ADVANCEMENT OF FUNDAMENTAL TECHNOLOGIES FOR RETRIEVAL OF FUEL DEBRIS

REMOTE CONTROLLED LASER CUTTING AND DUST GATHERING

PROJECT OF DECOMMISSIONING AND CONTAMINATED WATER MANAGEMENT IN THE FY2017 SUPPLEMENTARY BUDGET

PERFORMANCE REPORT

2019/07

CONTENT OF THE PRESENTATION

1. Background / Objective of Research

2. Project Outcomes

3. Application to Fukushima site

1. BACKGROUND & OBJECTIVES (REMINDER)

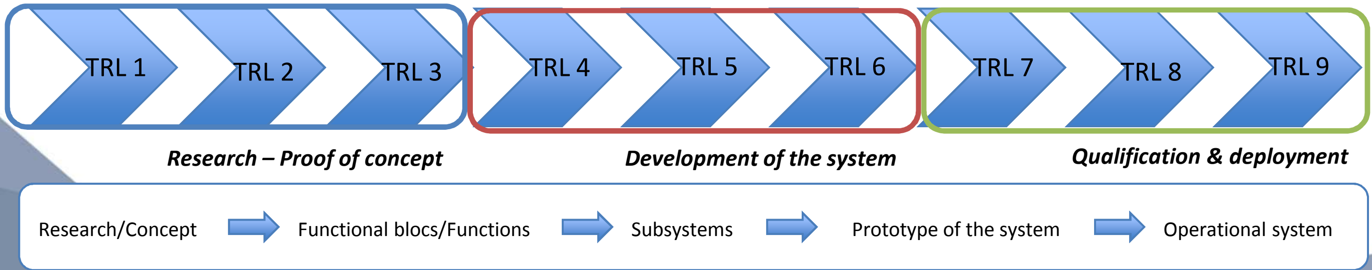
Fundamental Technologies for Fuel Debris Cutting

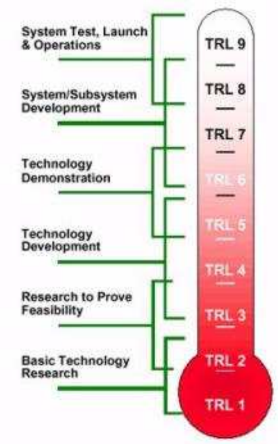
Reasons why this research is necessary

- Development of cutting and collection technologies on fuel debris with the Fukushima Dai-ichi damaged reactors environment
- Several cutting technologies developed depending on cutting configuration with TRL 3/6 to be developed further for site deployment (TRL5/7 foreseen at the end of the project)
- Management of secondary outlets, needing these outlets to be measured and collected

Use of the research results

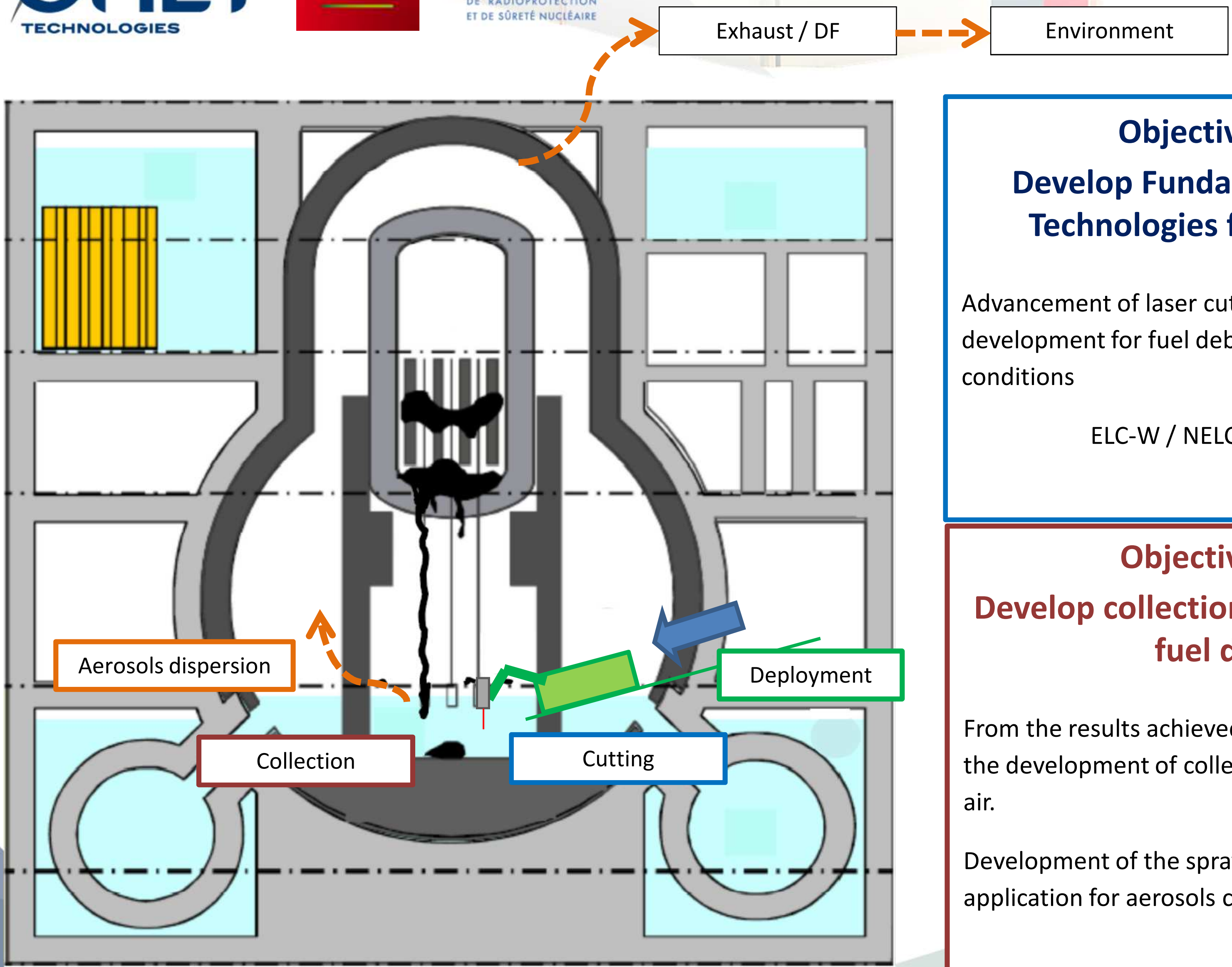
- Advanced cutting technologies with combined collection technologies for the different configurations expected to be found on site
- Extend secondary outlets knowledge for collection and treatment purpose
- Alpha emitters behavior for dispersion and release control





International TRL scale used for the studies

1. Background & Objectives (reminder)



Objective N° 1

Develop Fundamental Cutting Technologies for fuel debris

Advancement of laser cutting technologies development for fuel debris cutting in severe conditions

ELC-W / NELC-A / NELC-W

Objective N° 2

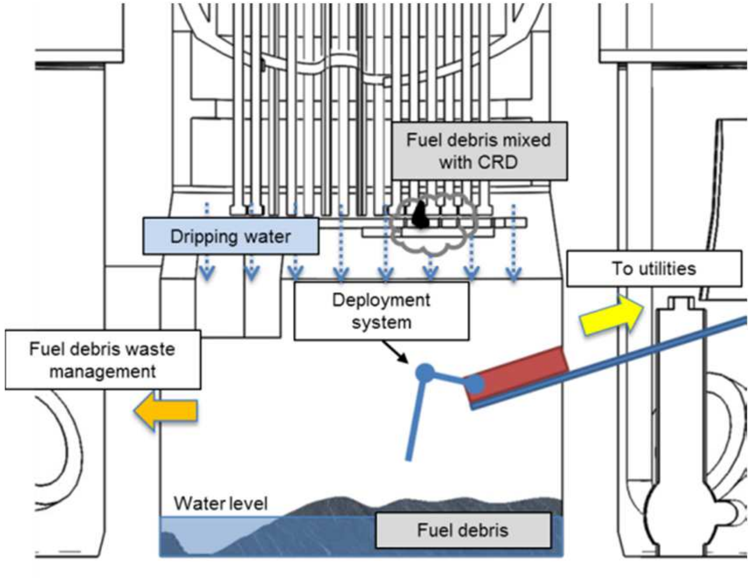
Develop collection technologies for fuel debris

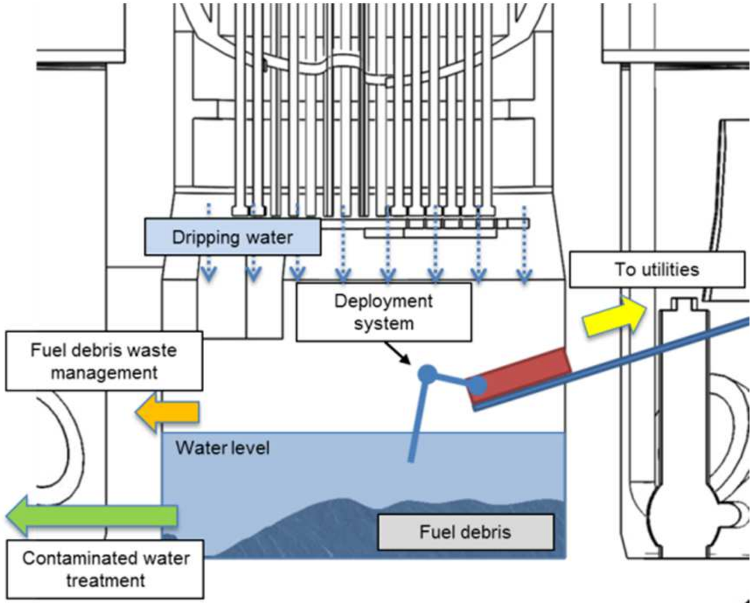
From the results achieved in FY2017, continue the development of collection technologies in air.

Development of the spray scrubbing technology application for aerosols collection.

1. BACKGROUND & OBJECTIVES
OBJECTIVE OF RESEARCH (REMINDER)

Strategy for cutting fuel debris and collecting dust and fumes





Environment assumptions - In-air conditions

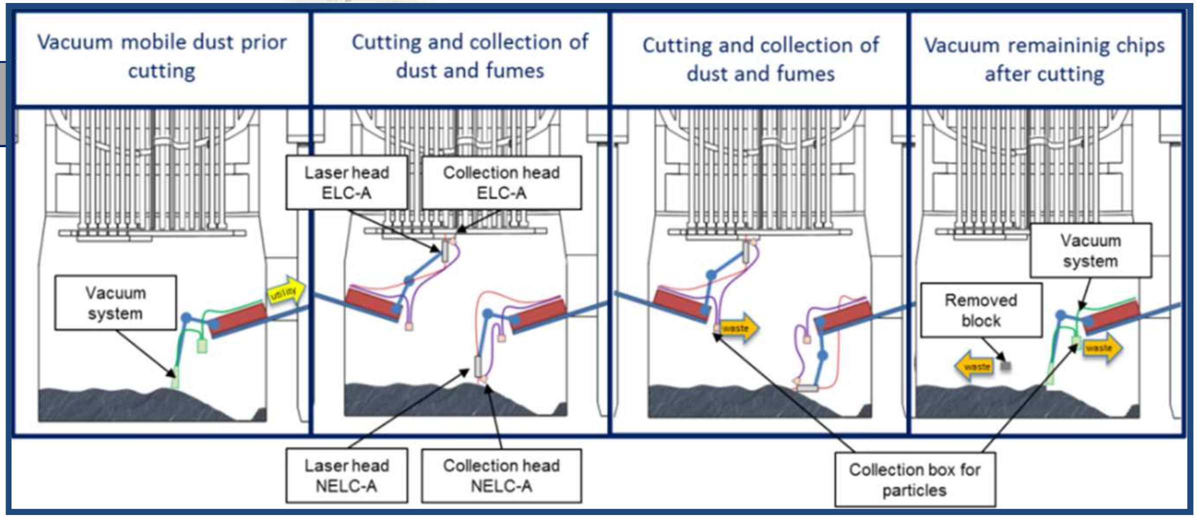
- Fuel debris in air with dripping water
- Accessibility to fuel debris through robotics means (out of scope)
- Massive debris emerging from water
- Fuel debris inside CRD and mixed with structure
- Utilities outside pedestal including HVAC (treatment out of scope)
- Waste management of fuel debris as solid waste (out of scope)

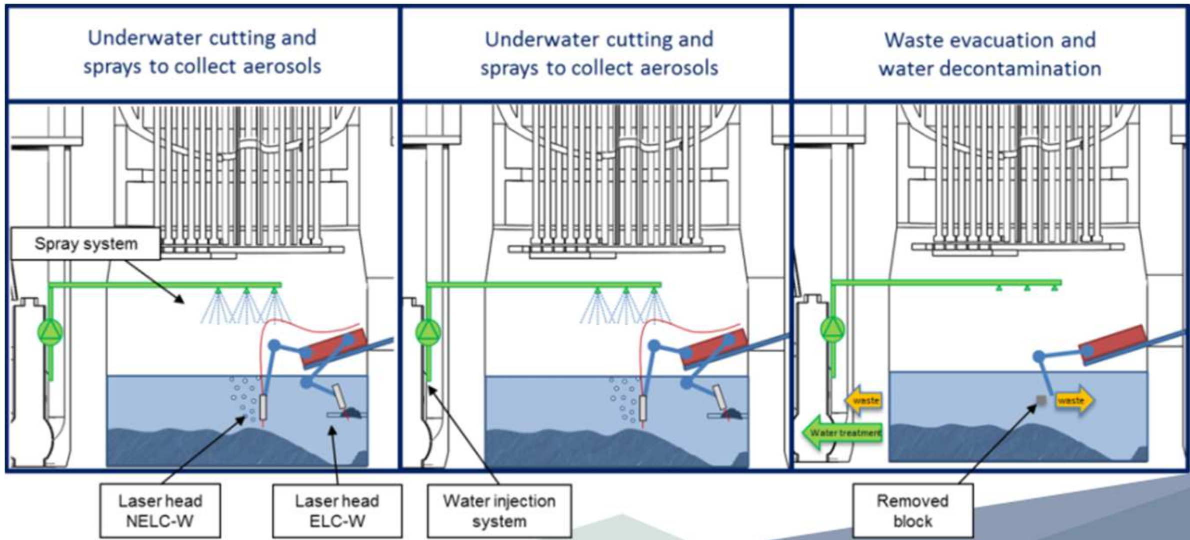
Environment assumptions - Underwater conditions

- Fuel debris underwater
- Accessibility to fuel debris through robotics (out of scope)
- Massive debris inside water and smaller debris inside water
- Utilities outside pedestal including HVAC (treatment out of scope)
- Waste management of fuel debris as solid waste (out of scope)
- Contaminated water treatment (out of scope)

1. Background & Objectives
Objective of Research (reminder)

Strategy for cutting





Acronyms:

- *ELC-A: Emerging Laser Cutting in Air*
- *NELC-A: Non Emerging Laser cutting in Air*
- *ELC-W: Emerging Laser Cutting under Water*
- *NELC-W: Non Emerging Laser Cutting under Water*

