PROJECT OF DECOMMISSIONING AND CONTAMINATED WATER MANAGEMENT (DEVELOPMENT OF TECHNOLOGIES FOR SCALING UP RETRIEVAL OF FUEL DEBRIS AND INTERNAL STRUCTURES)

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DEVELOPMENT OF DUST COLLECTION SYSTEM FOR FUEL DEBRIS

PERFORMANCE REPORT FOR FY2018 SUPPLEMENTARY BUDGET

(2022/01)

CONTENT OF THE PRESENTATION

1. BACKGROUND & PURPOSE

Development of Dust Collection System for Fuel Debris Processing

Reasons why this research is needed

- Prior to fuel debris retrieval, fuel debris processing is needed. Different fuel debris processing methods will lead to different retrieval strategies
- In order to retrieve fuel debris after it has been processed, it is necessary to collect as much data as possible concerning the final shape of the fuel debris (blocks, slags, dust, etc.)
- It is also mandatory to collect data concerning the airborne particles that are generated during the fuel debris processing for every processing tools (dust, aerosols)
- Finally, the mechanical behaviour towards the fuel debris and the Fukushima Daiichi situation must be assessed
- Following this data collection, it is possible to determine strategies to recover the fuel debris while implementing solutions in order to mitigate all the risks that have identified (safety management, mitigation of aerosols release, etc.) and to improve the operability of the systems (implementation, maintenance, etc.)

Project goal

- The goal of the project is to support the development of dust collection technologies contributing to the decommissioning of Fukushima Daiichi NPS of Tokyo Electric Power Company

Duration of the project

- April 2019 – May 2021 (2 years)

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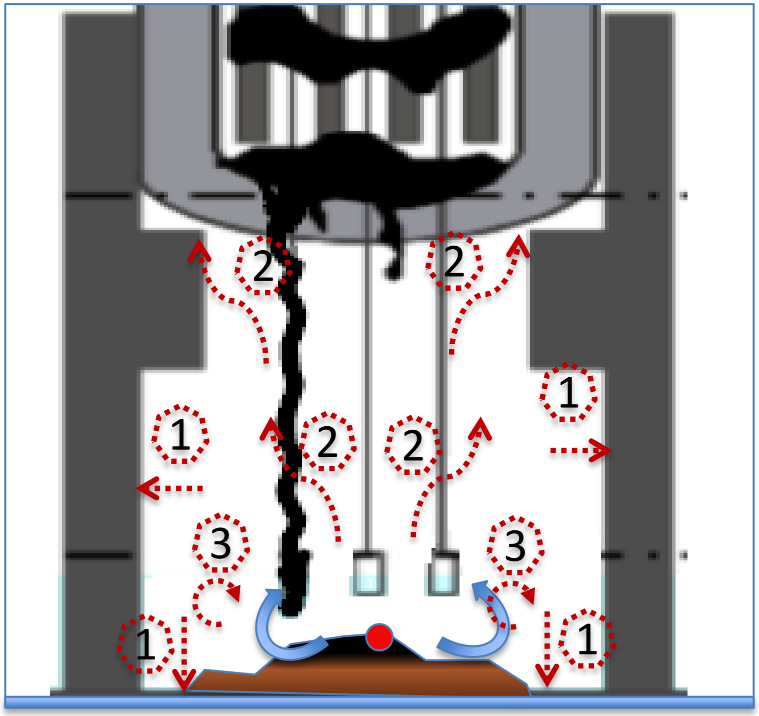
2. ITEMS OF WORK

Development for Dust Collection of Fuel Debris System

Dust collection strategies

Considerations for the development of dust and aerosols collection systems are based on the following statements:



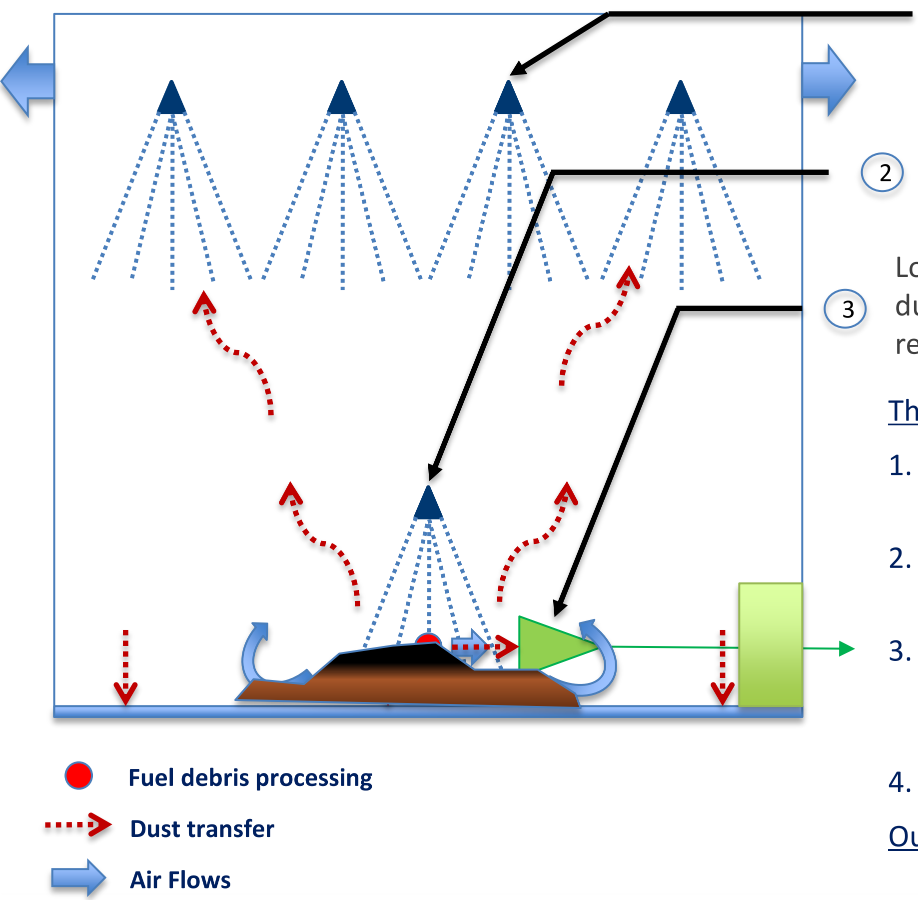
Fuel debris processing
Dust transfer
Air Flows

- During fuel debris processing, several mechanisms are involved to propagate dust generated :
  1. Dust deposition
  2. Dust transport by air flows
  3. Dust resuspension due to air flows
- These mechanisms are dependent of the processing method and the processed material, most influent parameters being:
  - The processing method (core boring, laser, grinder, etc.): each processing methods will generate different dust and aerosols characteristics
  - The fuel debris type and composition: previous showed that aerosols characteristics also depend on the characteristics of processed material
  - The air flows generated by the processing method: airflows transport aerosols. Therefore, this parameter must be considered for the implementation of systems
- Development of collection systems must be adapted to these constraints

2. ITEMS OF WORK

Development for Dust Collection of Fuel Debris System

Dust collection strategies – Strategies for spray scrubbing and for local collection



1 Multi spray – Global spray: a large area is covered. This system allows to collect the aerosols that have not been collected by other collection systems and that are not already deposited

2 Local spray: the area close to the cutting point is the target. This system could allow a good efficiency rate while minimizing the water consumption

3 Local collection: the collection device is implemented so it can collect the dust that is generated by the fuel debris processing. Dust and aerosols are recovered in the different filtering devices in adapted waste cans

<u>The study of applicability on site of these strategies focus on:</u>

1. Numerical simulations: calculations of deposition and collection of particles fractions for different scenario cases
2. Implementation of spraying system and evaluation of the operability on site (implementation of the system, water consumption)
3. Implementation of local dust collection in air and evaluation of the operability on site (implementation of the system, lifetime, maintenance)
4. Safety analysis

<u>Output data:</u> Assessment of the operability on site

2. ITEMS OF WORK

Development for Dust Collection of Fuel Debris System

Generalities – FY2019/2020 subsidy project

Following the previous achievements, the objectives of the subsidy project for FY2019/2020 is to focus on dust collection systems. In this frame, 3 main items have been identified:

1. Data collection on dust and aerosols:

   Data collection on dust generated during fuel debris processing operations. Fuel debris processing can either considered with mechanical tools (grinder, saw) or with thermal tools (plasma torch, laser cutting).
   Data collected will be used as input data for the development of dust and aerosols collection devices (especially for the spray scrubbing strategies and for the filtration system of local collection in air)

2. Development of dust and aerosols collection strategies
   1. Development of aerosols and dust collection by spray scrubbing techniques

      Spray scrubbing techniques must be adapted to the configurations on site and to the fuel debris processing tool that will be used. Different strategies are considered: global application or local application of spray scrubbing.

      Performances of systems are assessed both with experimentations and with numerical simulations
   2. Development of local extraction devices for dust and aerosols collection

      Local collection devices are especially designed to be tested with laser cutting techniques. Also, collection devices are connected to the dust extraction system: the goal is to be able to recover the dust that has been collected. Also, the filtration device is meant to be implemented in-situ: therefore development seeks the filtration efficiency and the best solutions to make the system able to work entirely remotely inside the Primary Containment Vessel (PCV)

3. Study of application on site and scenario assessment
   1. Implementation of devices

      Studies on the implementation of the systems on site and their use. Focus is also made on the operability of the system (maintainability, safety analysis, efficiency, etc.)
   2. Numerical simulations

      Starting from data acquired during the tests, numerical simulations are performed with pedestal modelization in order to procure first assessment of aerosols and dust collection efficiency in real case scenario

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2. ITEMS OF WORK

Project Methodology

This section explains the methodology and the relationships between the different items of work:

Input data from past projects, status reports, publications, etc.

Fuel debris simulant manufacturing

Tests with laser cutting and dust collection in air

Data collected:
- Aerosols collection efficiency
- Transportation and filtration of particles efficiency (dust and aerosols)
- Operability of collection devices

Test for different mechanical processing tools in air

Data collected:
- Aerosols characterization (mass concentration, size distribution)
- Characteristics of fuel debris after cutting (assessment of amount of dust, blocks, slags, etc.)
- First approach of mechanical behaviour of the processing tools

Input data for spray scrubbing development (local and global strategy)

Numerical simulations for spray scrubbing efficiency for various conditions

Spray scrubbing tests in TOSQAN facility with simulated aerosols

Spray scrubbing tests in DELIA facility with laser cutting and with and without dust collection devices in air

Proposal of the best strategies for dust collection and site applicability

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3. SCHEDULE OF THE PROJECT

Overview of project schedule – FY2019

APR. | MAY | JUN. | JUL. | AUG. | SEP. | OCT. | NOV. | DEC. | JAN. | FEB. | MAR.

Preparation of R&D program

ITEM 1 – DATA COLLECTION ON DUST EMISSION WITH DIFFERENT FUEL DEBRIS PROCESSING METHODS

- Choice of FD simulants
- Fuel Debris simulants manufacturing (MCCI and In-vessel simulants) – 6 batches in total
- Manufacturing report
- Test program & facility preparation – Disc saw
- Essential tests + report of the tests
- Improvement of facility (instrumentation) for complete disc saw tests
- Test program & preparation of tests – Core boring
- Design of equipment and supply for core-boring tests
- Preparation of DELIA facility for laser cutting with N_2

ITEM 2 – COLLECTION OF AEROSOLS BY SPRAY SCRUBBING TECHNIC

- Test program definition
- Design, supply of equipment and modification of TOSQAN facility for the realization of the tests – Single spray and multi nozzles spray
- CFD calculations – Tests of configurations through numerical simulations
- Preparation of tests for spray scrubbing with laser cutting (test program + supply of equipment)
- Tests – Laser cutting with spray scrubbing
- Tests report

ITEM 3 – LOCAL COLLECTION AND EXTRACTION OF DUST AND AEROSOLS

- Definition of local collection system & essential tests
- Improvement of design of collection systems & preparation of tests
- Tests & analysis of results
- Study & supply of transportation and filtration equipment
- Essential tests with and without laser cutting & analysis of results
- Study of applicability of solutions on site

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3. SCHEDULE OF THE PROJECT

Overview of project schedule – FY2020*

APR. | MAY | JUN. | JUL. | AUG. | SEP. | OCT. | NOV. | DEC. | JAN. | FEB. | MAR.

Update of Research Plan

ITEM 1 – DATA COLLECTION ON DUST EMISSION WITH DIFFERENT FUEL DEBRIS PROCESSING METHODS

- Preparation of core-boring tests
- Core-boring tests on FD simulants & analysis of results
- Improvement of facility (instrumentation) for complete disc saw tests
- Cutting tests with grinder on FD simulants
- Analysis of results
- Preparation of DELIA facility for laser cutting with N_2
- Laser cutting tests with N_2

ITEM 2 – COLLECTION OF AEROSOLS BY SPRAY SCRUBBING TECHNIC

- Design, supply of equipment and modification of TOSQAN facility for the realization of the tests – Single spray and multi nozzles spray
- Spray scrubbing tests in TOSQAN facility
- Study for the implementation of local spray during laser cutting
- Laser cutting tests with spray scrubbing
- Study of the applicability of the system on site & expected performances (tentative)

ITEM 3 – LOCAL COLLECTION AND EXTRACTION OF DUST AND AEROSOLS

- Design and procurements of local collection devices
- Laser cutting tests with representative materials
- Improvement, design of extraction prototype and expansion of system to mechanical FD processing tools
- Tests
- Final study of applicability of solutions on site

* Due to Covid-19 situation, delays occured on the project. Official termination date of project: 31 May 2021 (final report on 18/5/2021)

4. FINAL OUTCOMES
ITEM #1 – DUST PROPERTIES

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1. ITEM #1 – DUST PROPERTIES

Objectives

1. Gather dust properties for several processing methods (thermal / mechanical) to have data for collection system development*
2. Basic comparison of dust emission between several processing methods

** Complementary from IRID/JAEA CLADS project*

Tasks implemented in the frame of item 1

[1] Fuel debris simulants manufacturing

[2] Data collection on dust and fumes for mechanical tools (and plasma torch)

- 1: Tests with manual reciprocating saw and grinder in TRANSAT test bench
- 2: Test with automatized disc saw (grinder) in CAPIMIF test bench
- 3: Tests with plasma torch on CAPIMIF test bench
- 4: Tests with core boring tool in DELIA facility

[3] Data collection on dust and fumes for laser cutting (including tests with N_2)

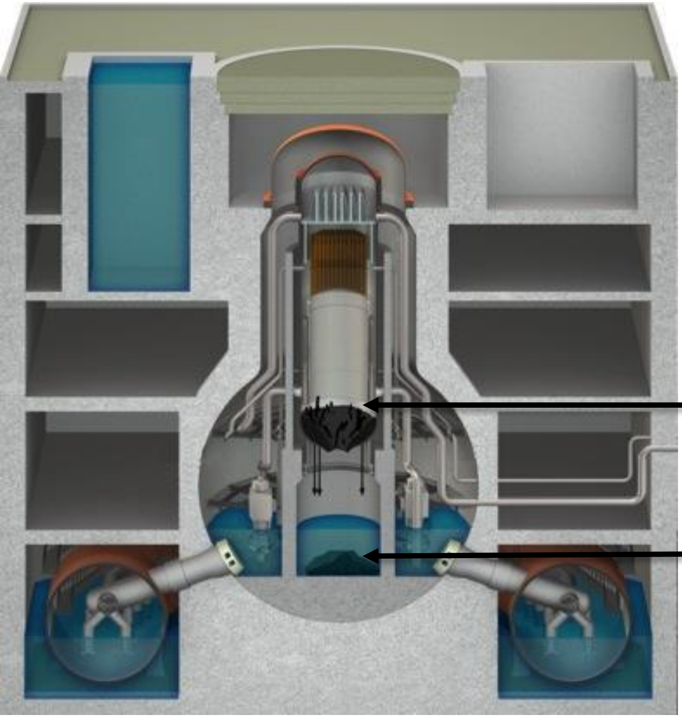
- 1: Tests on stainless steel
- 2: Tests on Ex-vessel fuel debris simulant
- 3: Tests on In-Vessel fuel debris simulant
- 4: Conclusions

[4] Data collection on dust and fumes for various cutting tools and conditions

4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[1] – Fuel debris simulants manufacturing

Objective: Manufacturing of representative fuel debris samples



Two compositions of fuel debris have been considered for the manufacturing of fuel debris simulant.

In-vessel composition has been determined from the average of Fukushima Daiichi unit 2 lower head debris composition

Ex-vessel composition has been determined in order to simulate a debris from interaction between the molten core and the concrete in the sump of Fukushima Daiichi unit 1.

Mixed oxide-metal in-vessel (1F2) fuel debris simulant (based on 1F2 average BSAF compositions)

Oxidic MCCI 1F1 simulant (based on 1F1 Robb and al. calculations with larger concrete content

Fuel debris simulants for in-vessel and ex-vessel compositions are provided to support the developments of technologies studied in the frame of the "Dust collection of fuel debris system" project

The fission product prototypes included (proportions typical of 10 years after accident) except Ru (for health regulation issue) are:

- Raw materials (natural isotopic composition) for Nd, Mo, Cs, Ba, La, Pd, Pm, Sr, Y, Te
- Powders: HfO_2, Zr, ZrO_2, CeO_2 (FP + Pu surrogate), SnO_2, B_4C for both compositions) and SiO_2, FeOx, Al_2O_3, Cr_2O_3 and CaO for the ex-vessel composition

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4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[1] – Fuel debris simulants manufacturing

Loads

In-Vessel fuel debris simulant blocks

	wt%		wt%
HfO_2	30.2%	CsOH.$H_2$0	0.08%
Zr	37.9%	BaO	0.05%
ZrO_2	19.8%	La_2O_3	0.035%
CeO_2	0.2%	PdO	0.033%
SnO_2	1.0%	Pr_2O_3	0.033%
B_4C	1.1%	Sm_2O_3	0.016%
Stainless steel 304L*	9.3%	SrO	0.024%
Nd_2O_3	0.12%	Y_2O_3	0.016%
MoO_2	0.09%	TeO_2	0.015%

Preparing VF-06 in vessel load

**304 L steel rods: 0.017 wt% C, 0.44% Si, 1.5 % Mn, 0.039% P, 0.027% S, 18.5% Cr, 8.07% Ni, 0.5% Cu, 0.08% N, 0.13% Co, 0.37% Mo*

Ex-Vessel fuel debris simulant blocks

	wt%		wt%
HfO_2	20.5%	Fe_2O_3	7.8%
Zr	0.6%	Nd_2O_3	0.09%
ZrO_2	11.7%	MoO_2	0.09%
CeO_2	0.2%	CsOH.H_2O	0.06%
SnO_2	0.2%	BaO	0.039%
B_4C	0.2%	La_2O_3	0.027%
Stainless Steel 304L*	5.6%	PdO	0.026%
Cr_2O_3	0.6%	Pr_2O_3	0.027%
Fe	2.9%	Sm_2O_3	0.019%
FeO	5.0%	SrO	0.019%
SiO_2	30.6%	Y_2O_3	0.011%
Al_2O_3	7.6%	TeO_2	0.012%
CaO	6.2%		

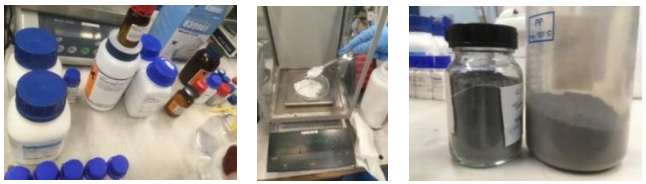
Preparing VF-10 ex-vessel load

4. Final Outcomes
Item #1 - Dust Properties

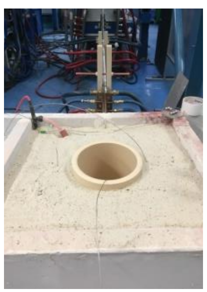
[1] – Fuel debris simulants manufacturing

Manufacturing process

1. Selection of raw materials

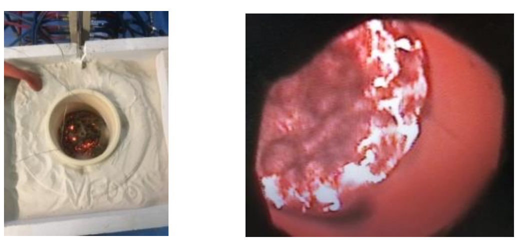


2. Set up of melting furnace



Crucible is filled with pellets and raw materials before melting

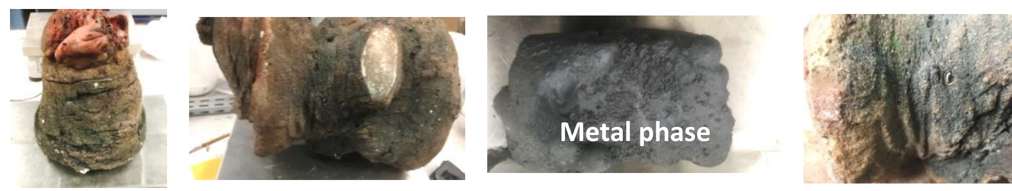
3. Melting operation



In-Vessel fuel debris simulant blocks

The total mass of in-vessel fuel debris simulant blocks produced is 35 kg. Various shapes have been obtained (4 melting procedures)

Ex-Vessel fuel debris simulant blocks



The total mass of ex-vessel fuel debris simulant blocks is 38 kg (including blocks of denser solidified metal) (4 melting procedures)

Apparent density for the different fuel debris simulants:

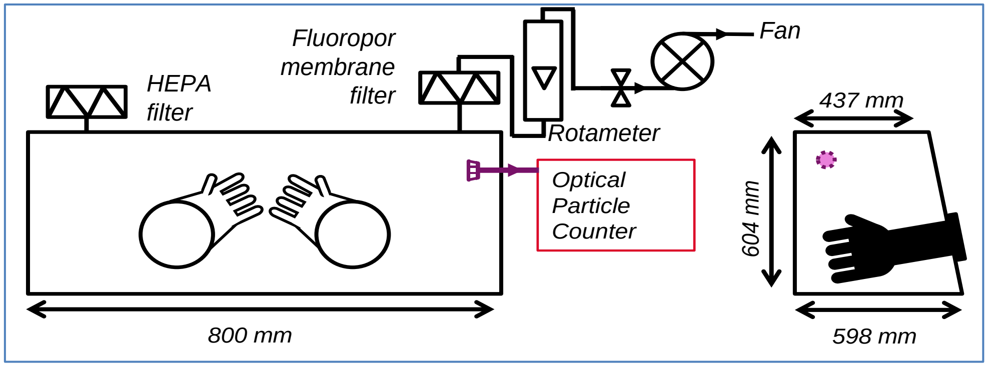
- **In-vessel block: ~4.7 $g.cm^{-3}$**
- **Ex-vessel oxidic block: ~2.6 $g.cm^{-3}$**
- **Ex-vessel metallic layer : ~5.8 $g.cm^{-3}$**

4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

1 – Tests with manual reciprocating saw and manual grinder in TRANSAT test bench

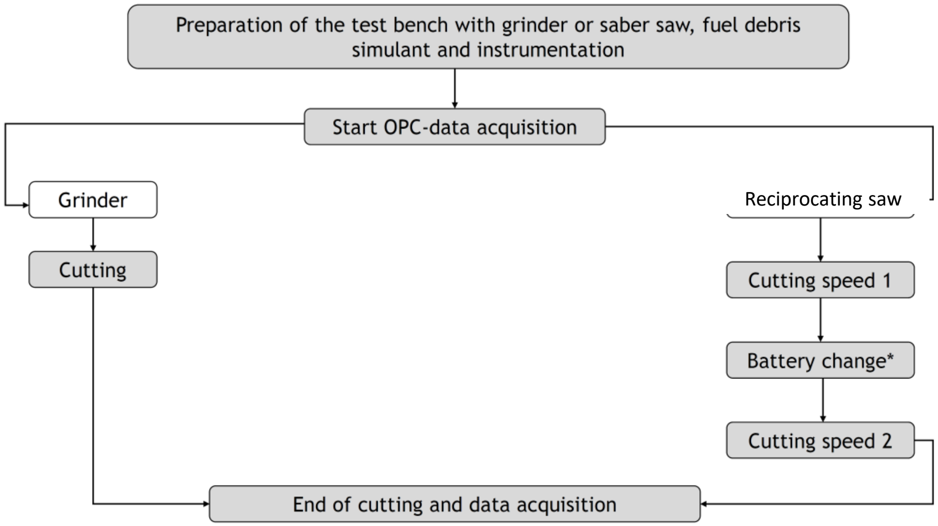
TRANSAT facility and instrumentation:



TRANSAT is a small glove box (250L). This facility is instrumented with an optical particle counter (GRIMM, size range 0,25 µm – 30 µm)

Cutting tests with a reciprocating saw and a grinder are performed manually inside the glovebox in order to obtain information about aerosols generation due to fuel debris simulant cutting with these two cutting tools.

