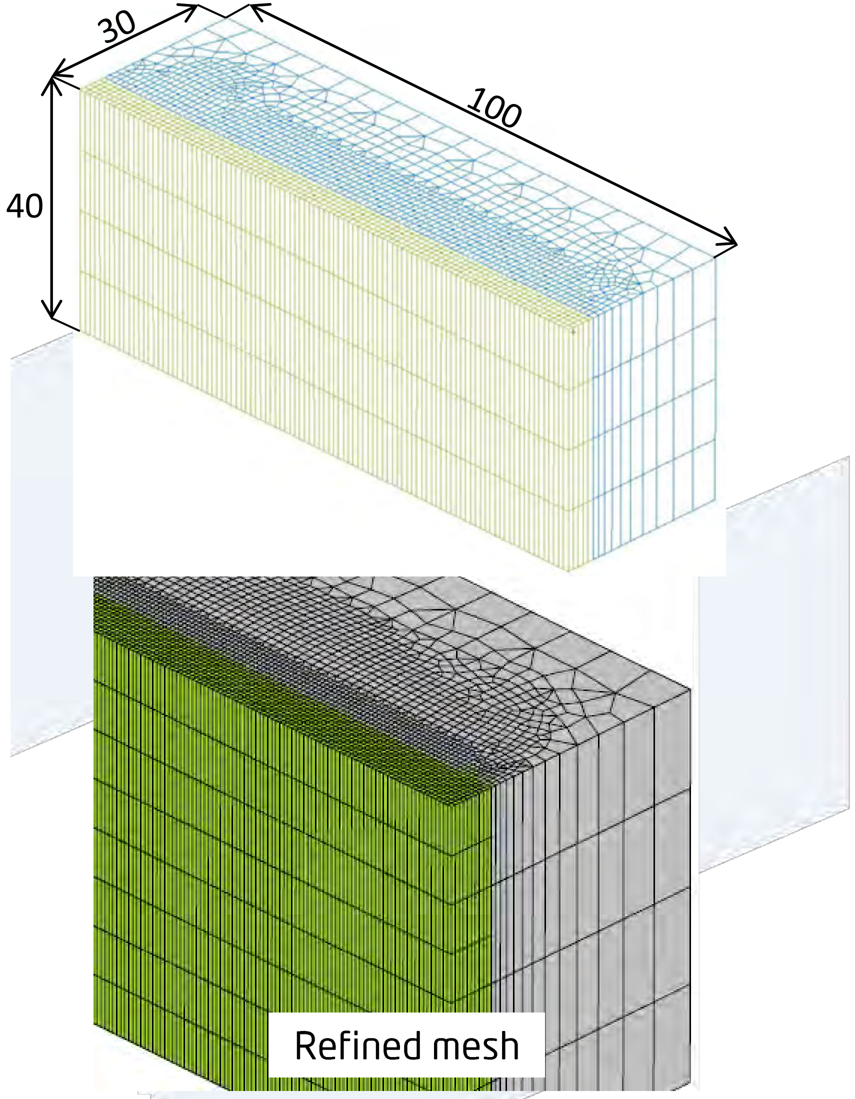
Cutting process thermal modelling



- One half of the sample modelled (symmetry)
- Explicit evolution of the geometry to model the cutting process
- Element removed according to the cutting speed
- 3 cutting speeds studied: $Vc = 5, 10, 2.5\ cm/min$
- Non linear transient thermal analysis
- T dependent material properties
- Heating source: $T_c = T_{fusion} + 500°C$
- Convection conditions at the external boundaries :

$$T_{ext} = 20°C \text{ and } h = 50\ W/m^2/°C$$

- Discretization time: ~3 time steps per element removing step
- Mesh discretization studied with a refined mesh
- Finite element size in the cutting area:
  - Base mesh: 1 mm and Refined mesh: 0.5 mm

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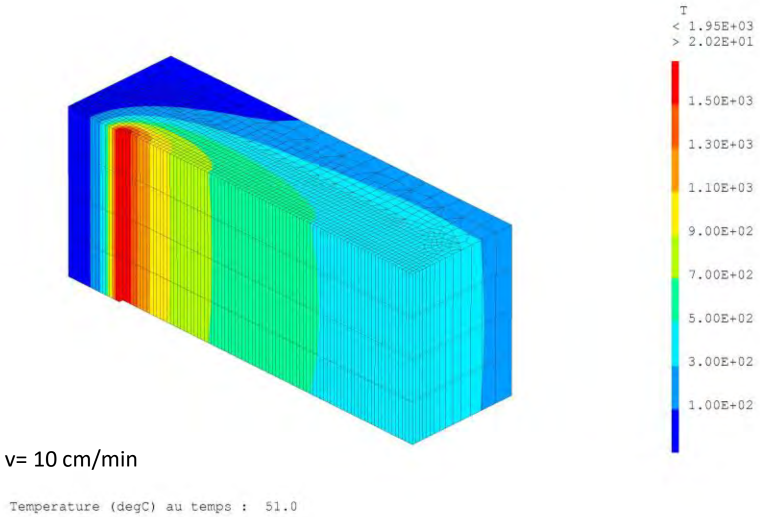
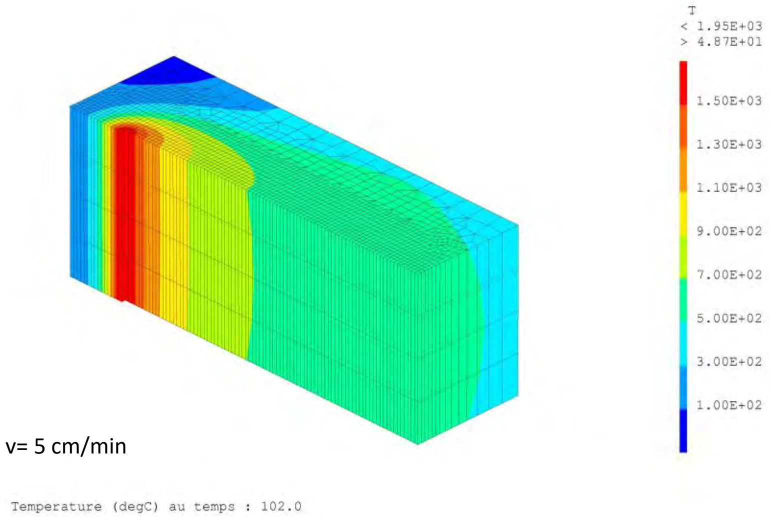
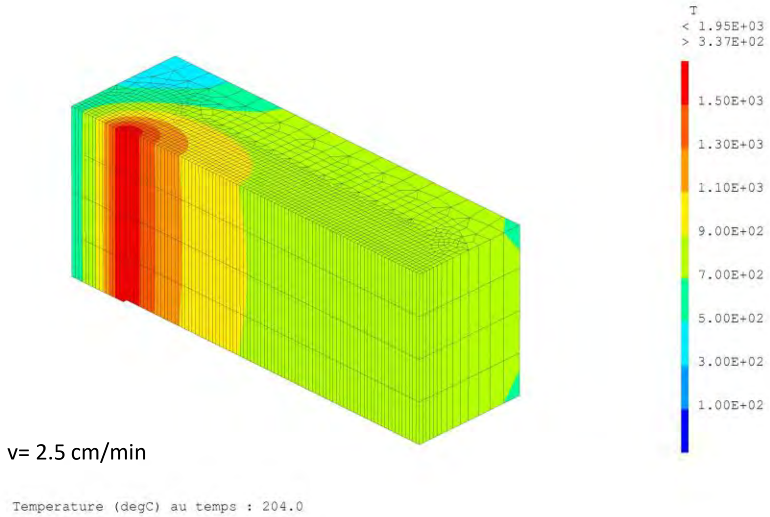
Computed thermal maps







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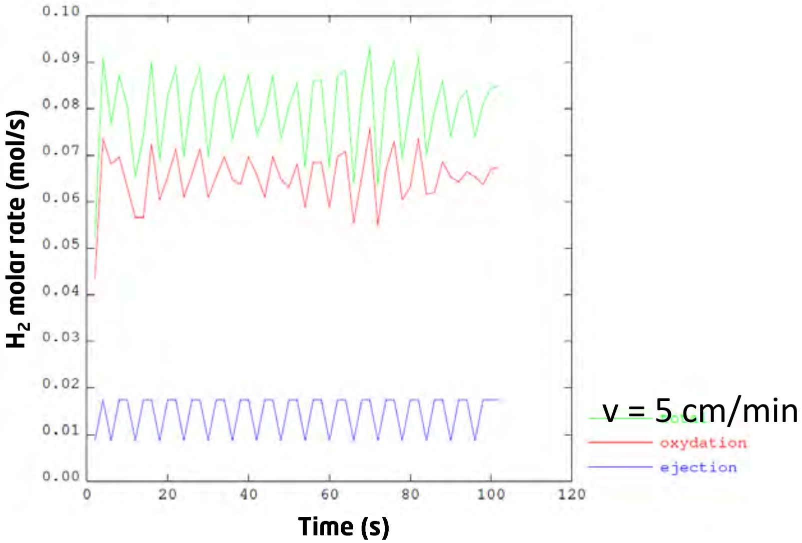
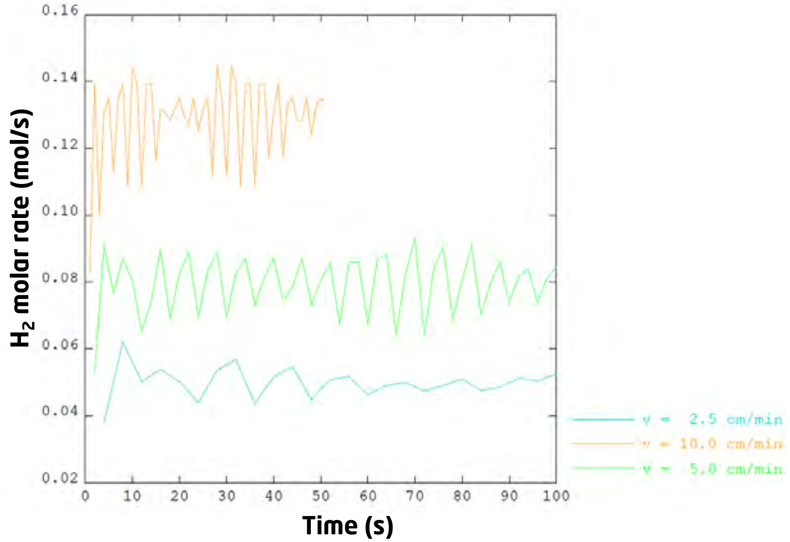
Calculation of H_2 release: Results





Conservative approach:

- Complete oxidation of all molten material
- Oxidation of surfaces, whose T > 1000°C
- 1 mol of Metal oxides → 1.5 moles of H_2

Amount of H_2 released for a 85 mm long cut

Cutting speed (cm/min)	Total amount of H_2 (mol)
2.5	10.40
5	7.99
10	6.46
5 (refined mesh)	7.08

(ρ : density, M: molar mass)

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Key findings for H_2 generation

- **Maximum recorded values for H_2 volumetric concentration never exceeded 4500 ppm (0.45%) which is lower than the Lower Explosive Limit (LEL) of H_2 set at 1%.**

- Parametric laws for H_2 in agreement with H_2 results obtained by numerical simulation

  ↳ method for bonding conditions demonstrated - needs additional testing and analyses to provide average H_2 production estimation whatever the laser-cutting process parameters

- Calculated H_2 values are significantly higher compared to those measured during testing (at least 10 times higher) - conservative approach overestimate H_2 volumetric concentration - additional analyses of scoria and dross are needed.

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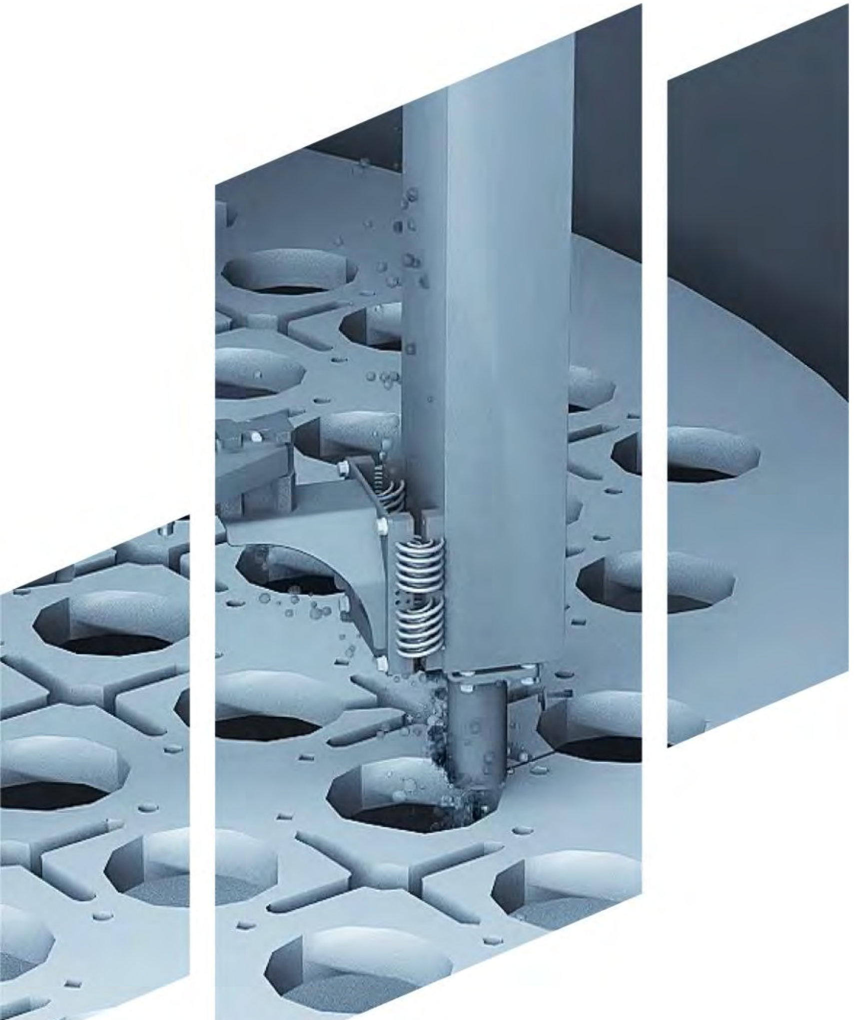
Laser Dismantling Environmental and Safety Assessment



Qualification of laser cutting technology and guidelines

Author: Mr. Timmy Sigfrids and Ms. Kristina Gillin (Vysus Group)

Date: 30/05/2024

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

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Qualification of laser cutting technology and guidelines

CONTENT

1. Overview of the technology qualification process (TQ process)
2. Technology appraisal
3. LD-SAFE technology goals
4. Technology qualification and certification
5. Development of guidelines
6. Guideline objectives and contents

Overview of the TQ process

- A systematic risk assessment and verification process that demonstrates that the uncertainties introduced by a novel technology, or a new process or application of an existing technology, have been considered and any associated risks have been controlled to as low a risk as reasonably practicable.

Technology appraisal

In a workshop with the LD-SAFE partners:

- Defined a set of technology goals related to performance, ease of use and safety compliance.
- Assessed Technology and Implementation Maturity Level (TML and IML) of each sub-component, as well as the maturity level regarding integration with other parts of the system and in a nuclear dismantling context.
- Created a risk matrix to distinguish between elements of the system with no, some or greater uncertainties related to use of laser cutting technology in nuclear decommissioning.