2. Project Outcomes

1. Laser cutting development

2. Dust and Fumes Collection in air development

   Final outcomes of the technologies

3. Spray Scrubbing Development

   Final outcomes on spray scrubbing

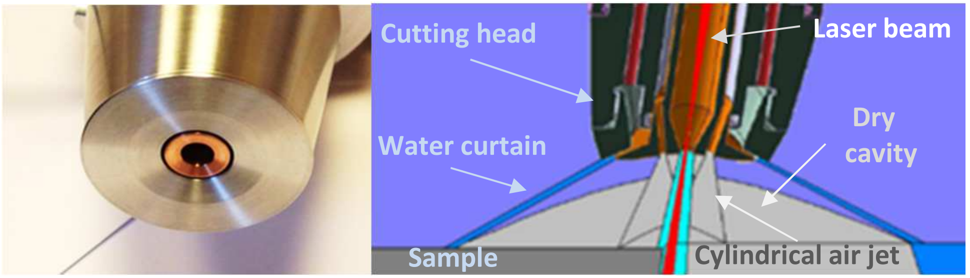
4. Dust & Fumes data acquisition

   Final outcomes on dust & fumes

ELC-W Development

Principle of the ELC-W cutting head: Dry cavity concept for cutting under water

- Laser beam propagates in air to avoid water absorption
- Dry cavity coaxial to the laser beam
- Molten material ejected by the assist gas airflow
- Water nozzle implementation for better stability and homogeneity

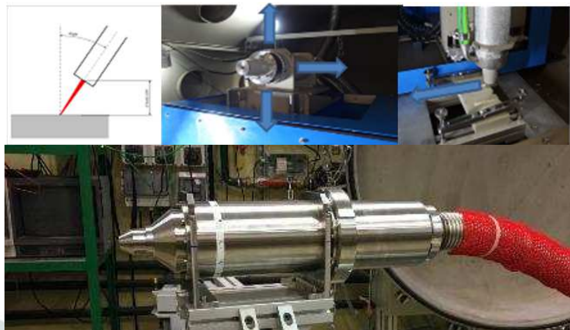


FY2017 Progress:

- Mechanical design corrections made to the ELC-W head model (beam centering, shutter operation, cylindrical airflow uniformity optimization)
- Characterization campaigns of the dry zone without laser and without kerf to optimize the parameters ➔ low water flow, low thickness of the water curtain and high air flow

FY2018 progress:

- Tolerance assessment tests underwater (stand-off, tilt, position – with/without water curtain, 35/560 cm H_2O)
  - Good results on ZrO2 30 mm thick samples : 5 to 20 mm stand-off , 20° tilt, different positions
  - No water curtain nozzle with the new airflow parameters
- Industrial design and manufacturing the first operational cutting head

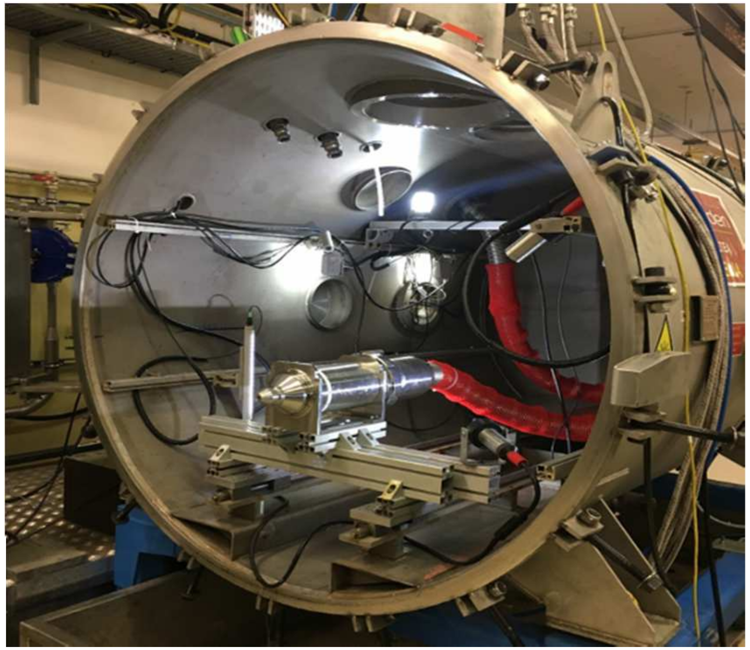


ELC-W Development

Specifications of the manufactured ELC-W cutting head

Specified by the CEA, designed based on CEA prototype, made by an industrial laser head manufacturer

- Operational prototype: 60 cm long, 15 cm diameter, 20kg without umbilical cable, no electronic components, water proof
- Simplified nozzle architecture : no water curtain
- Robust and efficient shutter (stop bubbles for video observation)
- Safety functions integrated: open and close shutter sensors, temperature sensors & thermoswitch
- Design for 16 kW
- Easy umbilical connection



Pre-design of umbilical and utility unit

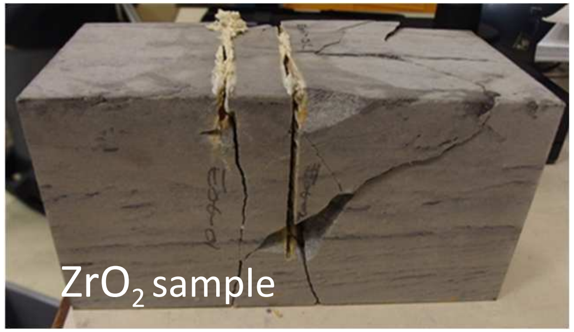
- Architecture done and safety functions defined
- Umbilical possibilities defined

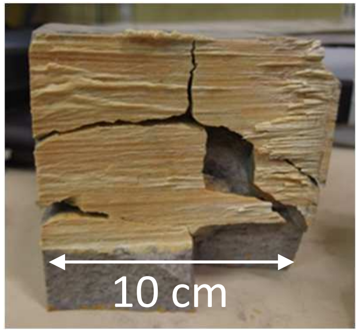
ELC-W Development

Tests results – Performances @8 kW

ZrO_2 :

- 100 mm cut under 560 cm of H_2O: the same cutting performances as in AIR
- For every tested thickness under 35 or 560 cm of H_2O the same maximum performances as in air had been reached





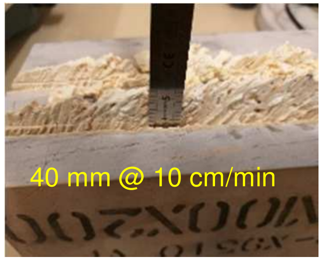
Stainless steel:

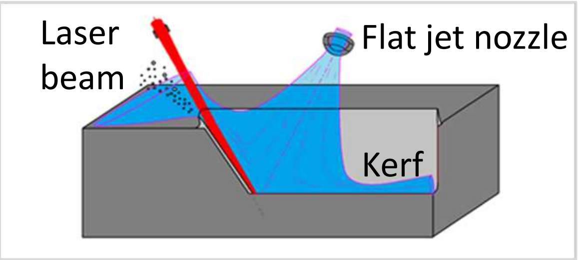
- Only 40 mm cut under 560 cm of H_2O instead of 100 mm in Air

Zirconium alloy :

- 30 mm cut under 560 cm of H_2O

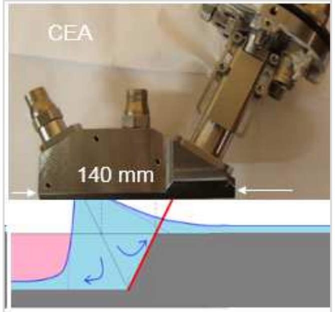
NELC-A Development





Principle:

- Assist gas air jet inclined to eject the molten material form the kerf
- Kerf's depth reaches 40 mm in nominal conditions



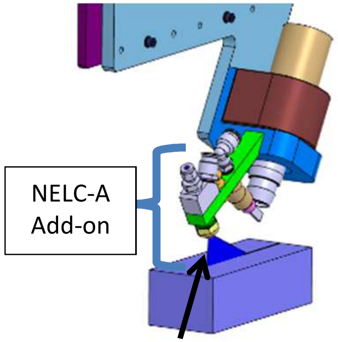
FY2017 progress:

- Flat jet nozzle implementation → compact design validation
- Process robustness validation (stand-off, tilt, starting point, cutting speed): very satisfactory results obtained

FY2018 progress:

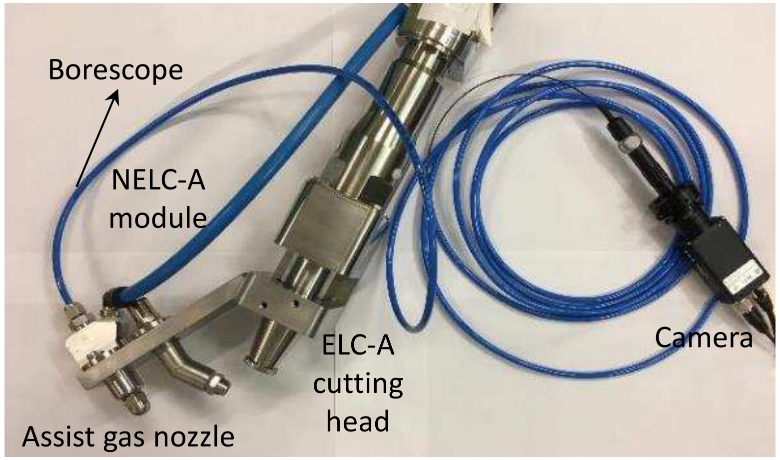
- Design, manufacturing and tests of a mechanical module added to the ELC-A industrial head for non emerging cuts (NELC-A)
- Study of the monitoring of the process

ELC-A industrial head



Flat jet nozzle

Cutting process monitoring

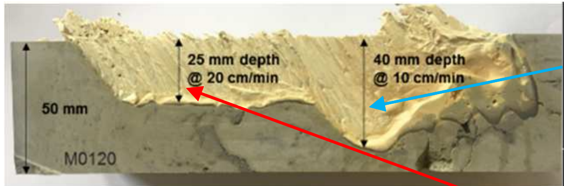


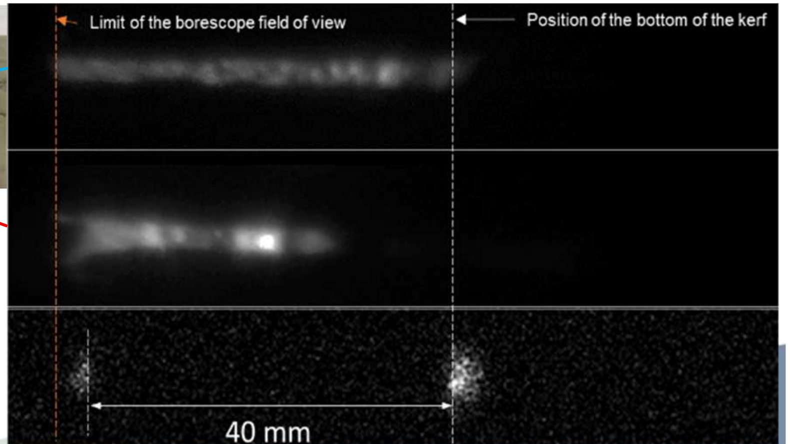
Device features:

- Remote observation of the laser cutting process
- Small diameter fits inside the assist gas nozzle
- No intrusiveness : the same cutting performances as without the borescope → 40 mm depth @10 cm/min
- 2 operation modes

Ranging Mode Operation:

- Distance measurement between cutting head and work piece
- Measurement accuracy ~ ±2 mm





Depth Gauge Mode Operation

- Depth measurement between of the kerf
- Measurement accuracy ~ ±2 mm

Real-time visualization of the distance between the cutting head and the bottom of the kerf

2. Project Outcomes

1. Laser cutting development

2. Dust and Fumes Collection in air development

Final outcomes of the technologies

3. Spray Scrubbing Development

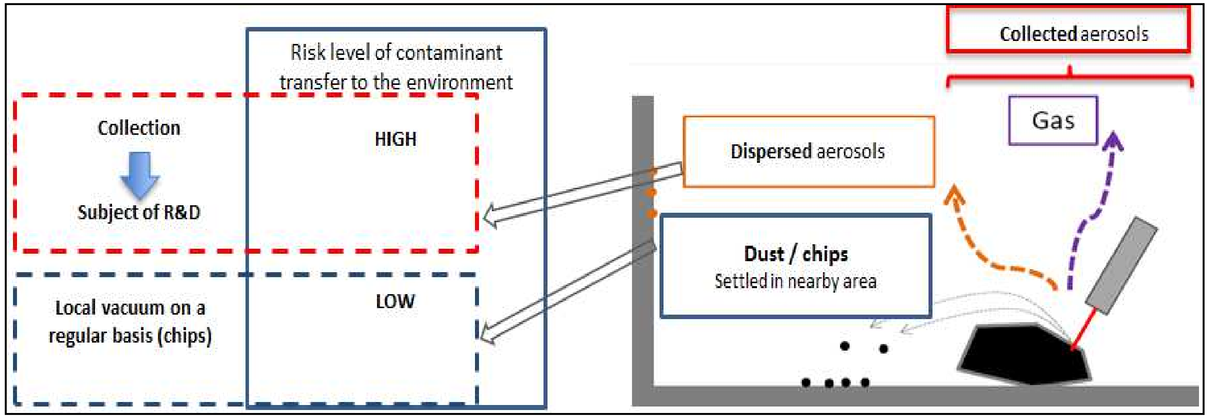
Final outcomes on spray scrubbing

4. Dust & Fumes data acquisition

Final outcomes on dust & fumes

Dust and fumes collection in air development – Overview (1/2)

Reminder: secondary outlets produced by laser cutting:



Laser cutting on fuel debris will produce:

- The fuel debris block that will be later recovered and treated as waste
- Chips, dross and dust that are settled in nearby area and that will need to be recovered and treated as solid waste
- Gas, fumes and aerosols that are dispersed, if not collected, in the PCV

Why do we focus on aerosols collection?

