PROJECT OF DECOMMISSIONING AND CONTAMINATED WATER MANAGEMENT

ONET TECHNOLOGIES

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IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

BOUYGUES CONSTRUCTION SERVICES NUCLÉAIRES

DEVELOPMENT OF DUST DISPERSION SUPPRESSION TECHNOLOGY

-

PUBLIC PRESENTATION

FEBRUARY 2024

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PROJECT ORGANIZATION

A. BACKGROUND & PURPOSE

Why the project is needed?

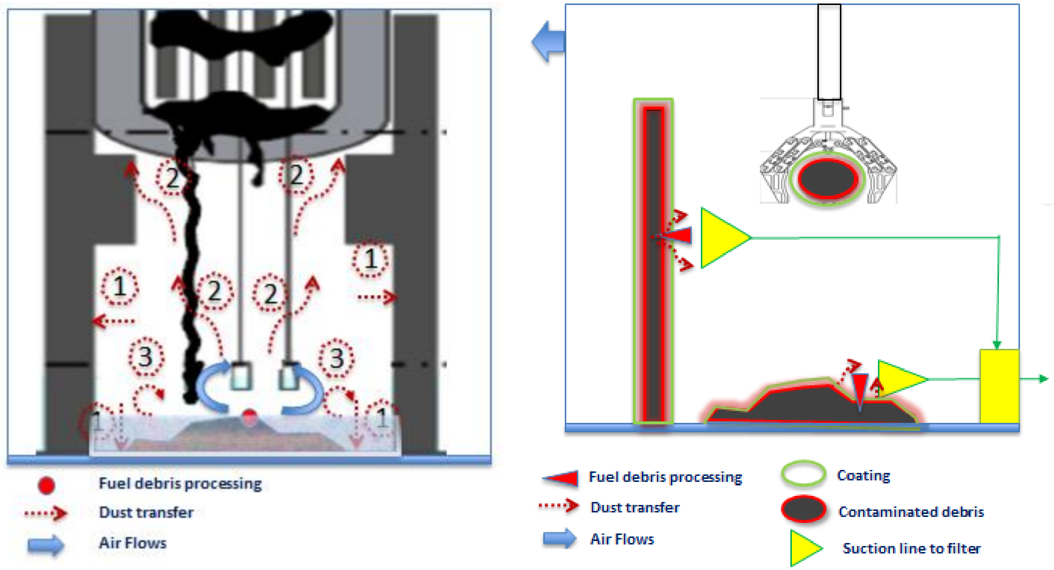
Dust resuspension and scattered sludge could cause safety and security issues regarding the containment of radioactive airborne particles. Therefore, elemental technologies are being investigated in order to minimize or even suppress the dispersion of dust when Fuel Debris is processed inside the Primary Containment Vessel (PCV).

Usage of the project results

The project results shall support the development of technologies contributing to the decommissionning of Fukushima Daiichi Nuclear Power Station(1F). More specifically, the results of the project shall help in the implementation of technologies for suppressing the dust dispersion.

Contribution of the project results

Currently, solutions such as local collection of dust or implementation of water spray have been studied in order to suppress the dust dispersion during the fuel debris processing. Nevertheless, dust dispersion can be caused not only during fuel debris processing but also by several other phenomenas: fuel debris removal, movement of remote controled arm inside the pedestal, fall of an object… This project focuses on implementation of solutions that shall allow to suppress dust dispersion by applying specific coating.