LD-SAFE System Decomposition (simplified)

Number	Component Name
1	Laser System
2	Laser Cable
3	Laser Head (water)
4	Laser Head (air)
5	Compressed Air System
6	Collection System (water)
7	Collection System (air)
8	Robotic System
9	Power Supply System (PSU)
10	Control System
11	Emergency Shutdown System (ESD)
12	Junction Box

LD-SAFE technology goals

Key area	Technology goal
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 Reduced hands-on human activities
Compliance and safety:	Manage the generation of radioactive aerosols and gases Increase visibility in underwater cutting Reduce/mitigate the impact of the laser beam residual power Compliance to regulatory requirements Safety assessment approval by regulator

Source: Onet Technologies

Technology qualification and certification

Based on the results of the technology appraisal:

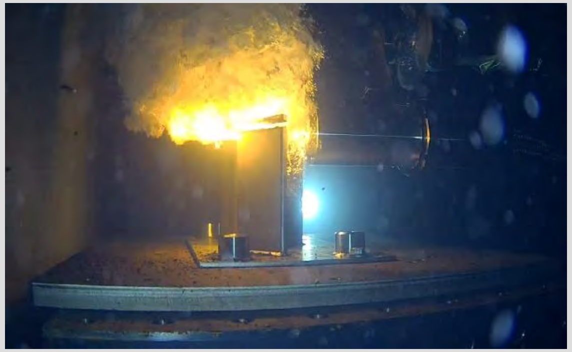
- Defined activities and assigned actions to partners to mitigate risks for relevant elements; documented the results in a technology qualification plan.
- Assessed emerging test results and other evidence provided by partners to determine whether each risk has been successfully mitigated.
- Periodical updates of the Technology Qualification Plan according to evidence submitted by all partners.

Upon the successful completion of all activities, a Technology Qualification certificate has been issued to document that the TQ process has been followed, and that all the qualification activities have been completed.

Examples of Qualification Activities:

- Water tightness and robustness of the underwater laser head and its umbilical
- Versatility of the underwater laser head (can be used in-air environment)
- Visibility of underwater laser head positioning

Evidence provided during underwater demonstrator



Source: Onet Technologies

Development of guidelines

From lessons learnt throughout the TQ process and other LD-SAFE project activities:

- Developed a Guideline document to support end users in the safe use of laser cutting in a reactor dismantling context.

Prior to completion of the LD-SAFE project, the Guideline will be updated to reflect any lessons learnt during the underwater demonstrator.

Source: Onet Technologies

The Guideline is a public deliverable, available on the LD-SAFE project website: https://ldsafe.eu/project-deliverable/

Guideline objectives and contents

The objective of the Guideline is:
To assist in planning for installation, operation and removal of the laser cutting system in a reactor dismantling context.

Intended users are organizations that:

- Are exploring laser cutting technology as an option and are looking to learn more about the safety aspects to facilitate selection of cutting technology.
- Have decided to use laser technology for cutting of reactor components and need input on the safety aspects that must be considered during planning, preparation for implementation.

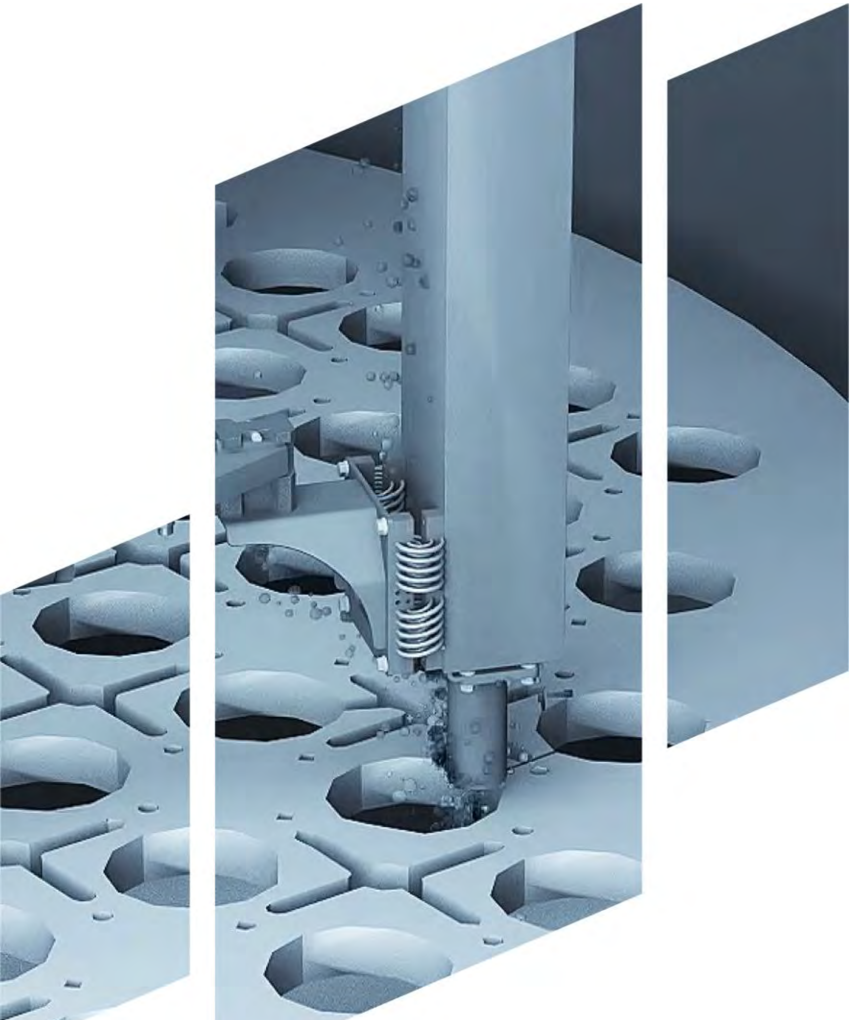
Examples of Guideline topics:

- Interfaces with the nuclear facility
- Operator training
- Installing the laser cutting system
- Preparing for each cut
- Heat
- Laser beam residual power
- Release of aerosols, dust, fumes and particles
- Hydrogen gas generation
- Visibility
- Maintenance
- Removal of the laser cutting system

The Guideline contains both informative text and guidance notes, such as:

Laser cutting should be automatically stopped upon loss of ventilation (supported by alarms for potential manual stops).

Laser Dismantling Environmental and Safety Assessment



SAFETY ASSESSMENT

Generic Safety Assessment and Independent Review

Authors: Xavier Masseau[1], Jesus Ruiz[2]
Patrice François[1], Tomas Recio[2]

1. IRSN, France. 2. Westinghouse, Spain.

Date: 30/05/2024

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

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SAFETY ASSESSMENT

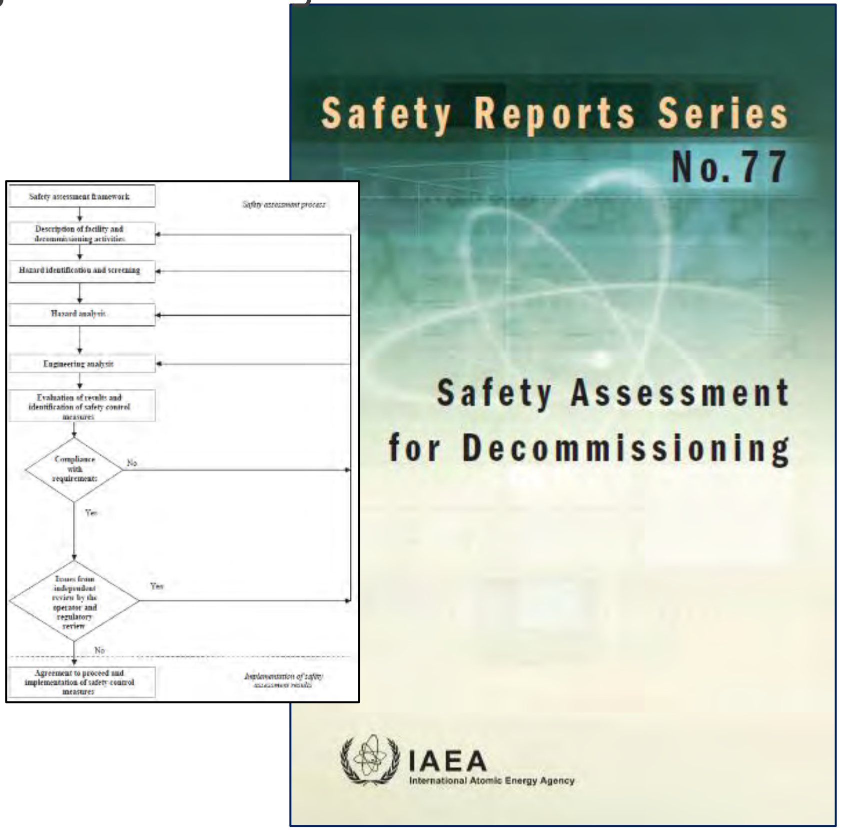
Objectives and Methodology

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

- Provide answers to the laser-specific safety concerns.
- Generic Safety Assessment available to the European market, reducing their licensing effort.

Methodology / Approach → Structured process following **IAEA SRS 77**

- Hazard Identification & Analysis: IAEA checklists + HAZOP study.
- Consequences evaluated in a deterministic manner, qualitatively & quantitatively (predefined radiological inventory & segmentation plan).
- Engineering analysis (safety measures & controls):
  - ➢ **Recommendation of design options** (for normal conditions) **and safety measures** (for abnormal/accidental conditions).
- Evaluation of Results (including **Risk Matrixes**).

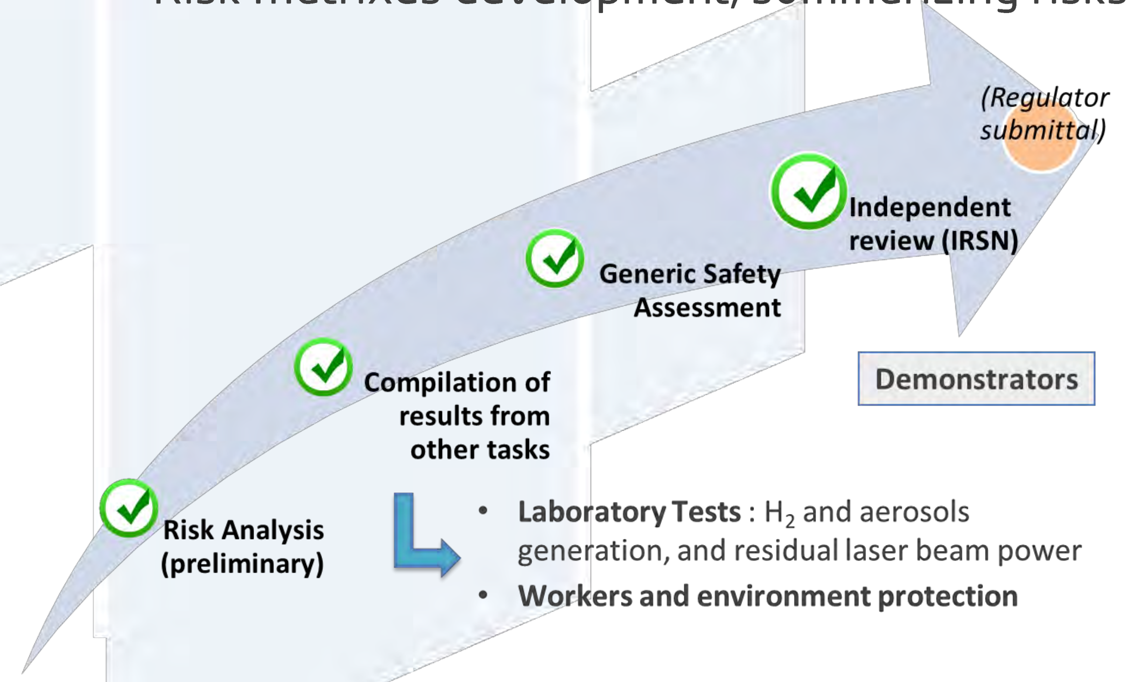


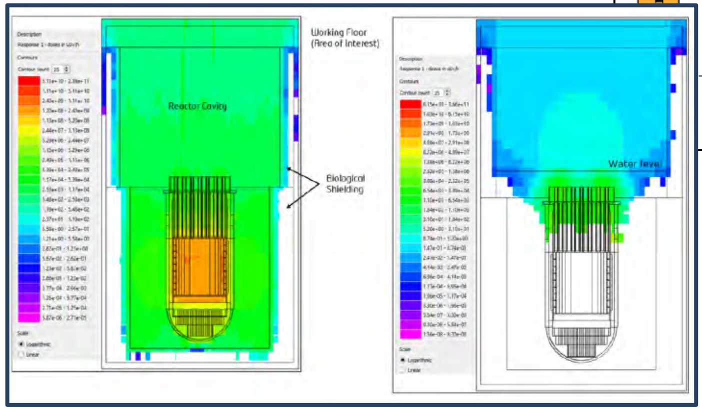
SAFETY ASSESSMENT

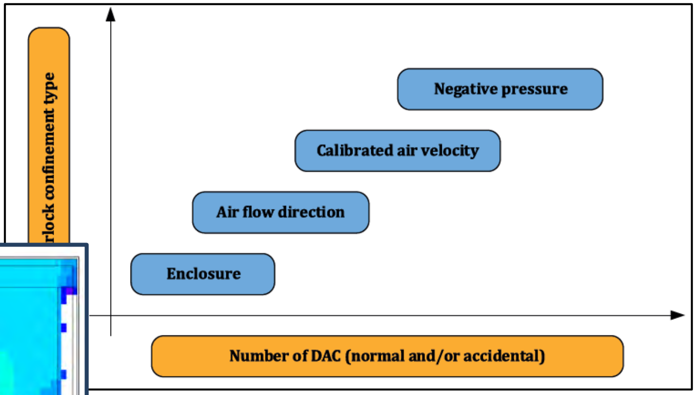
Relevant Activities

Relevant Activities for **Generic Safety Assessment** development:

- Risk analysis & evaluation, considering the results from other tasks, highlighting the outputs from laboratory tests.
- Dose rates analysis using MAVRIC for potential cutting scenarios.
- Confinement systems recommendations based on ISO 16647:2018, based on aerosols release rates.
- Risk Matrixes development, summarizing risks, design options, and safety measures and controls.