As secondary outlets of the laser cutting operations, they represent the most challenging matter:

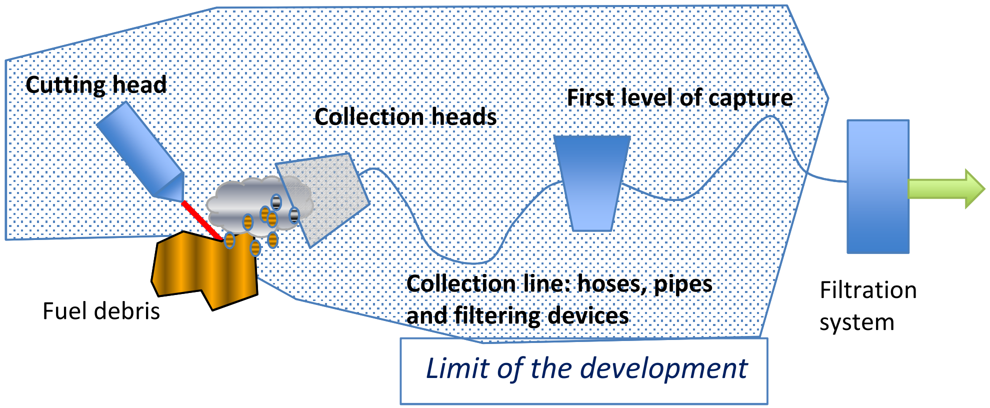
- From a safety point of view (risk of inhalable particles dispersion in case of loss of depression inside the PCV)
- From an operational point of view (necessity of a local collection)

Nevertheless, local collection cannot prevent the collection of some of the bigger particles that are produced such as chips, dross and dust: these particles must be also be treated by the collection system

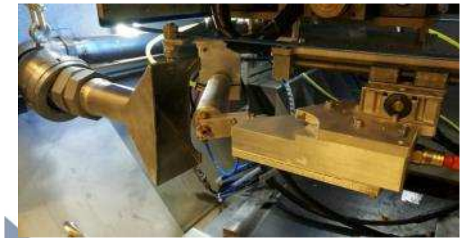
Dust and fumes collection in air development – Overview (2/2)

Axis of development from FY2016

- One collection head for each in-air configuration: ELC-A and NELC-A
- One first level of capture for the collected dust and chips
- One collection line to transport the aerosols, dust and chips to their filtration points



Progress FY2016 – FY2017



FY2016: Feasibility, first approach of in-air collection

FY2017: Specifications and design, manufacturing and tests of the first NELC-A and ELC-A collection heads embedded on the cutting head and cyclonic filter

- *Designed only for tests*
- *Study of influential parameters*
- *Very good performances in aerosols collection*

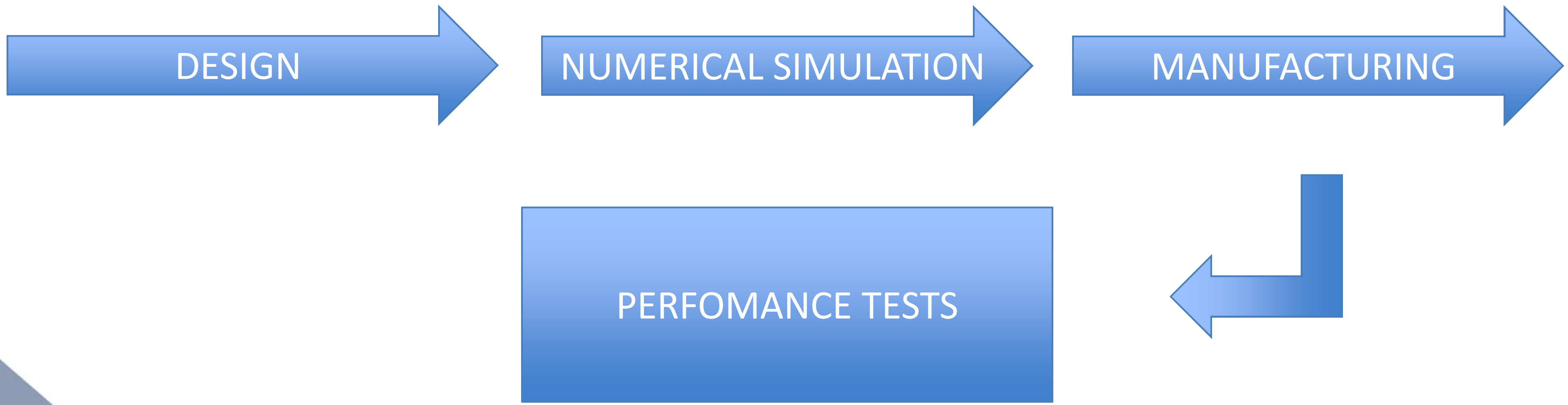
2. Project Items Outcomes

Dust & Fumes Collection in Air Development

Collection devices developments – NELC-A and ELC-A collection heads FY2018

Objectives of the FY2018: Collection head embedded on the cutting heads, optimization of the dimensions in order to ease operations on site, aerosols collection efficiency unaltered compared to FY2017

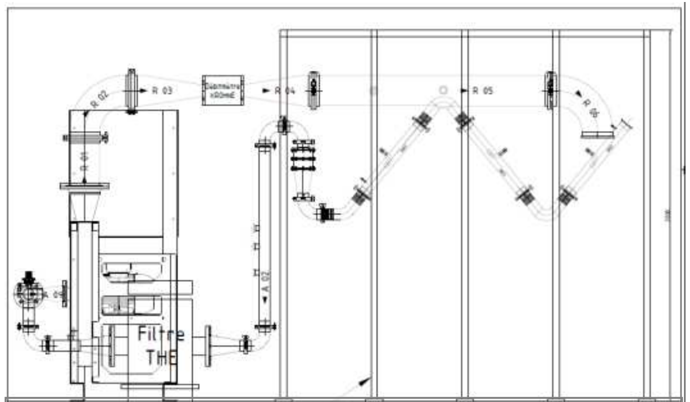
Phases of development: Design, numerical simulations, manufacturing of prototypes, tests to measure the performances



Collection devices developments – Filtration and transportation line

Objectives of the FY2018: Study and realization of a particles transportation line in which air is blown instead of being sucked and of a new first level of capture

Sedimentation filter: It aims to be placed in the transportation line close to the cutting point and to stop biggest particles. It is designed to work in every orientation

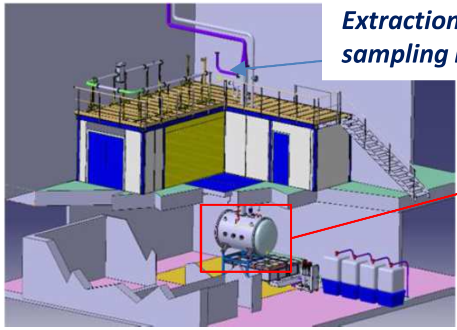


Drawing of the collection loop used for the tests

Tests with new transportation line: Transportation tests have been realized with the new transportation line. Positive results obtained but interfaces with the collection heads need to be improved and complementary tests need to be performed

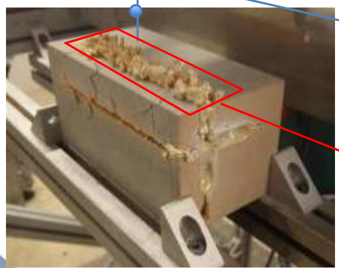
Collection performance tests – Overview

- The tests are performed in the DELIA facility (Saclay) on cast fused Zirconia blocks



- Secondary outlets produced by laser cutting:

Laser cutting on fused cast Zirconia block will produce:



Fused cast Zirconia block after a cutting operation

- Airborne aerosols: they are released in air and may present a safety problem for workers and environment on site if not properly collected
- Chips: the main part of the melted mass will stay stuck on the block, some of them will fall from it
- Dross and dust: they are settled in nearby area of the cutting point

Chips

Dross and dust

Collection efficiencies – Results for NELC-A configurations

- **Results for closed and open NELC-A configuration with cutting conditions**

The results are to be taken as order of magnitude

Configuration	Aerosols collection efficiency	Integrated aerosols collected mass (g)	Integrated aerosols dispersed mass (g)	Chips, dross and dust mass recovered (g)
NELC-A – Configuration 1	**> 98%**	15	0,3	11
NELC-A – Configuration 2	**> 96%**	11	0,4	11

Integrated aerosols collected mass: Aerosols mass that has to be treated by a filtration system

Integrated aerosols dispersed mass: Aerosols mass released that must be treated by HEPA filtration

Chips, dross and dust mass recovered: Recovered in cyclonic filter, mass fraction that will be treated as waste

View of the NELC-A collection head mounted on the cutting head inside DELIA

View of the block after 2 cuts (NELC-A configuration)

2. Project Items Outcomes

Dust & Fumes Collection in Air Development

Collection efficiencies – Results for ELC-A configurations

- **Results for ELC-A configurations with cutting conditions**

  The results are to be taken as order of magnitude

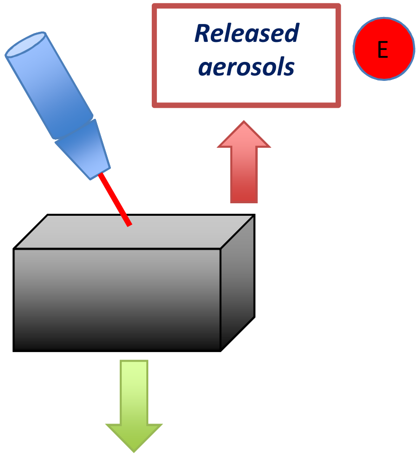
Configuration	Aerosols Collection efficiency	Integrated aerosols collected mass (g)	Integrated aerosols dispersed mass (g)	Chips, dross and dust mass recovered (g)
ELC-A - Configuration 1	**> 99%**	4	0.001	41
ELC-A - Configuration 2	**> 99%**	10	0.006	22
ELC-A - Configuration 3	**> 99%**	24	0.02	32


Tests implementation in DELIA

View of the block after 4 cuts (ELC-A configuration)

Projection of aerosols release – (Tentative/Order of magnitude) (1/2)

- **Fuel debris laser cutting:**



- *Cut block with adhering chips* (A)
- *Chips, dross and dust that fall* (B)
- *Chips, dross and dust collected in collection system* (C)
- *Aerosols collected and transported to a filtering point* (D)

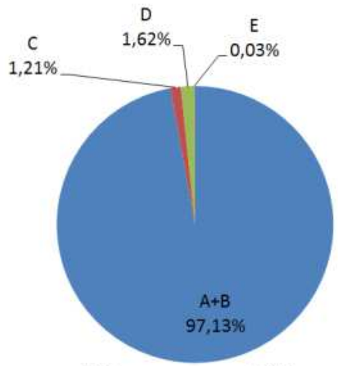
Retrievable and treatable as solid waste

- **1 kg cut block in NELC-A:**

Configuration	A	B	C	D	E
NELC-A – Closed	Approx 1Kg + adhering chips	B < 200 g	~15 g	~20 g	~0.4 g
NELC-A – Open	Approx 1Kg + adhering chips	B < 200 g	~15 g	~15 g	~0.5 g

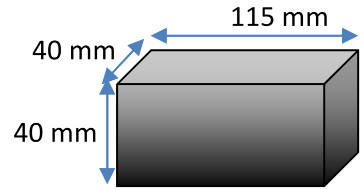
~1230 g of retrievable solid waste

0.4 – 0.5 g of released aerosols



Mass repartition

Released aerosols are inferior to 0.03 %tw of cut and retrieved fuel debris



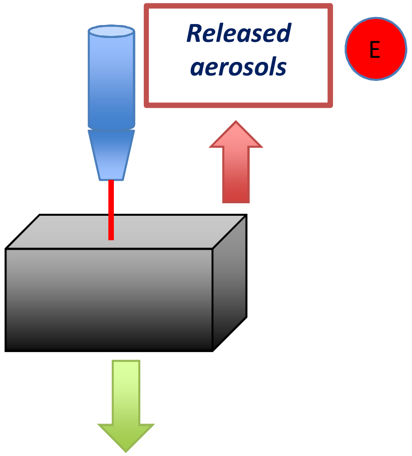
Theoritical block of fuel debris:

- *V = 184 cm³*
- *W = 993.6 g (density = 5.4 g/cm³)*
- *270 mm of cut*
- V_{kerf} *= 43 cm³*
- W_{kerf} *= 233 g*

2. PROJECT ITEMS OUTCOMES
DUST & FUMES COLLECTION IN AIR DEVELOPMENT

Projection of aerosols release – (Tentative/Order of magnitude) (2/2)

- **Fuel debris laser cutting:**



- *Cut block with adhering chips* A
- *Chips, dross and dust that fall* B
- *Chips, dross and dust collected in collection system* C
- *Aerosols collected and transported to a filtering point* D

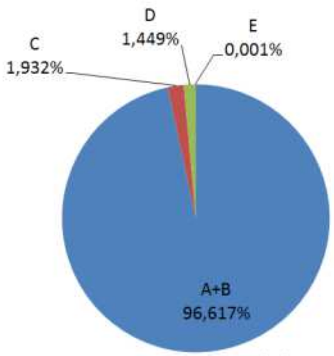
Retrievable and treatable as solid waste

- **1 kg cut block in ELC-A:**

Configuration	A	B	C	D	E
ELC-A – Configuration 1	Approx. 1 kg + adhering chips	B < 26 g	~25 g	~2.5 g	~6.10^{-4} g
ELC-A – Configuration 2	Approx. 1 kg + adhering chips	B < 35 g	~14 g	~6 g	~4.10^{-3} g
ELC-A – Configuration 3	Approx. 1 kg + adhering chips	B < 24 g	~20 g	~15 g	~12.10^{-3} g

~1050 g of retrieved waste (A–D)

< 0.02 g of released aerosols (E)

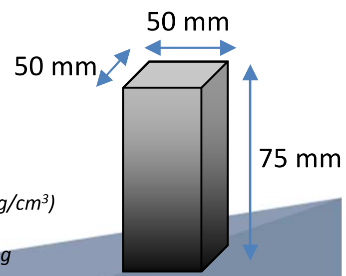


Mass repartition

Released aerosols are inferior to 0.001%tw of cut and retrieved fuel debris

Theoritical rod full of fuel debris:

- *$V = 187.5\ cm^3$*
- *$W = 1012.15$ g (density = $5.4\ g/cm^3$)*
- *50 mm of cut*
- *$V_{kerf} = 10\ cm^3$ $W_{kerf} = 54$ g*



2. Project Items Outcomes

2. Project Outcomes

1. Laser cutting development

2. Dust and Fumes Collection in air development

   Final outcomes of the technologies

3. Spray Scrubbing Development

   Final outcomes on spray scrubbing

4. Dust & Fumes data acquisition

   Final outcomes on dust & fumes

2. Project Items Outcomes
Spray Scrubbing Development

Progress from FY2016 to end of FY2018

Approaches with experiments with fuel debris simulants

Aerosol initial production
- Cutting tools (laser, other)
- Materials (ex, in vessel debris, others)

Airborne aerosol: Size, morphology, composition

FY2016/2017

Airborne aerosols versus cutting configurations
- Air
- Underwater → Pool scrubbing

FY2017/2018

Assessment of initial aerosol source term

Experimental and modelling approaches

Aerosol Transport
- Agglomeration
- Deposition

FY2017/2018

Mitigation means
Negative pressure
Aerosol collection system
Spray scrubbing
Filtration

FY2017/2018

Contribution to the assessment of contamination release in case of loss of containment

Underwater collection

- The main tasks for the development of underwater collection system in FY2018 are:
  - Development and validation of pool scrubbing model to predict airborne aerosol release fraction during underwater cutting at different depths
    - Laser cutting tests in DELIA facility
    - Pool scrubbing tests in TOSQAN facility with simulated aerosol
  - Design and specification of spray droplets characteristics with regards to 1F site conditions to achieve the best aerosol collection efficiency
    - CFD simulations of aerosol collection
    - Tests with single spray in TOSQAN facility including pool scrubbing phenomena
  - Enhancement and validation of CFD model of aerosol collection by single spray
    - Model validation based on TOSQAN spray test
  - Aerosol collection efficiency assessment by preliminary numerical simulations in 1F site

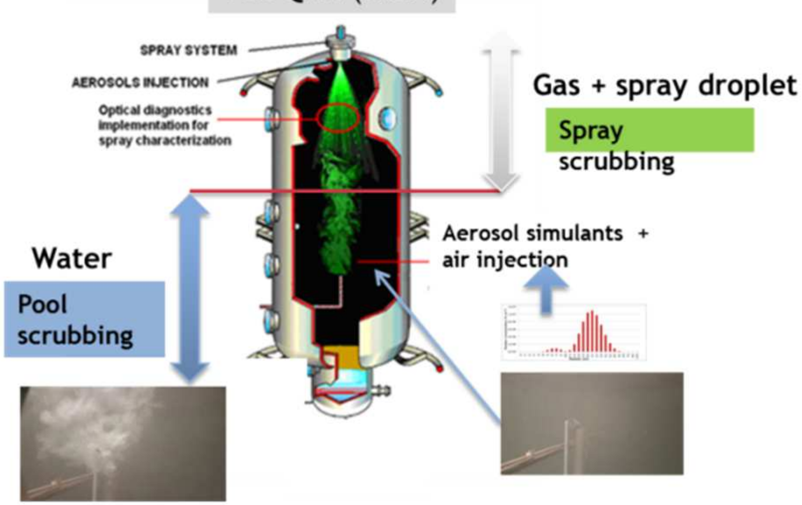
ONET TECHNOLOGIES · cea · IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