Test procedure and cutting parameters:



Operations are realized manually (no automation of devices). Therefore, cutting strenght has not been monitored and can have variations due to the operator.

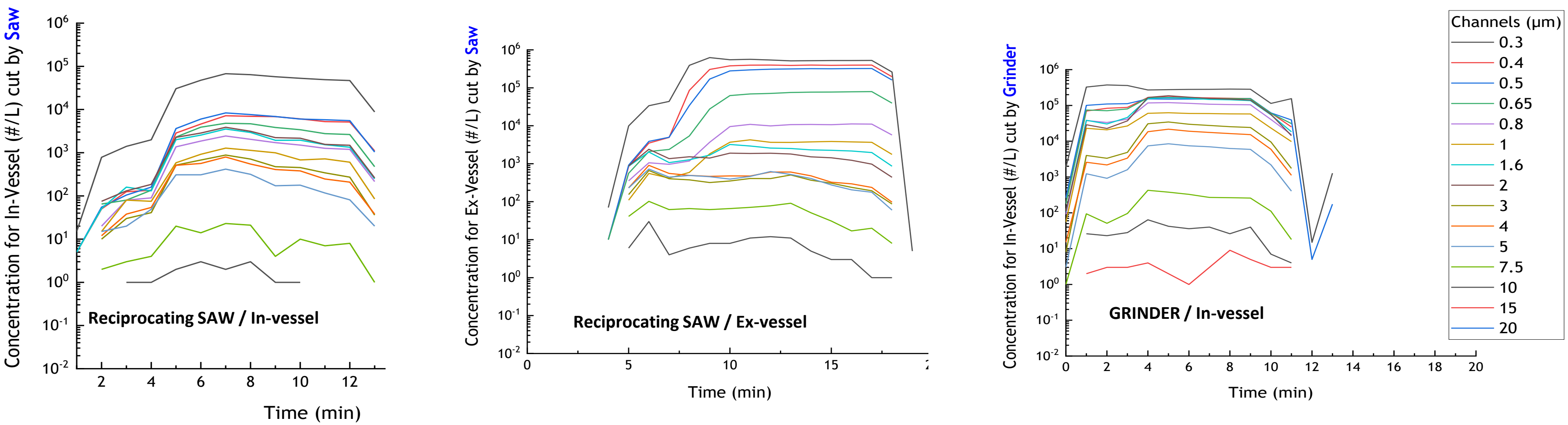
Picture of manual grinder in TRANSAT gloebox (left) and example of reciprocating saw

4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

1 – Tests with manual reciprocating saw and manual grinder in TRANSAT test bench

Results obtained concern the numerical concentrations of particles emitted for every size in the range [0,25µm;10µm] for the two cutting processes and for in-vessel and ex-vessel simulants:

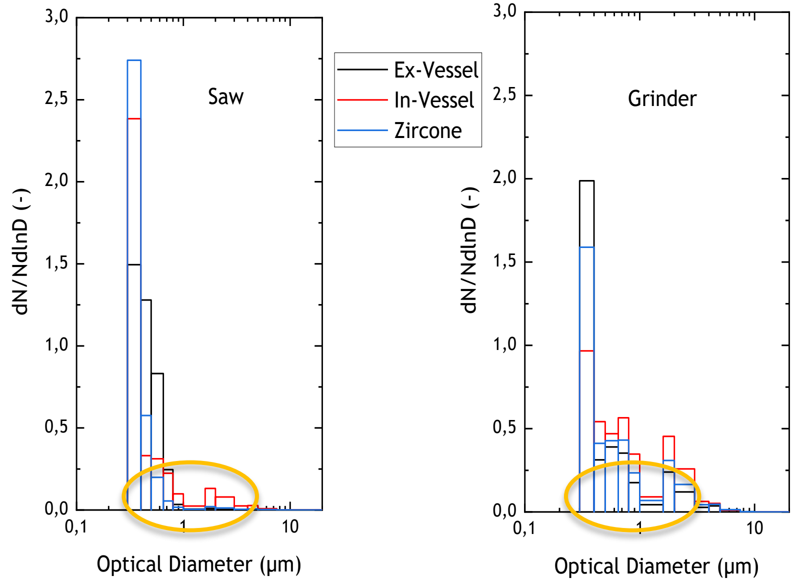


4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

1 – Tests with manual reciprocating saw and manual grinder in TRANSAT test bench

Relative particle concentration according to the size:



Main conclusions of the tests:

- Concerning the number of emitted particles:
  - With the same simulant (in-vessel), the grinder emits more particles, for every size;
  - With the same processing tool (reciprocating saw), more particles are emitted with Ex-vessel fuel debris simulants
- Concerning the particles concentration according to the size range:
  - The reciprocating saw and the grinder both produce high concentrations of very thin particles

[2] – Data collection on dust and fumes

2 – Tests with automatized disc saw (grinder) on CAPIMIF test bench

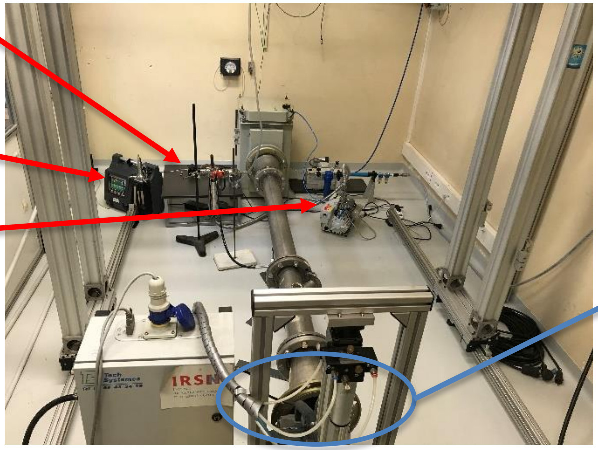
2.1 – CAPIMIF test bench and instrumentation:

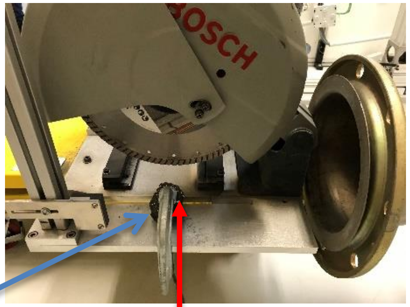
CAPIMIF is an airtight facility. It is composed of a test bench that can be instrumented in order to monitor aerosols characteristics during cutting operations. Monitoring concerns aerosol concentration in mass and numbers, electrical charges distribution, morphologies and physical and chemical analysis on some samples.
Also, particles mass concentrations are integrated with HEPA filter and particles morphologies are studied thanks to TEM and EDS vizualisation

Pegasor

ELPI+

DLPI





Fuel debris simulant

Data acquisition and instrumentation:

- Particle size distribution: integrated measurement with DLPI+ (30 nm to 10 µm)
- Particle size distribution: temporal measurement with ELPI+ (6 nm to 10 µm)
- Particles electrical charges: measurement with ELPI+
- Particle mass and number concentrations: measurement with Pegasor PPS sensor
- Particle morphology is realized with TEM visualization
- Particle composition is obtained by EDS based on TEM image

Cutting strength is monitored and constant through a cutting test thanks to the automatic grinder. Aerosols production has been monitored for various cutting strengths, cutting speeds and for different materials (fuel debris simulants)

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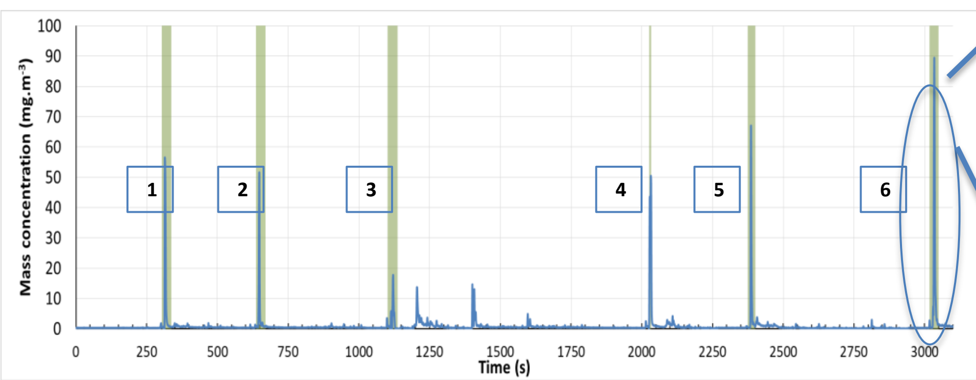
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

2 – Tests with automatized disc saw (grinder) on CAPIMIF test bench

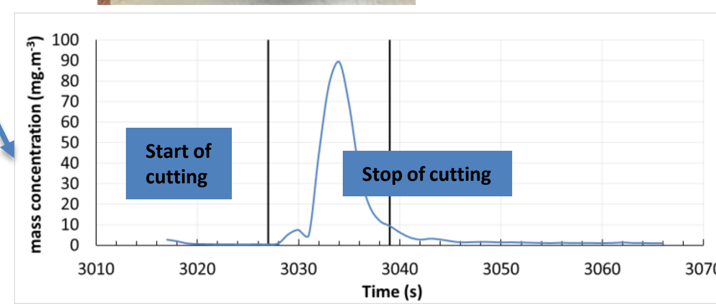
2.2 – Example of data collection on one specific experiment :
a – Calculation of $K_{airbone}$ ratio:

- Mass concentration is monitored during the 6 consecutive cuts (numbered from 1 to 6 in the figure below)
- Fuel debris sample has been weighted before and after the cuts: therefore, it is possible to determine the mass it has lost during the cutting
- $K_{airborne}$ represents the ratio between the mass of aerosols that has been emitted in comparison of the total mass that has been removed from the fuel debris simulant sample



Mass concentration for a sequence of 6 cuts

Measurement of material mass loss during cutting n° 6 on the Fuel Debris sample
$Mass_{material\_loss}$ = 31.2 g



Measurement of mass concentration integrated through the cutting time with measured airflow
$Mass_{airborne\_particle}$ = 73 mg

$K_{airborne}$ = 0.0023

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4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

2 – Tests with automatized disc saw (grinder) on CAPIMIF test bench

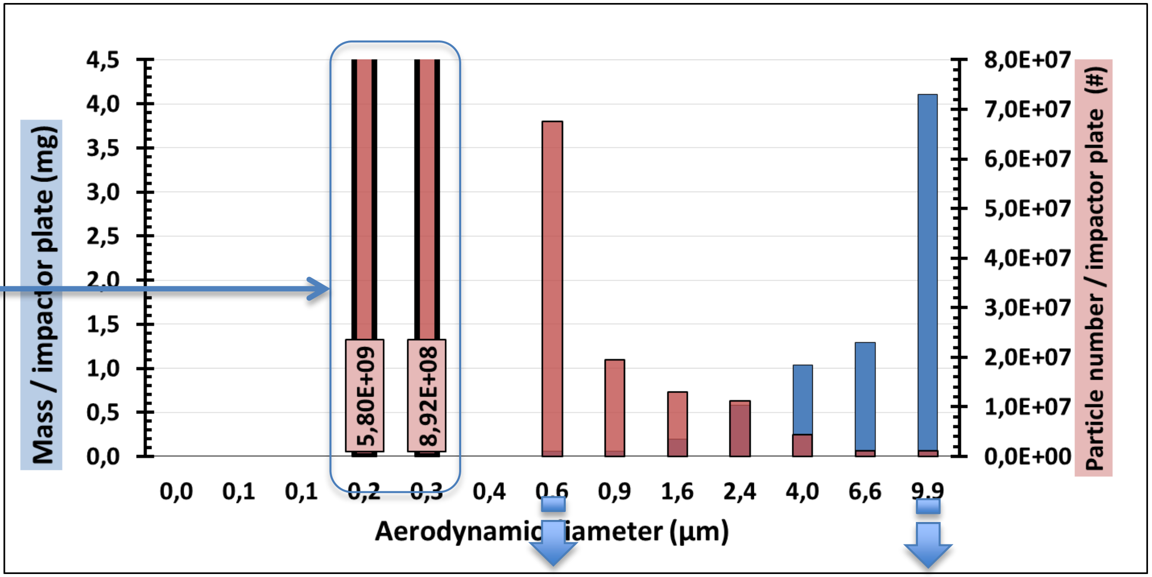
<u>2.2 – Example of data collection on one specific experiment :</u>

<u>b – Particles size distribution in mass and number:</u>

The graph below shows the distribution in mass and numbers according to the aerodynamic diameters of the particles. Data have been obtained during the 6 cuts of fuel debris simulant VF12.

The most important for the contribution in mass comes from the big particles. However, small particles are more important in number, especially for the particles with an aerodynamical diameter between 0.2 µm and 0.3 µm: this size is the critical one from the containment point of view (lowest point of efficiency of HEPA filter)

Critical particle sizes for confinement issues, low contribution in mass while highest one in particles number



View of impactor plates

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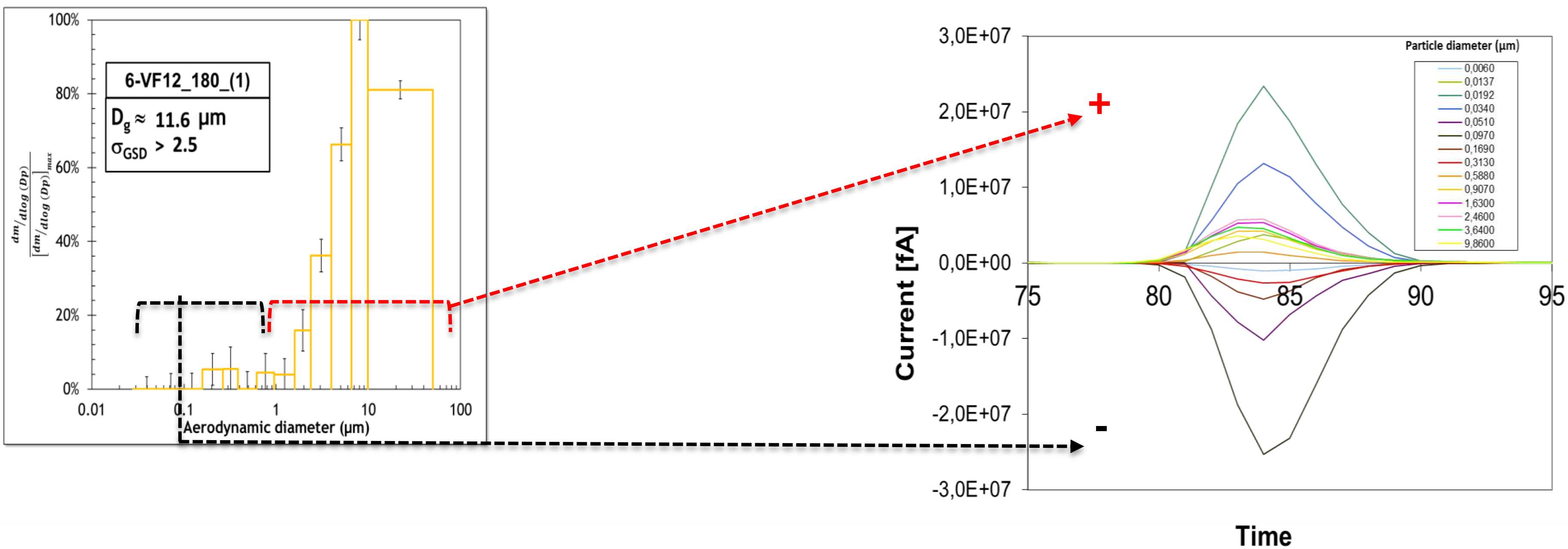
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

2 – Tests with automatized disc saw (grinder) on CAPIMIF test bench

2.2 – Example of data collection on one specific experiment :
c – Electrical charges:

The median aerodynamic diameter for the VF12 fuel debris simulant is 11.6 µm (top left figure). The cumulated mass shows that 90% of the total mass comes from particles with an aerodynamic diameter superior to 3 µm (bottom left figure).
Distribution of electrical charges is given on the right figure. Electrical charges have been measured thanks to ELPI+. Results show significant electrical charges with particles larger than 5 µm having positive electrical charge and particles smaller than 0.5 µm having negative electrical charge.



4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

2 – Tests with automatized disc saw (grinder) on CAPIMIF test bench

2.2 – Example of data collection on one specific experiment :
c – Electrical charges:

- Particles charge are induced by mechanical frictions (No such significant charges observed for particles generated by laser cutting)
- More investigations are needed in order to evaluate the consequences of the electrical charge for dust transportation, deposition and filtration
- Real fuel debris are expected to generate particles with high electrical charges due to radioactive content

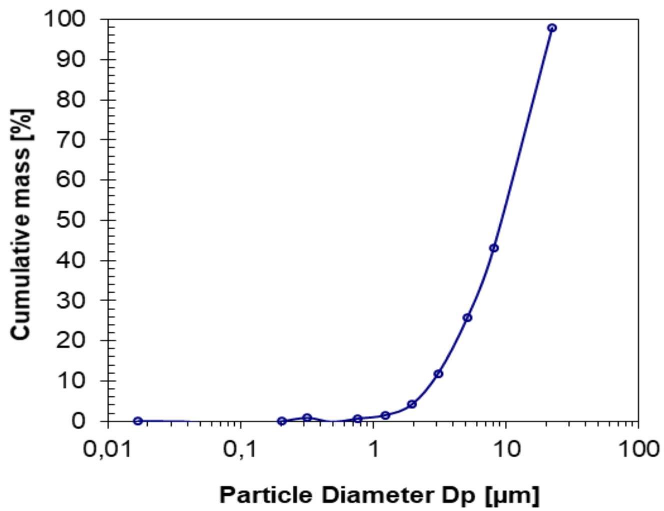


Figure on the left shows the cumulative mass of observed particles depending their diameter

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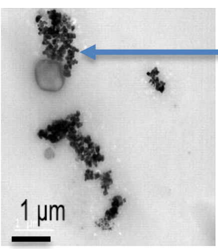
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

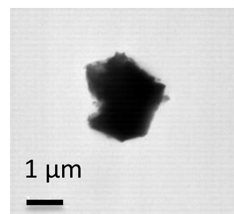
2 – Tests with automatized disc saw (grinder) on CAPIMIF test bench

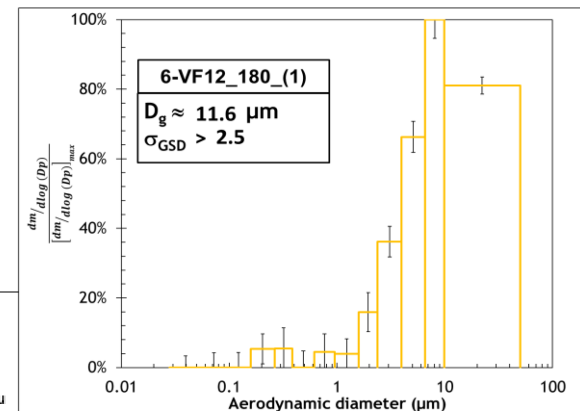
2.2 – Example of data collection on one specific experiment :
d – TEM and EDS vizualisations:

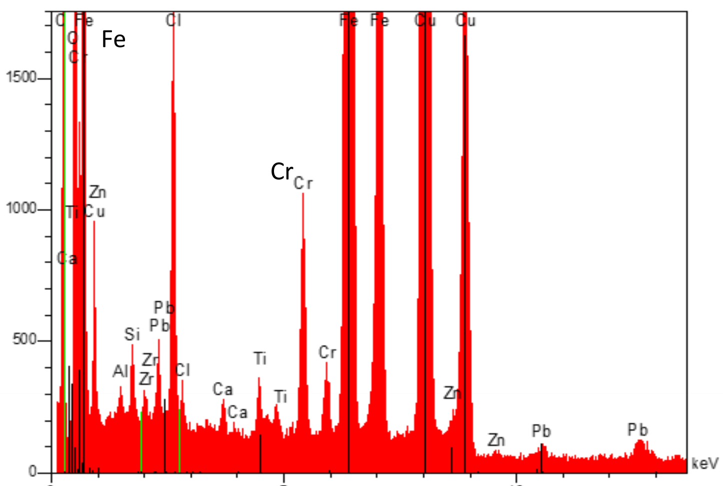
Particle visualization by TEM&EDS with physico-chemical analysis shows various morphologies and heterogeneous composition by particles. Various morphologies including aggregated particles with fractal patterns similar to the ones emitted during laser cutting are observed. This result was not expected for particle generation with a mechanical tool. In terms of composition, results underline heteregeneity for submicronic particles. This tendency seems different compared to the one observed for laser cutting (a homogenous composition was globally observed).

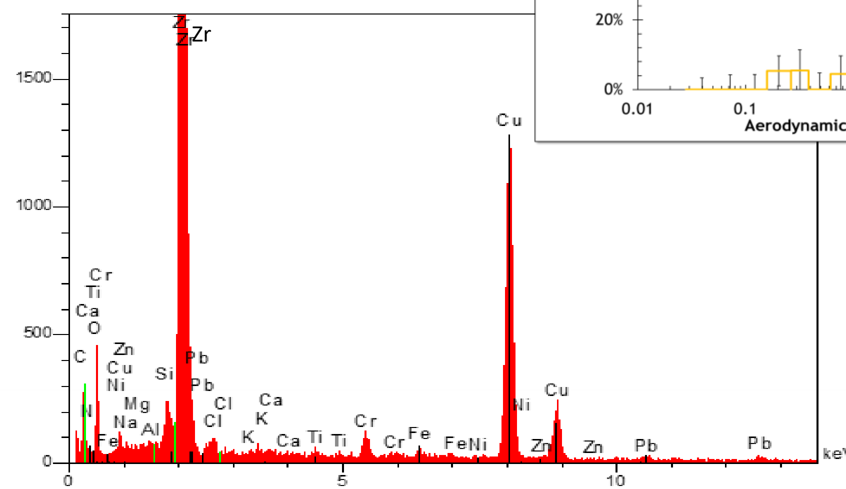


Aggregates of very fine particles (fractal like for laser cutting)









Cu is mainly coming from TEM grids and from stainless steel

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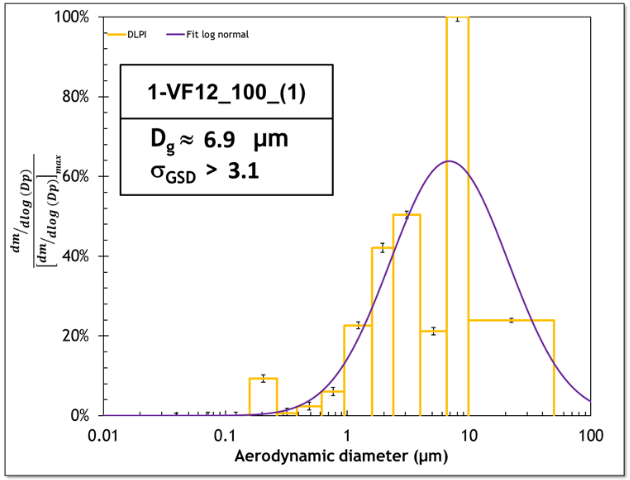
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

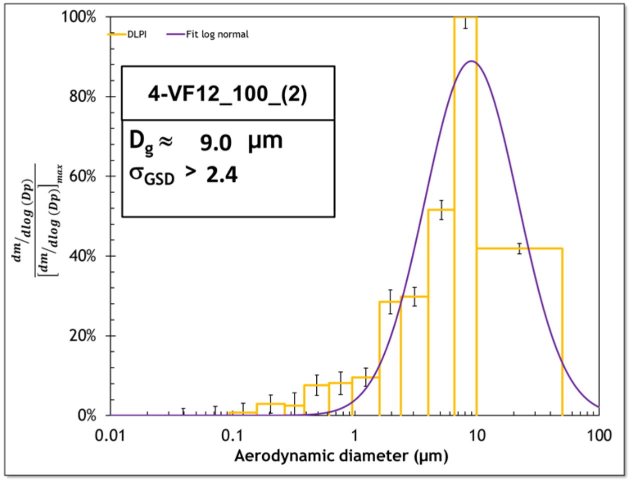
[2] – Data collection on dust and fumes

2 – Tests with automatized disc saw (grinder) on CAPIMIF test bench

2.2 – Example of data collection on one specific experiment :
e – Particles size distribution for a different cutting strenght:

Tests have been realized with different cutting strengths in order to observe the influence of this parameter in the particles emission. The figure below shows two cutting tests: each cutting test consists in 6 cuts, with 100N as cutting strength. Tests have been realized on fuel debris simulant VF12.