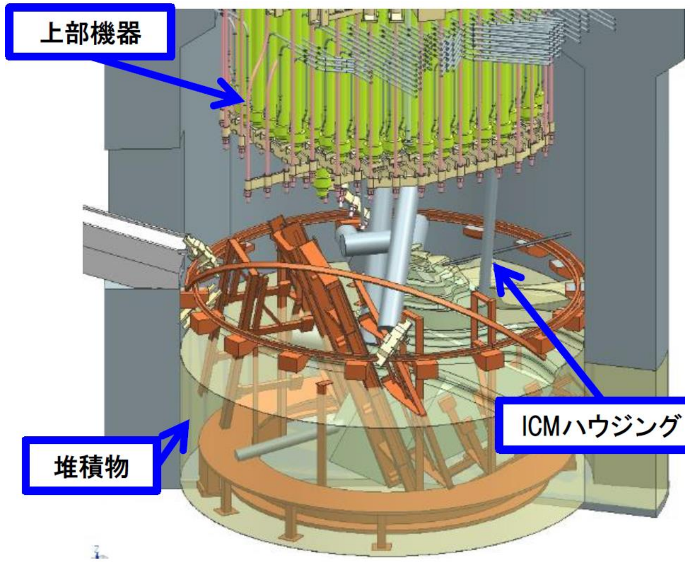


1. Particles that could deposit on the walls or on the ground
2. Airborne particles that could exit the pedestal
3. Particles that could fall into the water

Project goal:

The project aims at developping technique of injection and/or spraying of material (coatings) for dust suppression technology. Studies and tests will integrate as much as possible on site conditions and scenarios. Impact studies will be realized in order to verify the applicability of the solution.

B. GENERAL OVERVIEW – USE OF COATINGS, METHODOLOGY OF SELECTION & TESTS OF PROPERTIES



Picture from FY2018 Supplementary Budget Subsidy Program for the Project of Decommissioning and Contaminated Water Management International Research Institute for Nuclear Decommissioning (IRID) Final Report for "Development of Technologies for scaling up Retrieval of Fuel Debris and Internal Structures (FY2020)", released in August, 2021

Coating characteristics need to be consistent with its application. Indeed, coating characteristics shall be adapted whether it is applied in dry air, in wet air, with water dripping, on a vertical surface, by gravity, etc.

Furthermore, coating characteristics must be ajusted to the 1F conditions: high dose rate, remote controled operation, tight and cluttered area, etc.

Therefore, the first task of the project is to define what an applicable coating is, for what purpose (coating of Fuel Debris, coating of metallic equipment (such as a stainless steel beam), etc.) and for which location (considering the entry inside the pedestal by the X6 penetration, coating can be carried out oriented upwards or down).
For the upper elements, it shall be necessary to use a coating that can be sprayed and with a short pot life in order to avoid drips and have a good chance to reach as much surface as possible. On the other hand, it shall be necessary to use a coating more thick and with a longer pot life to be used with gravity for the bottom part. In this case, it is better to let the coating spread as much as possible to cover as much surface as possible. Also, coating properties must be searched whether it is intended to apply the product in air or underwater.

A market survey was needed in order to look after possible coating candidates: a possible candidate is a coating that can comply with operational characteristics (application by spray, by spreading, etc.) and that can comply with the 1F conditions (no degradation under high dose rate, works in high humidity rate or even under dripping water, etc.)

On the possible candidates, it is necessary to carry out essential tests in order to ensure they are fully applicable: for example, verify that a coating can properly cross-link under dripping water. The more accurate we get about coating selection, the more we focus the next tests on the coating candidates still in contention. More complex lab tests can be then carried out (such as irradiation tests) because the number of candidates is lower. Also, efficiency tests and operability tests can be carried out for the same reason: these tests are carried out only with the last candidates.
Finally, with the results of lab tests, efficiency tests and operability tests, it is possible to study and assess the impacts, whether it is positive or negative, of the use of coating, for the dust suppression of fuel debris inside the pedestal.

B. GENERAL OVERVIEW – USE OF COATINGS, METHODOLOGY OF SELECTION & TESTS OF PROPERTIES

The objectives of the project being to provide data and as much as possible conclusions about the future use of coating inside the pedestal of the units 1, 2 & 3 of 1F, the project has been through the following items:

- Definition of an « applicable coating » (which characteristics does the coating must comply with?) and first selection
  - It is mandatory to analyse the conditions on site by establishing the functional analysis of the future system
  - A market survey is conducted so it is possible to list the existing coatings that present interests of use
  - By comparing the analysis of the situation on site (functional analysis that gives all the requirements that a coating must comply with to be applicable) allows to reduce the number of coating candidates
  - To reduce the number of candidates, it is necessary to carry essential simple tests. Depending on the results of the tests that must determine if the tested coating comply with a mandatory requirement, the coating is excluded or kept in the list of coating candidates for the next steps of the project