2. Project Items Outcomes
Spray Scrubbing Development

Underwater collection – Experimental – Numerical approach

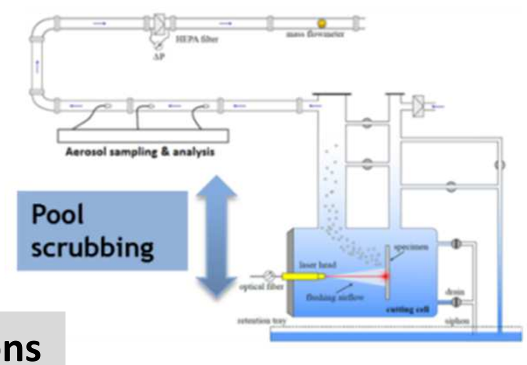
ANALYTICAL

TOSQAN (IRSN)

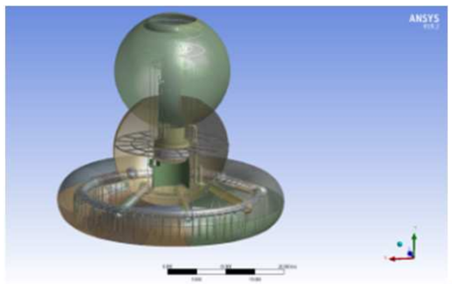


SEMI ANALYTICAL

DELIA - Laser cutting (CEA)



CFD numerical simulations



1F SITE

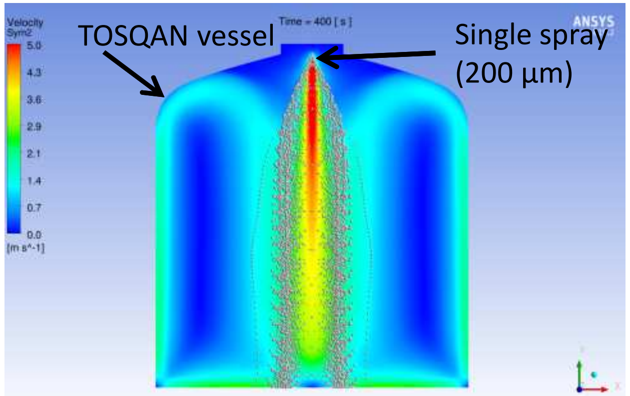
Validated tool for 1F site calculations

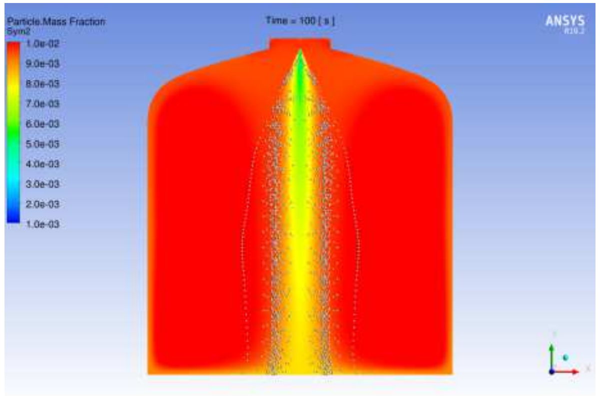
- Spray & pool scrubbing efficiencies
- Assessment of airborne aerosol release fraction
- Analytical data base for model validation
- Possibility to simulate other aerosol source terms emitted by different cutting tools

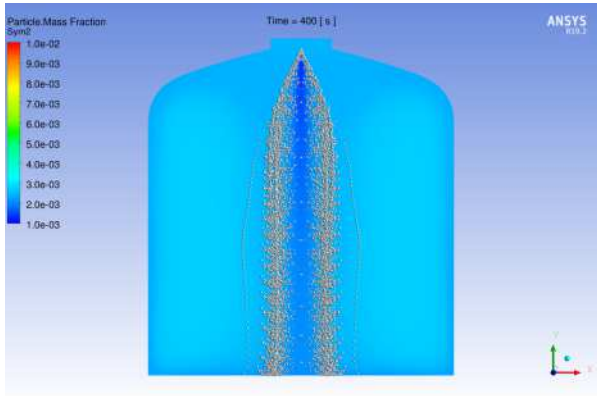
2. Project Items Outcomes
Spray Scrubbing Development

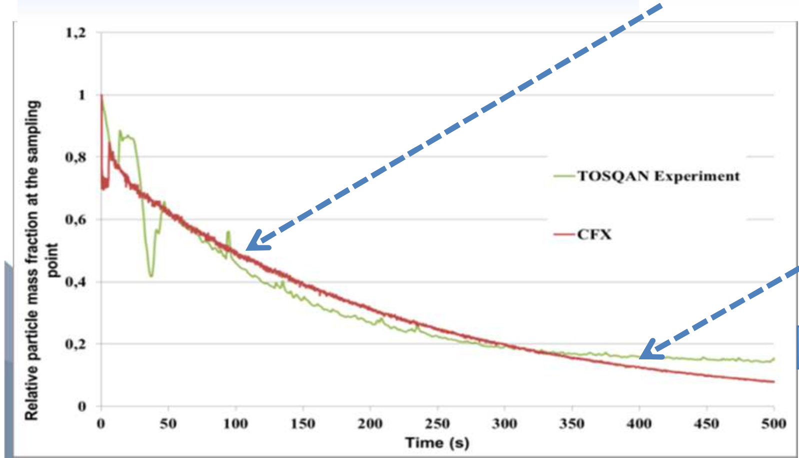
Underwater collection – Validation of spray modelling with TOSQAN spray tests

Gas velocity t=400s | **Particle mass fraction t=100s** | **Particle mass fraction t=400s**

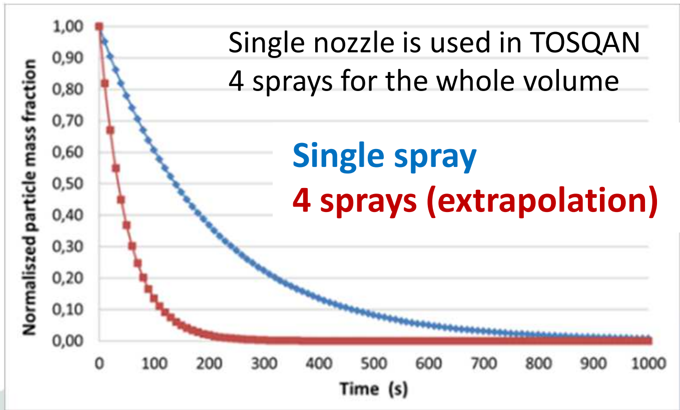






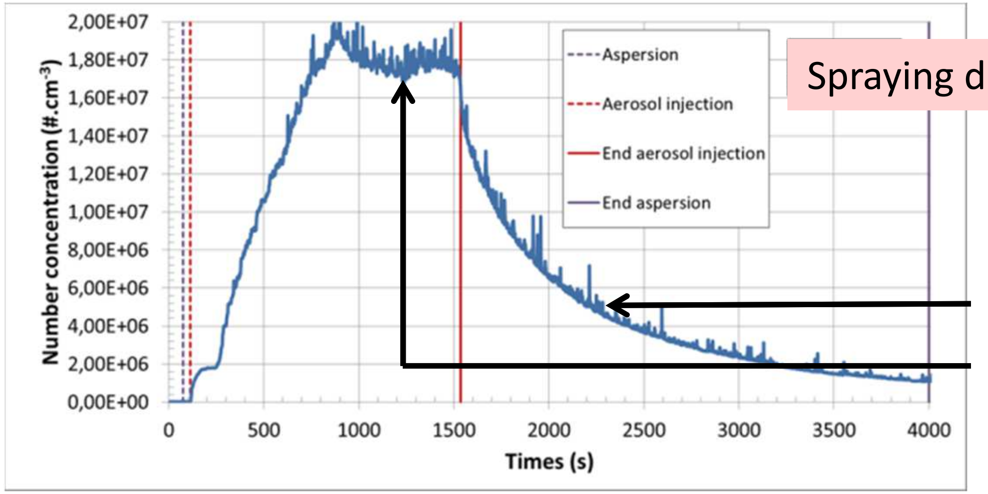


Good agreement



2. PROJECT ITEMS OUTCOMES
SPRAY SCRUBBING DEVELOPMENT

Different scenarios of aerosol emission within TOSQAN spray tests with single nozzle



Spraying during continuous aerosol emission

Aerosol concentration in TOSQAN

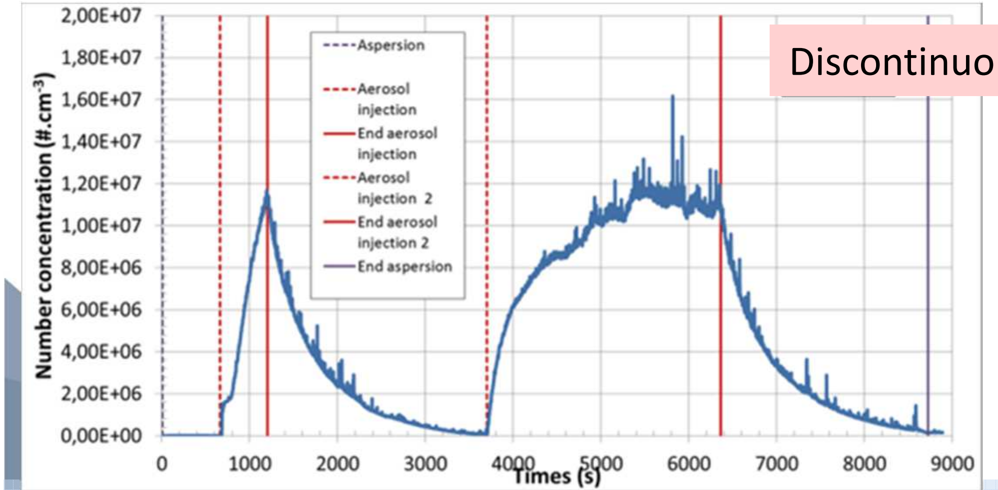
Aerosol concentration in TOSQAN at t=1500s

$$C_{(t\,>\,1500s)} = C_{t=1500s} * e^{-0.0014t}$$

Formula determined experimentally, 0.0014 = λ, removal rate

Aerosol concentration decrease

Equilibrium is reached between aerosol emission and aerosol collection by spray



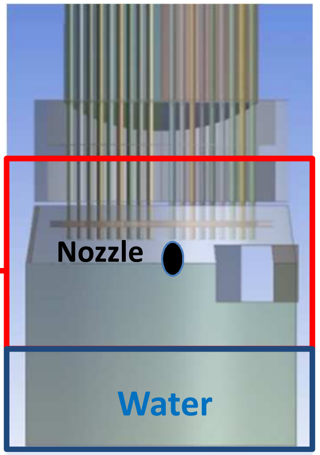
Discontinuous aerosol emissions

- Decontamination Factor determination for various aerosol source terms
- Underwater scenario is reproduced (pool scrubbing)
- Data base has been acquired to assess different strategies of mitigation
- TOSQAN experiments have feed a database to improve and validate numerical tool
- Simulation of 1F site conditions can be then achieved

2. Project Items Outcomes
Spray Scrubbing Development

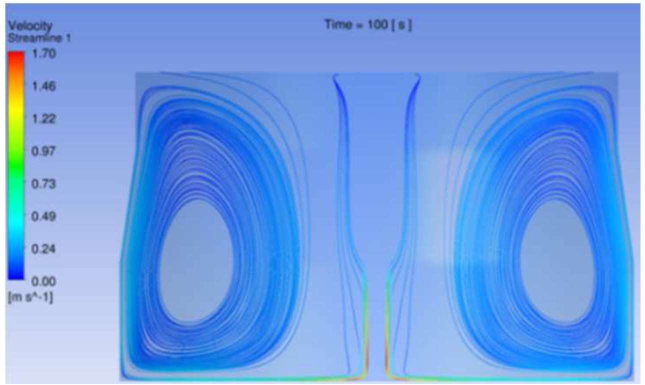
Single spray modelling in the geometry of 1F pedestal

Preliminary spray simulations for single spray

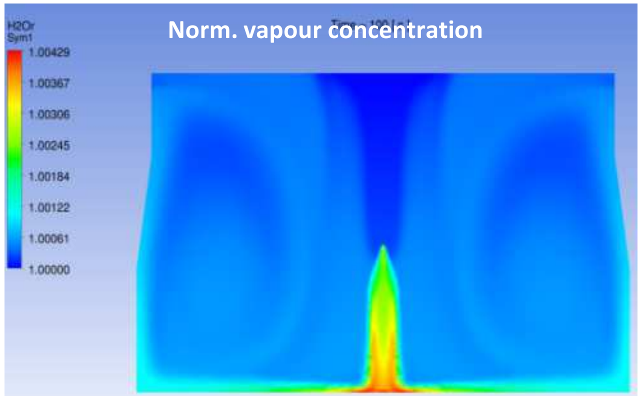


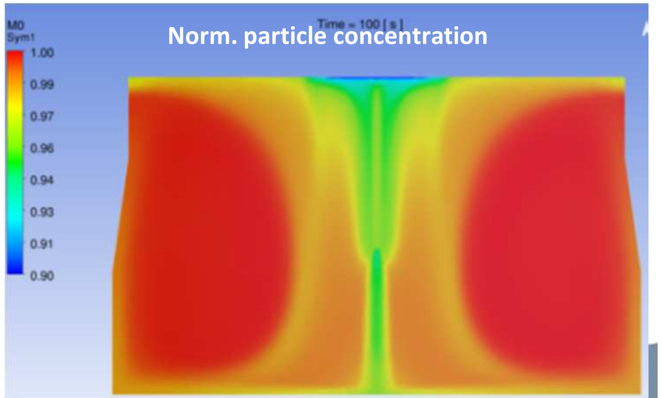
Conditions of the simulation

- Water level = 3 m
- Spray injection level = 1.6 m from the water
- Spray droplet mean size : 200 microns
- Aerosol (Ex-vessel) mean size ~ 200 nm
- $T_{gas} = T_{spray} = 20\ ^\circ C$



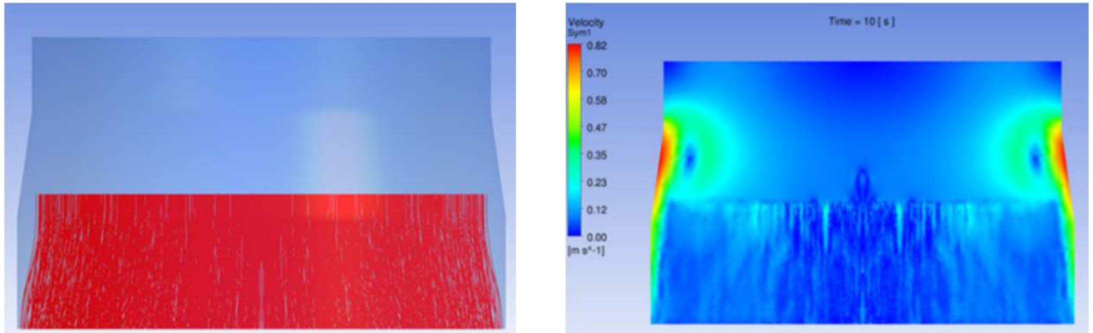
Simplified pedestal geometry for over water area