ISO 16647:2018

SAFETY ASSESSMENT

Risk Matrixes

Risk Matrix for normal conditions and Risk Matrix for Abnormal/accidental situations. Example:

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

SAFETY ASSESSMENT

Independent Review

Independent review of the Generic Safety Assessment (GSA): objectives

- Give independent position on the generic safety assessment methodology
  - Objectives, perimeter and limitations
  - Interactions with target NPP
  - What is covered and what is not: the boundaries between GSA and the target NPP safety assessment must avoid loopholes

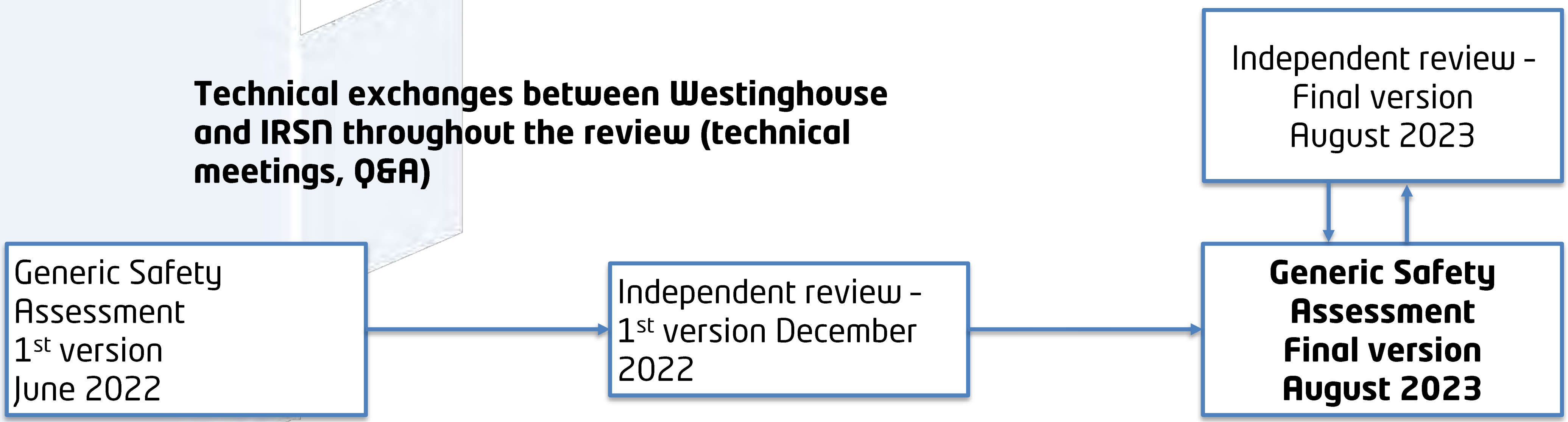
- Provide independent review on radiation protection/nuclear safety aspects
  - Relevant experience feedback
  - Hazards and aggressions with a defense-in-depth approach (prevention, detection, consequences limitation)
  - Interfaces with target NPP (utilities, storage, ventilation systems, …)

SAFETY ASSESSMENT

Independent Review: an iterative process

Independent review of the Generic Safety Assessment (GSA)

- Outputs of the review where:
  - Recommendations to be addressed in the GSA - final version
  - Recommendations to consolidate, with the demonstrator, data relevant for safety
  - Recommendations for the End User in order to help with the licensing process



SAFETY ASSESSMENT

Independent Review: outputs

11 recommendations have been made and where then integrated to the final GSA version on various topics:

- Interfaces between the LD-Safe GSA and the target facility: systems to used (power, fluids, ventilation, monitoring systems, handling means, radioactive waste management)
- Design options for the static containment (in-air cutting)
- Radiation protection (dose constraints for optimization)
- Discharges into the environment
- Hydrogen hazard
- Fire hazard (robotic arm)
- I&C and process monitoring
- Radiological consequences in case of an abnormal/accidental situation

SAFETY ASSESSMENT

Independent Review: outputs

3 recommendations have been made and were addressed in the frame of the industrial demonstrator tests:

1. Consolidation of the estimation of atmospheric concentrations during cutting by some measures
2. Consolidation of the hydrogen production during underwater cutting
3. Definition of the operational domain and consolidation of the relevant parameters to be monitored

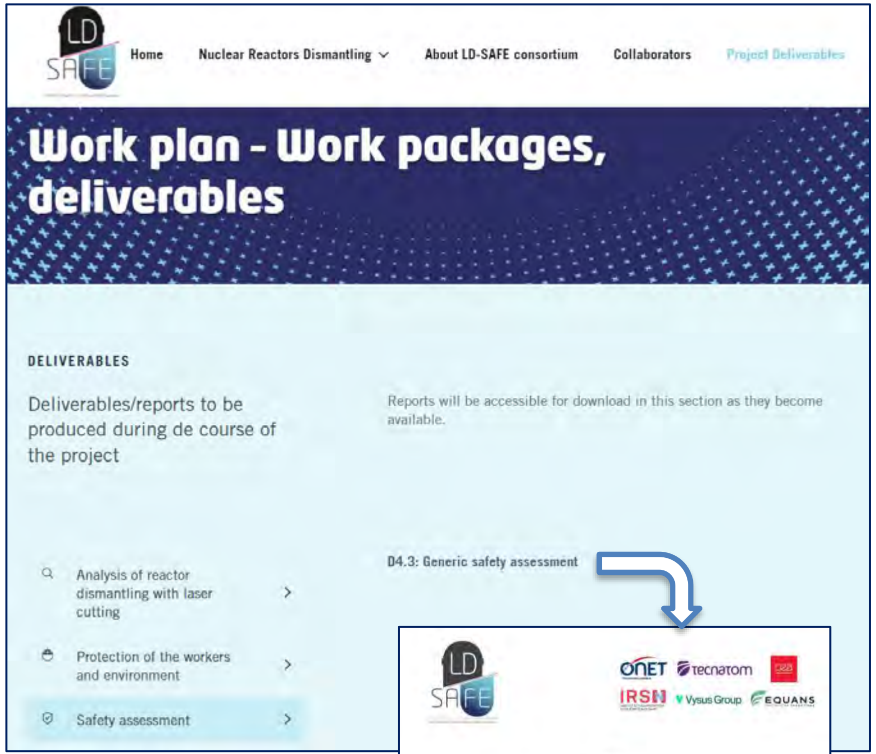
7 recommendations have been made to help End Users with the licensing process:

1. Compatibility of the existing systems of the target facility with LD-Safe equipment (utility power, fluids)
2. Check dose calculations to confirm the relevance of specific safety provisions
3. Check that the scenarios considered in the GSA are relevant (ex. Maintenance scenario)
4. Optimize radioactive waste to be generated when cutting complex geometries with laser (opportunity)
5. Confirm that the assumptions considered for accident scenarios are relevant for the target facility
6. Take benefit of the possibility to locate supporting systems in premises away from the cutting areas
7. Check that the off-site emergency plan remains relevant

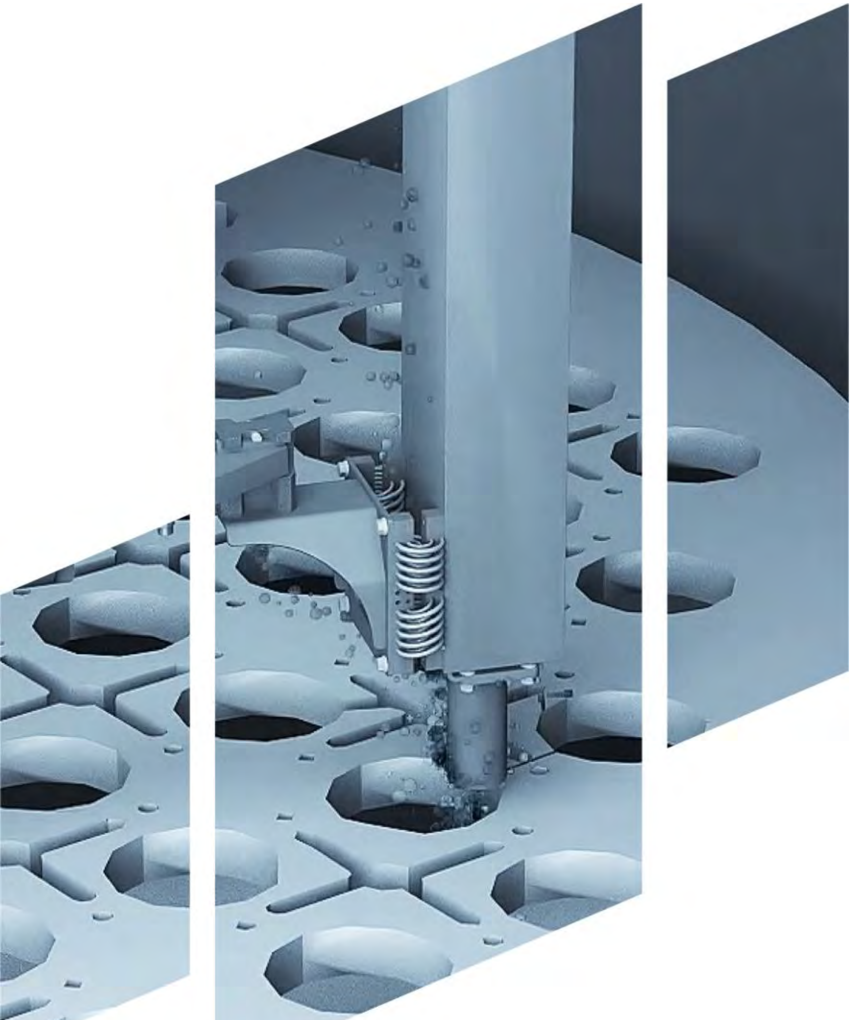
SAFETY ASSESSMENT
Conclusions

Conclusions:

- Generic Safety Assessment considering laser cutting specific risks (i.e., laser beam residual power, H2 and aerosols generation).
- RPV/RVI laser cutting can be at least as safe as the best techniques currently used → Paying attention to the identified hazards and observing the recommendations on safety measures and controls.
- Future End Users would have to adjust the evaluation to their specific conditions (i.e., radiological inventory and segmentation plan), but this assessment aims to reduce their licensing effort.
- Generic Safety Assessment independently reviewed by the IRSN, providing confidence about the process. IRSN recommendations were integrated into the final document.



Available at
www.ldsafe.eu



DEMONSTRATORS

Laser cutting system and cutting results

Authors:

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Date: 30/05/2024

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

Reminders
End Users' expectations for laser

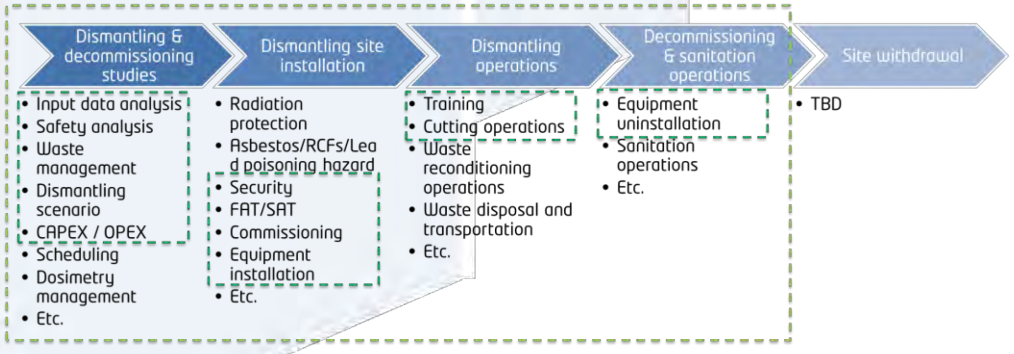
Dismantling RPV/RVI - Current situation:

- 2 to 10 cutting tools
- 1 to 6 handling systems
- Narrow spaces (low available footprint)
- Low accessibility of cutting tools
- Maintenance operations in nuclear area

End Users' expectations:

- Cutting high thicknesses and complex geometries
- Efficient underwater RVI cuttings
- Ease of use / Training
- Safety of workers / radiation protection
- Technology maturity evidence
- Reliability
- Cost & time improvement

Scope of work



Ambition: Validate the laser cutting technology for the dismantling of the most challenging components of nuclear power plants

Demonstration: Prove that laser cutting technology is mature (TRL7)

1. Development of a complete versatile laser cutting system dedicated to PWR and BWR components

2. Validation of laser cutting technology in operational environment (in-air and underwater) on the mock complex RVI cutting configurations

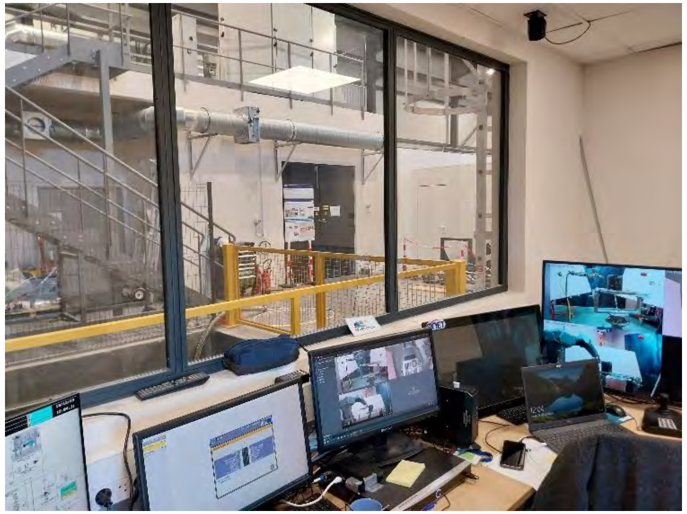
3. Technical validation: Demonstration of performance, ease of use and safety to facilitate its recognition and future use in the next dismantling activities

4. Financial advantages: reduction of costs and time

In-air demonstrator

HERA Facility

Underwater demonstrator



Onet Technologies' Technocenter

Laser cutting technology goals

PERFORMANCE

- ✓ Cutting speeds and maximum thicknesses
- ✓ Secondary waste reduction
- ✓ Improved reliability / robustness / versatility
- ✓ Cost and time reduction

Ability to cut ***in-situ*** every PWR & BWR RVI with **one tool**

Cutting speeds **optimization** for several thicknesses and geometries

EASE OF USE

- ✓ Both in air and underwater
- ✓ Reduced maintenance
- ✓ Reduce hands-on human activities

Easy implementation on site: only laser cutting head and umbilical are inside dismantling area

Versatile laser system: can be used both in-air and underwater

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 with regulatory requirements and safety

Ability to ensure and monitor **underwater cutting operations safely**

Compliance of laser system with regulatory standards

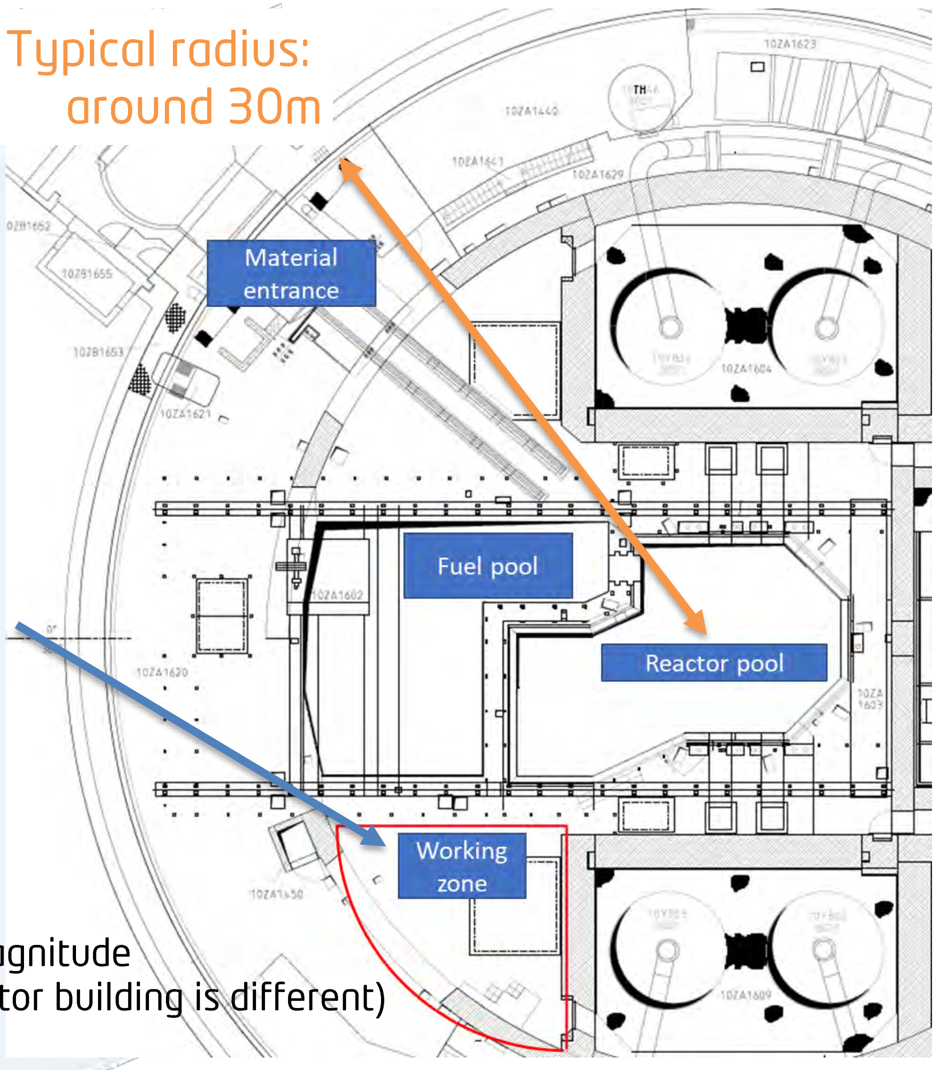
Development of the laser system

Reference environment

Typical radius: around 30m

Footprint around 50 m²

3 m max: Passage around all laser equipment



Order of magnitude (every reactor building is different)

- General reactor environment (from EQUANS experience) → i.e., footprint available to install laser equipment, dimensions of the passageways for the wires, pipes, optical fiber, etc.