- Verification that the selected coatings are efficient in various situations (= how the coating suppresses the dust resuspension phenomena)
  - Operational situations that can lead to dust resuspension are studied:
    - Resuspension due to air movement (due to an operating system or by the airflow of the ventilation system)
    - Resuspension due to water movement (due to the operation of fuel debris retrieval for instance)
    - Resuspension due to the fall of an object
    - Resuspension due to a cutting operation, whether it is a mechanical cutting operation or a cutting operation using the laser technology
    - ⇒ For all theses situations, it is important to confirm the efficiency of a complete coating operation but also it is important to assess the gain when the coating cannot be entirely deposited on a determined area (partial covering of an area)

  - Furthermore, it is important to determine whether coatings can affect the efficiency of a cutting operation. The questions to be answered are:
    - Does is it lower the cutting performance of a given cutting tool?
    - What and how much « new » particles are produced by the cutting of the coating? Do they represent an additional issue ?

B. GENERAL OVERVIEW – USE OF COATINGS, METHODOLOGY OF SELECTION & TESTS OF PROPERTIES

In the same time, it is very important to determine whether the coating can be applied on site with the future conditions of use. Future conditions of use concern the following topics:

- Determination whether one characteristics of coating not tested yet does not comply with one requirement of the functional analysis
    - Some more complex tests to be carried out to determine specific coating characteristics are mandatory (resistance to irradiation for instance)

    ⇒ These tests allow to reduce again the number of coating candidates (some of them are excluded because they failed to successfully pass a test)

    - Among these tests, some characteristics are determined only to give an information that will be useful for the study of impacts of the use of coatings on Fuel Debris

- Verification that the selected coatings are applicable on site
    - It is mandatory to ensure that the selected coatings can be applied on site. Therefore, tests with representative conditions must be carried out:
        - Since conditions of application of the coatings are also determined with the functional analysis, a representative mock-up is manufactured in order to carry out the tests with some representativity: lenght of application, areas of application, in air, with dripping water, underwater. The first step of these tests is to find out the correct settings for the use on site: they are the tests of applicability
        - Also, it is very important consider the feasibility of the coating operation on site with remote controled means and with indirect vision. Tests are carried out to verify this feasibility and are also meant to determine the limits of the process (verification of effective coating). They are the tests of operability.

Finally, in order to completely determine the applicability of a coating, specific studies are necessary in order to assess the impacts of the use of coating inside the pedestal. Impact studies concern: criticality, waste management, gas release, temperature exchange of Fuel Debris at the bottom of the pedestal.

C. ITEM OF WORKS – WORK PACKAGES

Development Progress	Investigate	Confirm efficiency & selection of coatings	Confirm operability	Assess impacts of use
Project Items (Steps) Work Package 1 Work Package 2 Work Package 3 Work Package 4	First selection of coating - Input Data gathering & Functional Analysis - Market survey - Essential tests for characteristics determination Fuel Debris simulants manufacturing **Preliminary cutting tests in order to qualify measurement devices and gather first input data on particles generated (core boring and disk cutter)**	Cutting tests - Core-boring, disk cutter & laser cutting Efficiency tests (assessment for complete and partial coating) - Tests with aeraulic, mechanical & water stress Lab tests of coating candidates to reduce their number	Feasibility tests on representative mock-up - Feasibility tests in air and with dripping water. Determination of specifications - Feasibility tests underwater. Determination of specifications Applicability & Operability tests on representative mock-up with remote controled robotic arm	Global impact assessment regarding applicability - Impact study on filtration devices - Impact study on waste management - Impact study on safety (criticality, gas) **Synthesis and conclusions**
Main Outputs	**First selection of coating, Fuel Debris simulants for the tests**	**More accurate coating selection, assessment of efficiency, evaluation of coating process vs cutting operations**	**Confirmation of applicability and operability and specifications for applications**	**Conclusion, proposal for the next steps**