Results:

- Tests show a variability of the particles size distribution for the same material. Also, variability in terms of mass concentration has been observed.
- $K_{airbone}$ was calculated and has a 30% variation: $K_{airborne}$ is between 0.0023 and 0.0035

- This variability both for the particles size distribution and mass concentration can be explained by the heterogeneity of the material. Therefore, it is difficult to conclude whether the force applied on the cutting tool has an influence or not. Tests must be conducted on homogeneous cast fused Zirconia blocks.

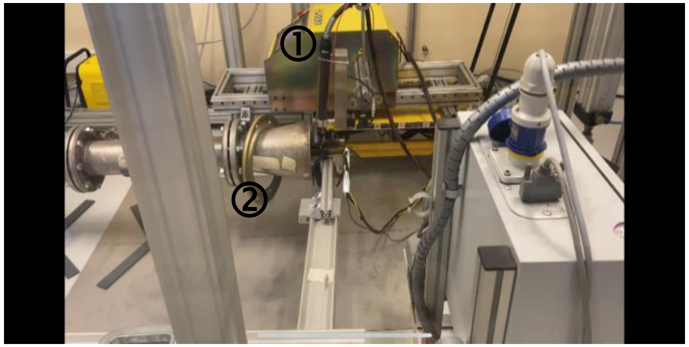
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

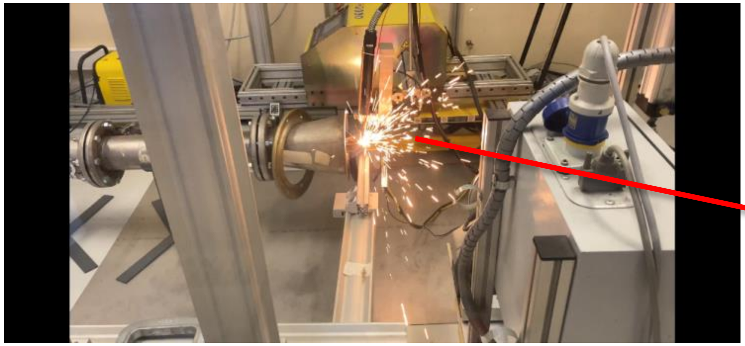
[2] – Data collection on dust and fumes

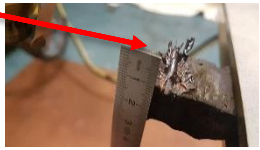
3 – Tests with plasma torch on CAPIMIF bench

Experimental set-up:

The plasma torch is implemented in front of the instrumented ventilation pipe for particle aspiration and measurement



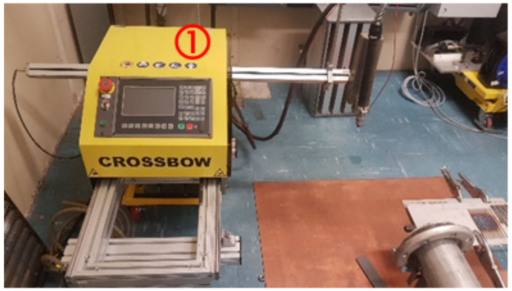


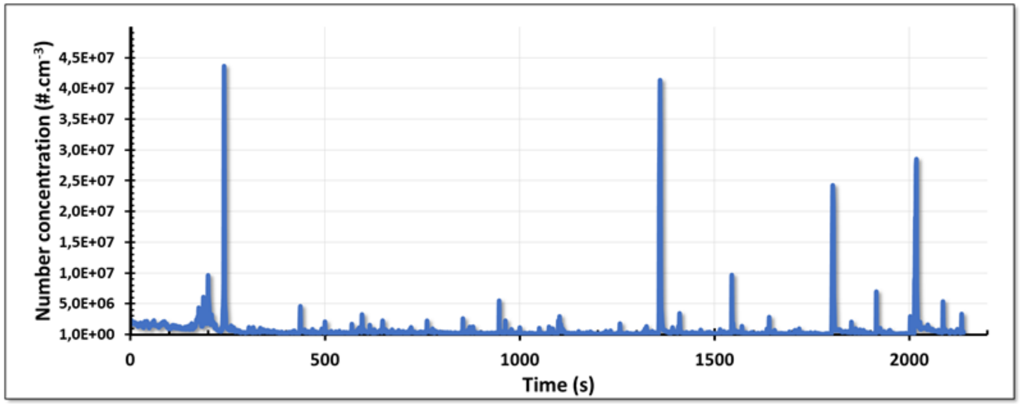


① Plasma torch (Power 180W)

② Ventilation pipe for particle suction and measurement

Particle number concentration during successive cutting/heating with plasma torch





Measurements:

- Particle concentration
- MET&EDS analysis

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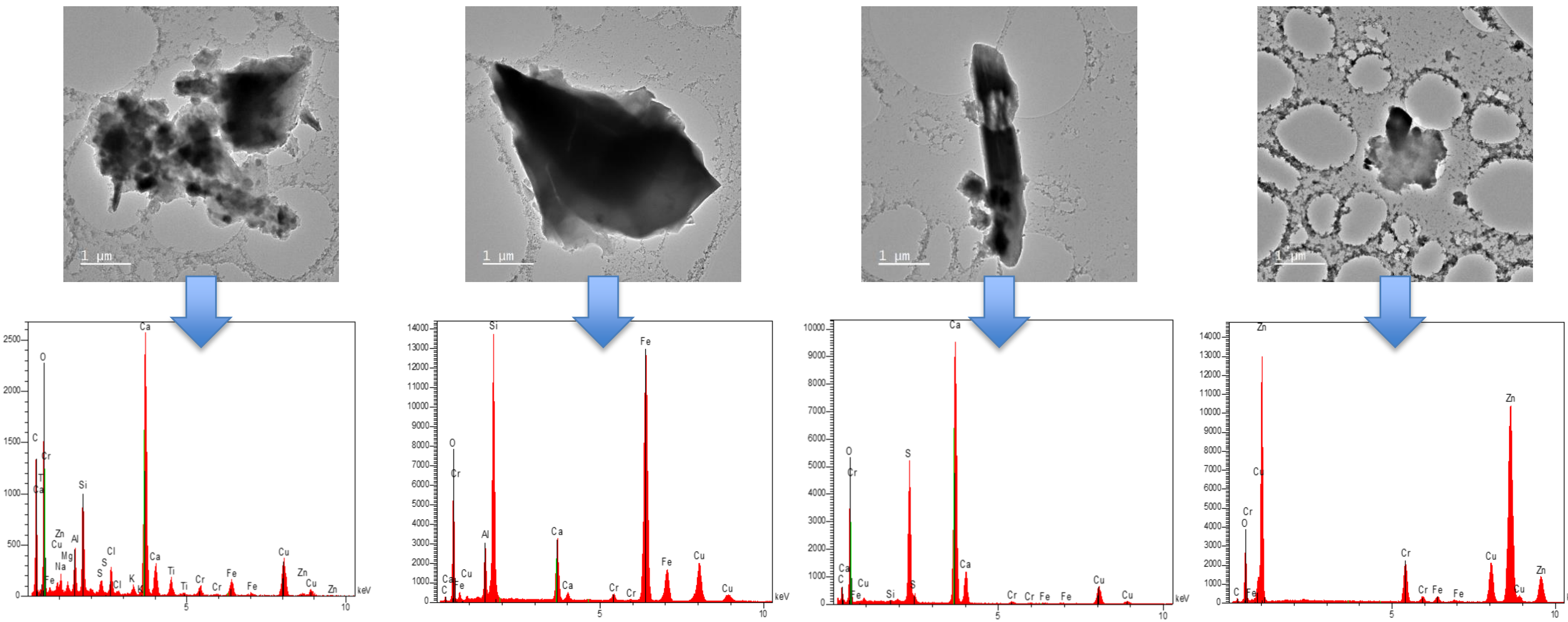
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

3 – Tests with plasma torch on CAPIMIF bench

Tests with Ex-vessel simulant – Particle morphology and composition by MET &EDS

Particle morphologies are quite varied: they can be angular, spherical or fractal. A particle with polydispersed size has been observed based on MET analysis, from 50 nm to more than 5 µm.



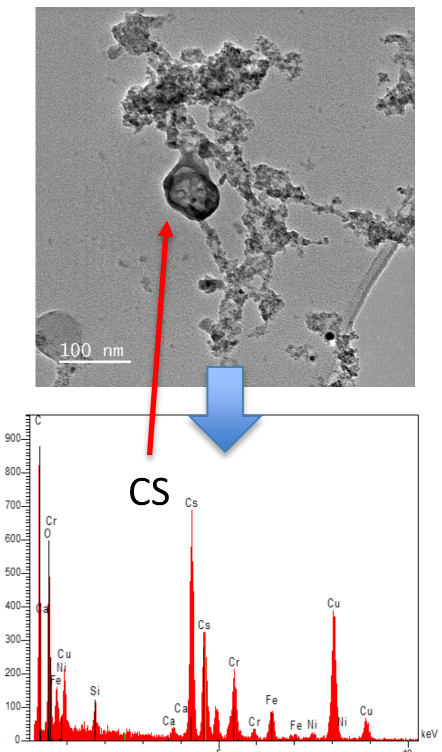
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

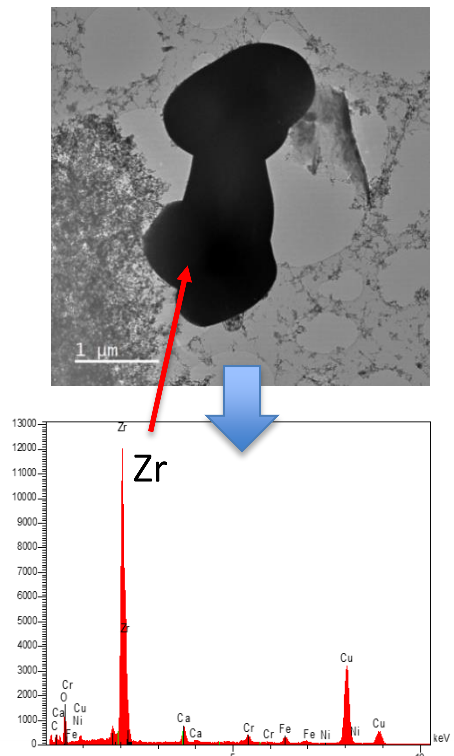
[2] – Data collection on dust and fumes

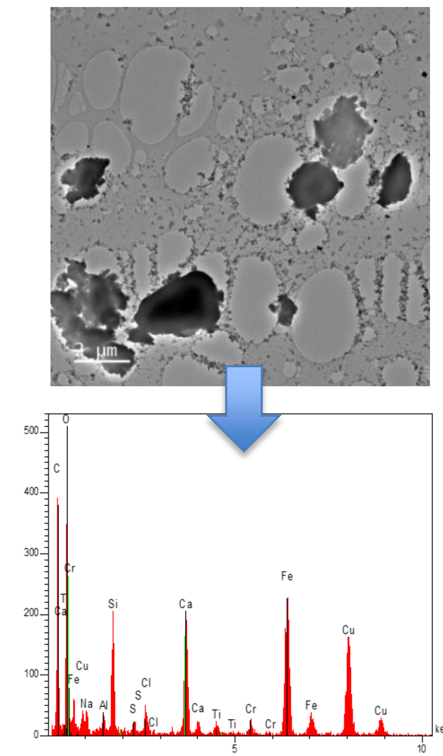
3 – Tests with plasma torch on CAPIMIF bench

Tests with In-vessel simulant – Particle morphology and composition by MET &EDS

The same tendency has been observed for In-vessel fuel debris simulant regarding particle morphology and particle size. Individual particles of Cesium and Zirconium have been observed. Particles of Cs and Zr have been identified.







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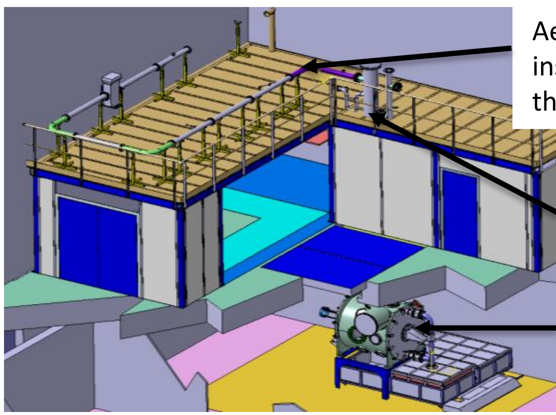
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

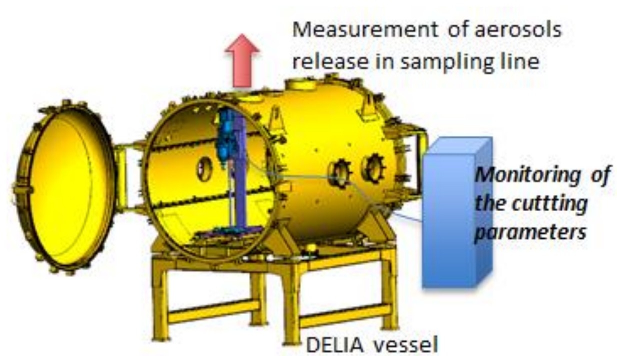
[2] – Data collection on dust and fumes

4 – Tests with core boring tool in DELIA facility

Core boring tool in DELIA facility:

DELIA facility is an airtight vessel with a chimney connected to an instrumented aerosols sampling ine





Pegasor

DLPI

For particle size distribution, integrated measurement with DLPI+ (30 nm to 10 µm)

For particle mass and number concentration (Pegasor PPS sensor)

Methodology applied:

- The cutting parameters are monitored and constant during all the cutting
- Different parameters that can have an influence on aerosols generation have been tested: tests cutting on cast fused Zirconia blocks, cutting on in-vessel and ex-vessel simulant blocks, influence of spray scrubbing
- Data monitored: cutting strength, cutting speed, water flow for spray scrubbing, air injection for air circulation in the vessel
- Data acquired: number and mass concentrations, particles size distribution, data for the study of the applicability on site of the core boring tool

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[2] – Data collection on dust and fumes

4 – Tests with core boring tool in DELIA facility

Core boring of in-vessel fuel debris simulant. The core boring produces, among others, dust and a solid block. The solid block is not automatically removed from the core boring tool

Core boring test on a cast fused Zirconia block. The core boring produces a very thin powder

Core boring test of ex-vessel fuel debris simulant. Bore coring appears to be difficult, even impossible, when the tool cuts into melted and compact metal cluster. Also, cutting tool is quickly damaged and needs to be changed frequently

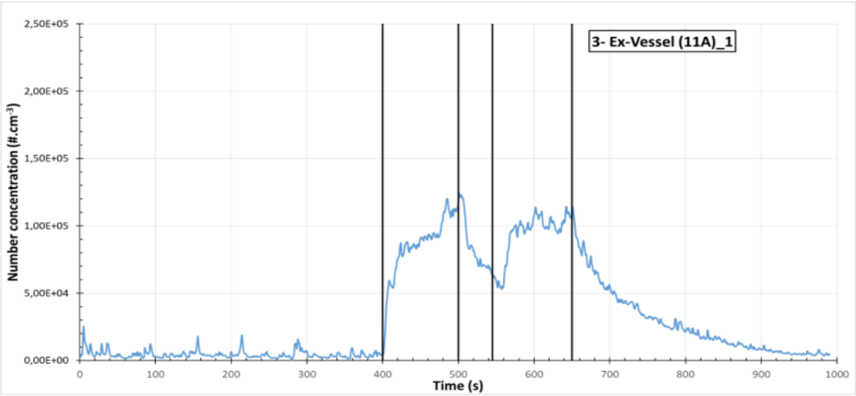
Core boring test on ex-vessel fuel debris simulant with spraying system on

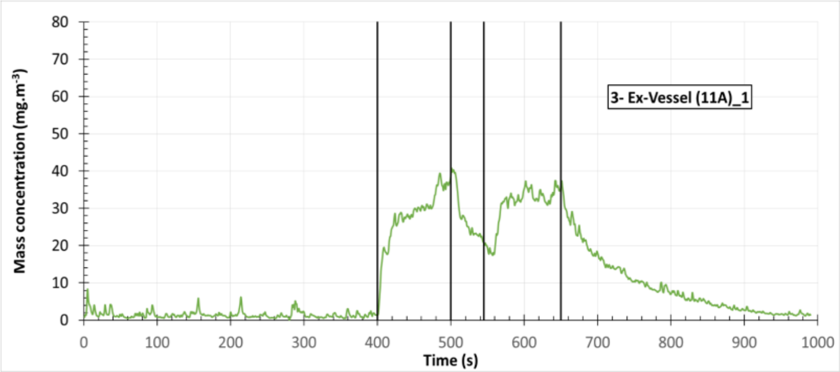
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[2] – Data collection on dust and fumes

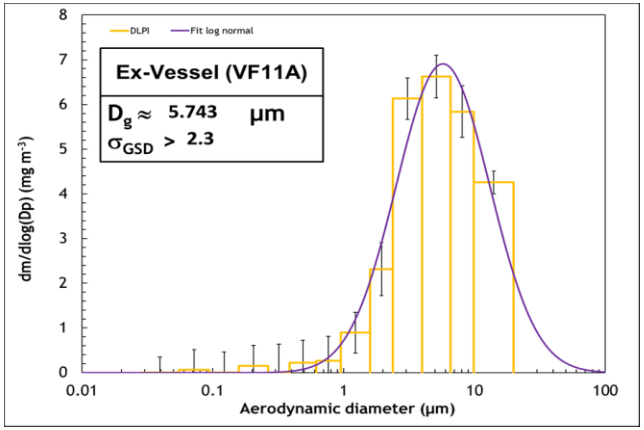
4 – Tests with core boring tool in DELIA facility

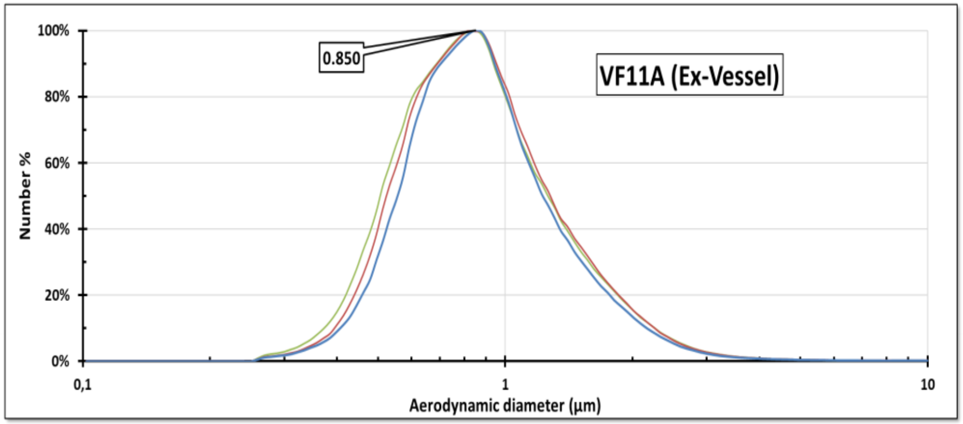
Results: Evolution of the concentration number of particles (left) and converted in mass (right) during the core boring of Ex-vessel fuel debris simulant 11A:





Particle size distribution of the particles: airborne particles sampled in the sampling line of DELIA facility (left) vs particles found at the vicinity of the core boring after the test (right):





4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[3] – Data collection on dust and fumes for laser cutting

Objectives of the tests:

The tests aim at establishing comparisons between secondary emissions generated by air and N_2 gas during laser cutting tets.

Progress/Methodology of the tests:

- Laser cutting tests in air are realized following the usual laser cutting protocol
- For the laser cutting tests using N_2 instead of air:
  - DELIA vessel is vented with nitrogen until O_2 concentration reaches 1% (which is more accurately representative of the 1F conditions)
  - Laser cutting starts with N_2 as assist gas
- For every laser cutting operation, aerosol generation is monitored and characterized in terms of:
  - Mass and number concentration (Pegasor sensor)
  - Particle size distribution (DLPI)
  - Particle morphology and composition (MET & EDS)
- Tests are realized with stainless steel (316L) plates and in-vessel and ex-vessel fuel debris simulants for both conditions:
  - Dry condition
  - Humidity conditions (generated thanks to spraying system) – HR=100%

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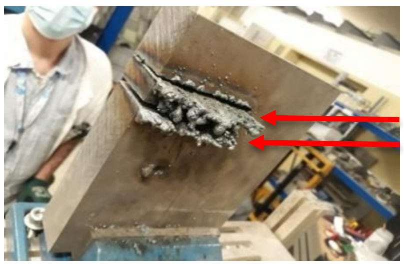
[3] – Data collection on dust and fumes for laser cutting

1 – Tests on stainless steel

Laser cutting tests have been realized on a stainless steel plate (316L, 40 mm thickness) successively in air and with N_2 in dry conditions. Figures below show the results of these tests.