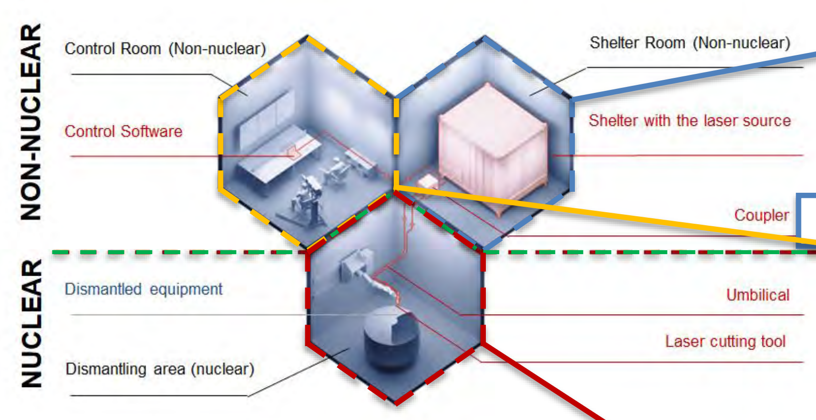
- Laser cutting system broken down into **4 areas:**
  - Cutting area
  - Control area
  - Interface area
  - Utilities area

- Implementation of end users' technical constraints
  - Main laser utilities can be implemented **outside reactor building**
  - Average length of optical fiber: **150 meters**

Development of the laser system

Architecture

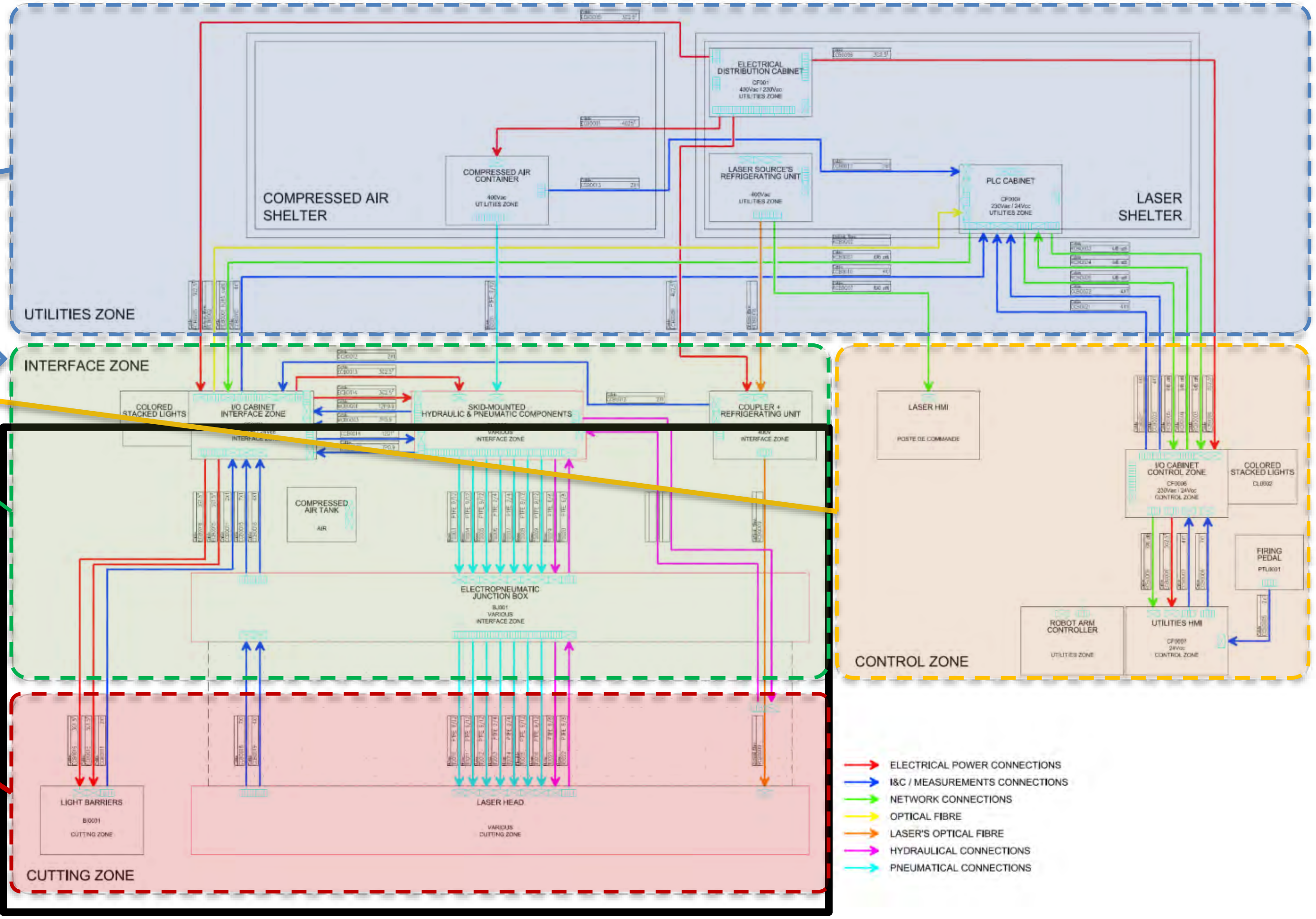
From requirements to technical solution



Main laser requirements:

- Laser power adjustable
- Main laser utilities implemented in shelters
- Can fit both in-air and underwater environment
- Easy implementation and use

Underwater interfaces between sub-systems



Development of the laser system

Key features of the subparts

Laser system fits inside 2 standard hi-cube 20' containers:

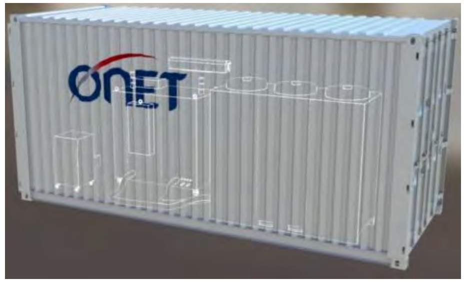
- 1 dedicated to the laser source and utilities
- 1 dedicated to compressed air generation (optional if NPP's air quality class / airflow don't comply with laser requirements)

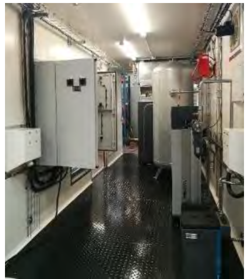
Why containers?

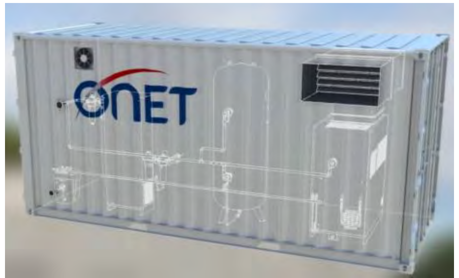
- Lack of available space inside reactor building
- Stored and installed outside reactor building
- Easy transportation by road, rail or sea

Key aspects:

- Easy connections to the laser system
- Designed to be safely lifted and transported (laser source installed on silent blocks)
- Laser maintenance directly performed inside the container
- Robustness, watertightness, modular design







Development of the laser system

Key features of the subparts

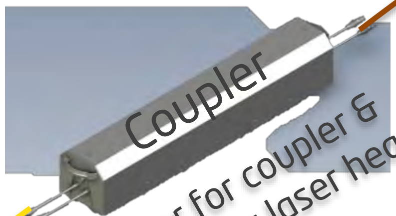
Laser supply line is:

Laser source — Optical fiber L100 m - ø300 µm — Coupler — **Robotic optical fiber** L50 m - ø600 µm — Laser head

16 kW laser source
+ 1 dedicated chiller

Up to 2x100 m of optical fiber
➔ **Mean distance in NPP between utilities zone / cutting zone = 150 m**

Optical fiber
L100 m - ø300 µm



1 chiller for coupler & underwater laser head

Robotic optical fiber
L50 m - ø600 µm

Fiber can follow robotic arm motion

Underwater umbilical to house all connections (optical fiber, pneumatic & hydraulic hoses, electrical wires

In-air 14 kW laser head

Underwater 16 kW laser head

Power modulation from 0.32 to 16 kW

Test performed with 14 kW laser head

➔ **Less than 3.5% difference between power setpoint and actual laser head output power**

Development of the laser system

Key features of the subparts

Laser shot pedal: servo-control device
➔ Necessary to perform human operation to launch laser beam

Laser source HMI

- Power modulation
- Monitoring of laser safety features
- Selection of optical output

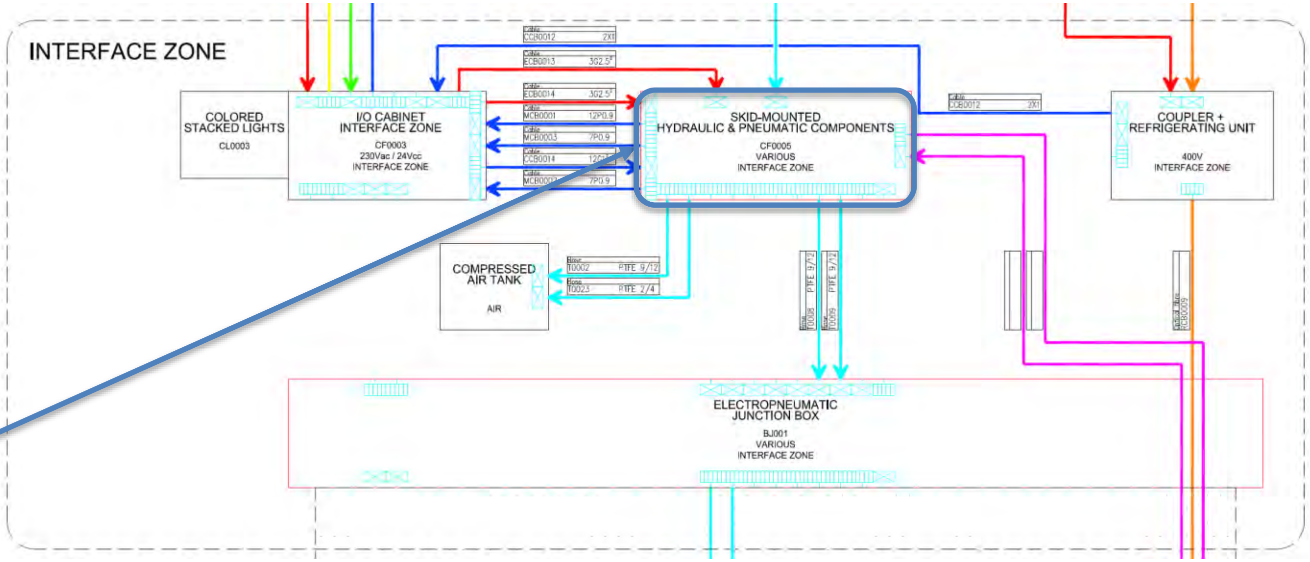
Laser system HMI

- Parameters setting (pressure, airflow) + safety sequence
- Opening/closure of the shutter
- Errors reporting
- Sequential operation (semi-automatic)
- Converter: safe mode in case of power loss

Development of the laser system

Key features of the subparts

In-air configuration

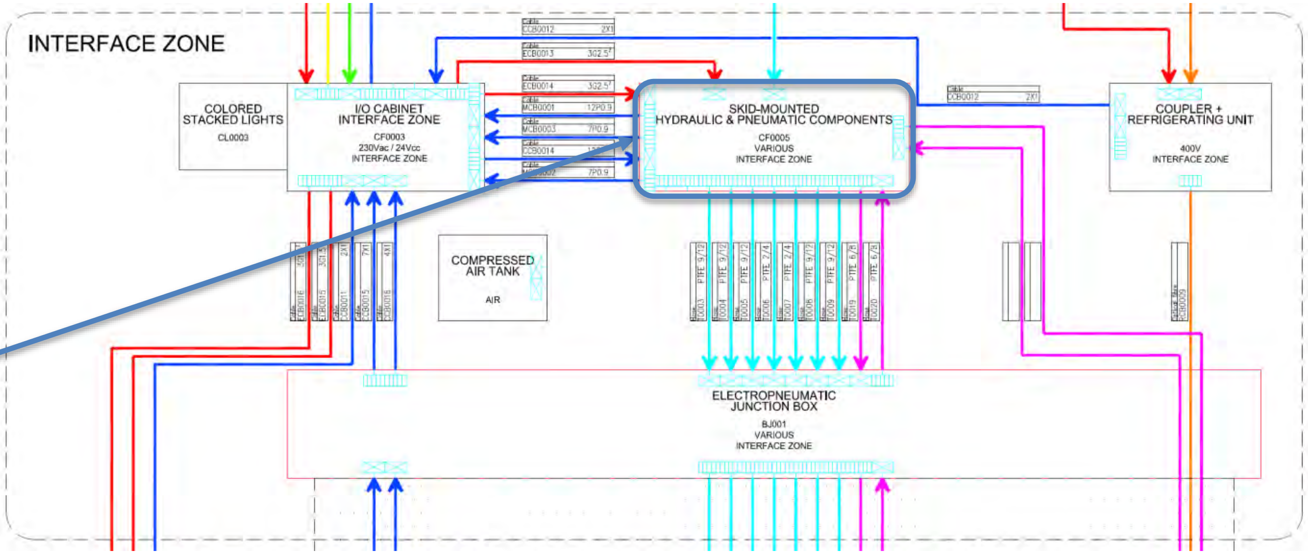


- Air quality: 1/3/1 (ISO 8573-1)
- Real time air quality monitoring: sensors all along air supply lines (humidity, temperature)

Development of the laser system

Key features of the subparts

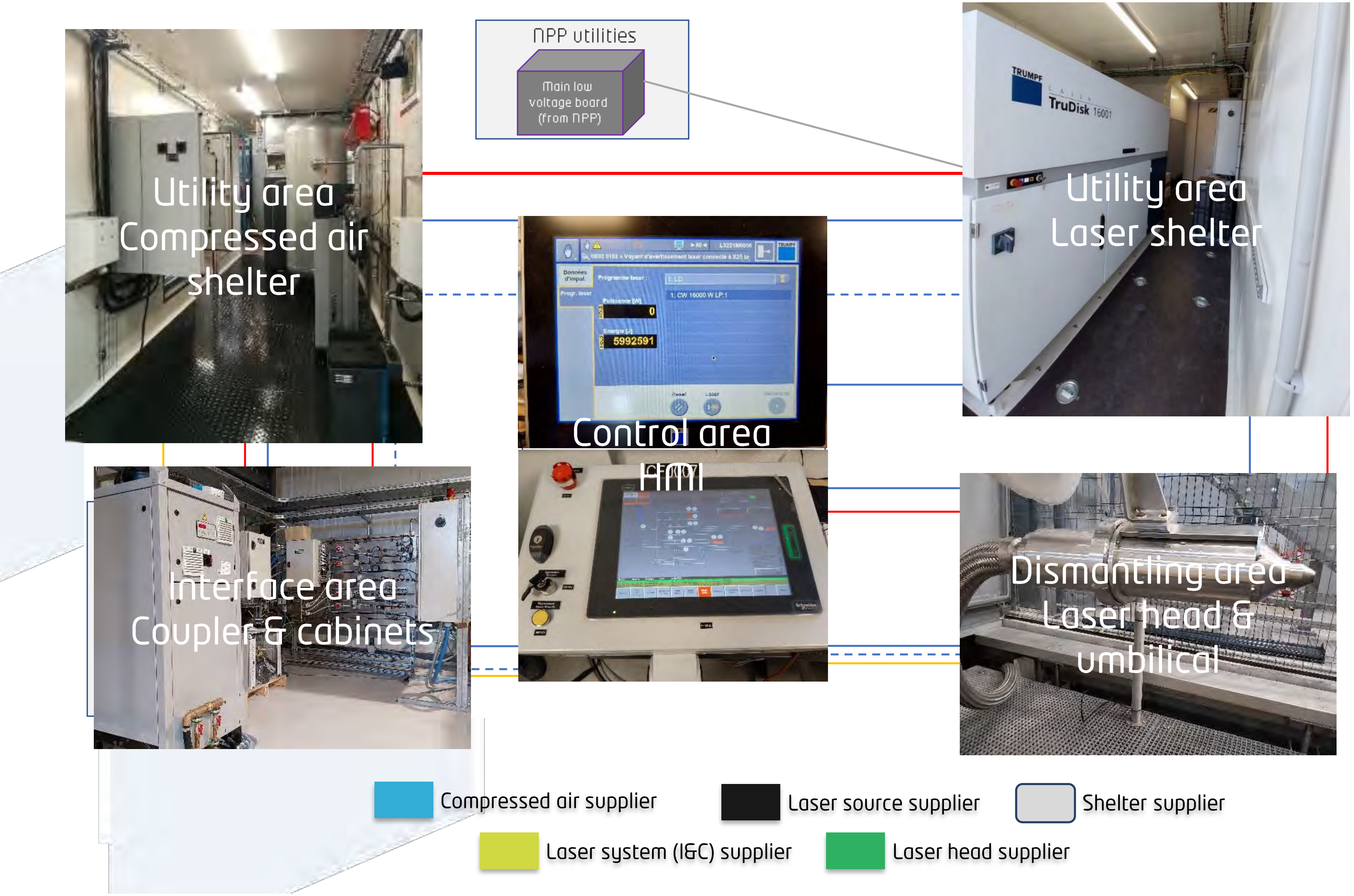
Underwater configuration



- **Only one** hydraulic & pneumatic skid to manage compressed air **for both configurations** and water cooling of underwater components
- Designed to be used with additional filtration systems