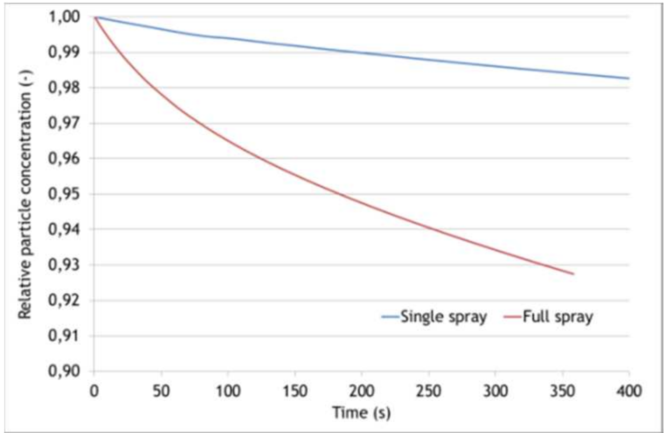




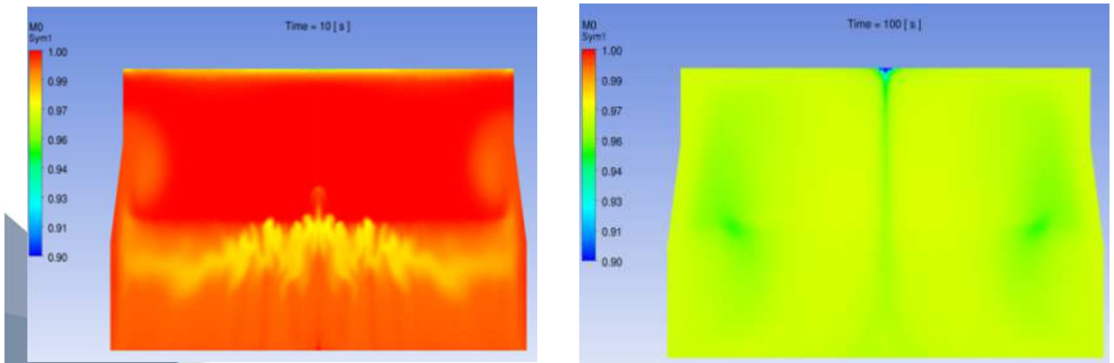
Full spray modelling in the geometry of 1F pedestal

Spray simulations for a full spray (with same conditions)





Norm. particle concentration



Enlargement of the spray area for sweeping the whole section of the pedestal

⇒ Better particle collection due to the greater area swept by the spray but particle entrainment weekly efficient

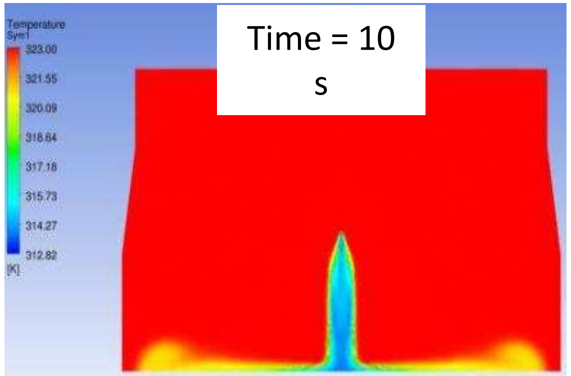
⇒ Need of implementing several single sprays rather than an enlarged spray

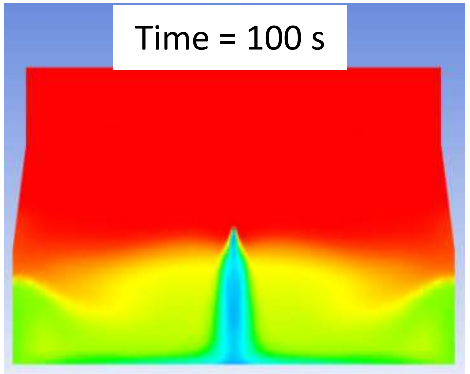
2. Project Items Outcomes
Spray Scrubbing Development

Thermal-hydraulics influence modelling in the geometry of 1F pedestal

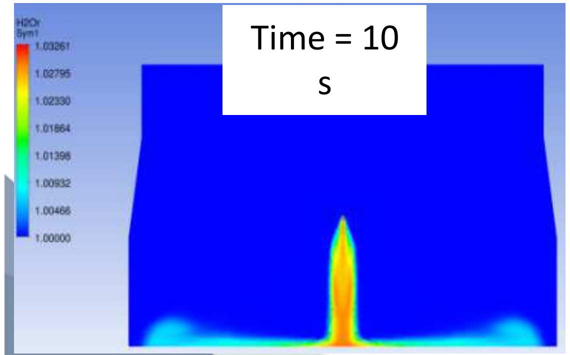
Gas temperature influence (T_{gas} = 303K and 323K)

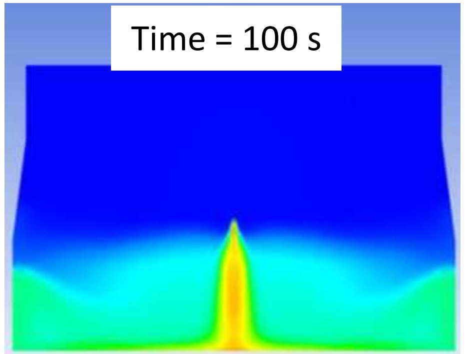
Gas temperature (T_{gas} = 323 K)

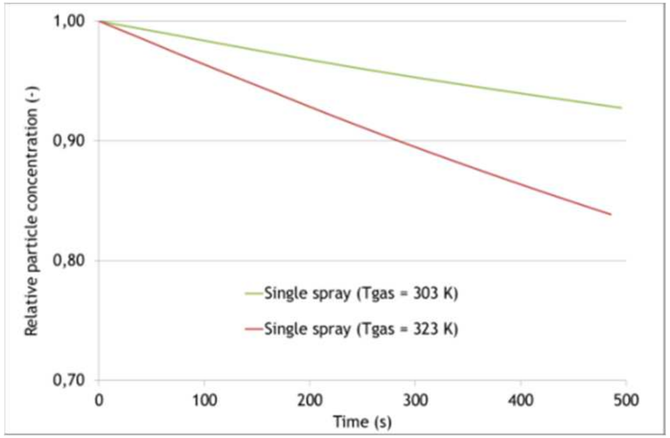




Norm. water gas concentration (T_{gas} = 323 K)







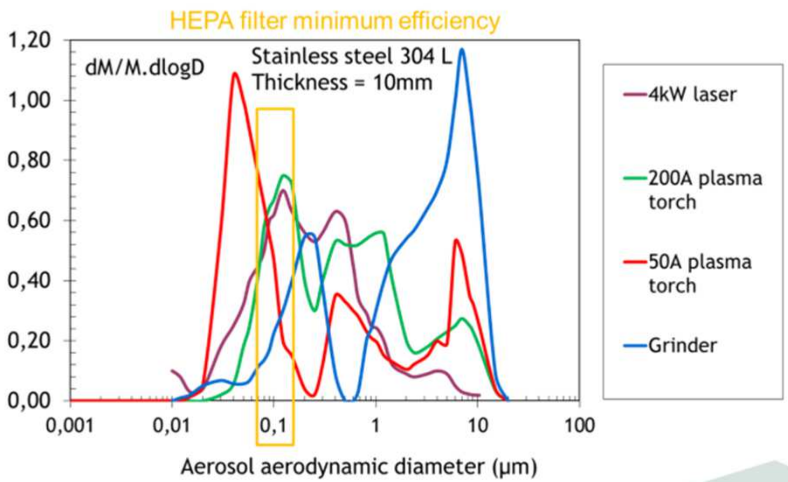
Different gas temperatures taken into account with different vapour concentrations

⇒ Better particle collection when the gas temperature increases

⇒ Capability to take into account ventilation conditions, obstruction and more realistic or changing conditions of 1F site

Synthesis

- Pool scrubbing efficiency analytical model was developed and validated based on laser cutting tests performed on DELIA facility for underwater conditions
- Spray design and specifications for best aerosol collection efficiency were determined
- Spray scrubbing CFD model was developed and validated based on analytical TOSQAN tests
- Both experimental and numerical approaches provide the capability to achieve relevant predictions of spray system mitigation mean for various cutting strategies



Porcheron *et al.* OECD PreADES meeting, Paris, January 25-29, 2019

2. Project Outcomes

1. Laser cutting development

2. Dust and Fumes Collection in air development

   Final outcomes of the technologies

3. Spray Scrubbing Development

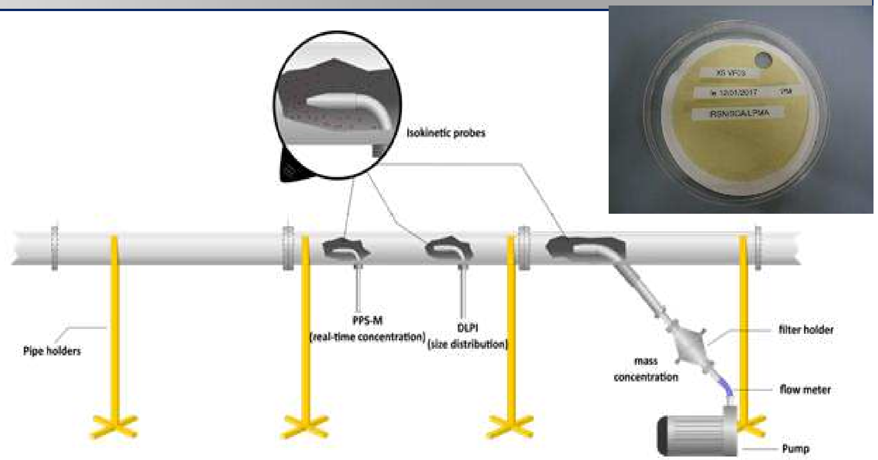
   Final outcomes on spray scrubbing

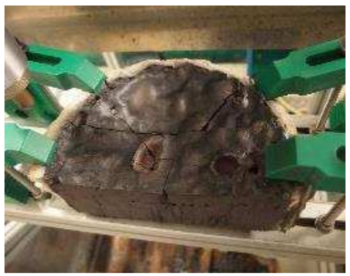
4. Dust & Fumes data acquisition

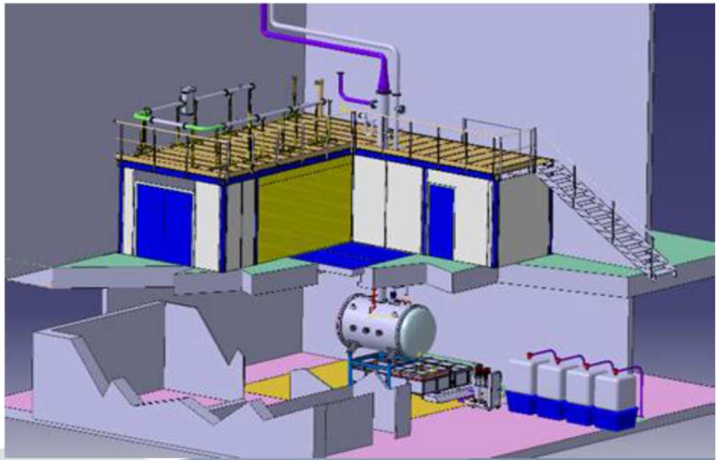
   Final outcomes on dust & fumes

Summary of experimental approach (1/2)

- Aerosol measurement during laser cutting of simulant fuel debris. In air/In water
- In-vessel and Ex-vessel (MCCI) fuel debris compositions have been simulated
    - UO_2 replaced by HfO_2 (thermal ppties)
    - Pu replaced by Ce
    - FPs : Natural isotopes (except Ru)
- Aerosols collected by Filters
- Collection + size distribution by 13-stage impactors





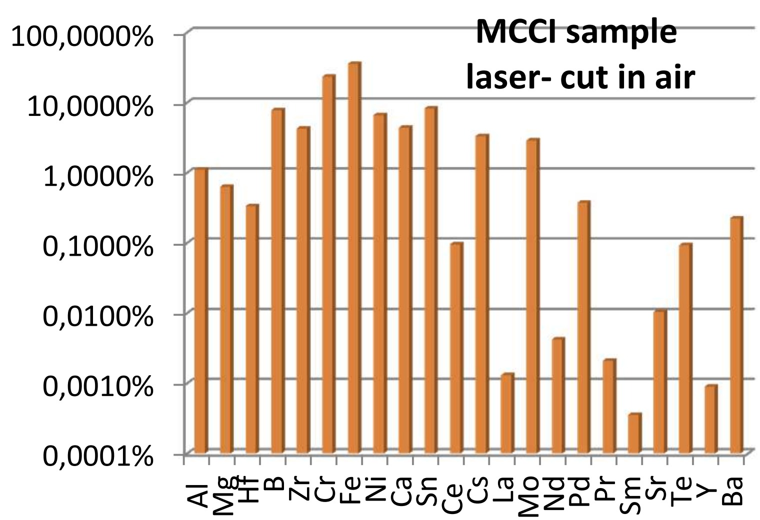


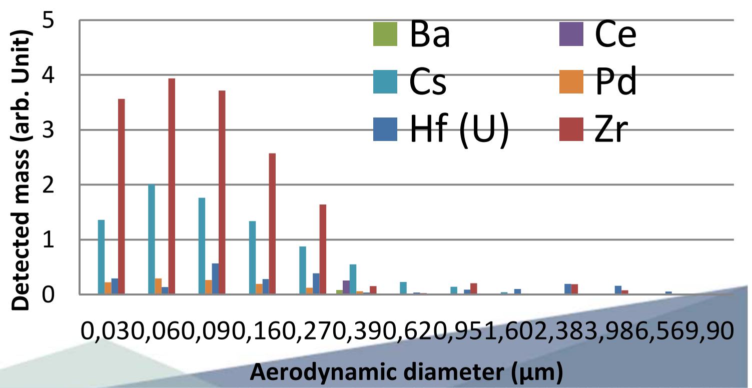
Summary of experimental approach (2/2)

For 1 m of cut	MCCI in air	MCCI underwater	In vessel in air	In vessel underwater
Dross	6 g		1.3 g	
Solid particles in water		0.25 g		0.9-1.4 g
Solution in water		0.35 g		~1 g
Aerosols	0.8 g	0.6 – 3 g	9 g	3-8 g
Total	7 g	1-4 g	10 g	5-10 g

From composition and isotopic inventory,
Aerosol masses are converted to radioactivity

For 1 m of cut	MCCI in air	MCCI underwater	VF-04 in air	VF-04 underwater
Dross	10^{11}		3.10^{11}	
Solid particles in water		3.10^{9}		$0.8\text{-}1.5.10^{9}$
Solution in water		4.10^{10}		$1\text{-}2.10^{10}$
Aerosols	3.10^{10}	2.10^{10} - 8.10^{10}	10^{10}	1-2. 10^{10}
Total	10^{11}	0.6-1.2 10^{11}	3.10^{11}	$2\text{-}4.10^{10}$





2. Project Items Outcomes
Dust & Fumes Data Acquisition

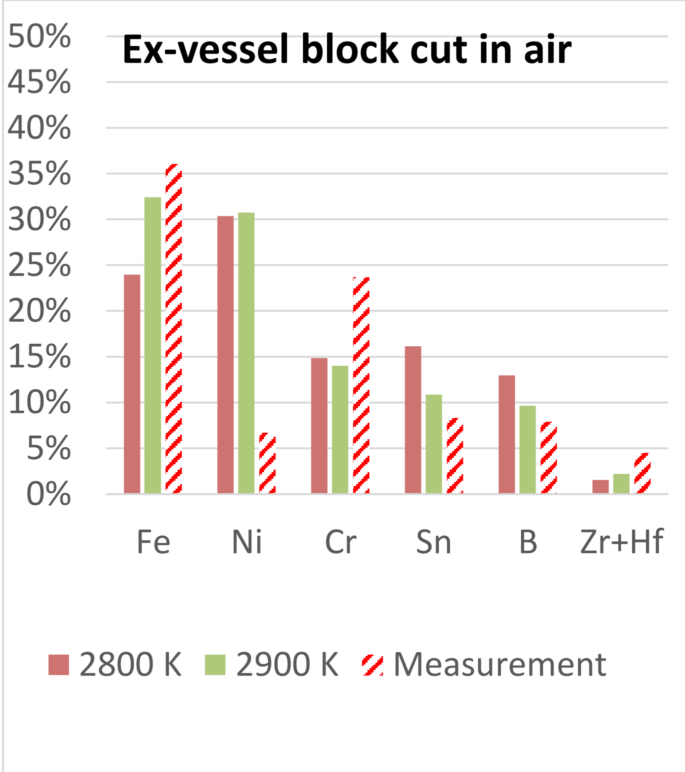
Modeling of Aerosols Release

Objectives

- Comparisons with chemical thermodynamic calculations
  - Determination of fraction of volatilized elements from a mass of fuel debris simulant
  - Determination of a calculation methodology approaching the measured aerosol compositions

Outcomes

- Aerosols are modeled as gaseous fraction from initial composition of the block
  - GEMINI thermodynamic code
  - NUCLEA database
  - equivalent temperature (2800 – 2900 K) corresponding to laser heating
  - A quantity of air or water/steam is considered in equilibrium with molten debris (quantity fit on experimental data)
- Quite good agreement with experiment on major elements in aerosols.