Slag shapes depending on the cutting configuration



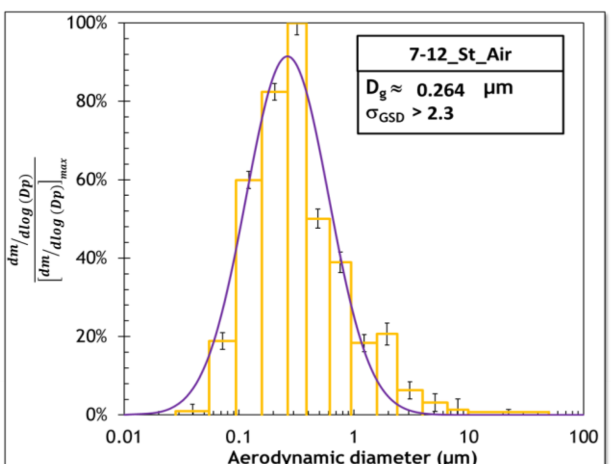
Air cutting
Nitrogen cutting

Air cutting
Nitrogen cutting

Adherent slag are less spread for N2 cutting

- The figure below shows the particle size distributions for laser cutting of stainless steel plate (316 L, thickness = 40 mm) for the cutting in air dry conditions

Air – Dry condition



- **A decrease of particle mass concentration with nitrogen in dry conditions for stainless steel compared to air condition has been observed**
- **Decrease of particle size for N_2 cutting compared to air cutting has been observed**

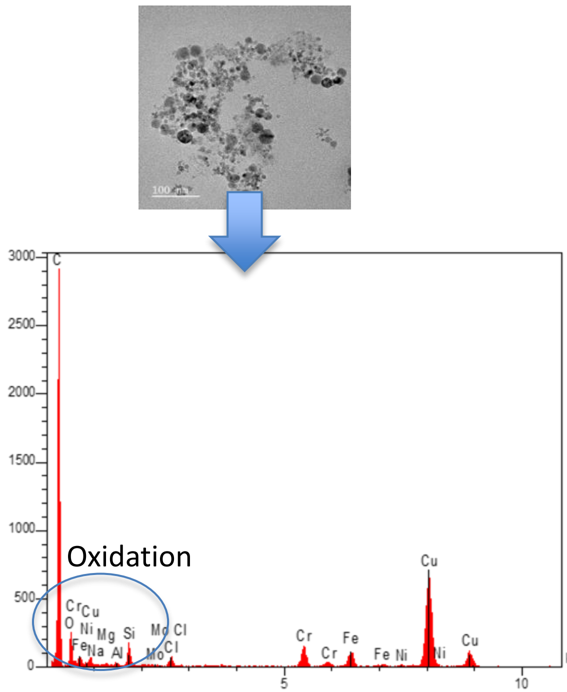
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[3] – Data collection on dust and fumes for laser cutting

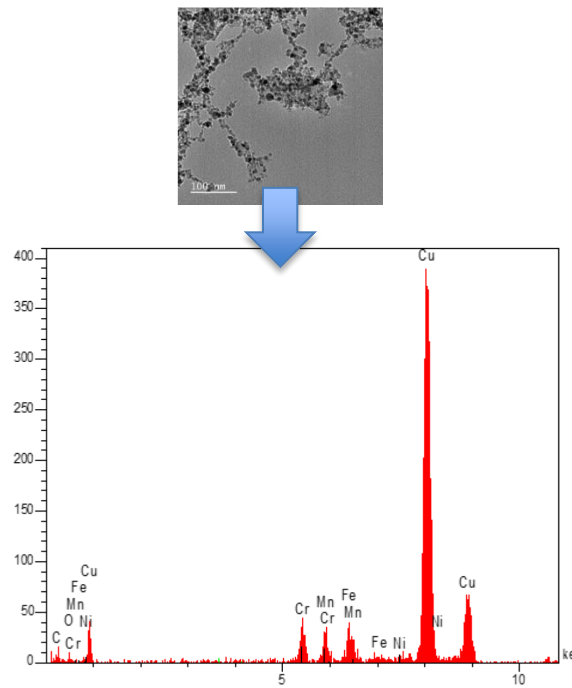
1 – Tests on stainless steel

Particle morphology and composition by MET &EDS

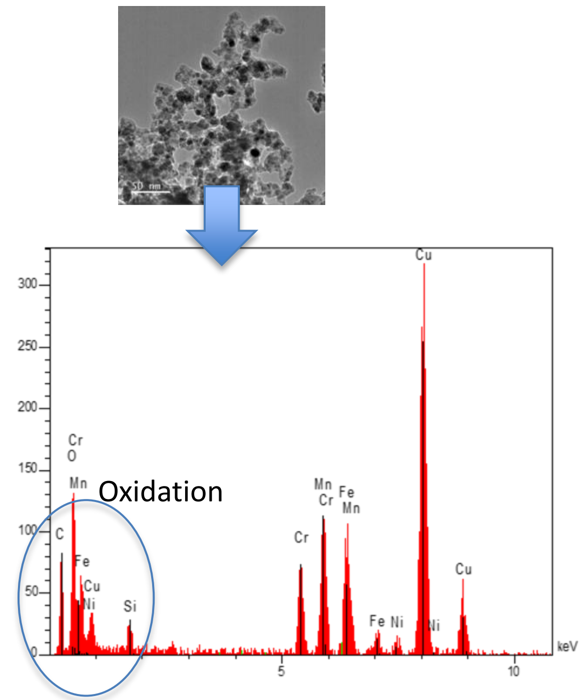
AIR – Dry condition



N2 – Dry condition



N2 + Humidity condition



N2 influence on morphology & composition

- Morphology is still fractal with about the same dimension (D_f close to 1.8)
- Decrease of primary particle size is observed (which is consistent with the decrease of aerodynamic diameter measured thanks to the DLPI)
- Oxidation is underlined for air and N_2 with humidity tests

4. Final Outcomes
Item #1 - Dust Properties

[3] – Data collection on dust and fumes for laser cutting

2 – Tests on Ex-vessel fuel debris simulant

Laser cutting tests have been performed on the same sample of ex-vessel fuel debris simulant in dry conditions with air and then with nitrogen.

- Sample thickness is similar for air and N_2 cuttings

Visually, no clear difference between air and N_2 cuttings on slag structure

A slight influence on particle number concentration is observed but no significant differences for particle mass concentration

No significant difference between nitrogen/air for ex-vessel simulant in terms of particle size, particle morphology & composition and particle number & mass concentrations is observed

[3] – Data collection on dust and fumes for laser cutting

3 – Tests on In-vessel fuel debris simulant

Laser cutting tests have been performed on the same sample of in-vessel fuel debris simulant in dry conditions with air and then with nitrogen. In-vessel simulant is expected to provide more influence with N2 gas due to its lesser oxidation than ex-vessel simulant

- Sample thickness is similar for air and N_2 cuttings

Visually, no clear difference between air and N_2 cuttings on slag structure

- **For dry conditions, N_2 cutting induces a decrease of particle mass and number generation compared to air cutting**
- **A slight influence of Nitrogen on particle size distribution for dry conditions is observed**

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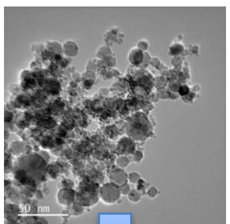
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

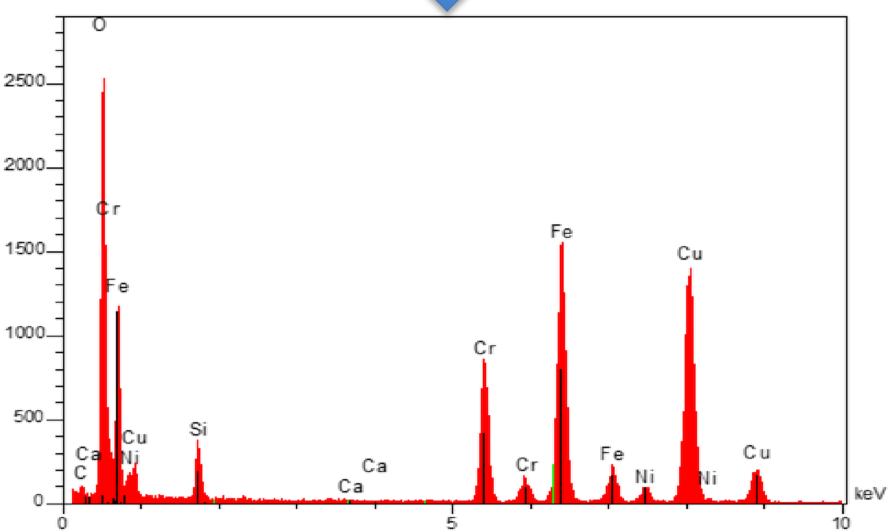
[3] – Data collection on dust and fumes for laser cutting

3 – Tests on In-vessel fuel debris simulant

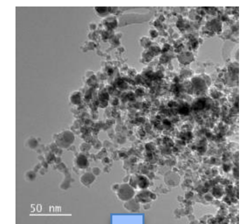
Particle morphology and composition by MET &EDS and particle size by DLPI

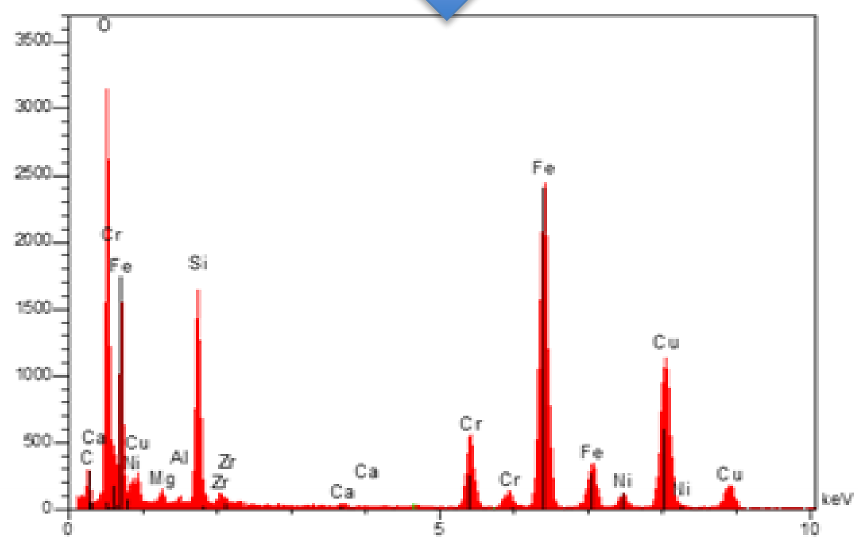
AIR – Dry condition





N2 – Dry condition





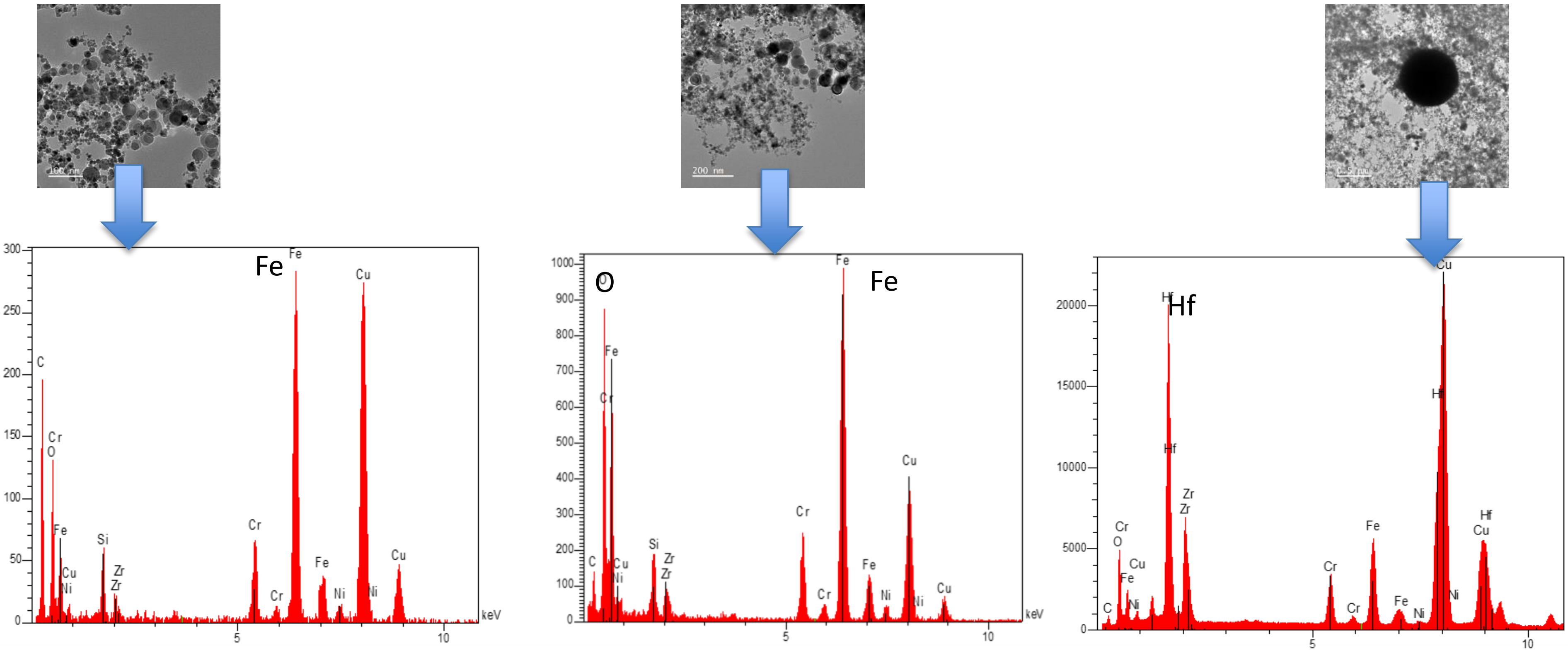
4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[3] – Data collection on dust and fumes for laser cutting

3 – Tests on In-vessel fuel debris simulant

Particle morphology and composition by MET &EDS and particle size by DLPI

N2 + Humidity condition



No nitriding reactions were characterized with EDS. Oxidation reaction are amplified for N_2 + humidity cutting

[3] – Data collection on dust and fumes for laser cutting

4 – Conclusions

Influence of N2 used as assisted and surrounding gas during laser cutting – 1F site conditions

- **Stainless steel:**
  - Strong reduction of particle generation (mass&number) by factors between 6 and 8 depending on dry or wet conditions
  - Wet conditions induce an increase of particle mass concentration and a slight increase of particle size
- **Ex-vessel simulant:**
  - No significant effect of N_2 for dry conditions. The content in O_2 in Ex-vessel simulant is important enough so oxidation is not enhanced by the addition of oxygen provided by water
  - No conclusion for wet conditions
- **In-vessel simulant:**
  - Reduction of particle generation (mass&number) in dry conditions for nitrogen
  - For nitrogen and wet conditions, important increase of particle generation (mass&number) compared to N_2 dry condition. No significant evolution of particle size with humidity. The oxygen content of the in-vessel simulant being low, additional O_2 due to humidity leads to strengthen oxidation reactions which increases aerosol generation
  - Complementary analysis of particle composition by X-ray photo-electron spectroscopy (XPS) would help us to improve the understanding of the results obtained with nitrogen for humidity conditions.

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4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[4] – Data collection on dust and fumes for various cutting tools & conditions

During FY2019 and FY2020, various tests have been performed with different cutting tools in various conditions leading to develop a database for airborne particle generation.

Cutting conditions investigated

- Tool (laser, mechanical, thermal)
- Fuel debris simulants (in and ex-vessel), stainless steel
- 1F site conditions (those that can be simulated)
    - Humidity rate
    - Rain/spray
    - Underwater
    - Air atmosphere
    - Nitrogen atmosphere

FY2019 & FY2020 trials

Cutting tool	Facility	Dry Air	Dry N2	Sprays (local & global)	N2 Humidity (100%)	Underwater cutting
Laser/Ex-vessel/In-vessel	DELIA	O	O (1% O_2)	O	O	* O (0.35m to 6m)
Laser/stainless steel	DELIA	O	O (1% O_2)	O	O	* O (0.35m to 6m)
Core boring/Ex-vessel/In-vessel	DELIA	O		O		
Wheel grinder/Ex-vessel/In-vessel	CAPIMIF	O				
Plasma torch/ex-vessel/In-vessel	CAPIMIF	O				
Reciprocating saw/Ex-vessel/In-vessel	TRANSAT	O				

*FY2017

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[4] – Data collection on dust and fumes for various cutting tools & conditions

Structure of analytical table for particle generation

Items for operating conditions of tests	Operating conditions	Particles data
Cutting conditions	Test bench name / location Cutting tool type Ambient conditions (dry, air, nitrogen, rain) Ventilation flow rate Other	Morphology Main composition
Fuel debris simulant or materials specifications	In-vessel, Ex-vessel, zirconia, stainless-steel Dimensions Composition, density, hardness	Size ▪ aerodynamic mass median diameter (D_g) ▪ Aerodynamic number median diameter (D_n) Geometric standard deviation (σ_g)
Cutting tool specifications	Disk diameter Rotation speed, pressure force ELC* or NELC**, Laser power, wave length, laser beam diameter	Electrical charges
Metrology for particles characterization	DLPI, ELPI HEPA filter Pegasor TEM & EDS	Mass / number concentration
Cutting performances / cutting issues	Cutting speed Kerf thickness and depth Tool blocking or damage	Airborne fraction coefficient Mass emission rate

** ELC: Emerging Laser Cutting* *** NELC: Non-Emerging Laser Cutting*

4. FINAL OUTCOMES
ITEM #1 - DUST PROPERTIES

[4] – Data collection on dust and fumes for various cutting tools & conditions

- The objective is to evaluate radioactive airborne release particles for safety assessment management during fuel debris cutting with various tools.
- The complexity of this work is linked to the following points:
  - Difficulty of comparison of experimental results obtained with various aerosols metrology measuring various physical magnitudes (particle size distribution in mass, in number, aerodynamic, electrical mobility, …)
  - Experimental uncertainties
  - Heterogeneity of fuel debris simulant giving a dispersion of experimental values
  - Repeatability of the cutting tool implementation or user effects
  - Well knowledge of safety assessment expectations from nuclear safety authorities

IRSN has developed the “BADIMIS” database used by French Nuclear Authorities (ASN) capitalizing dust resuspension results for accidental scenarios (see next slide). (May be used for further data collection work.)

FY2019&FY2020 results regarding particle generation are synthetized in analytical table.

Database on radioactive particles release phenomena

A total of 65 scientific and technical documents (theses, reports, articles, …) have been compiled and analysed in 75 distinct summary sheets, organized into 6 main categories of mechanisms :

- Aerodynamic entrainment
- Thermal phenomena (fire, combustion, pyrolysis, heating)
- Dispersal via pressure/explosion
- Cutting of materials with different tools (plasma arc torch, band saw, chainsaw, arc-air, arc-saw)
- Falling of material(s) or object(s)
- Others (vibrations, boiling, release and transfers caused by an operator walking)

4. FINAL OUTCOMES
ITEM #2 – DUST COLLECTION SYSTEMS

2. DUST COLLECTION SYSTEMS

Objectives

- Study, test and design suitable solutions in order to mitigate the aerosols release during fuel debris processing using spraying systems, including mechanical fuel debris processing tools, with local and global spraying strategies
- Design and test a first prototype for local collection of dust and aerosols in air for laser cutting and its expansion to mechanical tools

Tasks implemented in the frame of item 2

[1] Dust dispersion mitigation by spray scrubbing

- 1: Numerical simulations
- 2: Tests in TOSQAN facility with simulated aerosols
- 3: Assessment of spray efficiency for laser cutting

[2] Advancement of local collection during laser cutting

1. Improvement of local collection device
2. Collection efficiency and operability tests
3. Local collection and spray scrubbing with laser cutting

[3] Numerical simulations (CFD) in PCV geometry

[4] Operability tests

[5] Dust extraction system development

2. DUST COLLECTION SYSTEMS

Overview of the work achieved – Spray scrubbing & Local collection

Spray scrubbing strategy development

Numerical simulations:
First assessment of collection efficiency with droplets characteristics
p.45

Tests in TOSQAN with simulated aerosols
- Simulation of fuel debris processing with mechanical tools and laser cutting
- Tests with local and global sprays strategies

p.46-50

Spray scrubbing tests with laser cutting
- Laser cutting of fuel debris simulant
- With global and local spray strategies

p.51-52

Local collection of dust (laser cutting)

Preliminary tests
To work on coating and minimize deposition of molten material
Numerical simulations:
To improve aeraulics of collection heads with laser
p.53-54

Efficiency and operability tests
To prove that collection efficiency is high with representative materials
p.55-57

Dust extraction system

Design of dust extraction system
With definition of elements
p.66-69

Preliminary tests
Cyclonic filter, flexible hoses, self-cleaning HEPA filter
p.70-72

Laser cutting tests with local collection and filtration equipment
p.73-75

Local collection and spray scrubbing during laser cutting tests

Laser cutting tests with local collection and spray scrubbing strategies implemented together
p.58-59

Operability tests of local collection

Operability tests
To assess the feasibility of implementation on site
p.65

Extrapolation of results for on site conditions

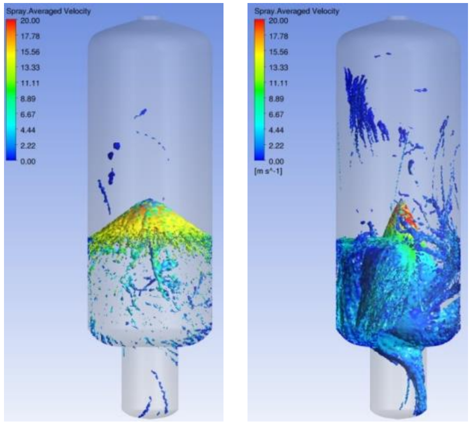
Numerical simulations in order to assess efficiency of both strategies in PCV
p.60-64

4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

[1] – Dust dispersion mitigation by spray scrubbing

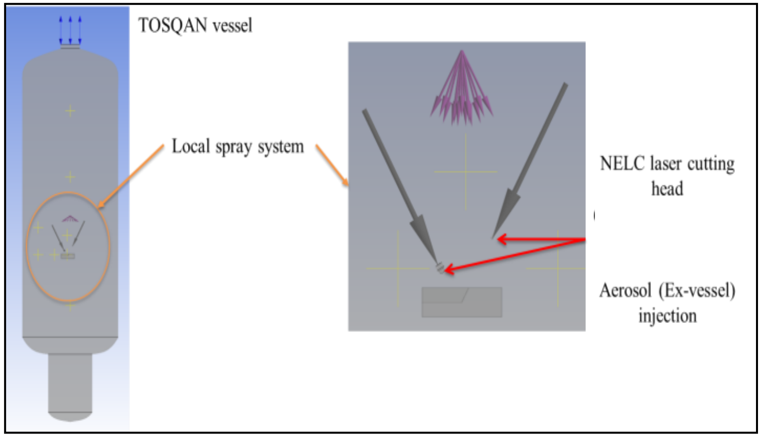
1 – Numerical simulations

- Objective: The objective of this task was to determine the most promising local spray characteristics to be implemented (droplets size, mass flow rate, position and orientation of the spraying nozzle)
- Input data: Aerosols characteristics gathered thanks to previous experiments, tools characteristics (airflows for the laser cutting for instance)



Example of numerical modeling results: view of droplets concentration in TOSQAN facility for laser cutting

Example of numerical modeling: Laser cutting NELC-A configuration implemented in TOSQAN facility to forecast the spray scrubbing efficiency for different spraying characteristics*



- Results of the study:
  - First assessment for aerosols collection efficiency with a local spray system for various tools (grinder, reciprocating saw, laser)

These characteristics for the sprays have been used for the tests in TOSQAN facility and in DELIA facility

***: NELC-A stands for Non Emerging Laser Cutting in Air**

[1] – Dust dispersion mitigation by spray scrubbing

2 – Tests in TOSQAN facility with simulated aerosols

2.1 – Overview of the tests

- Objectives:
  - Improvement of dust mitigation by spray systems coupling local and global sprays
  - Assessment of collection efficiencies for various particle generation (mechanical tools and laser)
  - Study of scenarios of local and global sprays activation for reducing water consumption

- Methodology:
  - Powders are used in order to simulate the aerosols generated during the fuel debris processing. They have been selected to be representative of each cutting tool that has been studied
  - Sensibility of droplets size for global spray have been studied
  - Time evolution of particle concentration in the vessel is monitored to evaluate the collection efficiency during various scenarios of cutting simulation

The tests aimed to assess mitigation efficiency of spray scrubbing strategy for different scenarios, for various cutting tools and for various global spray characteristics

Efficiency of spray scrubbing systems will be evaluated within following physical magnitudes:

- Particle removal rate (λ)
- Decontamination factor (DF) - $DF=(C_0-C_{t=1800s})/C_0$
- Initial and chosen time particle number concentration (C_0 and $C_{t=1800s}$)

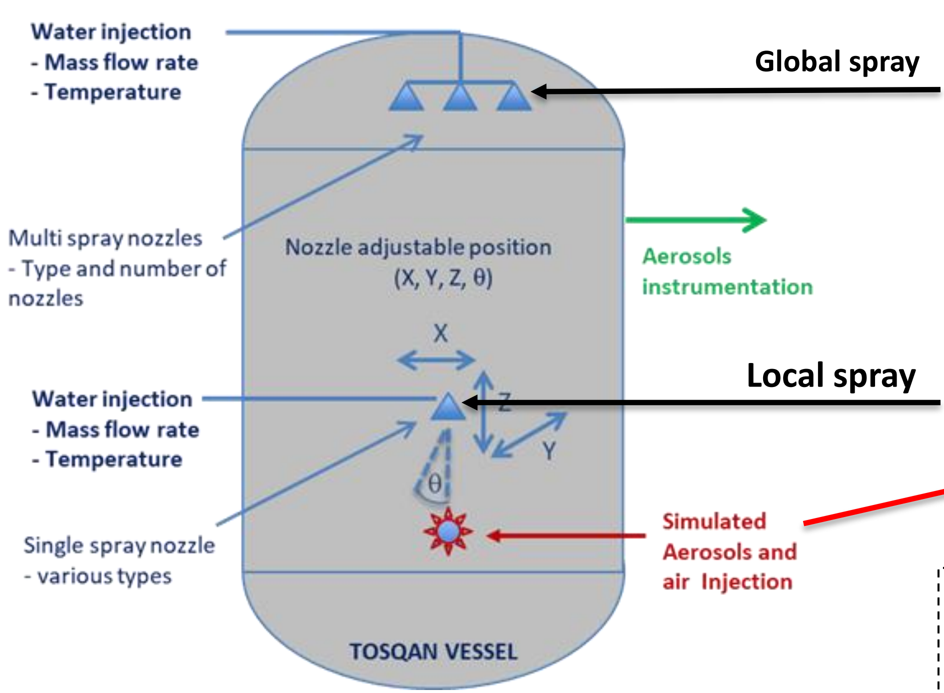
[1] – Dust dispersion mitigation by spray scrubbing

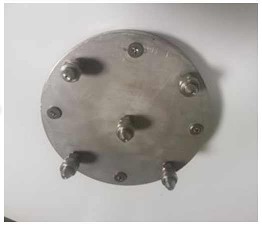
2 – Tests in TOSQAN facility with simulated aerosols

2.2 – Overview of the tests

The picture below describes TOSQAN facility. The global spray device is situated at the top. With global spray, all the surface of the vessel is covered with the droplets. Between 5 and 9 spray nozzles can be used depending on the test parameters.