Development of the laser system

Supply chain



Standard product for decommissioning

- Design and manufacturing files already completed (Ability to manufacture the exact same system)
- Manufacturing based on LD-SAFE's requirements
- Already duplicated for other customers
- Robust, tried-and-tested supply chain

➔Ready for industrialization

Demonstrators

For safety representativeness

Based on the Generic Safety Assessment and laser risk analysis

Laser hazards management

Laser beam residual power

Regulatory control

Laser safety expert for LD-SAFE

PYLA
CENTRE DE FORMATION
LASER, OPTIQUE, PHOTONIQUE
ÉLECTRONIQUE, HYPERFRÉQUENCES

Filtration system

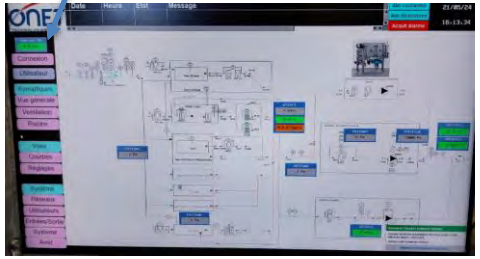
Aerosols management

Enclosure

Additional collection system

H_2 sensor…

…monitored in control room…



H_2 hazard management

…alongside with more parameters

- ΔP monitoring (negative pressure inside cutting environment)
- Air and water flow monitoring (filtration lines)
- Exhaust temperature
- I&C – Emergency stop loop / laser stop

Demonstrators

In-situ laser cutting scenario

Original state | **Final state**

PWR / BWR

Objectives

- Definition of a general cutting scenario for a PWR and a BWR
- Identification of the main cutting operations and constraints to perform in situ dismantling operations.

Why *in-situ*?

- In situ (low congestion of the underwater laser head) ➔More baskets for the waste in pool.
- Less bespoke systems/equipment
- Less heavy handling activities

} Reduction of technical risks and cost

Why underwater?

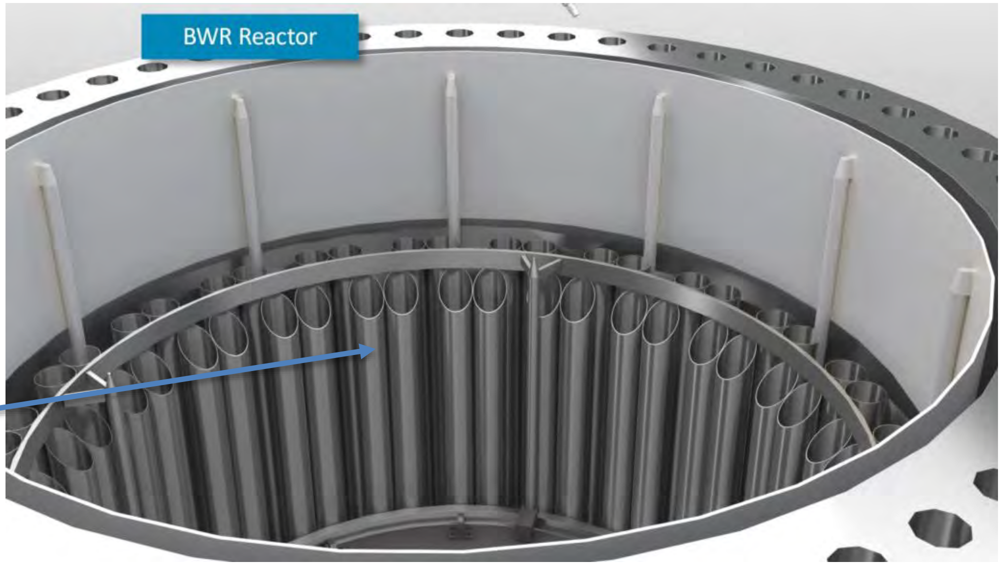
- Suitable for immediate dismantling after final shutdown
- Reduction of specific laser risks (laser beam residual power, aerosols)
- To be demonstrated: underwater cutting of all PWR & BWR's RVI

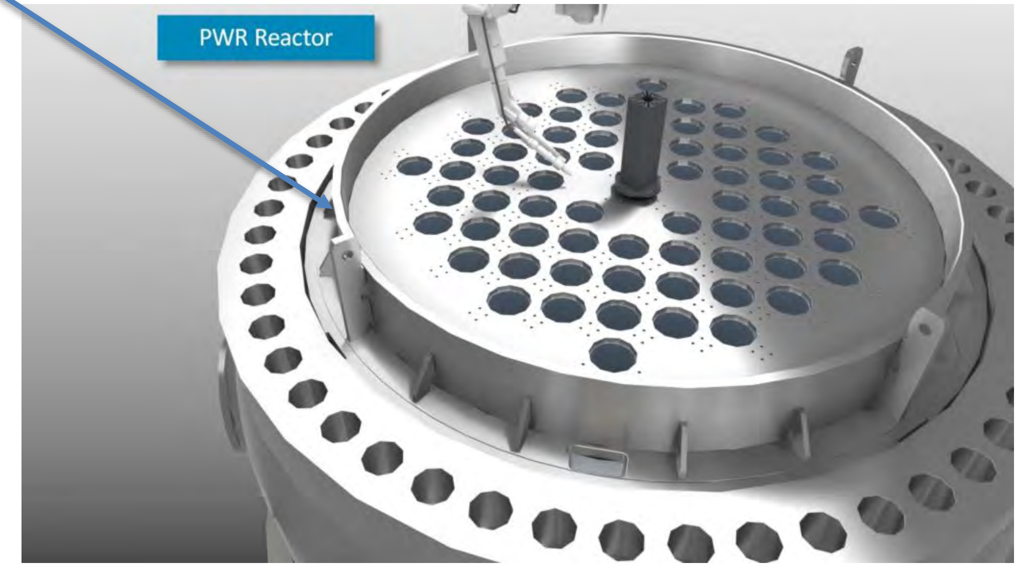
Demonstrators

Mock-ups

Requirements

- Complies with general cutting scenario
- Representative of the most complex configurations: geometry, multiple layers, environment congestion, thicknesses
- Material representative of actual PWR and BWR:
  - Scale 1:1
  - Thermal conductivity
  - Irradiation aging
- Modular: replaceable parts in case of failure
- Ability to be lifted: some pieces weighing up to 500 kg
- Fit within both demonstrators' environment: max. volume = 1x1x1m

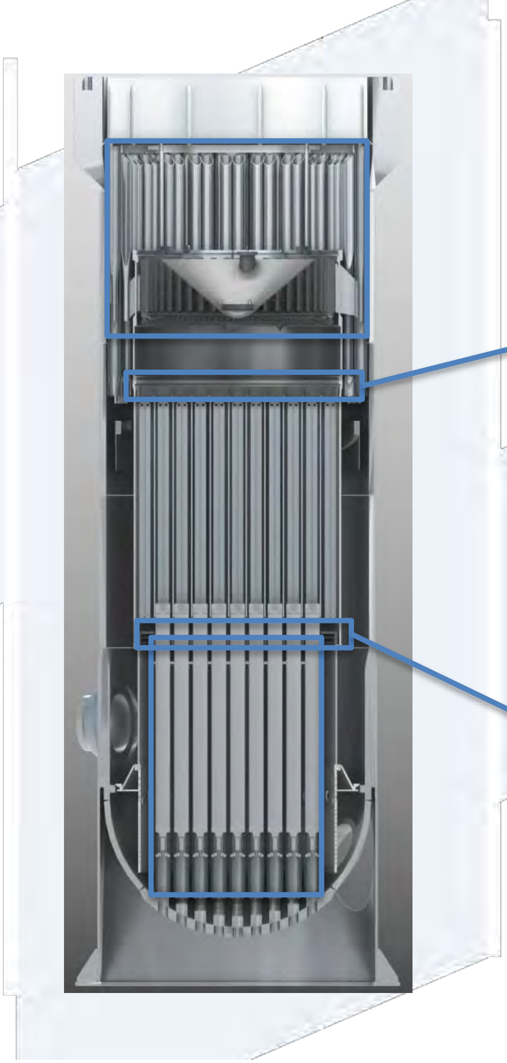




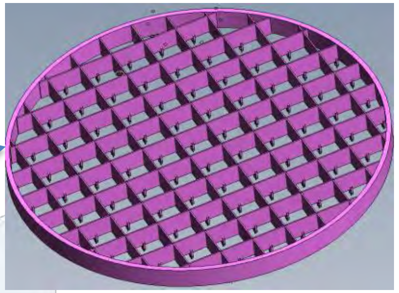
Demonstrators

Mock-ups

BWR sectional view

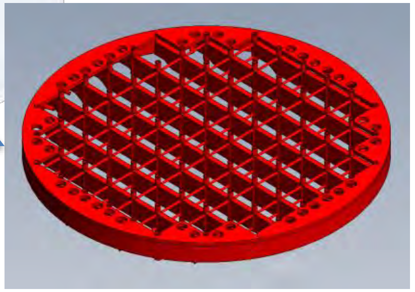


BWR's upper plate

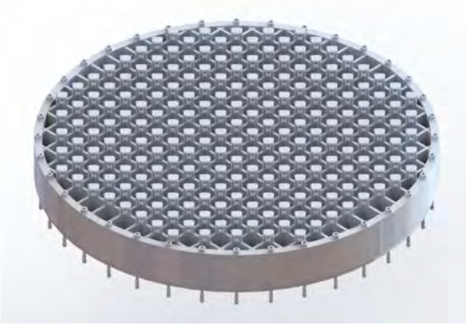


PWR's uppe plate

BWR's lower plate



PWR's lower plate

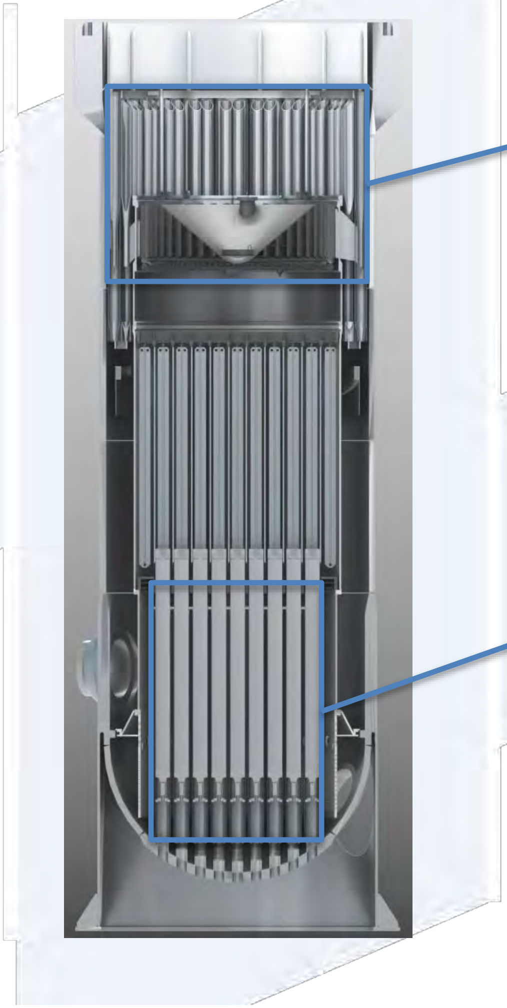


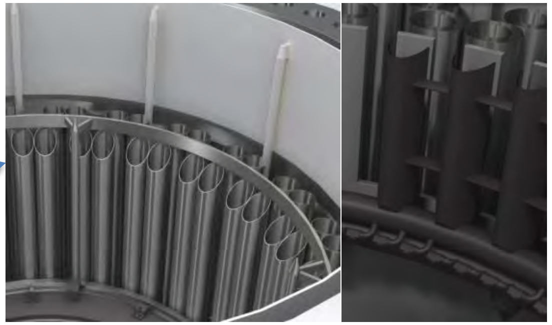
PWR sectional view

Demonstrators

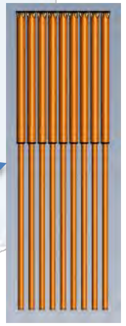
Mock-ups

BWR sectional view



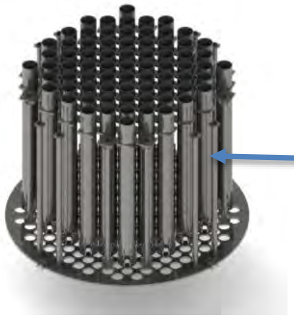


BWR's steam dryer tubes



BWR's control rods guide

PWR sectional view

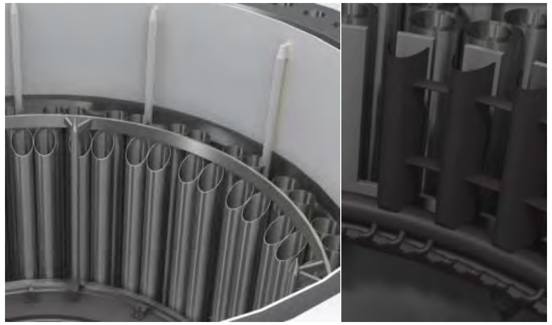


PWR's control rods guide

Demonstrators

Mock-ups

BWR sectional view



BWR's steam dryer tubes

PWR's control rods guide

PWR sectional view

PWR/BWR: Similar components (tubes, grid, plates)

Different diameters, thicknessess, ...