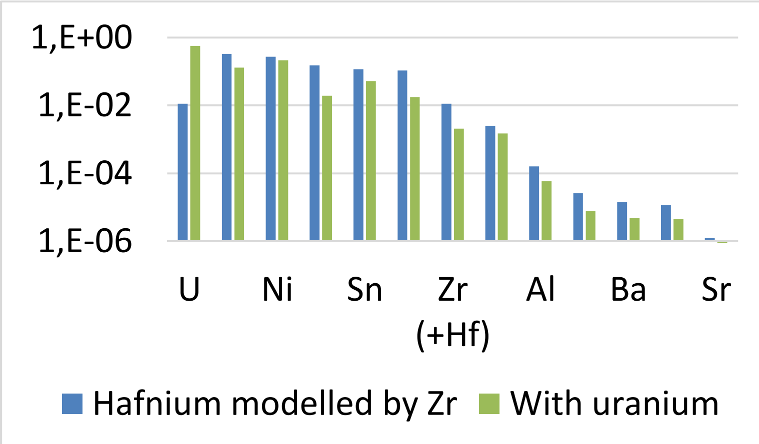
2. Project Items Outcomes
Dust & Fumes Data Acquisition

Modeling of Aerosols Release

Outcomes

- Use of the validated modeling methodology to other compositions
- Transposition to reactor cases
  - Estimation of aerosol releases for various fuel debris compositions and configurations
    - There is not only 1 “in-vessel” and 1 “MCCI” fuel debris composition !

- Role of Uranium
  - Replacement of U by Hf in simulant block (done for testing cutting ability not aerosol generation) leads to reduction of aerosol formation by more than 1 order of magnitude (MCCI composition) or a factor of 4 (in vessel composition).
  - Uranium becomes larger element in aerosols.
  - Need for tests with uranium (also for mechanical cutting) to confirm these theoretical results.

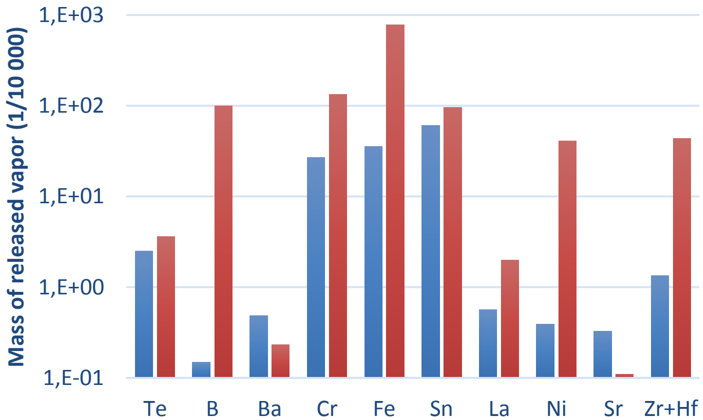


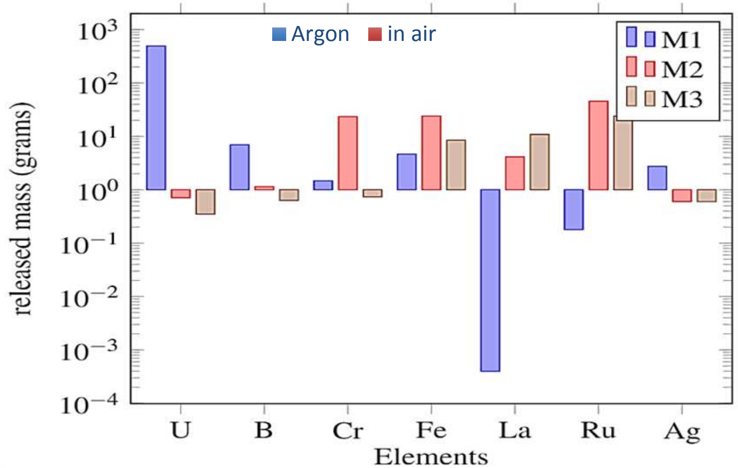
2. Project Items Outcomes
Dust & Fumes Data Acquisition

Modeling of Aerosols Release

- Effect of air vs. neutral gas used for laser cutting:
  - ~10 times less vaporization in neutral gas than in air (mainly due to steel oxide vaporization in air)
  - Barium and strontium release more in neutral atmosphere compared to air.

- Other fuel debris compositions
  - For instance, releases from 3 different composition of MCCI corresponding to 3 layers of melt in lower head
    - Heavy steel (with U) releases more U and less lanthanides than other compositions
  - The more oxidic fuel is mixed with concrete, the less the mass of released aerosols, but the larger the mass of released uranium.





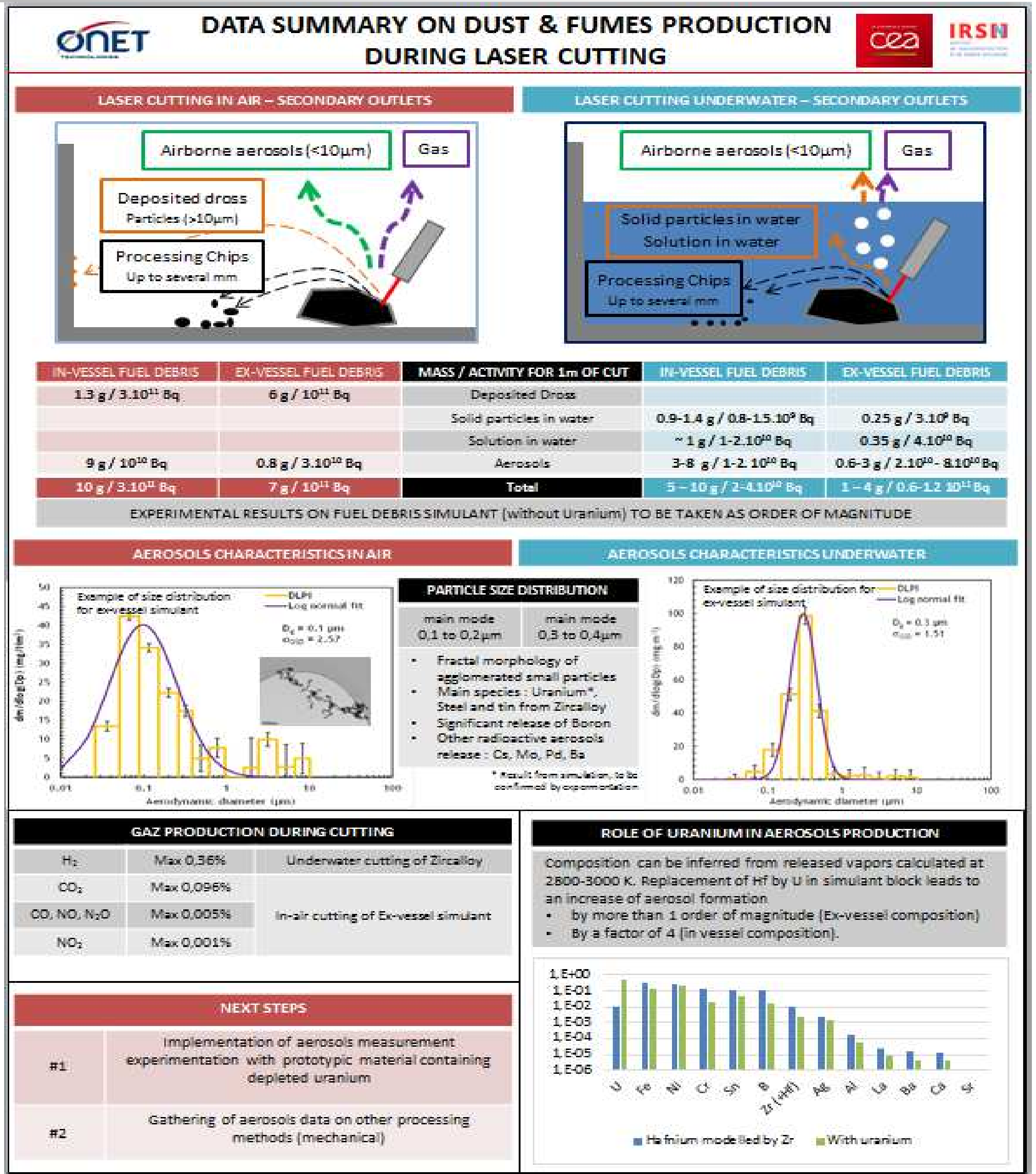
Final outcomes on dust & fumes

A unique set of data on aerosol characteristics have been acquired within these projects

- **Size distribution : low median diameter**
- **Composition of released aerosols different from fuel debris composition**
  - **Larger particles (> 1µm; low mass fraction): rich in (U ,Pu, Zr)O2**
  - **Fractal morphology of smaller particles (chain-like agglomeration of nanoparticles)**
  - **Composition can be inferred from released vapors calculated at 2800-3000 K (taking into account atmosphere, + water if necessary)**
    - **Capacity to predict different various fuel debris compositions**
  - **Uranium computed to be badly reproduced by simulant.**
    - **Need for data with prototypic material containing depleted uranium**

A unique set of data on aerosol characteristics have been acquired within these projects

- Size distribution : low median diameter
- Composition of released aerosols different from fuel debris composition
  - Larger particles (> 1µm; low mass fraction): rich in (U ,Pu, Zr)O2
  - Fractal morphology of smaller particles (chain-like agglomeration of nanoparticles)
  - Composition can be inferred from released vapors calculated at 2800-3000 K (taking into account atmosphere, + water if necessary)
    - Capacity to predict different various fuel debris compositions
  - Uranium computed to be badly reproduced by simulant.
    - Need for data with prototypic material containing depleted uranium


DATA SUMMARY ON DUST & FUMES PRODUCTION DURING LASER CUTTING

IN-VESSEL FUEL DEBRIS	EX-VESSEL FUEL DEBRIS	MASS / ACTIVITY FOR 1m OF CUT	IN-VESSEL FUEL DEBRIS	EX-VESSEL FUEL DEBRIS
1.3 g / 3.10¹¹ Bq	6 g / 10¹¹ Bq	Deposited Dross		
		Solid particles in water	0.9-1.4 g / 0.8-1.5.10⁹ Bq	0.25 g / 3.10⁹ Bq
		Solution in water	~ 1 g / 1-2.10¹⁰ Bq	0.35 g / 4.10¹⁰ Bq
9 g / 10¹⁰ Bq	0.8 g / 3.10¹⁰ Bq	Aerosols	3-8 g / 1-2 10¹⁰ Bq	0.6-3 g / 2.10¹⁰ - 8.10¹⁰ Bq
10 g / 3.10¹¹ Bq	7 g / 10¹¹ Bq	Total	5 – 10 g / 2-4.10¹⁰ Bq	1 – 4 g / 0.6-1.2 10¹¹ Bq

EXPERIMENTAL RESULTS ON FUEL DEBRIS SIMULANT (without Uranium) TO BE TAKEN AS ORDER OF MAGNITUDE

PARTICLE SIZE DISTRIBUTION

main mode 0,1 to 0,2µm	main mode 0,3 to 0,4µm

- Fractal morphology of agglomerated small particles
- Main species : Uranium*, Steel and tin from Zircalloy
- Significant release of Boron
- Other radioactive aerosols release : Cs, Mo, Pd, Ba

* Result from simulation, to be confirmed by experimentation

GAZ PRODUCTION DURING CUTTING

H_2	Max 0,36%	Underwater cutting of Zircalloy
CO_2	Max 0,096%	In-air cutting of Ex-vessel simulant
CO, NO, N_2O	Max 0,005%	
NO_2	Max 0,001%	

ROLE OF URANIUM IN AEROSOLS PRODUCTION

Composition can be inferred from released vapors calculated at 2800-3000 K. Replacement of Hf by U in simulant block leads to an increase of aerosol formation

- by more than 1 order of magnitude (Ex-vessel composition)
- By a factor of 4 (in vessel composition).