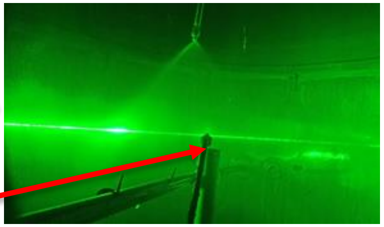
The local spray is situated closer to the injection point. Other characteristics are given on the picture.





5 to 9 spray nozzles can be used with different characteristics in terms of droplet size and in terms of water flow:

- Large droplet size
- Small droplet size



One single nozzle is used:

- Large droplet size

Characteristics of powders injected to simulate the aerosols:

- For laser cutting: 0.4 µm (single mode distribution)
- For wheel grinder: 0.5 µm - 5 µm (bimodal size distribution)

[1] – Dust dispersion mitigation by spray scrubbing

2 – Tests in TOSQAN facility with simulated aerosols

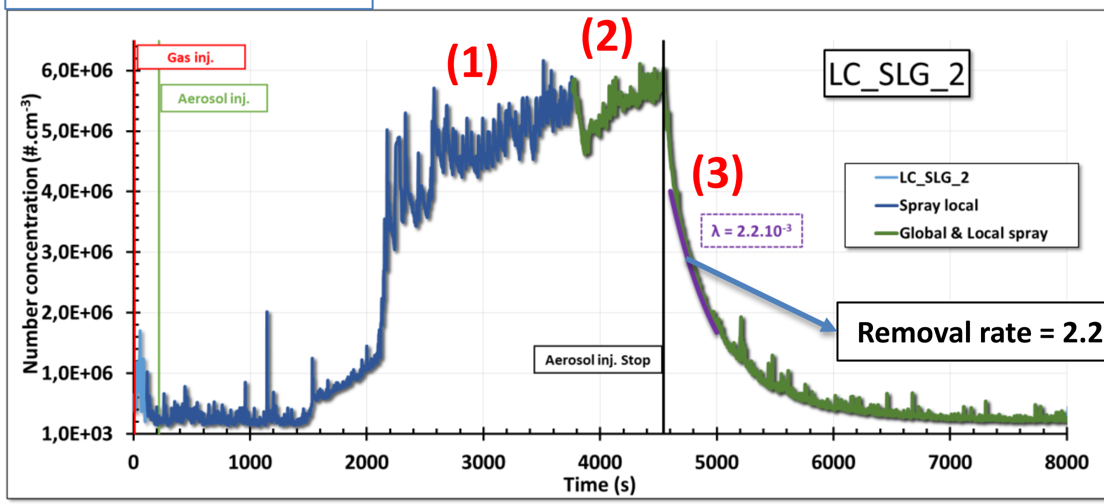
2.3 – Simulation of laser cutting with global spray (big droplets) and local spray

Test scenario consists in 3 phases for the laser cutting operation. Large droplets size is used for the global spray.

- (1) Particle injection + Local spray on (= cutting operation starts with only local spray on)
- (2) Particle injection + Local/Global sprays (= cutting operation with both strategies of spray scrubbing on)
- (3) Particle injection stopped + Local/Global sprays (= cutting operation is stopped but sprays are still on to collect the remaining particles)

The graphic below shows the evolution of concentration in number of particles inside TOSQAN vessel:

Laser cutting simulation



Removal rate = $2.2.10^{-3}$ s^{-1}

$$\frac{dN_{aerosol}(t)}{dt} = -\lambda . N_{aerosol}(t) + \cancel{\frac{dN_{source}(t)}{dt}} - \cancel{\frac{dN_{deposition}(t)}{dt}}$$

$DF = (C_0 - C_{t=1800s})/C_0 = 0.91$

[1] – Dust dispersion mitigation by spray scrubbing

2 – Tests in TOSQAN facility with simulated aerosols

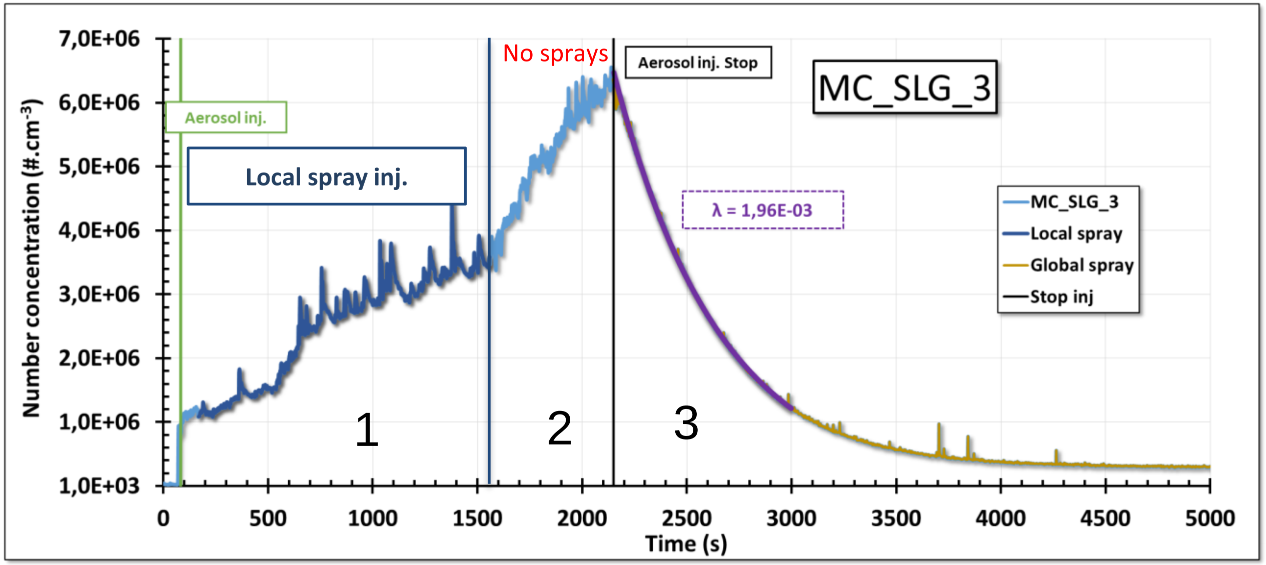
2.4 – Simulation of laser cutting with global spray (small droplets) and local spray

Test scenario consists in 3 phases for the laser cutting operation. **Small droplets size is used for the global spray.**

- (1) Particle injection + Local spray on (= processing operation starts with only local spray on)
- (2) Particle injection only (= processing operation with spraying systems off) showing an increase of particle concentration
- (3) Particle injection stopped + Global sprays (= cutting operation is stopped and global spray is started again)

The graphic below shows the evolution of concentration in number of particles inside TOSQAN vessel:

Laser simulation



$DF=(C_0-C_{t=1800s})/C_0=0.93$

[1] – Dust dispersion mitigation by spray scrubbing

2 – Tests in TOSQAN facility with simulated aerosols

2.5 – Conclusions on local/global spray scrubbing efficiencies

- During particle generation (cutting phase), local spray is very efficient to mitigate aerosol dispersion and to confine particles in the lower part of the vessel which decrease the mean airborne particle concentration in the vessel
- Global spray activation in addition to local spray during the cutting phase does not bring a significant improvement on collection efficiency
- Influence of global sprays is similar for particles generation representative of laser and mechanical cuttings with higher efficiency obtained for highest water mass flow rates
- The mitigation strategy could be based on the activation of the Local spray during cutting phase and on the activation of the Global spray at the end of the cutting phase to clean the gas volume above the local spray area
- The use of fine droplets for global spray out of the cutting phase (no gas injection inducing airflow in the vessel) allows to save drastically water for mitigation systems by spray
- Even if sprays systems do not reach efficiency close to 100%, they reduce strongly the dispersion of aerosols compared to the case of simple sedimentation.

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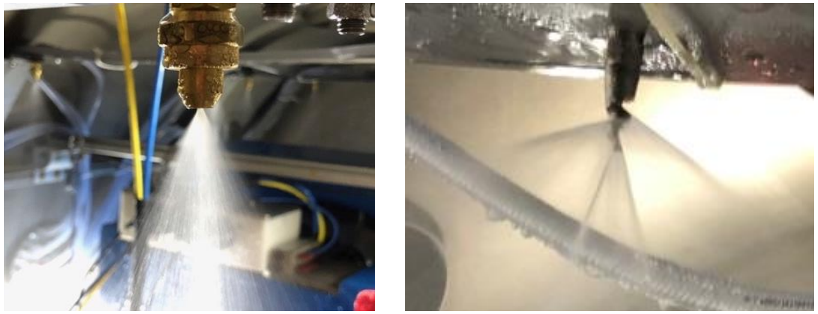
4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

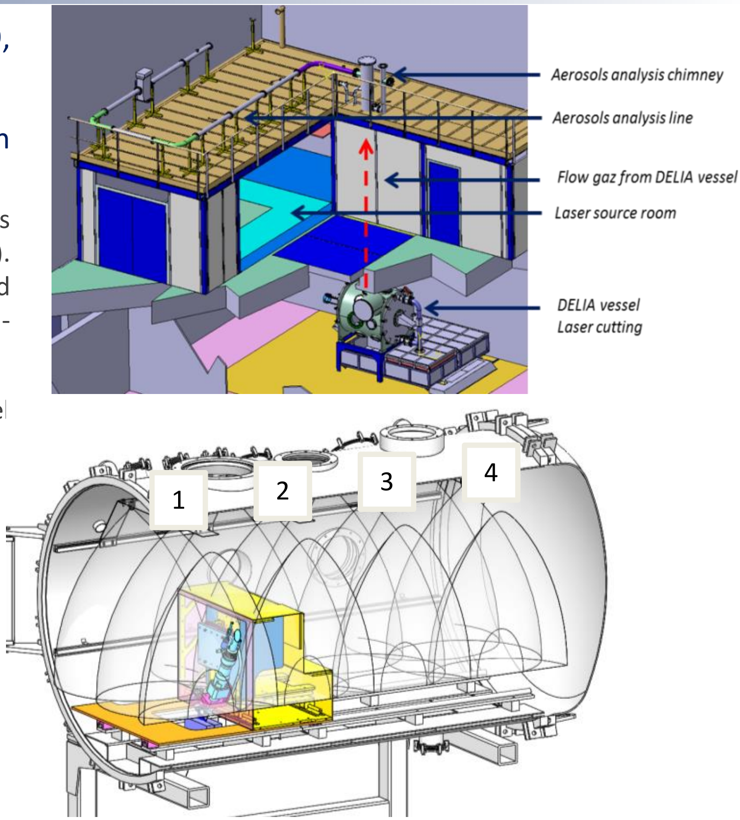
[1] – Dust dispersion mitigation by spray scrubbing

3 – Assessment of spray efficiency for laser cutting

- Two sets of tests have been realized in DELIA facility: first set of tests in October 2019, the second set of tests in November 2020
- Objectives of the tests were to assess the efficiency of spray scrubbing strategy with laser cutting:
  - First set of tests: tests of two different spraying nozzles and different spraying configurations in DELIA facility (number of nozzles, from 1 to 12 spraying nozzles used in the same time). Assessment of collection efficiency on cast fused Zirconia blocks, fuel debris simulants and stainless steel for different laser cutting configurations (in air emerging cut and non-emerging cut, underwater)
  - Second set of tests: tests of local spraying strategy on cast fused Zirconia blocks and fuel debris simulants



Two different spraying nozzle used during the first set of tests. The one on the picture in the right has a larger spraying cone



View of DELIA facility. The bottom figure shows the implementation of the laser cutting head and the 12 spraying nozzles (4 ramps of 3 nozzles). It is possible to use 1 to 12 spraying nozzles

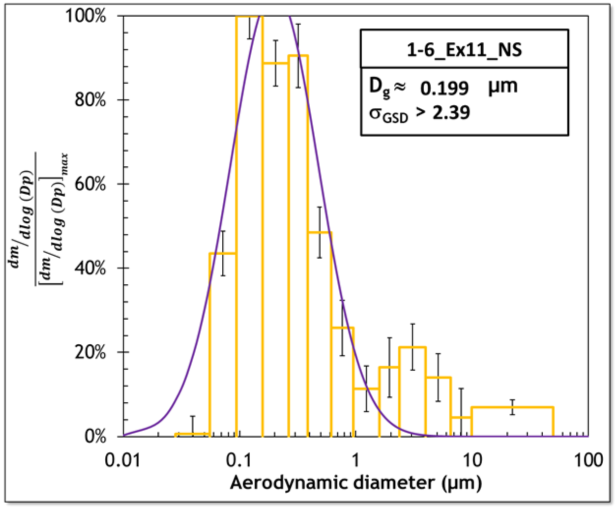
4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

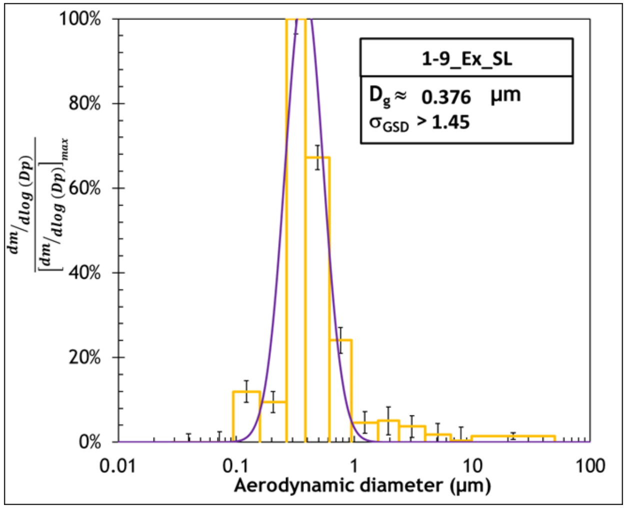
[1] – Dust dispersion mitigation by spray scrubbing

3 – Assessment of spray efficiency for laser cutting

Efficiency of spraying systems are determined by comparing the airborne particles concentrations in the aerosols analysis line (same cutting is realized successively with and without spray).

Results:





Comparison of aerodynamical without spray (left) and with spray (right): spray tends to increase the mean diameter of generated particles

Implementation of devices:

Global spraying system (left) vs local spraying system (right).

For every configuration tested, results show a decrease of airborne particles release: depending whether concentrations are measured in mass or in number, the decrease is between 25% to 70%. Spraying system is more efficient with larger particles. Also, it has an influence on the aerodynamical diameter of the particles: the median diameter increases, which is beneficial for filtering systems. Results are similar whatever the spray strategy (number of nozzles, local or global strategy).

4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

[2] – Advancement of local collection during laser cutting

1 – Improvement of local collection devices

Objective: Collect particles as close as possible of the cutting point while lowering the deposition of molten material inside the collection heads in order to improve their lifetime on site and while ensuring that the aerosols collection efficiency is not altered (ratio above 90% of collected airborne particles in the range [0.01µm; 1 µm]).

Note: The efficiency of local collection devices were already proven in the previous project. The current project aims at developing first operational prototypes

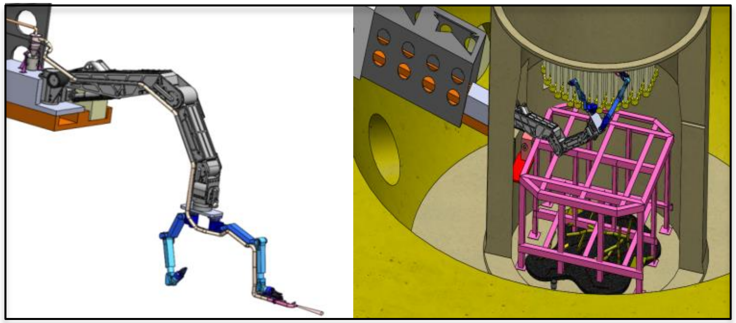


Illustration for an application on site of laser cutting in air

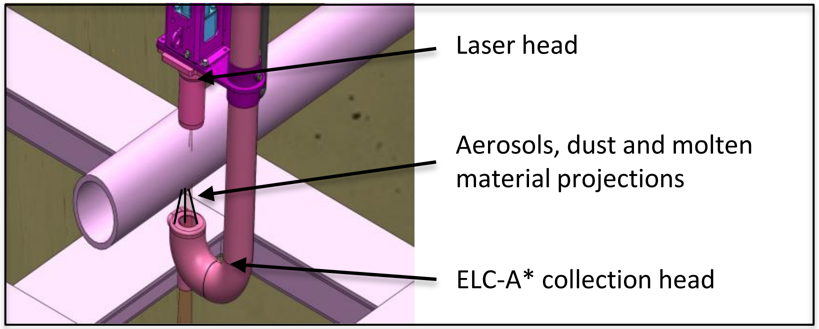


Illustration: cutting an element (with or without fuel debris) creates not only aerosols but also molten material projections

Progress during the project:

Start with prototypes of FY2018

→

Work for the improvement of systems:
- Essential tests for the increase of collection heads lifetime and geometry optimization
- Aeraulic studies

→

Tests in DELIA facility in order to assess airborne particles collection efficiency on representative material

→

Work on applicability:
- Tests with robotic arm
- Studies of remote operations, maintainability, operability, safety, etc.

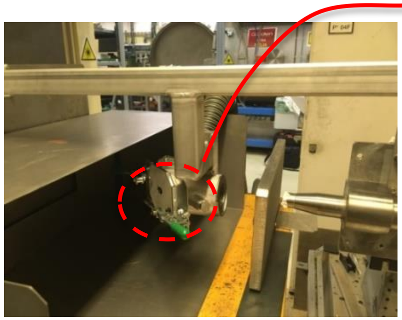
***: ELC-A stands for Emerging Laser Cutting in Air*

[2] – Advancement of local collection during laser cutting

1 – Improvement of local collection devices

Essential tests to improve lifetime of collection heads:

- Essential tests have been realized on simplified collection devices. Different materials have been tested in order to lower the molten material deposition. Results proved to be efficient for the duration of the tests that have been held.



Work on aeraulics

- It is important to work on aeraulics in order to ensure that there is no point of retention. Also, it is important to ensure that airborne particles are sucked into the exhaust. Essentials tests helped with the design.

Design and manufacturing of prototypes

- Design is based following essential tests and simulation work
- Design integrates the following functions:
  - Capability to be mounted remotely on the same laser cutting head
  - Be fitted with mechanical interface for the robotic arm
  - Be able to be adapted to different shapes to be cut

[2] – Advancement of local collection during laser cutting

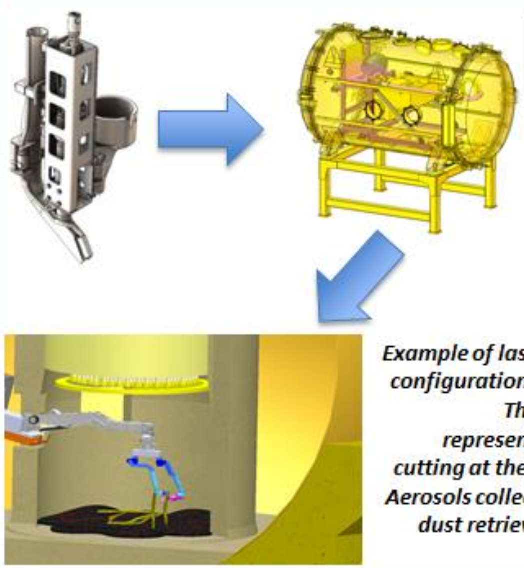
2 – Collection efficiency and operability tests

Collection tests in DELIA facility with laser cutting on representative material:

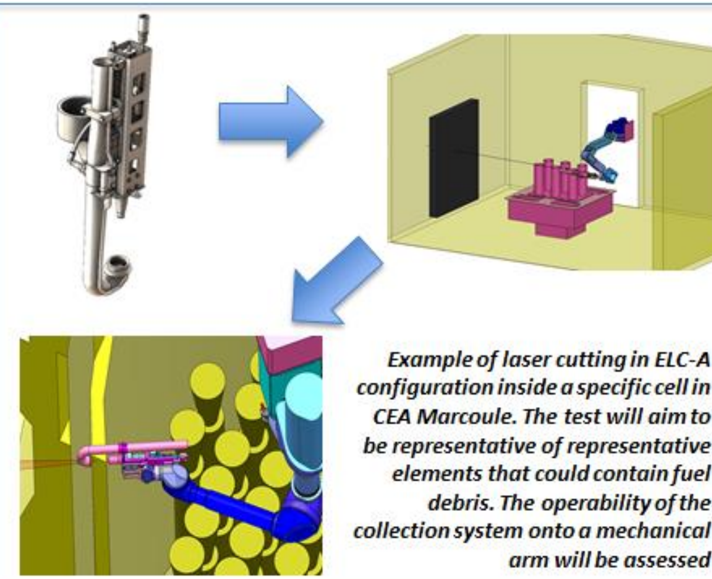
Previous work prove the collection system to be very efficient (over 90% of very thin airborne particles generated by laser cutting collected).

Therefore, the goal was to measure the collection efficiency with representative material for the two laser cutting configurations (emerging and non-emerging).

Collection efficiency tests are realized in DELIA facility. The measurements concern the airborne particles concentrations, in number and in mass: more precisely, measurements are realized in the collection line (measurement of particles collected) and in the extraction and sampling line (measurement of airborne particles that are dispersed).



Example of laser cutting in NELC-A configuration inside DELIA vessel. The test will aim to be representative of fuel debris cutting at the bottom of the PCV. Aerosols collection efficiency (and dust retrieval) will be assessed during the tests



Example of laser cutting in ELC-A configuration inside a specific cell in CEA Marcoule. The test will aim to be representative of representative elements that could contain fuel debris. The operability of the collection system onto a mechanical arm will be assessed

Reminder: NELC-A = Non-Emerging Laser Cutting in Air, ELC-A = Emerging Laser Cutting in Air

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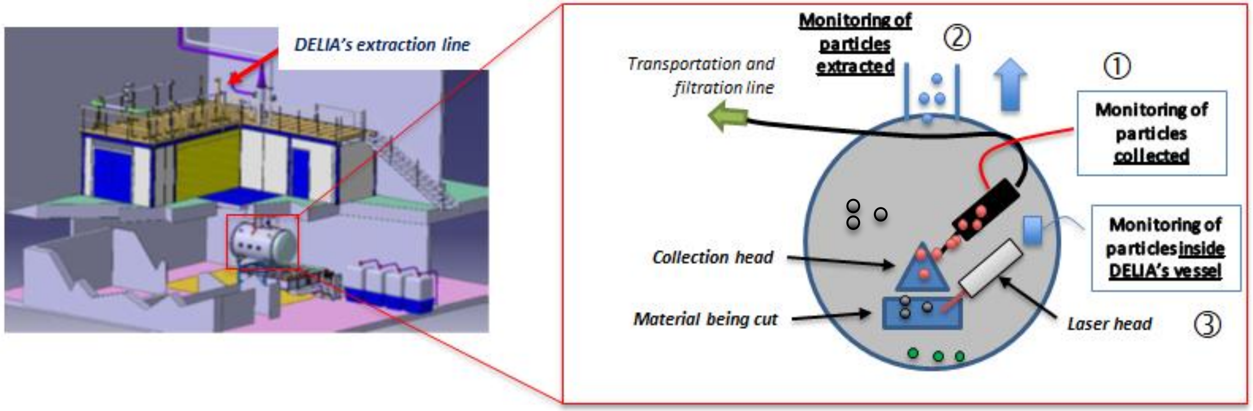
4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

[2] – Advancement of local collection during laser cutting

2 – Collection efficiency and operability tests

Methodology of collection efficiency measurement:



Means of measurements:

- Concentration number: Pegasor in the range [0.01 µm – 3 µm]
- Mass measured on filters in the range [0.01 µm – 10 µm]

Airborne particles are monitored in 3 locations in order to measure the fractions that are :

1. Collected by the collection head (ELC-A or NELC-A depending on the configuration tested), → Collection
2. Sucked into DELIA's extraction line (that represents the fraction of dispersed aerosols) and → Extraction
3. Inside DELIA's vessel (that represents the "ambiant" particles) → Ambiant

The collection efficiency is determined by the ratio: $\mathbf{Efficiency} = 1 - \dfrac{\mathbf{Aerosols\ Concentration\,Extraction}}{\mathbf{Aerosols\ Concentration}_{\ Collection}}$

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4. FINAL OUTCOMES

ITEM #2 - DUST COLLECTION SYSTEMS

[2] – Advancement of local collection during laser cutting

2 – Collection efficiency and operability tests

- ELC-A configuration:

Tests have been performed to assess collection efficiencies when cutting a tube, a tube filled with cast fused Zirconia block, a tube with a tube inside. Tests with collection head alone and collection associated to spraying system have been realized.