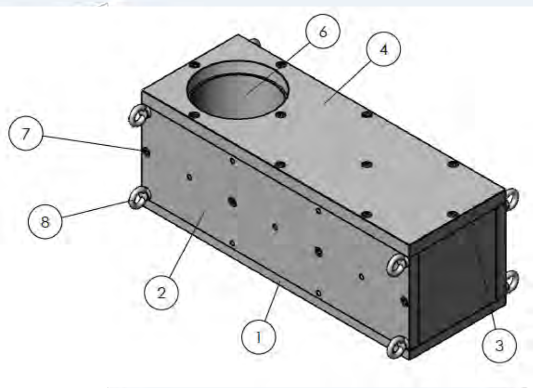
➔ **Mock-ups based on the most challenging configuration**

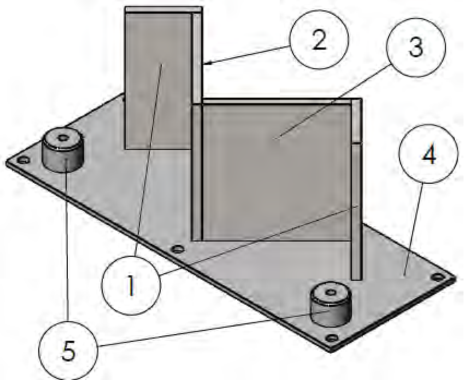
Demonstrators

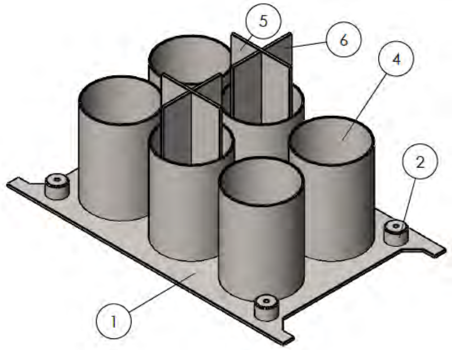
Mock-ups

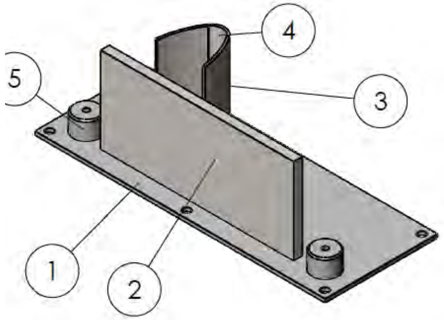
Developed by EQUANS

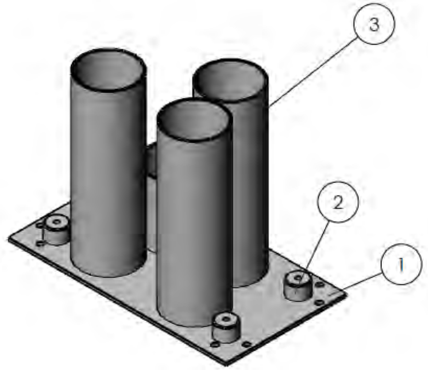
Internals	#	Subpart	Image	Description	Relevant characteris	Real dimensions (mm)	Possible model
Control rod guides 	1.1	Hollow tubes	As shown on left	Hollow tubes	Outer diameter Inner diameter Length	273 264,5 (thickness 8,5) ~2600	Set of 13 tubes of length 300 with otherwise correct dimensions
	1.2	Lower tube fixations		8 blades at 45° of each other; fixed on flat square and on the exterior of hollow tube (dimensions written above)	See plan for shape of blades (22*60*330 overall) Tubes -> see dimensions above Square side	260	Blades are 22*60*330 indented rectangles Squares are not hollow in the middle Squares are screwed on a plate Not all tubes need to be fixed like this (1-3 is OK)







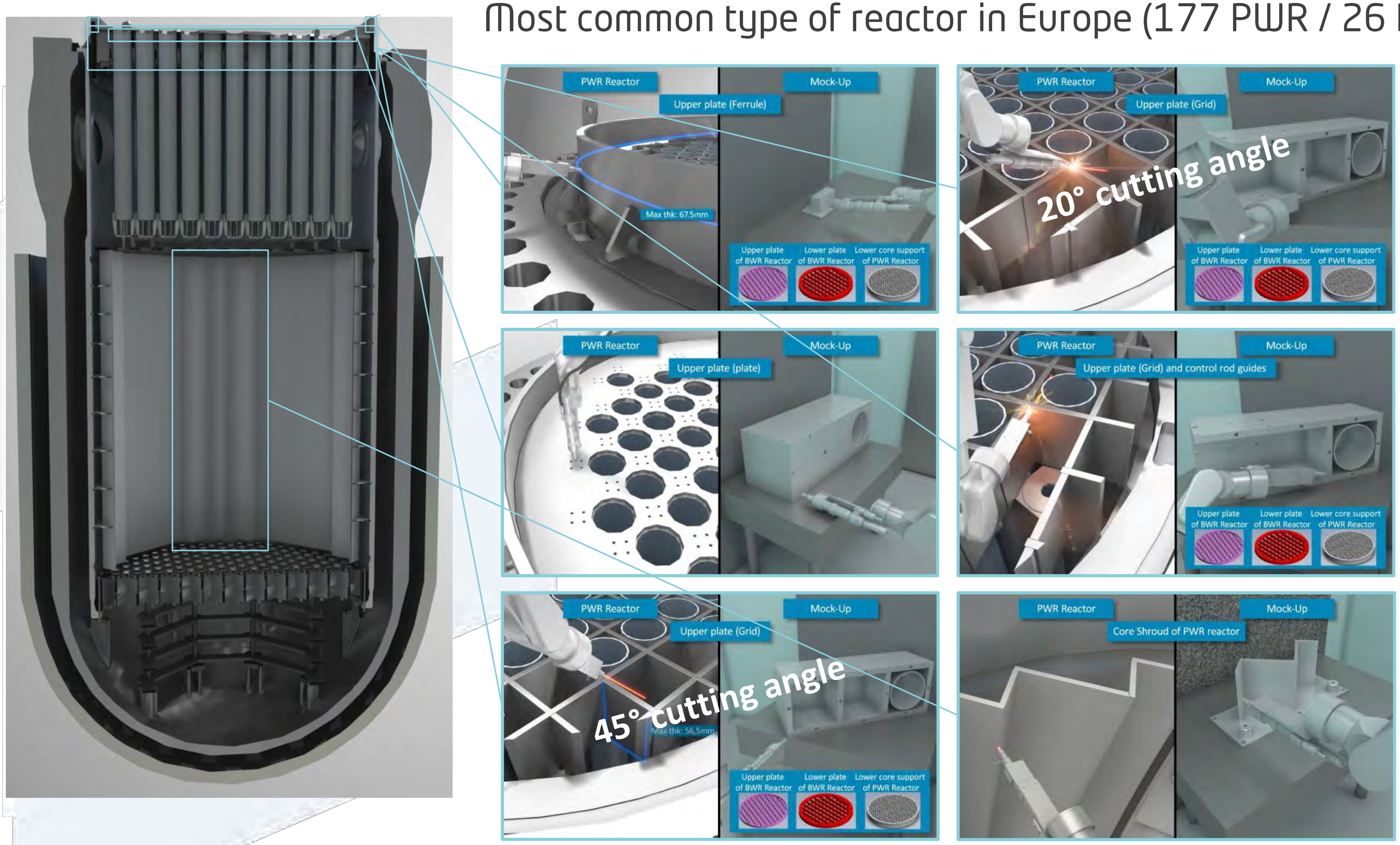




Demonstrators

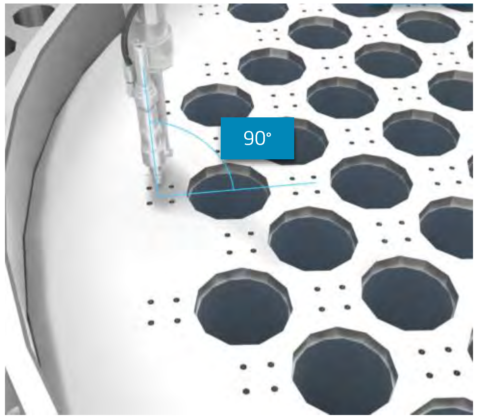
PWR reactor – Main challenges

Most common type of reactor in Europe (177 PWR / 26 BWR) among 22 countries



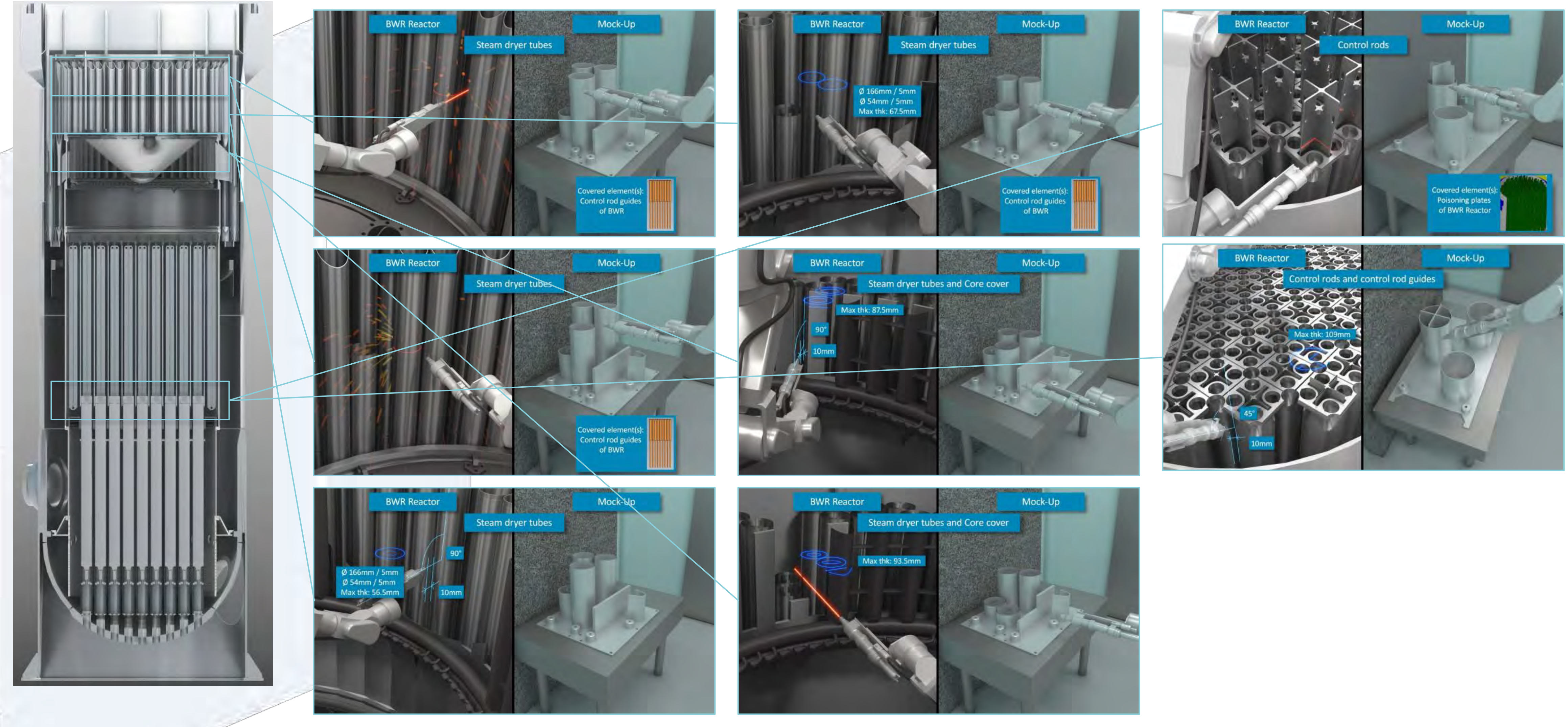
Recommended parameters

- Stand-off : 30 mm (in-air) / 10 mm (UW)
- Cutting angle: 90°
- Power :
  - In-air laser head: 14 kW
  - Underwater laser head: 16 kW



Demonstrators

BWR reactor – Main challenges

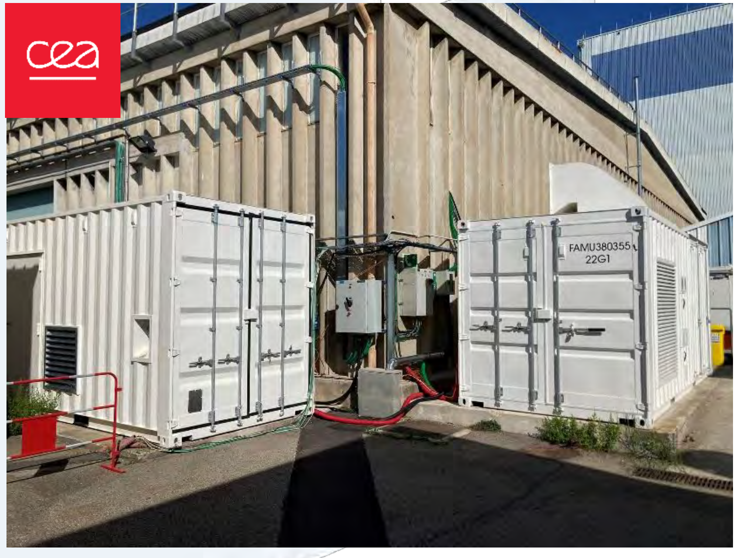


Demonstrators

In-air demonstrator’s configuration – HERA facility

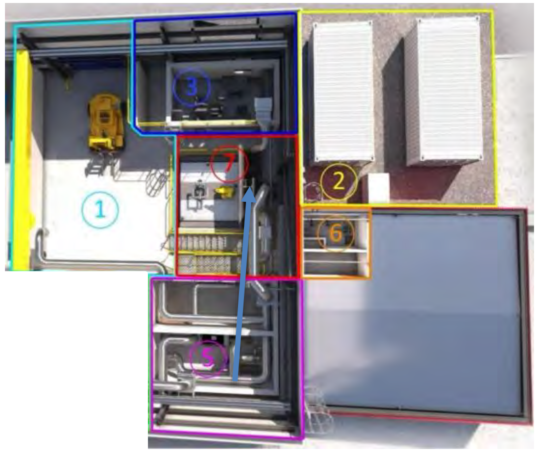
Cutting cell

Utility zone : shelters area



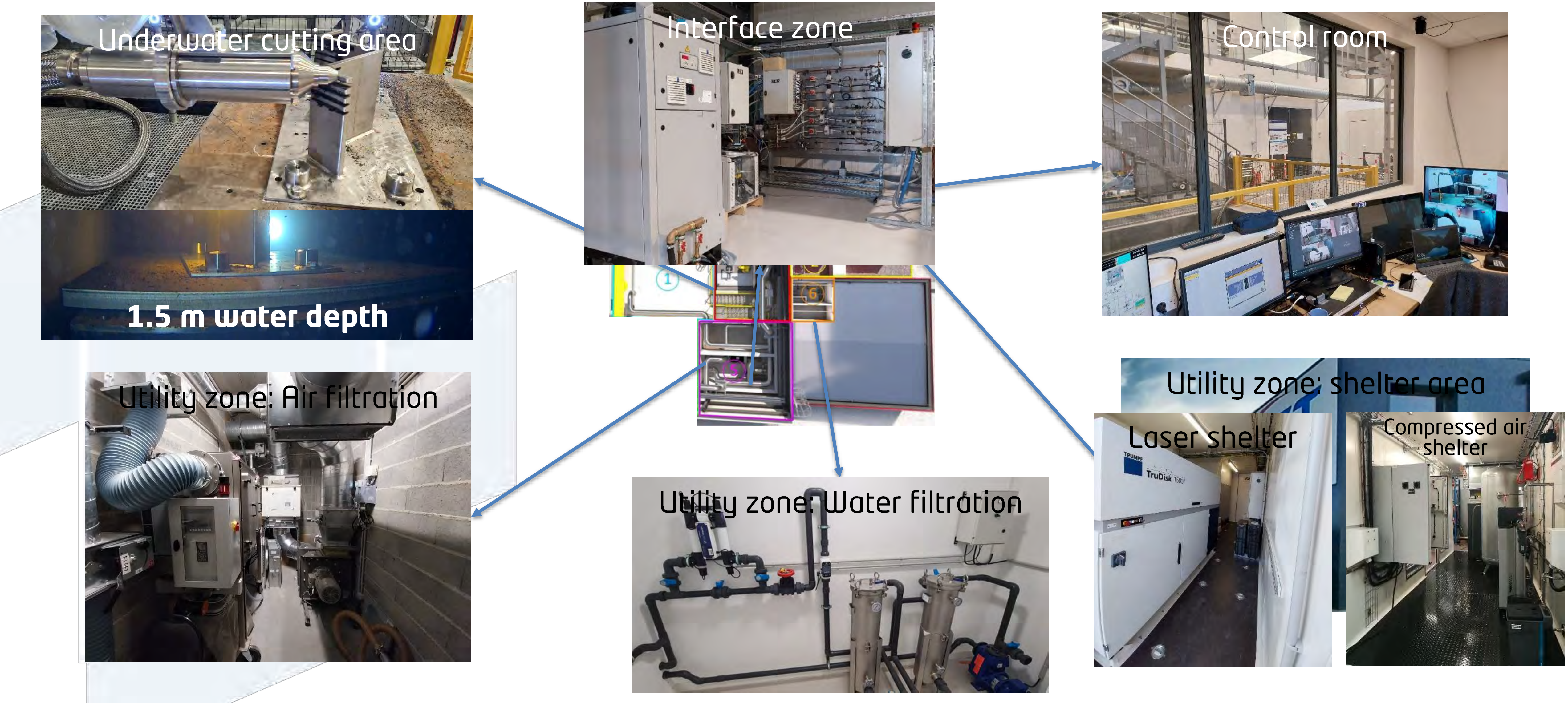
Demonstrators

Underwater demonstrator’s configuration



Demonstrators

Underwater demonstrator's configuration



Demonstrators

Main tests

- **Performance:**
  - **Laser performance** tests (highest cutting speed on stainless steel mock-ups for various thicknesses & geometries.
  - Cutting tests of PWR/BWR **reactor components** (with representative configurations; e.g., cutting angles, standoff, maximum thickness to cut).
  - **Availability rate** of the system during cutting operations
  - Show laser cutting tools can do **specific cutting shapes** (not just linear cutting moves).
- **Ease of use:**
  - Demonstration of **underwater operation** (including umbilical management with robotic arm moves; and turbidity/visibility underwater)
  - **Versatility** of underwater cutting head (to cut in-air environment).
- **Compliance with safety and regulatory standards**
  - Checking the impact of **laser beam residual power** for cutting operations closed to and in the direction of RPV.
  - Evaluation of **dust generation** (non-adherent scories).
  - Checking aerosol collection efficiency of the **laser collection system** (with collection head).