NEXT STEPS

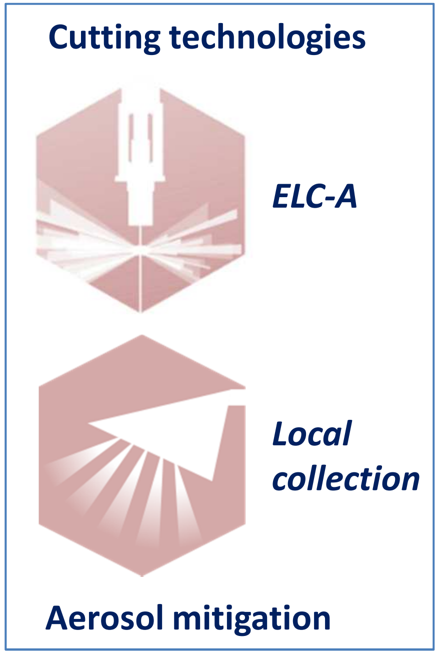
#1	Implementation of aerosols measurement experimentation with prototypic material containing depleted uranium
#2	Gathering of aerosols data on other processing methods (mechanical)

Cutting scenarios in air – ELC-A and NELC-A

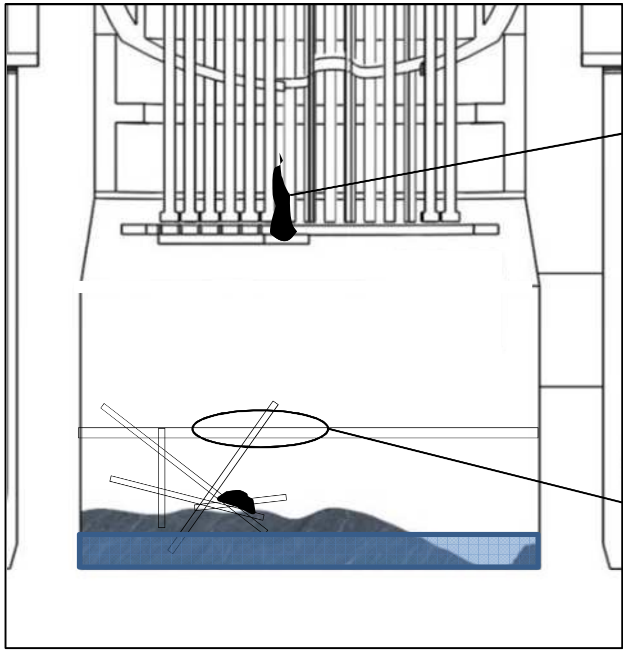
- **Assumptions (under confirmation with IRID):**
  - Non immerged material
  - High humidity (about 100%)
  - Tight environment, confined space
  - High radioactivity level
  - Massive blocks laying on walls and floor (fuel Debris)
  - Internal structures at various elevation inside RPV/PCV (CRD housings, gratings, beams, pipes…)

- **Solutions to be developed:**
  - Define cutting implementation procedure to remove small blocks
  - Propose suitable equipment to handle the cutting tools and the embedded collection system
  - Define the most appropriate technologies (ELC or NELC) for each potential situation
  - Design very robust solutions able to face the severe conditions (high radioactivity, poor accessibility, humidity, …)

Cutting scenarios in air – ELC-A (1/2)



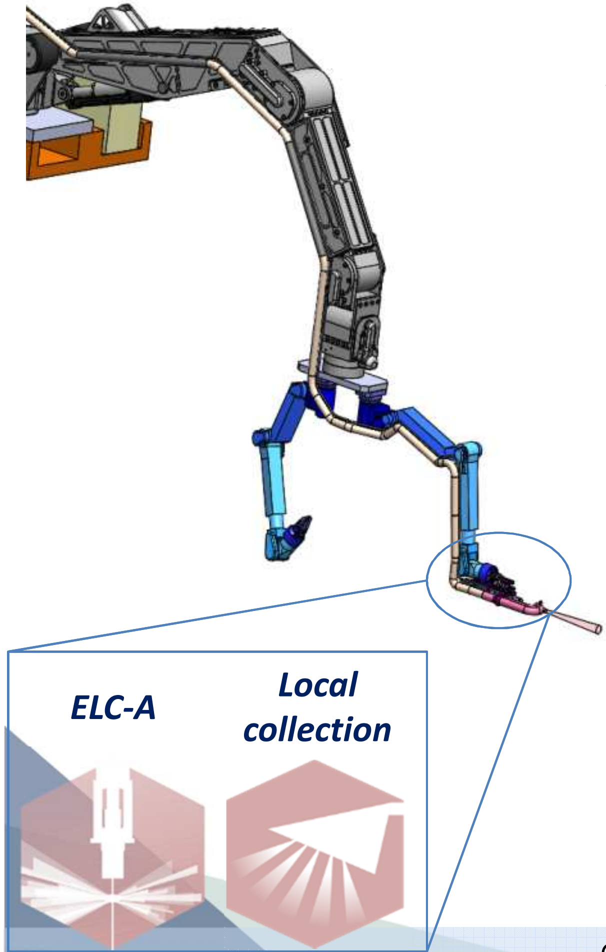
Cutting technology ELC-A associated with local collection as aerosols mitigation means



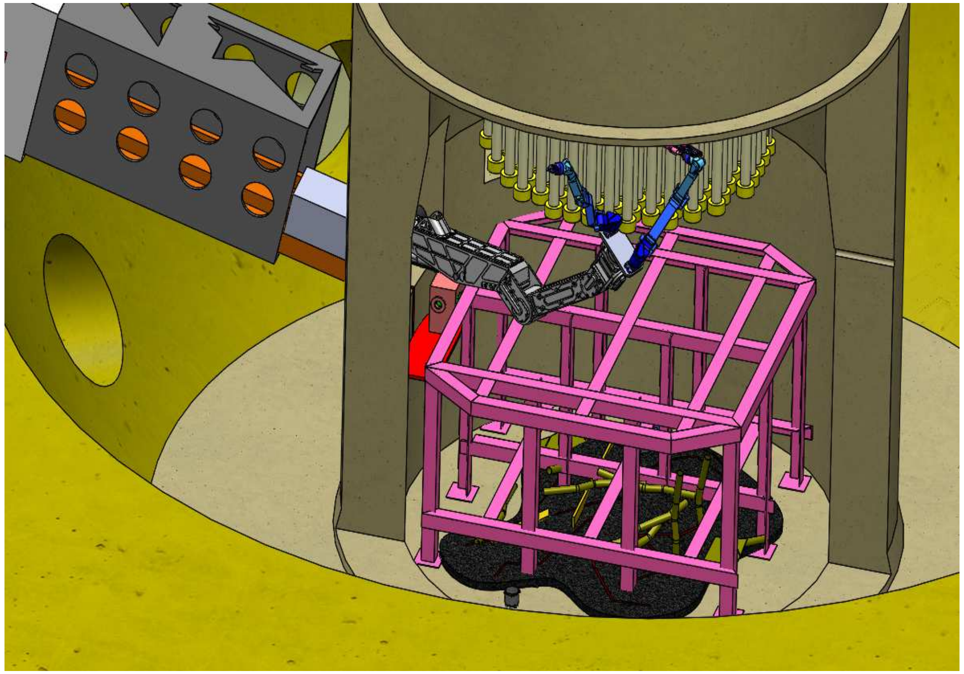
ELC-A technology could be used in air for the cutting and retrieval of the following items

- CRD & CRD housings
- Melted objects solidified on CRD
- Platform structures, gratings, beams,… on which fuel debris has solidified
- …

Cutting scenarios in air – ELC-A (2/2)



With the ELC-A cutting head mounted on one arm and a handling device mounted on a second, it is possible to cut and retrieve different from the totom of the reactor



The ELC-A cutting head can be used to cut the CRD housings in air for example
It can also be used to cut and retrieve pieces of structures, gratings, etc.

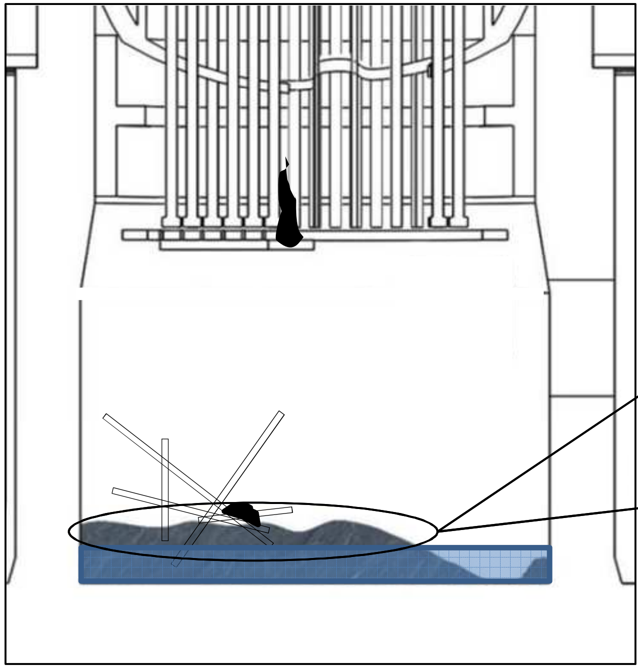
Cutting scenarios in air – NELC-A (1/2)

Cutting technologies

NELC-A

Local collection

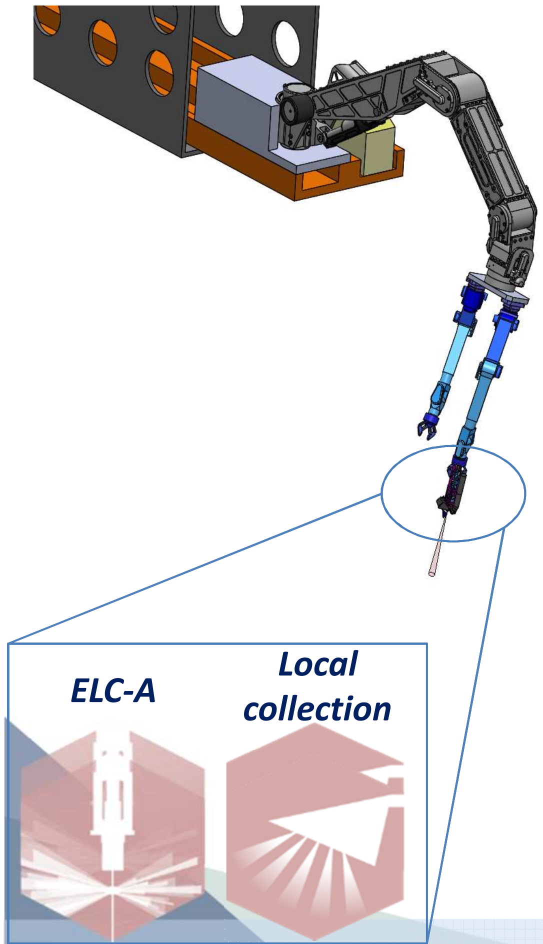
Aerosol mitigation



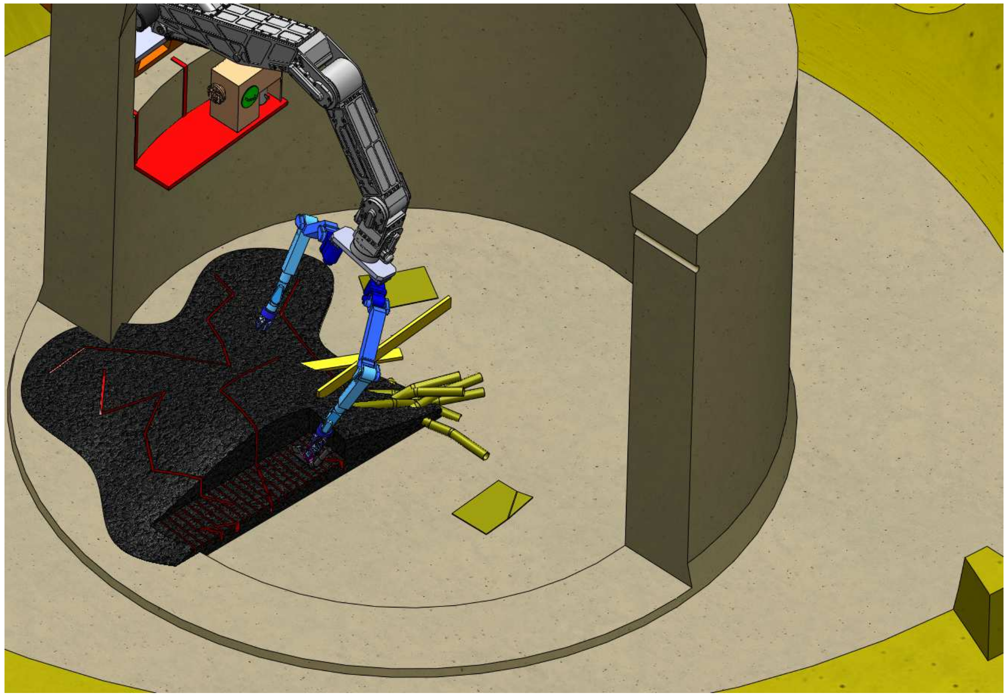
Cutting technology ELC-A associated with local collection as aerosols mitigation means

NELC-A technology could be used in air for the cutting and retrieval of the molten material (fuel debris) at the bottom of the PCV

Cutting scenarios in air – NELC-A (2/2)

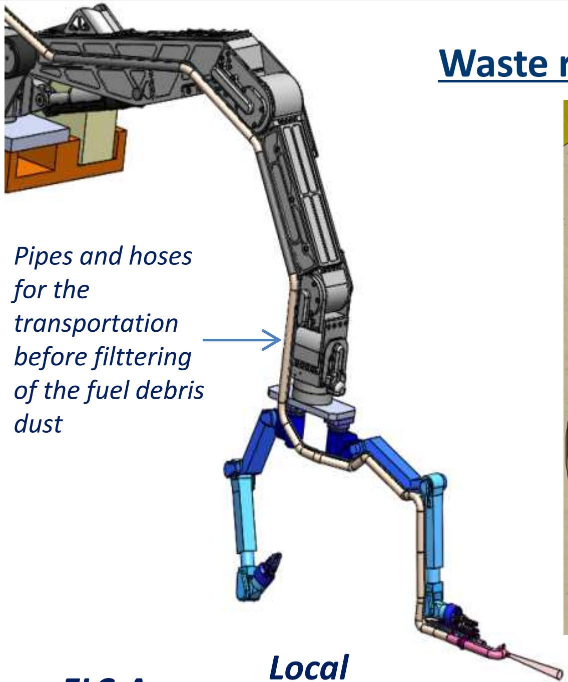


With the NELC-A cutting head mounted on one arm and a handling device mounted on a second, it is possible to cut and retrieve different items at the bottom of PCV

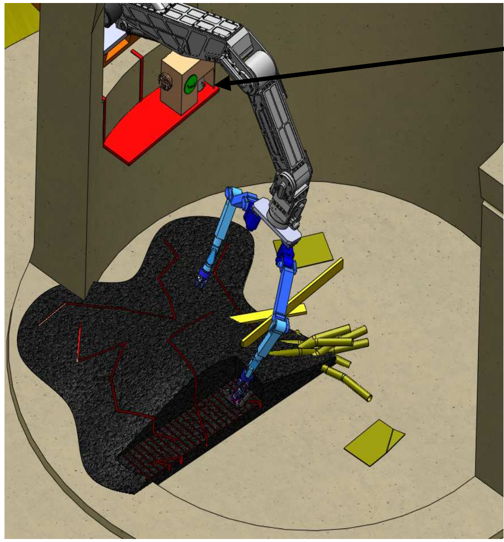


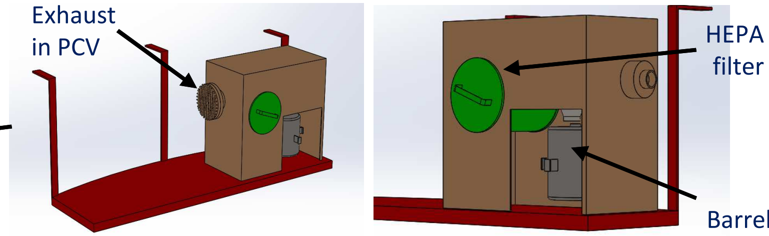
Solid fuel debris melted onto the floor and not covered by water

Cutting scenarios in air – Dust retrieval for ELC-A and NELC-A



Waste retrieval for in-air cutting





Filtration device (for instance, cyclonic filter) with collection barrel + remotely handlable HEPA filter: collection of chips, dross and dust. HEPA filter and barrel to be retrieved and treated as solid waste when needed.
Platform to be entered in the same time as the carrier and telescopic arm are implemented into the PCV

Another solution can be to place a fan and the filtering system in a specific room at the vicinity of the PCV

ELC-A ***Local collection***

As an order a magnitude, 300 g of fuel debris in the barrel will represent a dose rate of 50 mSv/h at 1 m distance. The critical mass would be about 10 kg

Pieces cut to be retrieved by a specific arm able to carry solid wastes and place them in specific barrels for treatment

Cutting scenarios underwater – ELC-W and NELC-W

- Assumptions:

  Same as in air conditions with the following additional constraints:
    - Fully immerged material (under few centimeters or several meters)
    - Poor visibility

- Solutions to be developed:
    - Define cutting implementation procedure to remove small blocks
    - Propose suitable equipment to handle the cutting (without collection system – impossible under water)
    - Design very robust solutions able to face the severe conditions (high radioactivity, poor accessibility, humidity, …)
    - Propose suitable equipment to implement the spray scrubbing system and manage the interfaces such as:
        - Installation equipment for lifting, assembling or anchorage
        - Supporting : fixed to the walls, floating on the water or attached to existing steal structures
        - Piping : flexible or rigid, quantities , dimensions, …