All configurations gave high collection efficiency rates (above ≈ 93% when considering number concentrations and around 85% when considering mass concentrations). Coating of collection head proved to be efficient during these tests (few deposition that is easy to remove).

- NELC-A configuration:

Tests have been realized with fuel debris simulants and cast fused Zirconia blocks to be representative of material at the bottom of the pedestal.



4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

[2] – Advancement of local collection during laser cutting

3 – Local collection and spray scrubbing with laser cutting

Tests have been performed to assess collection efficiencies when cutting a tube, a tube filled with cast fused Zirconia block, a tube with a tube inside for ELC-configuration. Tests with collection head alone and collection associated to spraying system have been realized.

For NELC-A configuration, tests have been realized on cast fused Zirconia blocks, cast fused Zirconia blocks implemented in such a way that they formed "stairs" geometry and on two surfaces of a same block of fuel debris simulant (one plane surface, one uneven surface).

The goal of the tests is to measure the efficiency of the collection system with representative geometries.

Cutting/Local collection configuration	ELC-A			NELC-A							
Specimen test	Zirconia block	Stainless steel pipe		Zirconia block		Zirconia block "stairs"		Simulant VF10 – Plane surface		Simulant VF10 – Uneven surface	
Spray scrubbing (local spray – 1 nozzle)	Spray off	Spray off	Spray on	Spray off	Spray on	Spray off	Spray on	Spray off	Spray on	Spray off	Spray on
Average number concentration efficiency of collection line	97%	95%	96.5%	90.5%	92.5%	85%	-	87%	88%	73.5%	-
Average mass concentration efficiency of the collection line	96.5%	84%	85%	81%	82.5%	63%	-	81%	83%	54.5%	-

- **Efficiency rate is high. Mass concentration efficiency is a bit lower for tests on tubes than for cast fused Zirconia blocks → due to the non-flat surface of the tubes as opposed to zirconia blocks.**
- **Spraying systems has a positive impact on the aerosols collection:**
    - **It induces a slight increase of collection efficiency in the collection line**
    - **Both concentration number of aerosols collected and dispersed (extraction) are lowered**

[2] – Advancement of local collection during laser cutting

3 – Local collection and spray scrubbing with laser cutting

Lifetime assessment: NELC-A collection head

During the collection efficiency tests with the collection head NELC-A, first assessment of lifetime could have been realized.

➡ 70 cuts have been carried out with the NELC-A collection head on different samples (cast fused zirconia, fuel debris Ex-vessel or In-Vessel)

70 cuts ≈ 10 m cutting length

Deposits have been observed on the head during the cutting of fuel debris simulant samples but have been mostly washed out thanks to the use of spray

Conclusions

- Collection efficiency rates due to the collection heads remain high on representative materials
- Collection efficiency in NELC-A configuration is dependent on the distance between the collection head and the material that is cut
- Collection heads are more efficient on very thin particles, a little less with bigger particles (over a few microns)
- Sprays have a slight impact on the collection efficiencies rates of the NELC-A and ELC-A collection heads but they lower the aerosol concentration in the extraction line as well as in DELIA's vessel ambiance. Spray collects about 30% of airborne particles generated
  ⇒ Spray scrubbing system collect aerosols, for one part before the collection heads, and also in the vessel: the fraction of dispersed aerosols is lowered
- Spray system is more efficient on bigger particles compared to the thin ones

Collection heads and spraying systems are complementary: the association of the two systems improve the collection efficiency rates and lower the total quantity of airborne particles that go to the different systems (collection, extraction)

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[3] – Extrapolation of results – Numerical simulations (CFD) in PCV

1 – Strategies for aerosols collection and dispersion in PCV global geometry

Objective:

The main objective of CFD calculations in the PCV* geometry is to evaluate strategies of spray systems implementation during and between cutting phases. CFD calculations can help for the design and implementation of the best strategies for aerosol removal.

Methodology:

- Different scenarios of spray activation (local and global) allowing to limit and reduce the aerosol dispersion and accumulation in PCV are simulated as in the experimental approach with TOSQAN tests. Input data for the calculations come from the results of experiments of dust and fume characterization. Output data is the particle mass concentration in the PCV.
- Results of the different calculations are compared. Therefore it is possible to assess the efficiency of each strategy and optimize the solution to be implemented on site. These scenarios are simulated by CFD code and compared between them in order to optimize the collection and the contamination release
- Different options are considered for these scenario depending on their collection efficiency primarily, but also on their complementarity:
  - Local collection
  - Local spray collection
  - Global spray collection

⇒ Each of them may be activated on demand

* PCV = Primary Vessel Containment

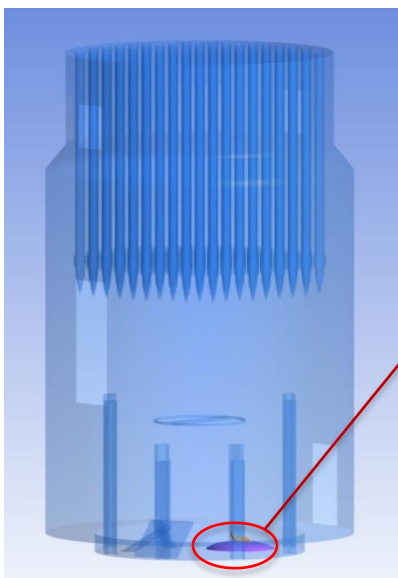
[3] – Extrapolation of results – Numerical simulations (CFD) in PCV

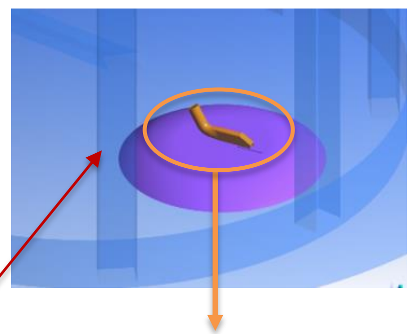
2 – Modelling description

The two figures present the geometry that has been modelled (pedestal with CRD and clutter) and the characteristics of the dust collection devices: this scenario considers fuel debris processing at the bottom of the pedestal with laser cutting in NELC-A configuration.

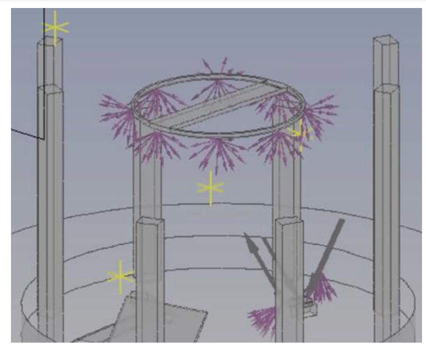
⇒ 3 dust collection systems are implemented: local extraction (= collection head), local spray and global spray.

- Complete geometry of pedestal with CRD and clutter
- Deposit on the ground more representative of melt fuel debris pile

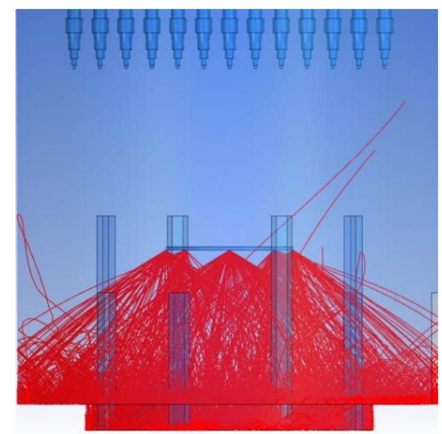


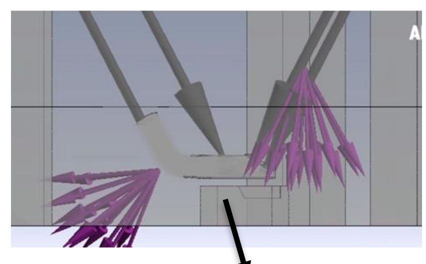


NELC configuration for consideration in this scenario: fuel debris is processed with laser cutting and NELC-A collection head is implemented



1 spray bar with 8 nozzles and large angle: it represents a global spray configuration, covering of large area at the bottom of the pedestal





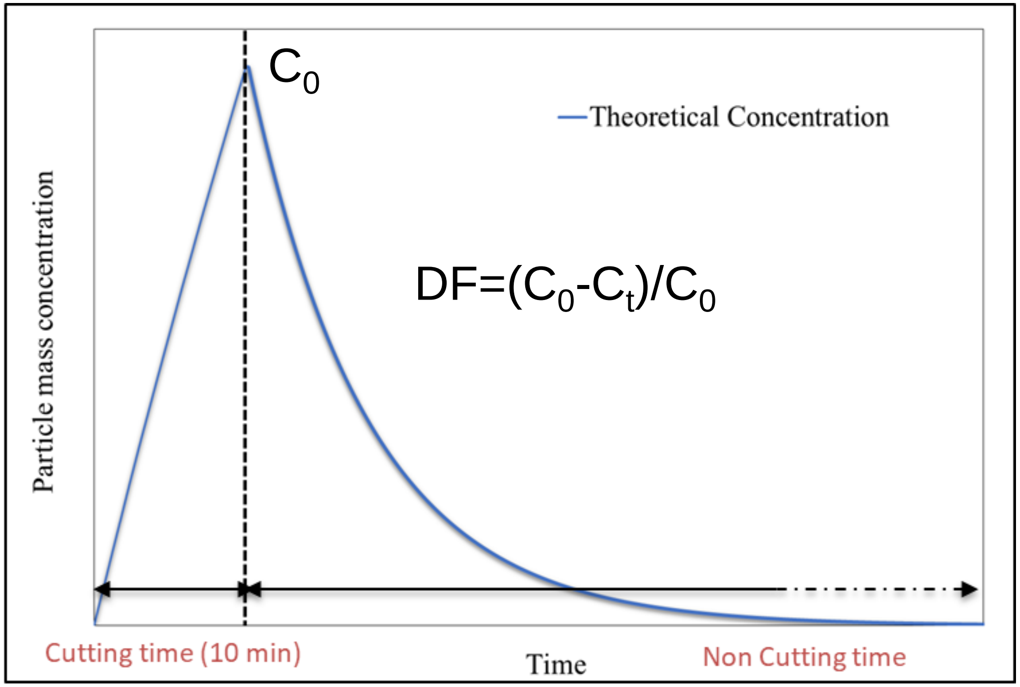
- 2 local spray nozzles with small angle are implemented close to the NELC-A collection head

[3] – Extrapolation of results – Numerical simulations (CFD) in PCV

3 – Scenarios description

The scenario consists in alterning the phases of cutting and non-cutting:

- During the first phase, laser cutting produces aerosols. Part of these aerosols are collected (by the local extraction or by the sprays), and the non-collected aerosols will accumulate in the PCV
- During the second phase, the concentration of accumulated aerosols will decrease by collection (spray and extraction)



For this scenario, a cutting time of 10 min is considered and the non cutting time has to be evaluated depending of the concentration time evolution or Decontamination Factor (DF)

The challenge is to optimize the phases of the scenario in order to limit the aerosol accumulation in the PCV and to stay always below a threshold to define

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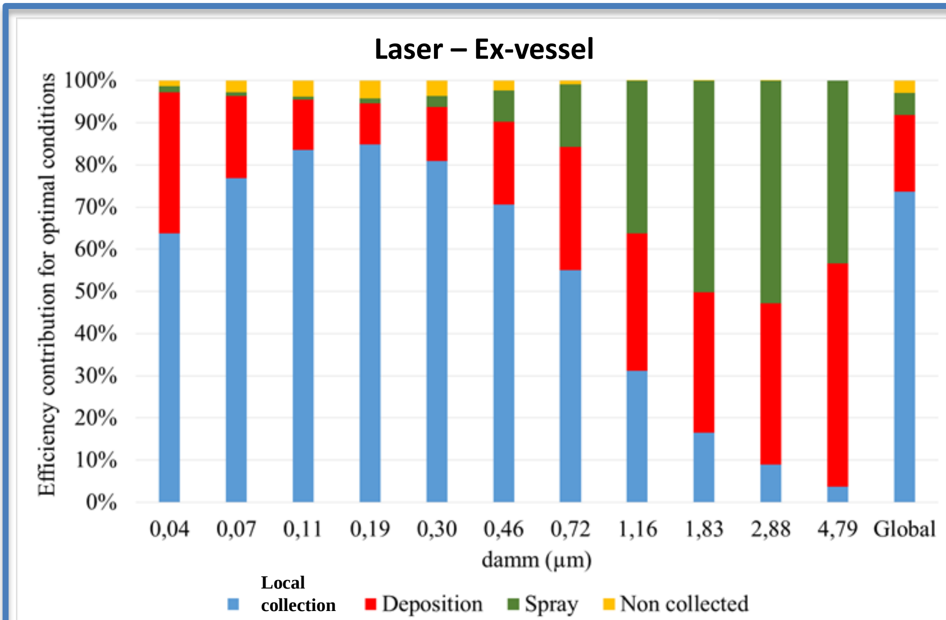
4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

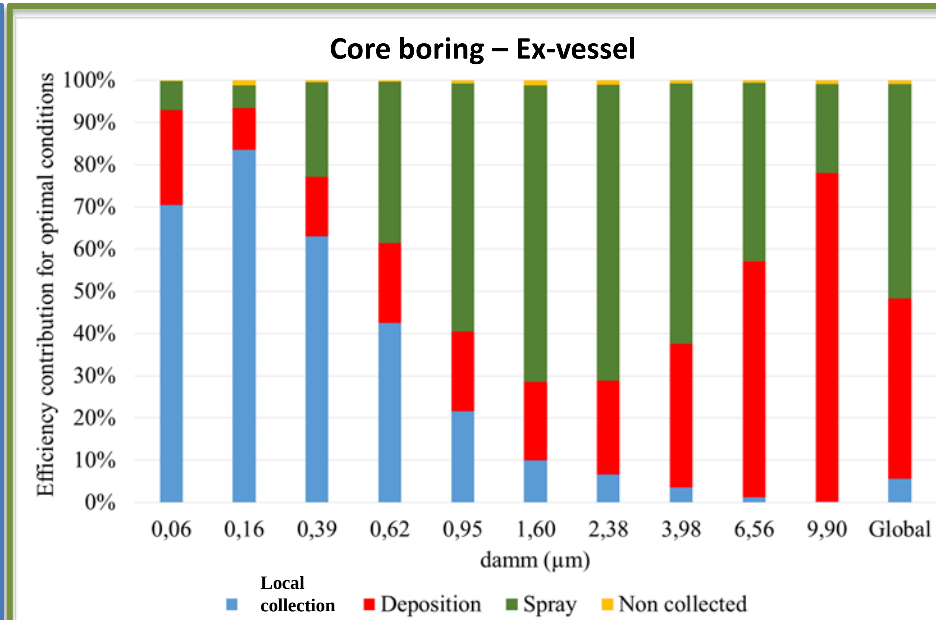
[3] – Extrapolation of results – Numerical simulations (CFD) in PCV

4 – Calculation results & interpretation

The figure below shows the fraction of particles that is collected by the local extraction (=NELC-A collection head, in blue), the fraction that is collected by the spray scrubbing systems (in green), the fraction of particles that are deposited and the fraction of aerosols that remains non-collected (thus dispersed, in yellow), for two PSD from two cutting devices (Laser and Core Boring)



- *Best extraction efficiency for smallest particles.*
  Local extraction is more efficient with small particles



- Best spray efficiency for biggest particles
  Spray scrubbing is more efficient with bigger particles

It may be noticed that the non collected fraction is overvalued because the particle collection by the wall liquid film is not implemented in the model

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4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

[3] – Extrapolation of results – Numerical simulations (CFD) in PCV

5 – Conclusion & prospects

- The scenario studied here highlights the **very good efficiency of the coupling of collection means** (extraction, local and global spray) **according to the experimental data acquired on DELIA and TOSQAN facilities**

⇒ **Whatever the size distribution** of emitted particles by the cutting devices, the collection means are efficient and **only a few amount of particles are not collected** thanks to the addition of the mitigation means

- This scenario highlights also the **difficulty to collect small particles (0.1 µm)** regardless of the cutting device or the mitigation means used because it is inherent to this particle size **due to their low collection efficiency by droplets**

⇒ Even with efficient collection devices, **a fraction of small particles will inevitably accumulate** inside the PCV and will need to be removed / **treated**

- To improve the removal of small particles, it can be benefic **to increase the extraction volume flowrate**

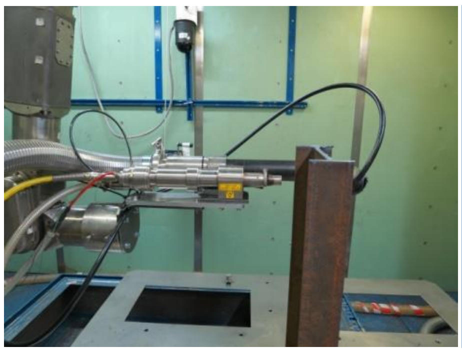
⇒ This can be done with a local extraction device or **by using the global extraction and ventilation system of the PCV**

[4] – Operability tests of local collection system

Presentation of the tests

Tests have been realized in a specific cell with a remote controlled arm in order to assess the operability of the collection system. Cutting tests have been realized on materials representative of inner parts of the PCV (gratings, tubes, beams).





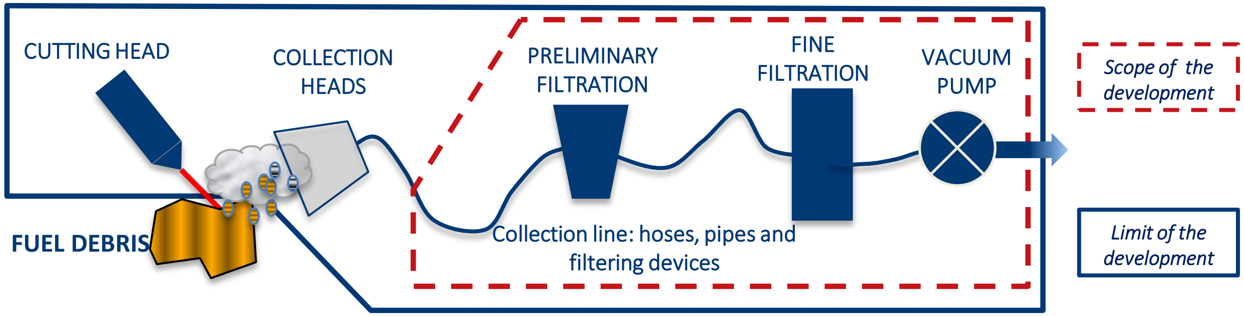

These tests prove that the prototypes of collection devices are capable of working in real cutting conditions (geometrical).

4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

[5] – Dust extraction system

1 – Design of the dust extraction system

- Development of a system able to transport and filter particles emitted during laser cutting operations and collected by the collection head. Its extension to mechanical tools is also assessed.
- This design needs to take into account on-site conditions and constraint functions as radioactivity, criticality, humidity, remotely operated, fire risk,…



CHALLENGES FOR DUST EXTRACTION SYSTEM | EXTERNAL PROJECT

TRANSPORT OF PARTICLES (DUST AND AEROSOLS)
- Retention of chips
- Deposition
- Pressure loss
- Incandescent particles
- Flexibility

PRELIMINARY FILTRATION (SEPERATION SIZE 10 µm)
- Separation size
- Dust collection by a remote controlled arm
- Pressure loss
- Volume size
- Constraints of implementation

FINE FILTRATION
- Clogging
- Side waste (used filter media)
- Dust and filter media collection by a remote controlled arm
- Resistance to radiation

VACUUM PUMP
- Maintenance
- Resistance to radiation
- Constraints of implementation

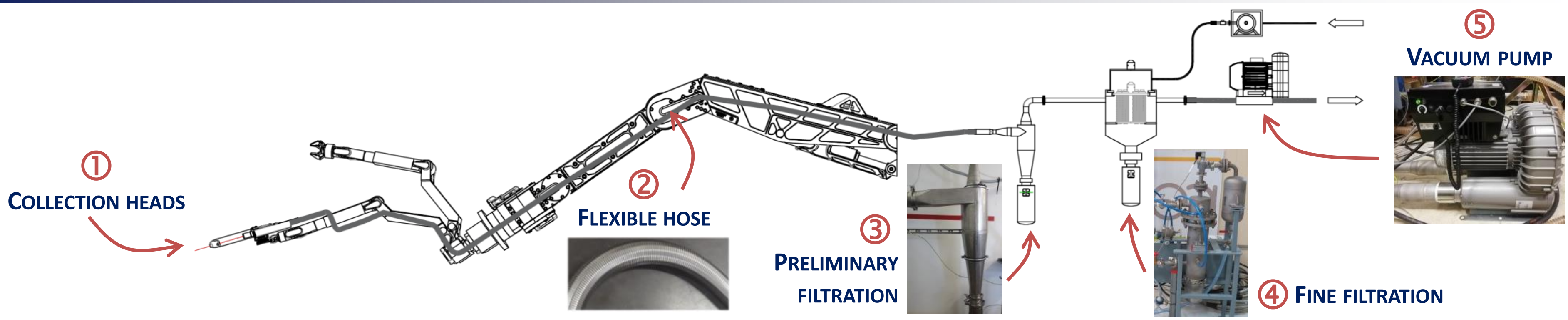
FINAL FILTRATION BEFORE EXHAUST

To be studied out of the frame of dust collection development project

4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

[5] – Dust extraction system

1 – Design of the dust extraction system



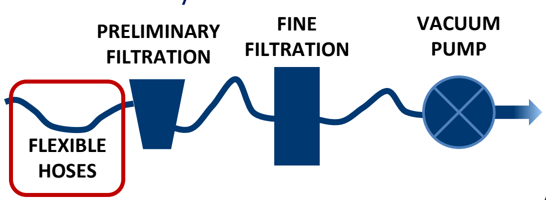
REF.	PRESENTATION OF MAIN EQUIPMENT	LIST OF DATA COLLECTED DURING FY2020
①	The **collection head**, placed near the cutting area, collects the particles produced during fuel debris processing operations.	- Collection efficiency with or without spray-scrubbing - Operability and lifetime
②	A **flexible stainless steel hose** is used to transport the particles while maintaining the levels of mobility of the remotely operated arm.	- Pressure drop and transportation efficiency - Resistance to incandescent particles
③	The **cyclonic filter** (preliminary filtration) protects the pulse-jet filter and the vacuum pump from incandescent particles and collects the dross and chips.	- Pressure drop and filtration efficiency - Mass collected during laser cutting operations
④	The fine filtration system composed of stainless steel cartridges and a self-cleaning device using compressed air.	- Self-cleaning efficiency in laboratory conditions - Filtration efficiency, self-cleaning efficiency and mass filtered during laser cutting operations
⑤	The **vacuum pump** creates a negative pressure inside the line in order to transport the particles collected.	- Transportation efficiency

[5] – Dust extraction system

1 – Design of the dust extraction system

CHALLENGES FOR FLEXIBLE HOSES

- Retention of chips
- Deposition
- Pressure loss
- Incandescent particles
- Flexibility



FLEXIBLE HOSES

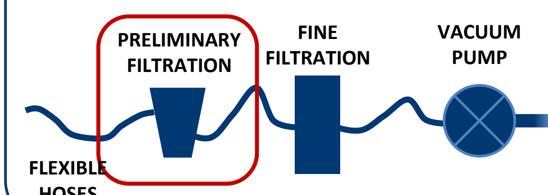
Flexible hoses are needed to keep the degrees of mobility of the remotely operated arm.
Studies and tests have been carried out in order to find a flexible capable of meeting the challenges imposed by on-site and operating conditions.

Two important parameters to meet the challenges:

- Air velocity inside: need to be superior to particles sedimentation rate. It induces the flow rate and the inside diameter of hoses
- Composition of the flexible hoses: structure (smooth interior or not) and material.