Results

Highlights

Laser cutting technology allows *in-situ* dismantling of PWR and BWR

- **200 cutting operations** performed
- Every mock-up has been correctly cut
- Limits of the cutting tool have been explored
- Cutting scenarios have been assessed and adjusted
- **Laser beam residual power:** most challenging configurations assessed, and impact mitigated
- Aerosols generation concentration: laboratory tests confirmed at larger scale
- Hydrogen risk: lower explosive limit not reached

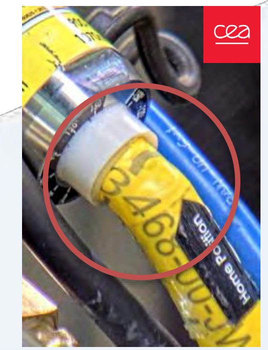
Underwater

In air

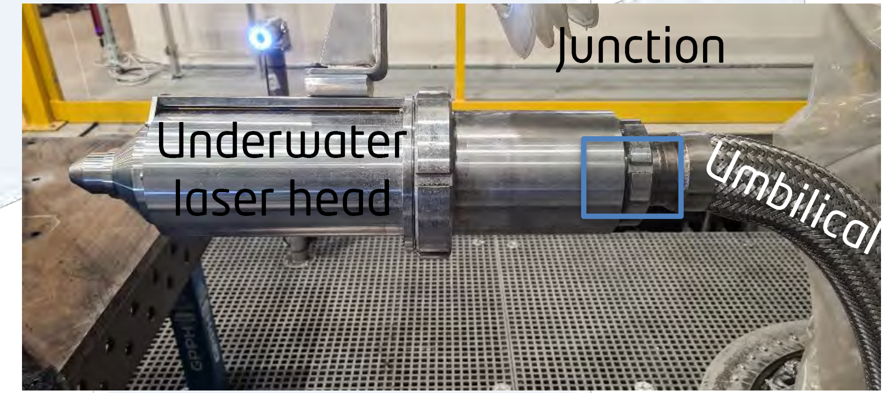
Results

Qualification tests

After 100 cutting operations



In-air (left) and UW (right) connections



- No damage after 100+ cutting operations
- Watertight (monitored with sensors)

➔ **Proven robustness of the underwater tool**

Evolution of water clarity

Before first cutting operation

After 80 cutting operations

After 110 cutting operations

18 water samples to see water clarity
Laboratory analysis for turbidity
[Fe] < [Ni] << [Cr]

Water: 45 m^3
Flow: 12 m^3/h
Filtration: 25 and 1 µm
UV bacterial treatment

New filter

Clogged filter

Total cutting length: 23 m

<u>Possible mitigation means:</u>

- Water volume inside RPV: **485 m^3**
  ➔More dilution in real dismantling conditions
- Optimized filtration system based on lab. analysis

Results

Performance tests

Main goal:
Explore the limits of the laser cutting tools

100 mm-thick block cutting

- ✓ Optimal speed
- ✓ Assist gas flow rate: low influence on cutting performances

In-air cutting

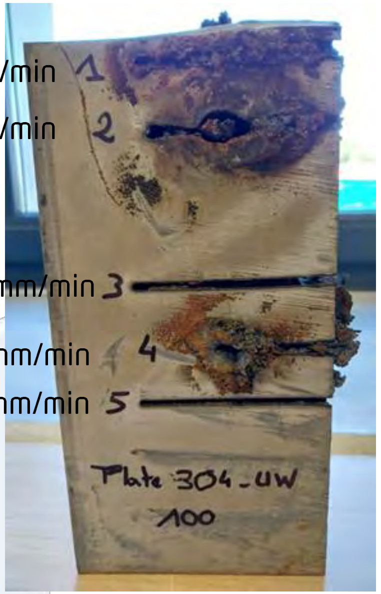
Front view

Side and rear view

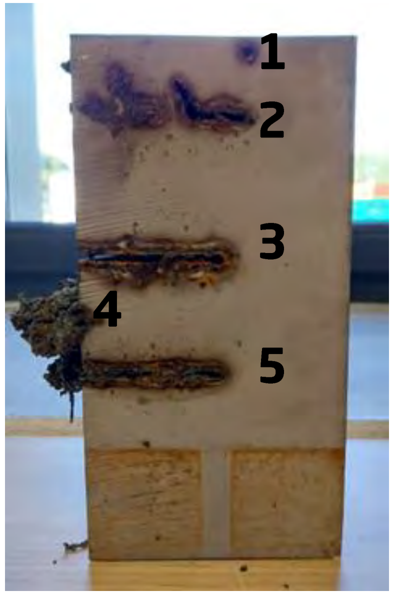
Underwater cutting

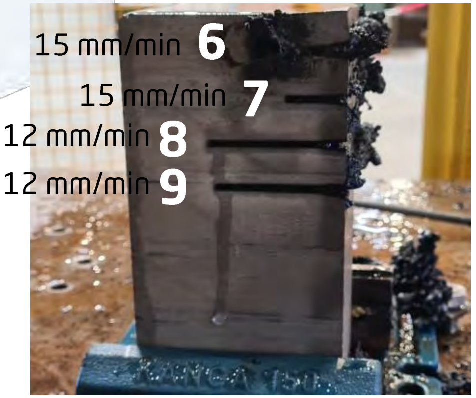
10° cutting angle

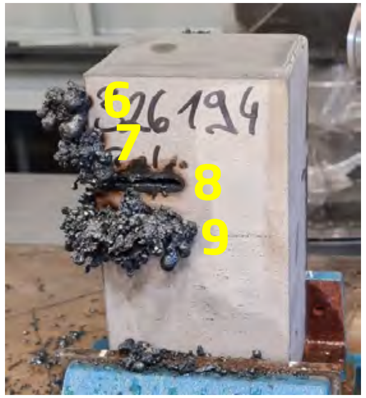
Front view



Rear view

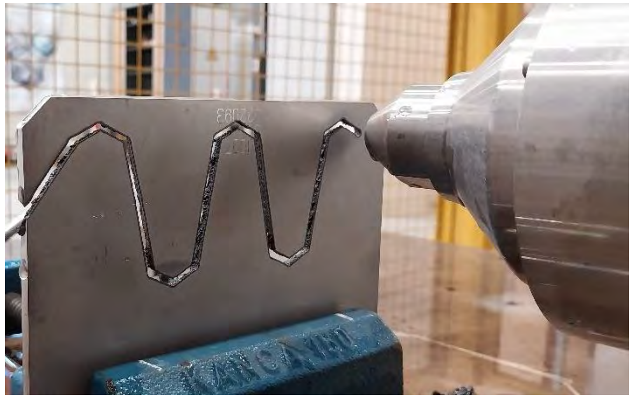






Complex trajectories:

- ✓ Addressing challenging configurations
- ✓ Waste package optimization



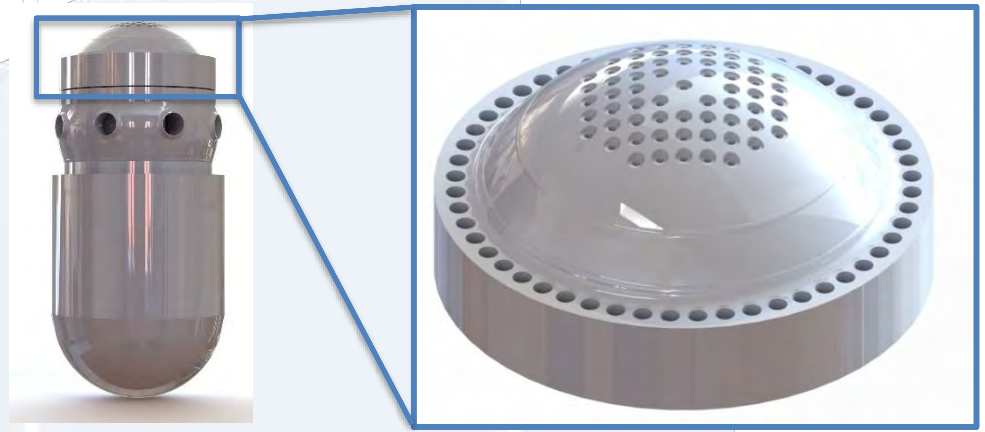
Results

Mock-ups tests

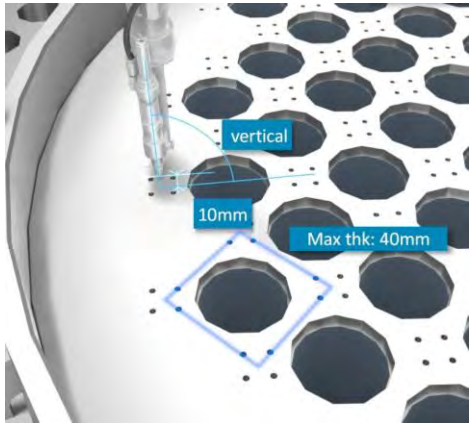
Main goal:
Cut PWR's upper plate *in-situ*

First and most challenging internal for PWR
Allows top-down cutting scenario

In-air



Step 1: upper plate



In-air

UW

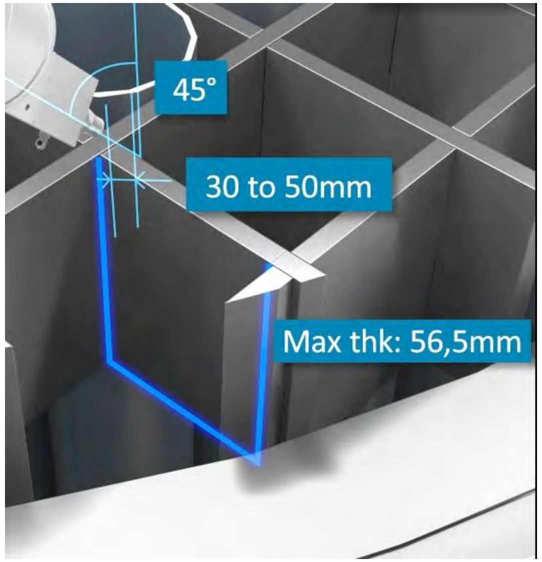
Results

Mock-ups tests

Main goal:
Cut PWR's upper plate *in-situ*

First and most challenging internal for PWR
Allows top-down cutting scenario

Step 2: Grid - 45°



In-air

UW

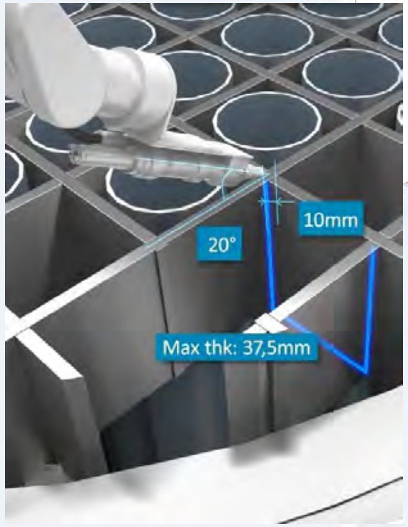
Results

Mock-ups tests

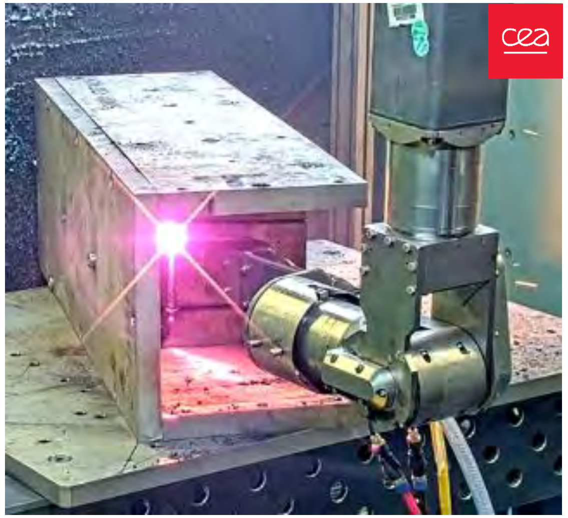
Main goal:
Cut PWR's upper plate
in-situ