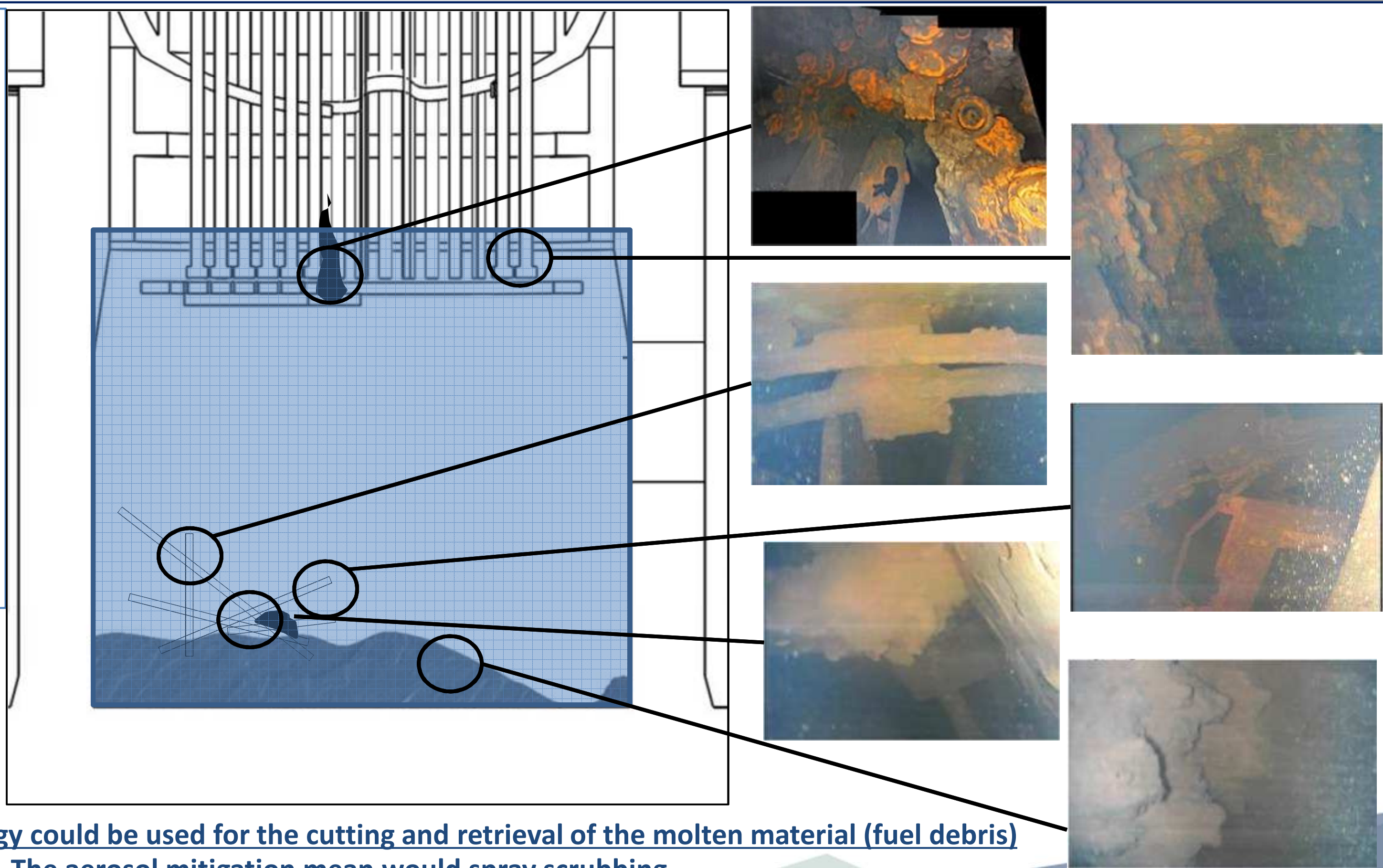
Cutting scenarios underwater – ELC-W and NELC-W

Cutting technologies

ELC-W

Spray and pool scrubbing

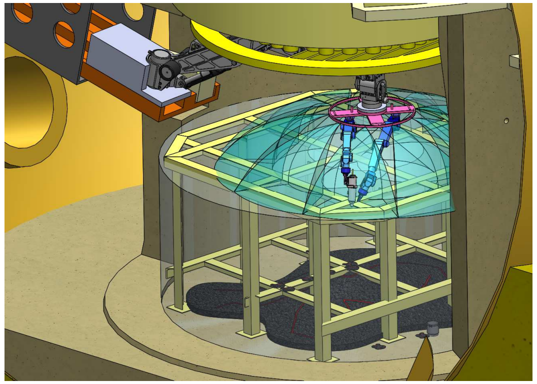
Aerosol mitigation

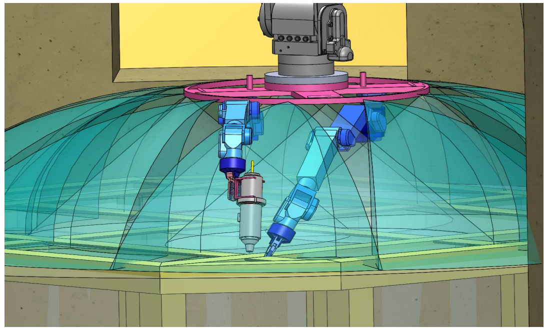


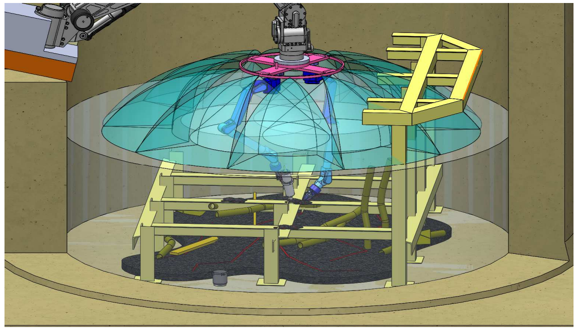
ELC-W and NELC-W technology could be used for the cutting and retrieval of the molten material (fuel debris) that are situated underwater. The aerosol mitigation mean would spray scrubbing

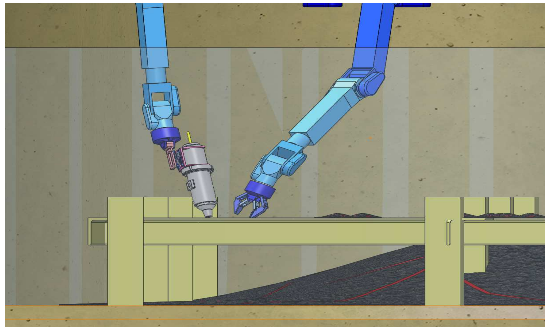
Cutting scenarios underwater – ELC-W and NELC-W

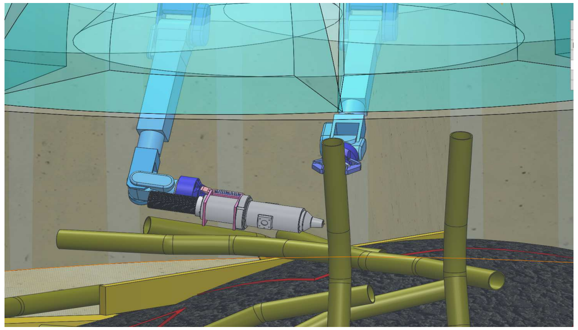
With ELC-W and NELC-W technologies, it can be possible to integration the spray scrubbing system to the mechanical arm that bears the tools. In this configuration, the reached area by the spray scrubbing can be large enough to cover all the aerosols scattering



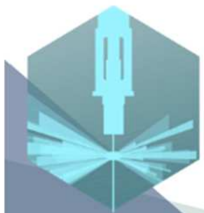








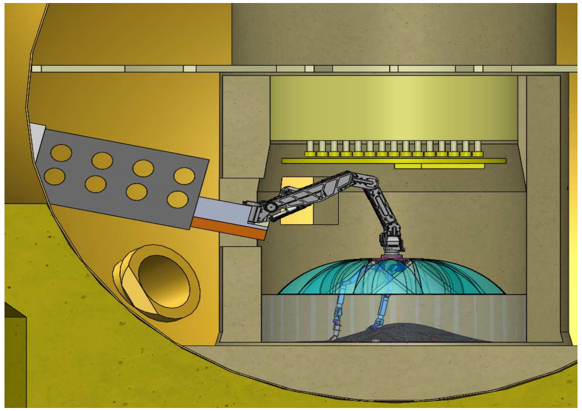
ELC-W

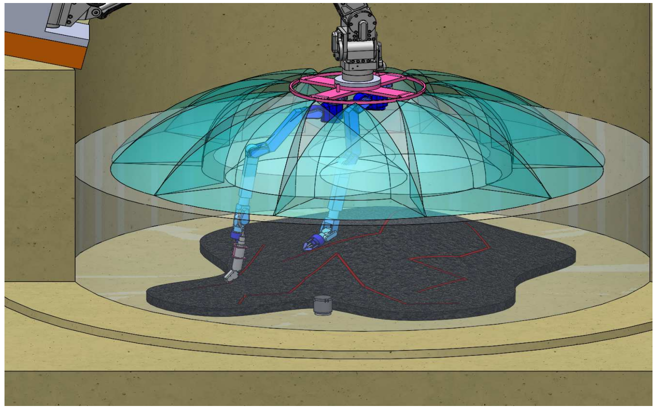


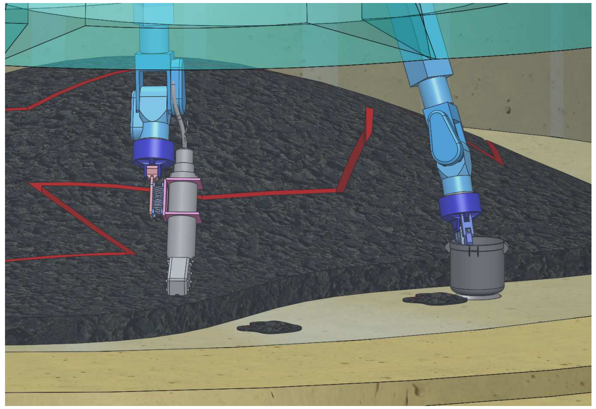
Spray and pool scrubbing

On the pictures above, one mechanical arm is bearing the ELC-W cutting head that can cut element such platforms, gratings, bars, etc. The spraying system is mounted onto the mechanical arm and stays above the water level

Cutting scenarios underwater – ELC-W and NELC-W





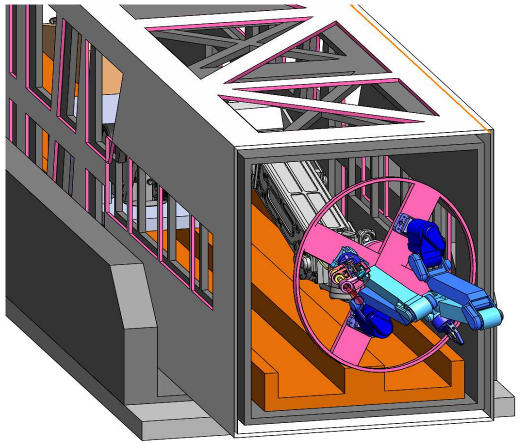


Solid fuel debris cut on the floor

The spray scrubbing system is mounted onto the telescopic arm. 14 spraying nozzles could cover a large surface under which the cuts are realized (it represents approximatively a 5 m^3/h waterflow)

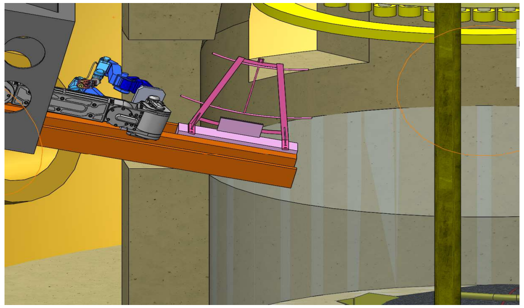
NELC-W

Spray and pool scrubbing

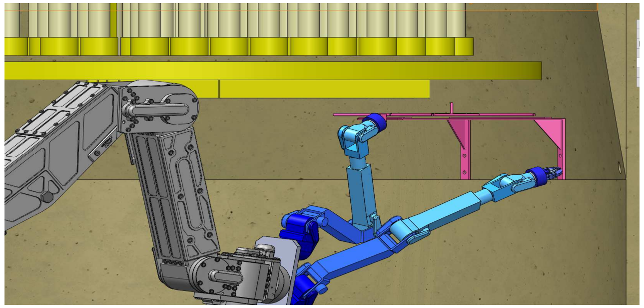


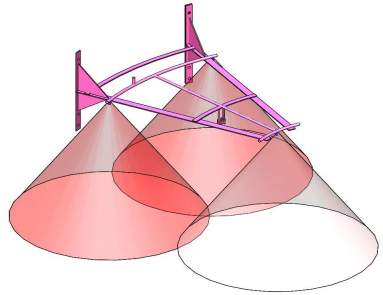
Entry of the system into the PCV

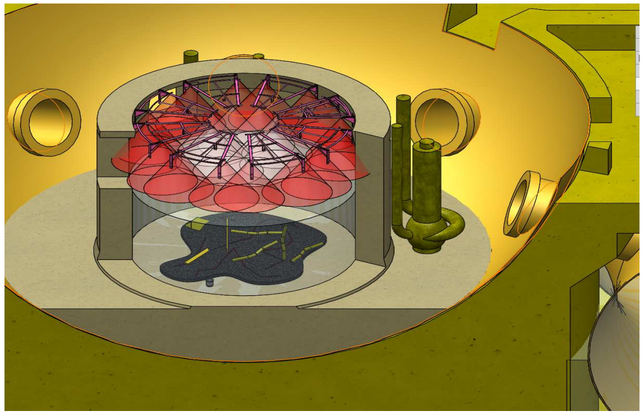
Cutting scenarios underwater – Other solution for spray scrubbing implementation

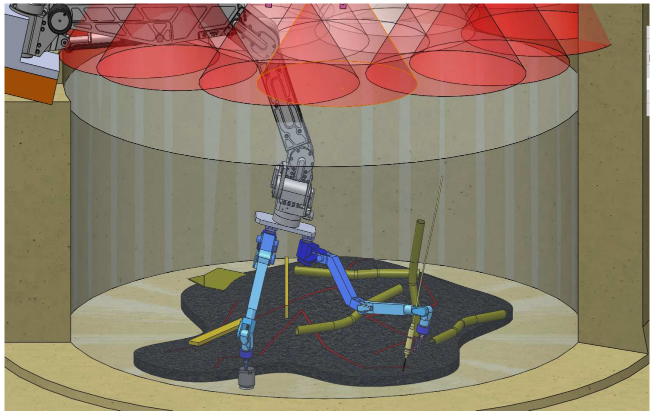


Entry and implementation of one module









NELC-W

Spray and pool scrubbing

In case it is possible to drill modules onto the pedestal's walls, the spray scrubbing system could be implemented as it is shown on the pictures (8 modules of 3 spraying nozzles each will cover the entire surface of the pedestal)

Conclusion

- This project has achieved significant results in laser cutting development, dust and fumes knowledge and aerosols mitigation
- Fuel debris retrieval will need complementary tools to overcome the various conditions and situations to be faced : laser can be considered as one robust system for site application even if challenges still exist (NELC-W).
- The collection technologies have proven their efficiency, tests on more realistic material along with design improvement are now necessary to confirm full applicability
- Spray scrubbing is considered as a key technology for inhibiting aerial diffusion of the dust and could be applied to other cutting techniques