CHALLENGES FOR PRELIMINARY FILTRATION

- Separation size
- Dust collection by a remote controlled arm
- Pressure loss
- Volume size
- Constraints of implementation



PRELIMINARY FILTRATION: THE CYCLONIC FILTER

The cyclonic filter has been designed in order to reach the best trade-off between segregation rate, pressure drop and dimensions.

The main role of this device is to protect the rest of the line from incandescent particles and to collect the dross and chips in order to slow down the fine filtration system clogging.

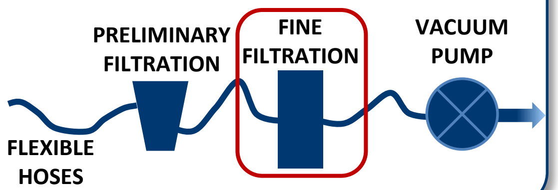
4. FINAL OUTCOMES
ITEM #2 - DUST COLLECTION SYSTEMS

[5] – Dust extraction system

1 – Design of the dust extraction system

CHALLENGES FOR FINE FILTRATION

- Clogging
- Side waste (used filter media)
- Dust and filter media collection by a remote controlled arm
- Resistance to radiation



FINE FILTRATION : CHOICE OF THE TECHNOLOGIES

Different technologies and designs have been under study for the filtration of thinnest particles. For each technology, input data about laser cutting (characteristics of dust and aerosols), expected efficiencies and on-site constraints were taken into account. It has been decided to manufacture a self-cleaning metallic filter prototype for the tests.

INSTRUMENTATION USED FOR TESTS IN ONET TECHNOLOGIES PREMISES AND IN DELIA VESSEL

OBJECTIVES	TYPE OF MEASUREMENTS
Study of the transport efficiency	- Measurement of masses of particles injected at the entrance of the line and the ones that are collected inside the cyclonic filter's can & visual observation of potential damages due to incandescent particles on flexible hoses
Data collection on preliminary filtration	- Pressure drop - Mass of particles collected inside the cyclonic filter's can
Data collection on fine filtration (filtration efficiency, clogging, self-cleaning efficiency)	- Mass concentrations of aerosols upstream and downstream of the filter & aerosols size distribution according to the aerodynamic diameter - Pressure drop
Data collection to extrapolate for the on-site system	- Temperature and humidity in the room and inside pipes with and without the spray scrubbing

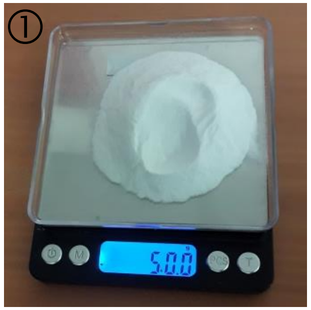
[5] – Dust extraction system

2 – Preliminary tests

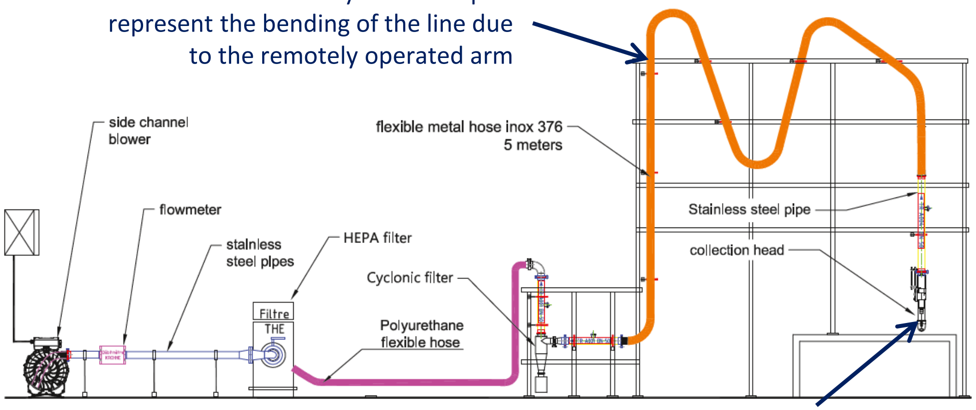
2.1 CHARACTERIZATION OF TRANSPORTATION WITH THE DUST EXTRACTION SYSTEM

Tests were held in Onet Technologies premises. The dust extraction system has been implemented in order to be representative of a configuration on site.

The tests aimed to determine the characteristics of the dust extraction system (pressure drop) and verify the capability of the system to recover dust and chips in representative conditions.



Dust extraction system set-up to represent the bending of the line due to the remotely operated arm



Collection head with a kerf and laser head mock-up to inject dust and chips with an airflow rate representative of the one occurring during laser cutting operation

Transportation efficiency tests have been done with alumina powder (①), titanium and iron (②) granules and chips of zirconia coming from previous laser cuts (③). The transportation tests concern the first part of the dust extraction system from the collection head to the cyclonic filter in which particles are recovered (in orange in the figure of the right, flexible hoses are made in stainless steel). The transportation efficiency goes from 95 % to 100 % depending on the particles.

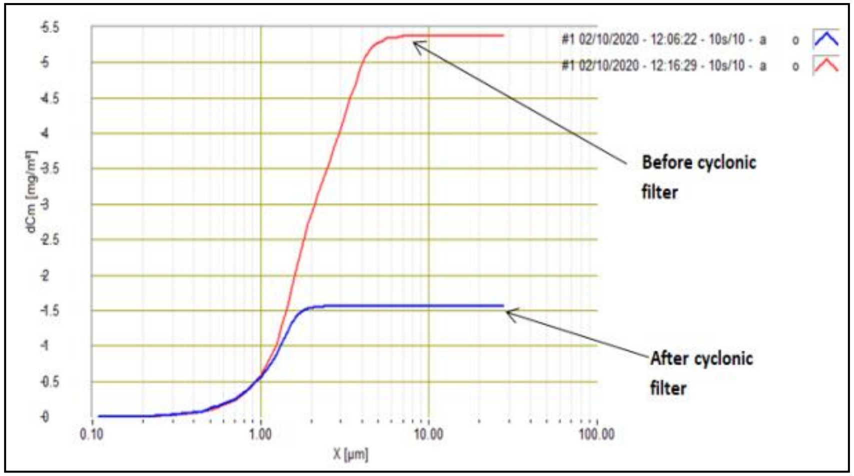
[5] – Dust extraction system

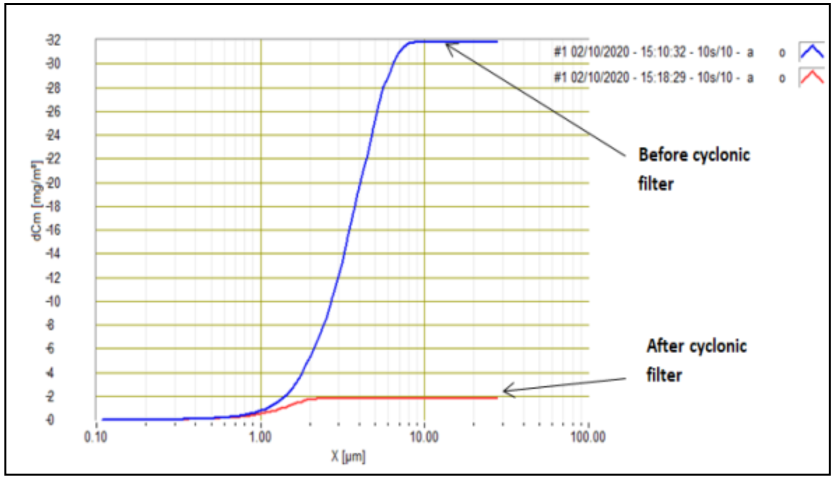
2 – Preliminary tests

2.2 PRELIMINARY TESTS OF FILTRATION DEVICES – CYCLONIC FILTER

Cyclonic filter has been designed in order to reach the best trade-off between segregation rate, pressure drop and overall dimensions. Its main role is to protect the rest of the line from incandescent particles, collect dross and chips that have entered the dust extraction system during cutting operations and filter smaller particles in order to slow down the clogging of the fine filtration system.

Preliminary tests have been realized in order to qualify the cyclonic filter and establish its performances in lab conditions.





Example of mass concentration measurements before and after the cyclonic filter with polydispersed aerosols with different mean aerodynamical diameters (3.1 µm and 4.7 µm)

Conclusions of the qualification tests in lab facilities:

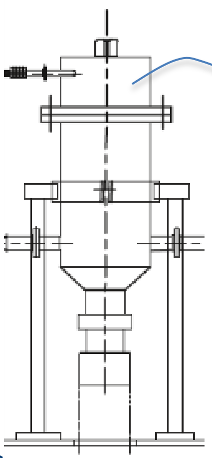
- The pressure drop of the cyclonic filter is around 750 Pa for a 200 $m^3.h^{-1}$ airflow
- In these conditions, tests results are that more than 99% (in mass) of particles with an aerodynamic diameter greater than 2 µm are collected

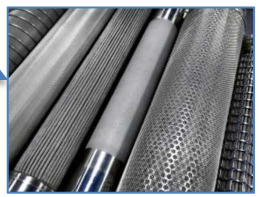
[5] – Dust extraction system

2 – Preliminary tests

2.3 PRELIMINARY TESTS OF FILTRATION DEVICES – SELF-CLEANING METALLIC HEPA FILTER

The fine filtration level is a HEPA filter composed of a vessel containing stainless steel cartridges (filtering media) and self-cleaning device.

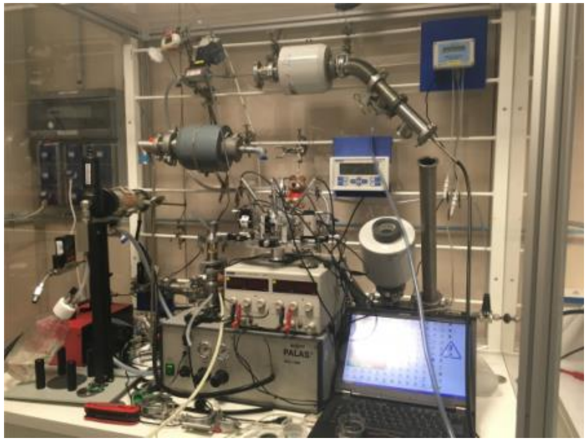


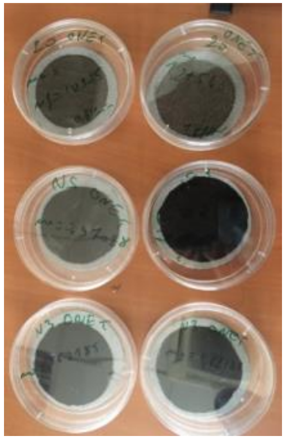


The vessel can contain one or more metallic cartridges

Drawing of prototype

In order to optimize the design of the filter, preliminary tests have been conducted in lab facility on samples. These samples were different stainless steel grid that can compose the cartridge.





Two compositions of cartridges (number of layers and type of mesh) have been determined to be promising following these tests (Configuration 1 with 2 layers of very thin mesh and Configuration 2 with 1 layer of ME mesh and 1 very thin mesh)

The self-cleaning filter has also been qualified on a specific test bench with a calibrated powder to be representative of aerosols produced during laser cutting operations.

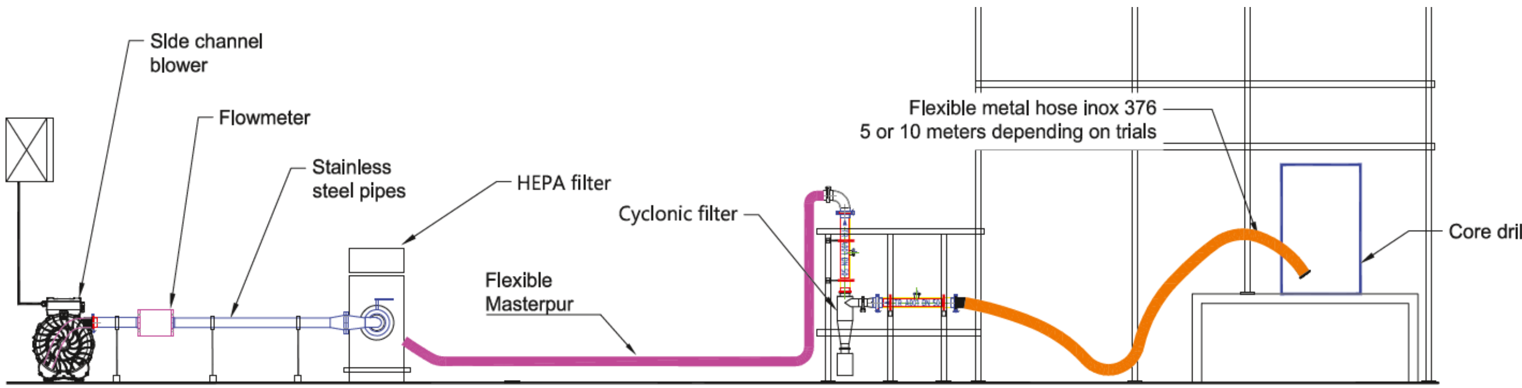
[5] – Dust extraction system

3 – Test of the dust extraction system with core boring

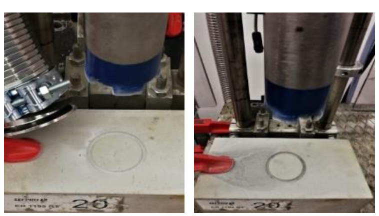
Test conditions

Two tests were done in order to carry out preliminary tests on the dust extraction system in the presence of core boring operation (same as the one used in [2]-4). The set-up is presented below. For the first one, the flexible stainless steel hose was fixed to the core drill near the cutter and the air flow rate of the line was adjusted to 200 $m^3.h^{-1}$ to extract the dust. For the second trial, no extraction was in operation.

The cut were done on cast fused zirconia blocks and the core drill had the following settings: cutter diameter 52 mm (diamond core for dry coring), cutting speed 900 rpm, micropercussion on (improved dust evacuation), lowering control cylinder pressure 1 bar



Results



The cast fused Zirconia block is almost clean after the trial with extraction (on the left), which is not the case without extraction (on the right).

View of particles collected by the cyclonic filter during the core boring operation.

Complementary trials would be needed in order to calculate a ratio between the particles produced and the particles collected. However these first results are promising for a use of the dust extraction system with mechanical cutting.

[5] – Dust extraction system

4 – Test of the dust extraction system with laser cutting

TESTS OF DUST EXTRACTION SYSTEM WITH LASER CUTTING IN DELIA FACILITY

The tests aimed to verify the performances of the dust extraction system with laser cutting: the performance of the self-cleaning HEPA filter, the resistance to incandescent particles of the flexible hose, the mass of particles collected.

In order to do so, collection system is implemented to the laser cutting head: dust and aerosols are collected into the collection line. Number and mass concentrations of aerosols are monitored inside the collection line so it is possible to quantify the particles that enter the collection system. Monitoring is realized before and after the self-cleaning filter: number and mass concentrations in order to verify the filtering performance and the evolution of the pressure drop. It is therefore possible to monitor the evolution of the pressure drop with the evolution of aerosols concentration.

MAIN RESULTS OF THE TESTS

- Flexible hoses are resistant to incandescent particles.
- For both tested cartridges, filtering efficiency of pulse jet filter is above 99.99%.
- The cartridge Configuration 2 has a slower increase of the aeraulic resistance and so a longer life time. The self-cleaning cycles give also a better regeneration for this cartridge.
- Due to the layer of filter medium, which has a coarser mesh size, the duration of the depth filtration is increased and the adhesion surfaces for the particles and therefore the adhesion forces are reduced. This result is consistent with tests in lab facility on filter media samples.
- Nevertheless, self-cleaning of the cartridge, for laser cutting, needs to be optimized.

	Configuration 1	Configuration 2
Mass of zirconia aerosols filtered to reach 50 mbar for the first time	About 1.89 g	About 2.0 g
ΔP after 1st cleaning	46.6 mbar	25 mbar
ΔP after 2nd cleaning	48 mbar	38 mbar

[5] – Dust extraction system

5 – Conclusions

MASS BALANCE FOR A ONE-METER CUT

Cutting conditions:

- Laser head power: 7.5 kW
- Air flow rate on the transportation and filtration line: 200 $m^3.h^{-1}$

(*): Mass estimated from the accumulated mass of 1 cartridge with a flow rate of 16.7 $m^3.h^{-1}$ and transposed for a flow rate of 200 $m^3.h^{-1}$ (12 cartridges)

	Zirconia	In-Vessel VF05
Average cutting depth	35/40 mm	50 mm
Mass of particles collected by the cyclonic filter	77.6 g	60.1 g
Mass of particles filtered by the fine filtration*	8.3 g	18.9 g

Conclusions

- The dust extraction system prove to be efficient for particles transportation (particles generated by laser cutting)
- The **flexible** stainless steel hose chosen is **resistant to incandescent particles** and **easy to handle**
- The **cyclonic filter** enables to have **higher filtration efficiency** with **lower pressure drop**, compared to previous ones, while having a **reasonable size and weight** to be handling by a remotely operated arm.
- The **self-cleaning filter** has a **good filtration efficiency**. The **lifetime** of the cartridge has been **increased** by a new combination of stainless steel grid. Further studies and tests are expected in order to:
  - Improve the self-cleaning performances with laser cutting. Several options could be studied to do so in the future.
  - Validate the functioning of the complete filtration line when high rates of humidity are involved.

4. FINAL OUTCOMES
ITEM #3 – APPLICATION ON SITE

3. APPLICATION ON SITE

Objectives

- Assess the applicability of the system under development

Tasks implemented in the frame of item 3

[1] Study on applicability

1: Overview of the global system
2: Dust collection head
3: Filtration system (tentative)
4: Filtration system (tentative) implementation
5: Spraying system
6: Cutting scenarios and maintenance operations

[2] Safety analysis assessment

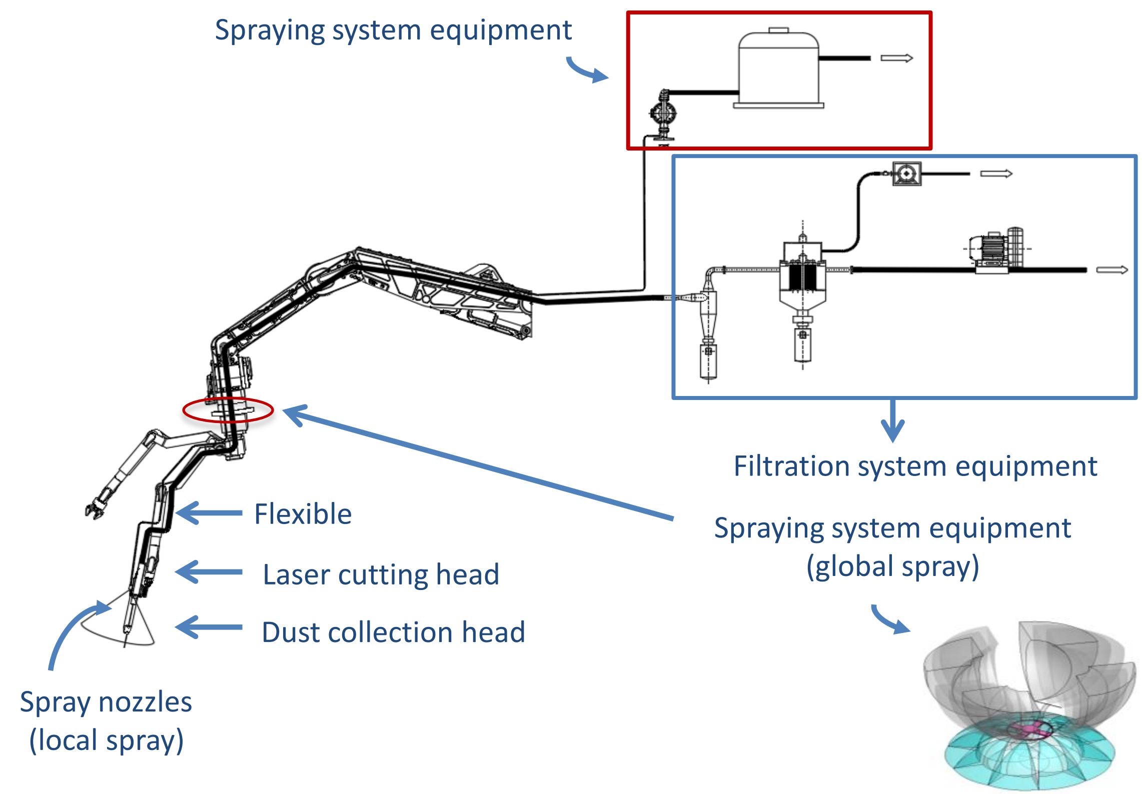
1: General safety analysis
2: Safety analysis applied to the dust extraction system with laser

[1] – Study on applicability

1 – Overview of the global system

The global laser cutting system is divided in four different parts :

- The laser head
- The dust collection head:
  - A Collection head for Emerging Laser Cutting in Air (ELC-A)
  - A Collection head for Non Emerging Laser Cutting in Air (NELC-A)
- The filtration system including:
  - A cyclonic prefiltration
  - A fine filter (Pulsejet filter)
  - A vacuum pump
- The spraying system including:
  - A global system
  - A local system



4. FINAL OUTCOMES

ITEM #3 – APPLICATION ON SITE

[1] – Study on applicability

2 – Irradiation performance of the laser cutting system components

The system is developed to be highly resilient to irradiation. The summary of irradiating performances for each material is presented in the table on the right.

All components that should be in high ambient dose rate have a **performance higher than 10^7 Gy** except for seals and electronic components.

The degradation of seals could leads to minor leak in the system after 10^6 Gy. Considering the low pressure in the system and the probability to replace the component including seals before to reach 10^6 Gy, the risk is very low and without consequences.

For electronic components, the countermeasure is to put them away from the high ambient dose rate (outside the Primary Containment Vessel) and to facilitate the replacement of equipment.

Material	Components	Lifetime (Gy)
Wire	Pulsejet	10^8
PUR (polyurethane)	Flexible hose	10^7-10^8
Motor	Turbine	5 x10^7
Fiberglass	Stainless steel flexible hose (seals)	10^7
Connectors	Pulsejet	10^7
Seals	Pulsejet, cyclonic filter,..	10^6 - 10^7
Electronic components	Turbine and control pannel and sensor	**10^2 - 10^3**

Source : « Résistance aux rayonnements ionisants des matériaux » and « Compilation of radiation damage test data », CERN

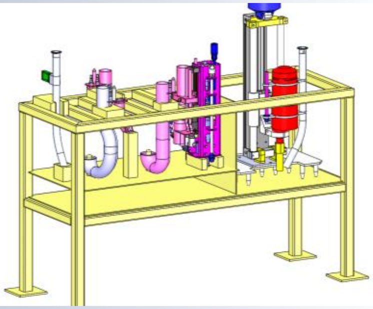
In case of failure, **replacement of each component is easy and quick done by the robotic arm**.

[1] – Study on applicability

3 – Dust collection head

Collection heads are designed to be easily and quickly set up on the laser head. The ease of change of these tools allows to store them in a small tool rack inside the PCV. Collection heads can be designed for any fuel debris processing tools

To increase the durability of collection heads, they are coated with a non adhesive material



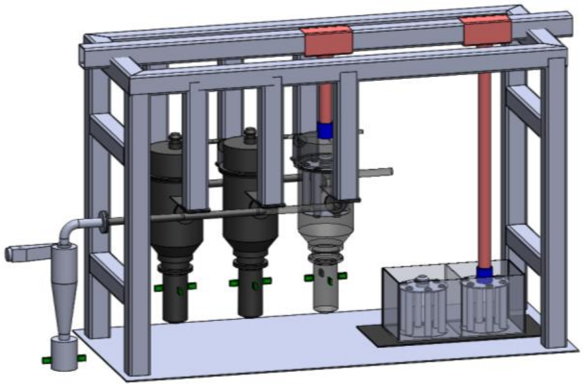
4 – Filtration system (tentative)

The filtration system is composed by a cyclonic filter, a self-cleaning filter and a vacuum pump.

The implementation of the filtration system takes into account the priority to cutting operations:

- The on-site filtration system should be composed by **one cyclonic filter** and **three fine filtration filters**. Two of them operate in series and the third one is used in replacement of one of the two others (in case of problems or maintenance). Number of filters shall be determined with specific studies
- **Sets of cartridges** for the fine filtration system could be integrated into the rack for replacement whenclogging appears.