First and most challenging internal for PWR
Allows top-down cutting scenario

Step 3: Grid - 20°



In-air



UW

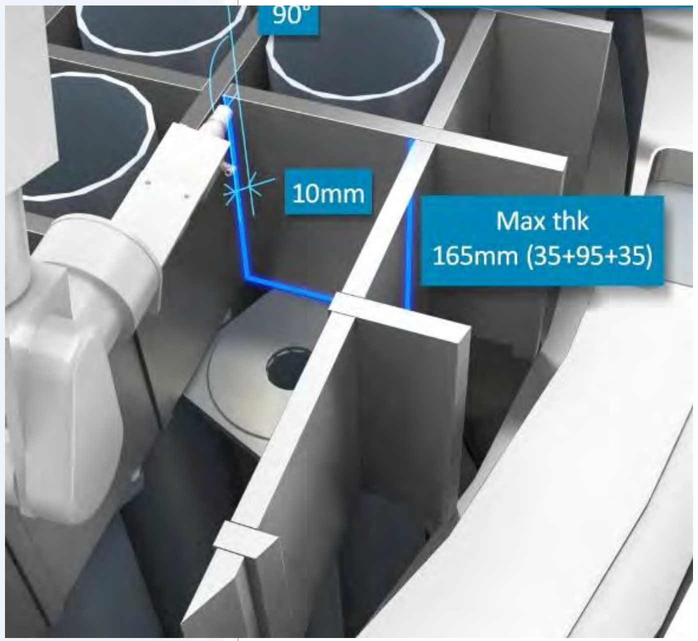
Results

Mock-ups tests

Main goal:
Cut PWR's upper plate *in-situ*

First and most challenging internal for PWR
Allows top-down cutting scenario

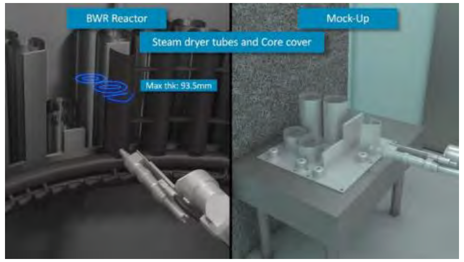
Step 4: Grid + control rod guide



In-air

Results

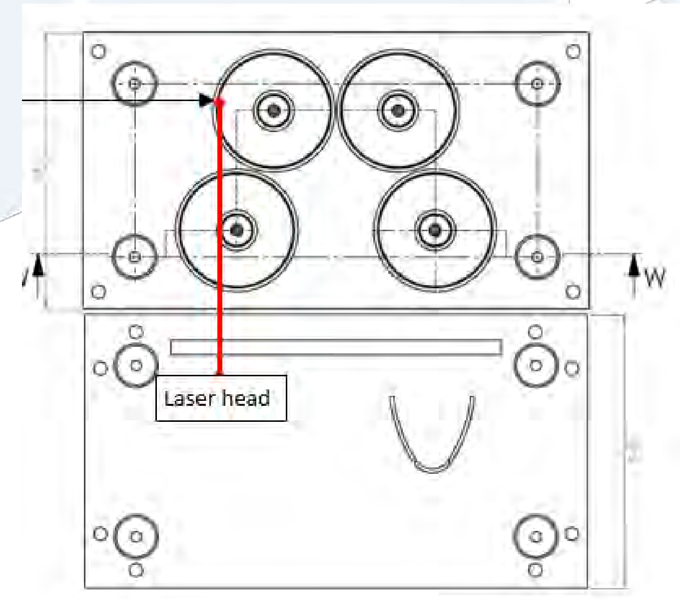
Mock-ups tests

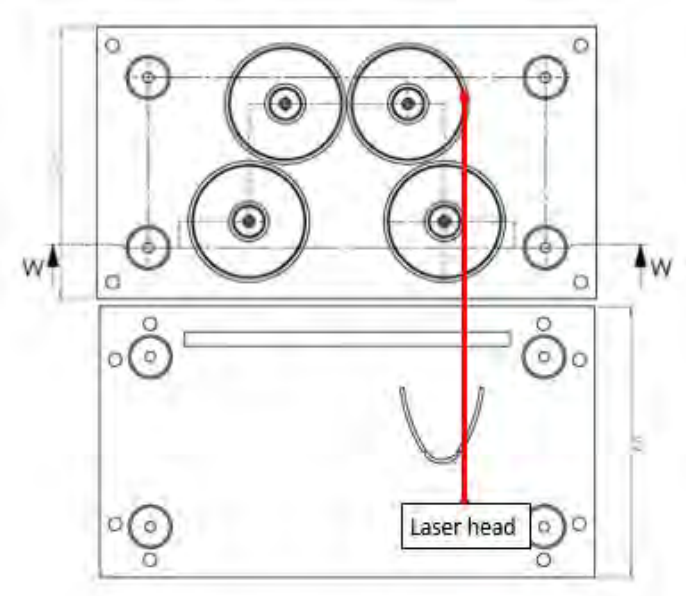


Main goal:
Assess the dismantling speed for tubes

In-air cutting highlights

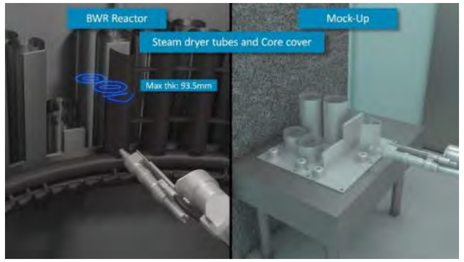
- ✓ Several layers cut in a single pass:
  Cumulated thickness = 125 mm
- ✓ Versatility of laser system: in-air cutting test performed with both in-air and underwater cutting heads
- ✓ Comparison of in-air and UW laser parameters:
  - ❖ In-air: 14kW - 7,5 mm/min
  - ❖ UW: 16 kW - 7,5 mm/min





Results

Mock-ups tests



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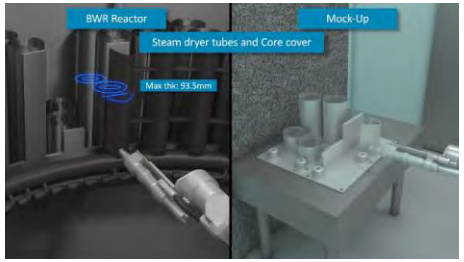
Underwater cutting highlights

Results

Mock-ups tests



Main goal:
Assess the dismantling speed for tubes

In-air cutting highlights

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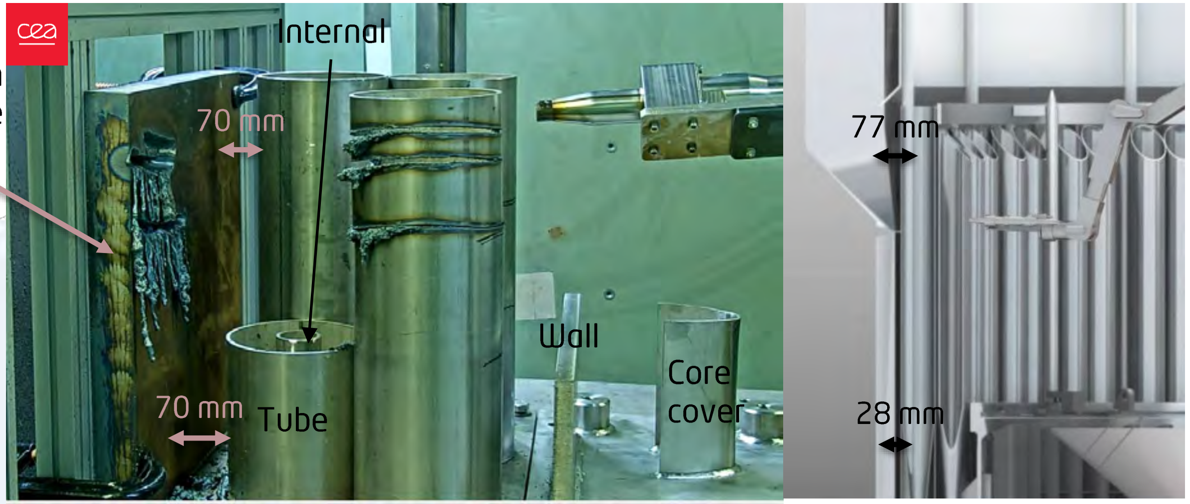
  Cumulated thickness = 125 mm
- ✓ Versatility of laser system: in-air cutting test performed with both in-air and underwater cutting heads
- ✓ Comparison of in-air and UW laser parameters:
  - ❖ In-air: 14kW - 7,5 mm/min
  - ❖ UW: 16 kW - 7,5 mm/min

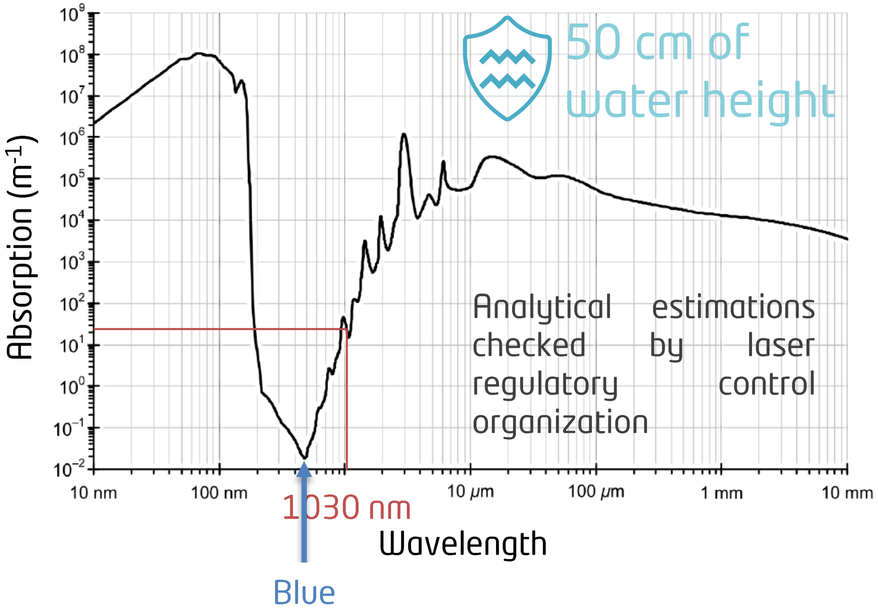
Underwater cutting highlights

Underwater:
Unable to cut several layers at the same time
➔ "Carve" a way through the tubes

Results

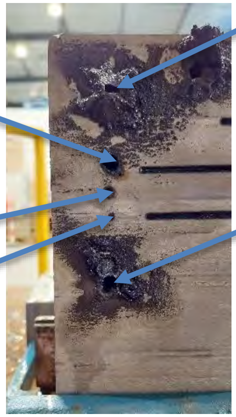
Laser beam residual power





Without laser parameters adjustments

Underwater

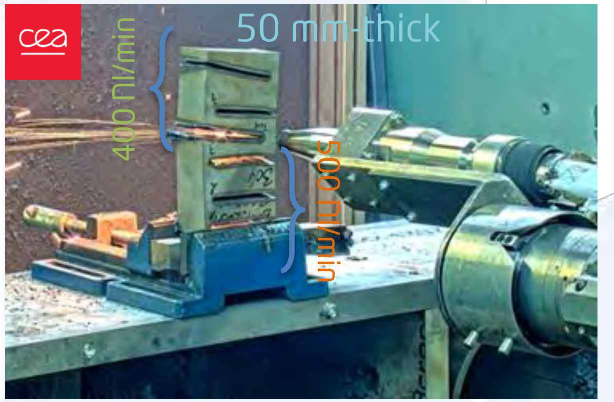


Results

Secondary waste

In-air assist gas flow rate's influence on mass loss

- ➢ 500 Nl/min flow rate: 1077 g/m
- ➢ 400 Nl/min flow rate: 633 g/m



Static containment

Filtration

- In-air demonstrator
  2 filter changes
  Replacement if DP = 600 Pa
  ➔ 78 (out of approx. 100) laser cutting operations before 1st change
- UW demonstrator
  Krantz: Self-decloggable 2-stage filtration machine
  0 filter change (replacement if DP = 1000 Pa)
  - 1st filter: DP_{init} = 250 Pa / DP_{fin} = 530 Pa
  - 2nd filter: DP_{init} = DP_{fin} = 230 Pa

  ➔ Around 100 laser cutting operations

Mitigation means:

Dynamic containment ➔ recommendations Generic Safety Assessment:

Water mist collection, water spray, spray droplets, fixative coatings

➔ Combination of several mitigation measures to address every ranges of particle sizes

➔ Adjustment of laser parameters

➔ Further tests should be done to improve knowledge on the matter

Results

Aerosols generation

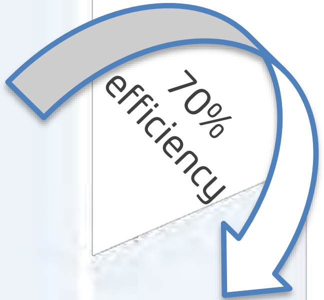
IRSN's conclusions:

- Pool scrubbing at 1 m depth reduces by a **factor ~ 2 to 3 the mass generation of particles**
- Underwater condition leads to a **slight increase of particle size** compared to non-underwater condition

Water influence on aerosols generation

In-air

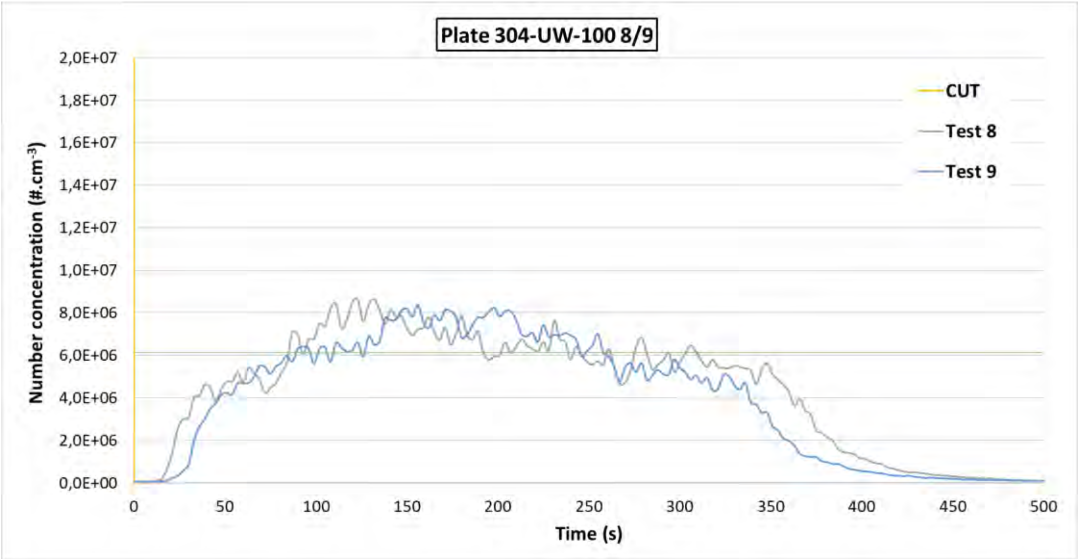
2.01 10^7 #/cm^3



Underwater

6.02 10^6 #/cm^3

PEGASOR's data synthesis



Laser VS PAC: based on available bibliography

	Aerosols generation		Particles size distribution	
	LASER	**PAC**	**LASER**	**PAC**
In air	20 g/m	80 g/m	D ≈ 200 nm	D ≈ 100 nm
Underwater	10 g/m	30 g/m	**D ≈ 250 nm**	D ≈ 50 nm

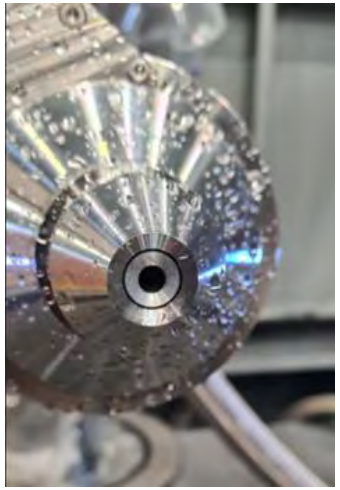
Results
Feedback

Public deliverable will summarize the results

TRL 7 is reached:

- Laser supply chain proven and established
- Performed complete **installation and commissioning** at CEA Marcoule:
  - Real nuclear site installation conditions: secured access, heavy lifting authorization
  - 3 weeks (without technical issues) / 2 operators from delivery to commissioning
- **Training**: only 1 week (robotic arm and laser system) / 2 operators (without remote operation experience)
- **Operational feedback**:
  - All the most challenging configurations can be cut in-air and underwater
  - Remote operations:
    - ✓ Stand-off: 5-15 mm underwater / Large tolerance in-air
    - ✓ Positioning difficulties addressed. Collisions occurred with no impact on laser head.
    - ✓ Laser heads can comply with different robotic arms
  - Visibility underwater:
    - ✓ Can be difficult to apprehend whether cutting is successful or not
    - ✓ Can be easily solved with suitable filtration system and flowrate
- **No maintenance** during operation: laser system availability rate > 95%.
- **Uninstallation/removal**: no special consumables / Special care to manufacturer's requirements
- **Safety**: main topics addressed
  - Laser beam residual power: no risk underwater / managed in air
  - Aerosols generation: water depth influence, assist gas influence in-air, additional collection system allows reduction of aerosols generation tested during LD-SAFE for specific configurations
  - No radiolysis risk: LEL far from reached

Before



After

Robust design of the laser shelter: Optical calibration unaffected after transportation from CEA Marcoule to Onet's Technocentre

Collection head

Results

Cost & time

Laser cutting technology allows significant cost & time reductions in comparison with the most common tools used in the decommissioning market (mechanical tools)

- **CAPEX:**
  - 1 unit → **50% cost reduction** / 10 units → **70% cost reduction**
  - Mechanical tools: Numerous lifting machines and bespoke systems
  - Laser technology: **Major investment is reusable** (installed in non-nuclear area)

- **PWR's segmentation activities duration:** calculated as follows

Cutting number by component		Unit processing time		Total time				Unit processing time		Total time			
44	UPPER PLATE	53	min	2332	min	2332 Minutes =	39 Hours	11	min	484	min	484 Minutes =	8 Hours
15	TOP FERRULE	65,7	min	985,5	min	985,5 Minutes =	16 Hours	24	min	355,5	min	355,5 Minutes =	6 Hours
15	LOWER FERRULE	67,6	min	1014	min	1014 Minutes =	17 Hours	26	min	384	min	384 Minutes =	6 Hours

	Minutes	Hours	Days	Days + Hazards	Year	Month
Total processing (preparation / cutting / removal)	92759	1546	155	232	1,15	13,8
Cutting processing only	15341	256	26	38	0,19	2,3

➔ Using laser technology: **30% time reduction**