These features should be sufficient to allow a full cutting step without changing filters.



Dust filtered by the cyclonic filter and self-cleaning system and full cartridges of fine filtration system can be put into cans designed to be **compatible with unit cans and storage canisters.**

All filtration components are gathered in a specific rack and they are **easily manipulated by the robotic arm.**

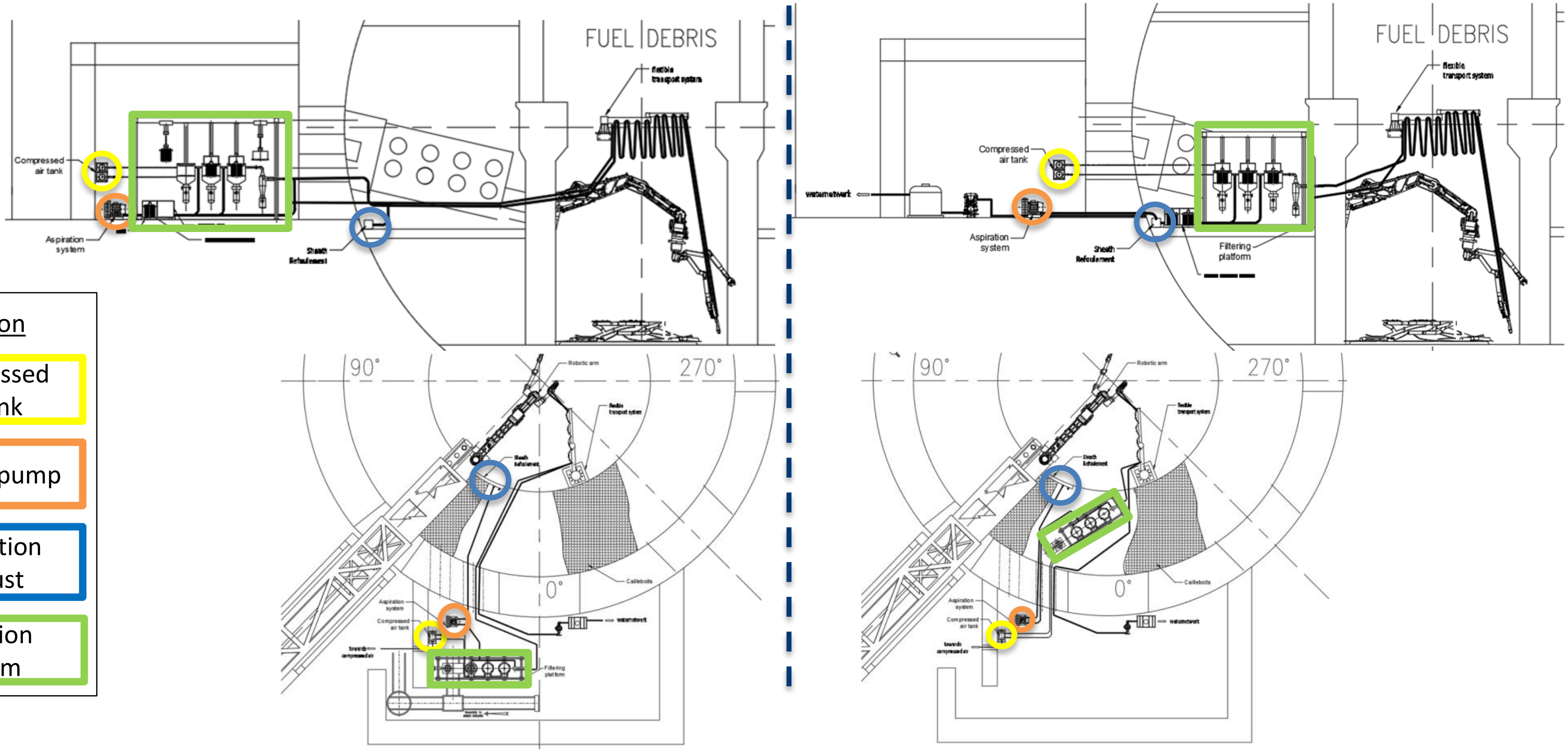
4. Final Outcomes
Item #3 – Application On Site

[1] – Study on applicability

5 – Filtration system (tentative) implementation

Two implementations are considered for the **side access** :

- A rack with filtration component inside the PCV and compressed air tank and vacuum pump outside the PCV. The arm is used to do all filter replacement operations (left side).
- All components outside the PCV. Remote controlled equipment is needed to do filter replacement operations and a specific conveyor is needed to evacuate cans fill of dust (right side).



Caption

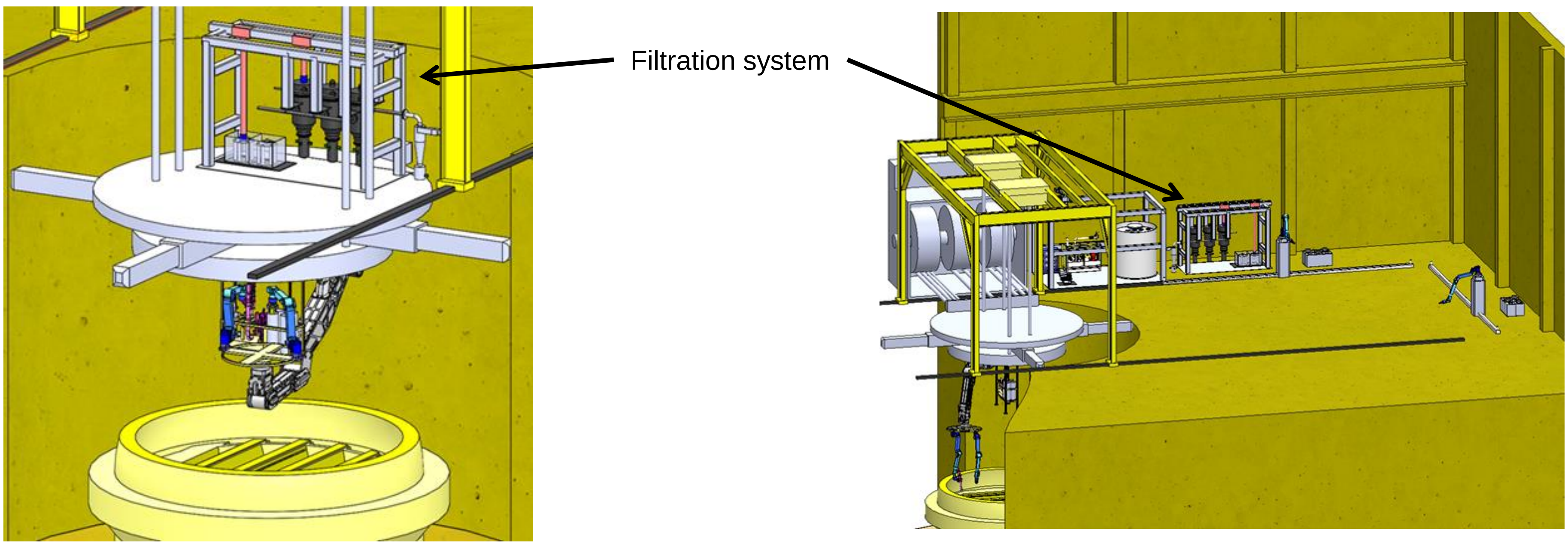
- Compressed air tank
- Vacuum pump
- Ventilation exhaust
- Filtration system

[1] – Study on applicability

5 – Filtration system (tentative) implementation

Two implementations are considered for the **top access** :

- A rack with filtration component on the top of the moving platform and compressed air tank and vacuum pump on the top of the PCV. The arm is used to do all filter replacement operations (left side).
- All components on the top of the PCV. The arm can be used to do filter replacement operations but remote controlled equipment could be used to not lift up the platform (right side).



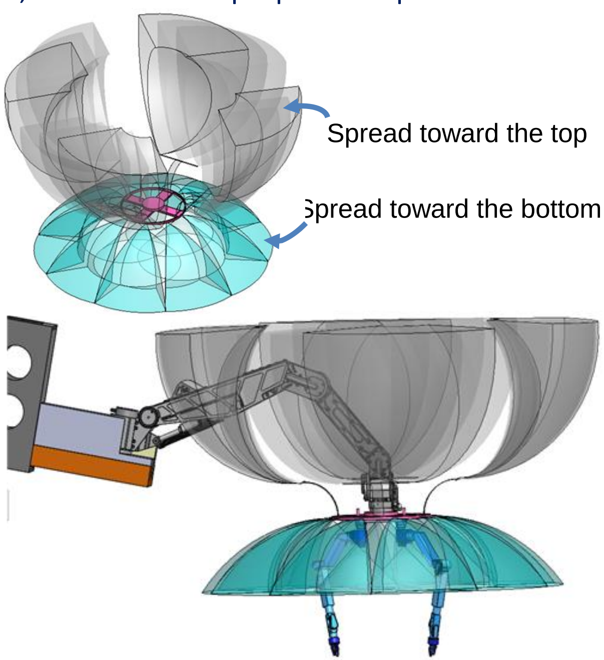
[1] – Study on applicability

6 – Spraying system

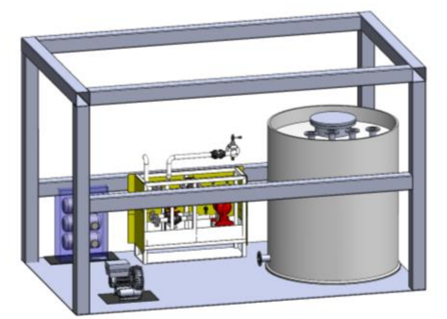
The spraying system is divided in two different systems:

- The **global system** used to cover a maximal volume of the pedestal volume. The nozzles can be disposed on a spreader on the robotic arm. Several nozzles spread water toward the bottom of the pedestal. They cover a large surface . Others kind of nozzles create spread water toward the top in order to create a fog.
- The **local system** includes several nozzles disposed on the laser cutting head.

In addition, a water tank is proposed to provide half an hour of spray scrubbing in case of loss of water supply.



Global spray scrubbing



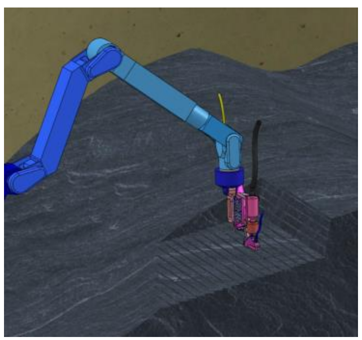
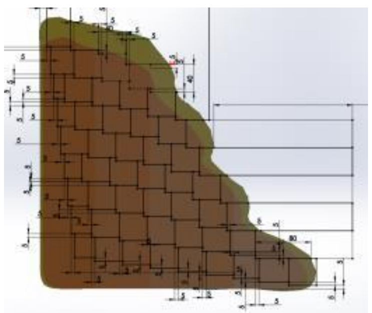
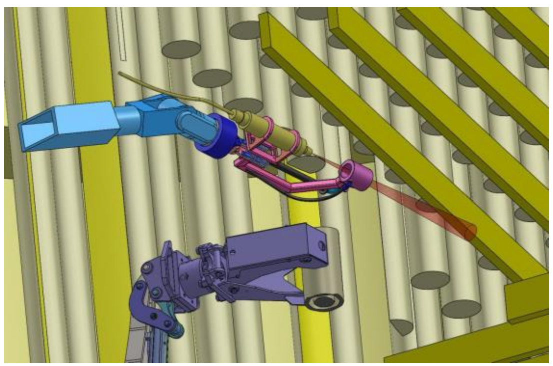
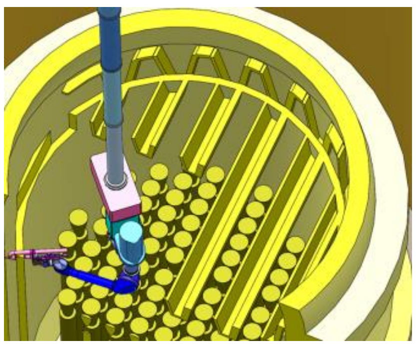
Water tank and spray scrubbing equipment rack

[1] – Study on applicability

7 – Cutting scenario and maintenance operations

Past achievements

- Cutting scenario for the lower part of the PCV including CRD cutting and fuel debris cutting in the pedestal.
- Cutting scenario for the upper part of the PCV including all identified component (from steam dryer to bottom of RPV)
- Analysis of the fuel debris retrieval method in the bottom of the pedestal (retrieval speed, aerosol production per hour)

Remainder of constraints take into account

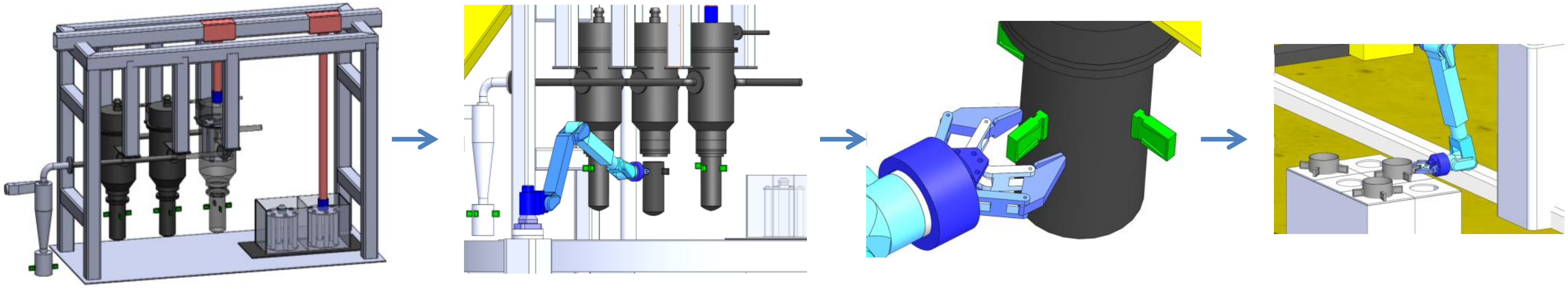
- Keep an atmosphere inside the PCV as clean as possible
- Optimize the system to be adjustable and compatible with IRID's deployment solutions
- Optimize the system to have no maintenance during the cutting process (few hours)
- Maintenance operations have to be fast and easily done with a remote controlled arm
- Equipment weight inferior to 100 Kg and compatible with PCV robotic arm entrance
- All components have to be compatible with storage canister size or they can be easily cut or dismantling

[1] – Study on applicability

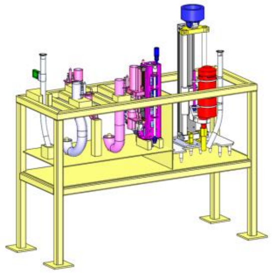
7 – Cutting scenario and maintenance operations

Study focused on **operability** and **maintenance operations**.

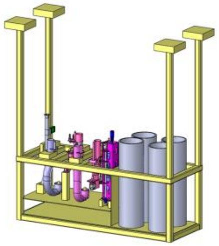
The rack of the filtration system is made to be assembling by the robotic arm **and all components are easily catch by a clamp**. To lower spread contamination, the size of cans that receive dust and filters from pulsejet are compatible with storage canister. There is no need to cut highly contaminated waste for size reduction. Images below show handling operation of cans.



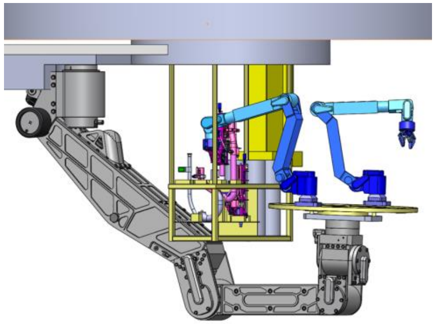
Tools (cutting tools, collection heads, suction tools) are disposed in a rack. Compatibility with existing cutting scenarios was checked.



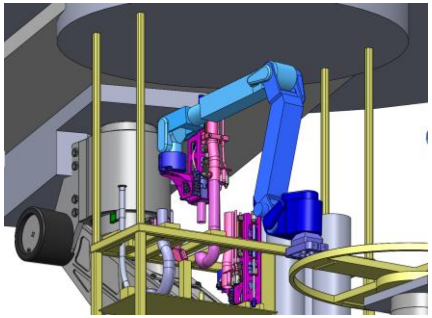
Rack for side access



Rack for top access
(under the plateform)



Changing tool operation



Changing tool operation

ONET TECHNOLOGIES cea IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

[2] – Safety analysis assessment

1 – General safety analysis

Definition of principle and safety functions:

Two main functions were identified :

- Contain and limit radioactive material in the PCV
- Maintain subcriticality

Definition of general prevention measures and constraints

A Preliminary safety analysis has been made about the general laser cutting technology :

Safety related events or operations	Risk(s) and potential consequences	Suggested provisions
	All activity	
		Any opening of a containment barrier should be compensated by a reproduction of this barrier, as close as possible to the radioactive materials.
	Activities on utilities	
Loss of coolant for the laser source and/or the coupler	Laser source or coupler overheating, resulting in a risk of fire departure.	Automatic stop of the source if gaps identified on a temperature measure. Inflammable materials in the surroundings of the fiber are identified and relocated if necessary.
Optical fiber path	Damaging optical fiber, leading to the creation of a "hot spot" resulting in a risk of fire departure.	The path of the optical fiber is studied and labeled and/or physically protected if necessary. Inflammable materials in the surroundings of the fiber are identified and relocated if necessary.

[2] – Safety analysis assessment

1 – General safety analysis

Safety related events or operations	Risk(s) and potential consequences	Suggested provisions
Preparation of tools, material, maintenance		
Maintenance of the arm and cutting/collecting tools (replacement of filters…)	Human intervention on the equipment can be requested, implying a risk of internal exposure to radioactive material and external exposure to radiations.	The design of the safe zone for maintenance and evacuation of retrieved debris/induced waste shall take into account human intervention according to the technical and physical options available for this area. For example, filters are clogged quite quickly which means they have to be replaced on a regular basis. Shielding and containment parameters are to be set according to: Dose rates in the area Contamination on the equipment The ALARA ("As Low AS Reasonably Achievable") approach The type of extraction chosen (to the general HVAC system or in close cycle inside the PCV) Induced nuclear waste is limited to the minimum requested.
Passage of the umbilical (power, fluids, etc.) through the PCV	Breach of PCV containment and release of aerosols outside the PCV.	The rail passage into the PCV does not present containment requirements since containment is assured by the safe zone. However aerosols collection is implemented as close as possible to the cutting process.

[2] – Safety analysis assessment

1 – General safety analysis

Safety related events or operations	Risk(s) and potential consequences	Suggested provisions
Collect and cutting activities		
Operations inside the control room		
Control of the laser head	Since the laser beam is very powerful and has a long range, an error in its piloting may result in cutting walls or structures that are important for safety (walls of RPV). The end result could be a loss of containment of radioactive materials.	The laser beam is not effective unless triggered by the operator. If the operator stops moving for too long, a mechanism could automatically detect it and stop the beam.
		Before the cutting operation, a double check shall be performed by a person who is not the operator.
		Power delivered by the laser source shall be periodically checked.
Operations inside the PCV		
Cutting pieces of fuel debris	Criticality event due to remaining fissionable radionuclides (U235, Pu239, Pu241, Cm244, Am 244…) in the corium and due the enveloping moderating water.	Geometry and mass of corium retrieved pieces adapted to the operation to ensure non criticality.
	Laser shot in stationary position implying damage on parts located behind the target.	Shutdown of the laser after X seconds passed in stationary position.
	Laser shot on prohibited/ weak area implying damage on parts, structure and equipment.	“Safeguards” included in the operational software - Laser can shot only on authorized area - Laser can shot during a limited duration in stationary position
	(in air) Fire due to the presence of ignition source (laser, heat, incandescent particles…) and inflammable materials (Flexible collection system, flexible cables…).	The flexible collection system or cables (pipes…) materials should be fire retardant
	Pressure increase inside the PCV due to laser air supply.	A regulation system could be linked to the PCV exhaust ventilation. In case of a closed cycle collection system, the impact on the aeraulic of the PCV is to be studied.
	Inert gas injected in the PCV is polluted by oxygen brought by the laser cutting process, increasing the risk of fire departure.	Air is replaced by nitrogen for laser cutting.

[2] – Safety analysis assessment

1 – General safety analysis

Safety related events or operations	Risk(s) and potential consequences	Suggested provisions
Operations inside the PCV		
Collecting dust in the collection box and/or HEPA filter	Criticality event due to the contained fissionable material in the collection box and/or HEPA filter.	Criticality is to be studied regarding foreseen geometry/composition of the collection systems and dust spectra/composition.
		Filters are to be chosen adequately with the risk of criticality they present. Especially, they must be sized to take into account the criticality risk.
	Criticality event in hoses due to an accumulation of fissionable material.	The flow rate and hoses path is to be implemented to limit accumulation.
		The hoses' diameters are chosen so that in case of accumulation, there is a guaranty of not reaching critical mass.
		Control of dose rate along the hoses on a regular basis.
	Too high quantity of particles collected in the pre-filter system resulting in a leakage of radioactive materials	Prefilter system clogging is to be checked on a regular basis and replaced accordingly.
All operations	Fall of an equipment resulting : - in suspending radioactive dust, - in potentially modifying the corium structure (sub-critical in initial state).	The number (redundancy) and strength of provisions for this case are to be adapted in the frame of the acceptable risk in the PCV and in the frame of PCV ventilation systems. Especially, the necessity for a seismic behavior study of on-site installed equipment (aspersion system, robotic arms...) should be reviewed.
		A video surveillance system is an example of provisions for detecting the risk.
All operations	Loss of functionality or integrity of equipment due to irradiation fluence or corrosion leading to a fall.	Maintenance processes or design specifications should take these physical phenomena into account.

[2] – Safety analysis assessment

1 – General safety analysis

Safety related events or operations	Risk(s) and potential consequences	Suggested provisions
Operations inside the PCV		
Set up of the aspersion system	Loss of functionality during underwater cutting resulting in an accumulation of fumes in the PCV.	The number (redundancy) and strength of provisions for this case (redundancy, limitation) are to be adapted in the frame of the acceptable risk in the PCV and in the frame of PCV ventilation systems.
		A video surveillance system and/or measures of water flow rate are example of provisions for detecting the risk.
	Fall of equipment/materials on the aspersion system from above.	Same as above.
	Water level increase due to the spray system.	Spray regulation according to the global water level
Loss of collecting capability	No collecting of dust and fumes implying a dispersion of radioactive material during in-air cutting activities.	Alarm or on low flow rate level inside the hoses.
		Laser power shutdown.
		The current state of the reactor being in an initial degraded mode, the aim is to not degrade even more this state.

[2] – Safety analysis assessment

2 – Safety analysis applied to the dust extraction system with laser

The following countermeasures and constraints do not include general safety measures about laser cutting technology previously presented

Risk	Origin	Countermeasures / Constraints
Radionuclides Dispersion	Cutting operation	• Use collection head and spray scrubbing system. The fraction of aerosols that remains non-collected is about a few percent (see task 3.4) • Provide a water tank to ensure water supply for half an hour in case of problem • Keep the full system of filtration in depression • Use an inert gas for outlet gas of the laser cutting head (N_2 environment lower the radionuclides dispersion) • After filtration, release the air inside the PCV to use the global ventilation External measures : • The PCV global ventilation must take into account the air supply of the laser head • Inert the PCV (N_2 environment lower the radionuclides dispersion)
	Drop of load and shock on the filtration system	• Protect cans that receive dust from shock and drop of load by using a rack and by disposing cans below filters.
	Earthquake	• Stop cutting operations and reduce dispersion while cutting by using associated countermeasures. • Use a rack to stabilize the filtration system and to protect cans receiving dust.
Criticality	Fissile material in the fuel debris (the critical mass is 46 kg)	• The size of each element of the system is limited to forbid an accumulation of 23 kg of dust • The cans used to receive dust is a unit can or a smaller can

[2] – Safety analysis assessment

2 – Safety analysis applied to the dust extraction system with laser

Risk	Origin	Countermeasures / Constraints
Fire	Cutting operation	• Fire proof material for equipment in contact with sparks or incandescent particles : - Collection head in stainless steel - First part of the collection hose in stainless steel - Cyclonic filter in stainless steel - Pulsejet filter in stainless steel
Hydrogen explosion	Accumulation of fuel debris in the filtration system	• No volume that could lead to a gas retention in the filtration system • Limited the mass of fuel debris in the filtration system (especially in cans that receive dust)