D. SCHEDULE OF THE PROJECT

2021 — 09 10 11 12
2022 — 01 02 03 04 05 06 07 08 09 10 11 12
2023 — 01 02

FINAL REPORT

WP1

- INPUT DATA GATHERING
- PRE-SELECTION OF COATINGS
- WORLDWIDE BIBLIOGRAPHY
- FIRST SELECTION PROCESS
- ESSENTIAL TESTS
- Fuel Debris SIMULANTS MANUFACTURING
- CHOICE OF COMPOSITIONS
- PROCUREMENT & MANUFACTURING
- REPORT

WP2

- PRELIMINARY CUTTING TESTS CORE BORING WITH ACTIVE FUEL DEBRIS SIMULANT
- TESTS
- REPORT
- CORE BORING TESTS
- TEST PROGRAM
- TESTS
- REPORT
- PRELIMINARY CUTTING TESTS – DISK CUTTING
- TESTS
- REPORT

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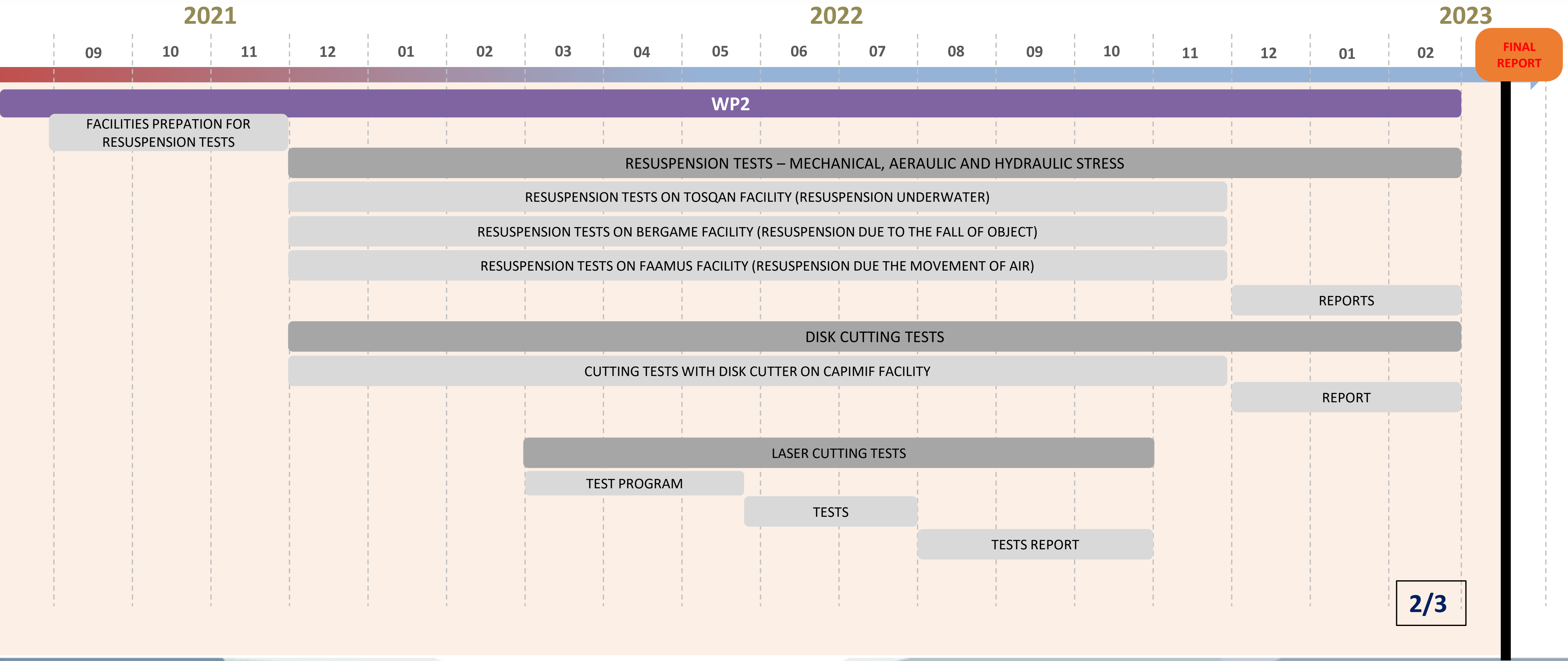
D. SCHEDULE OF THE PROJECT



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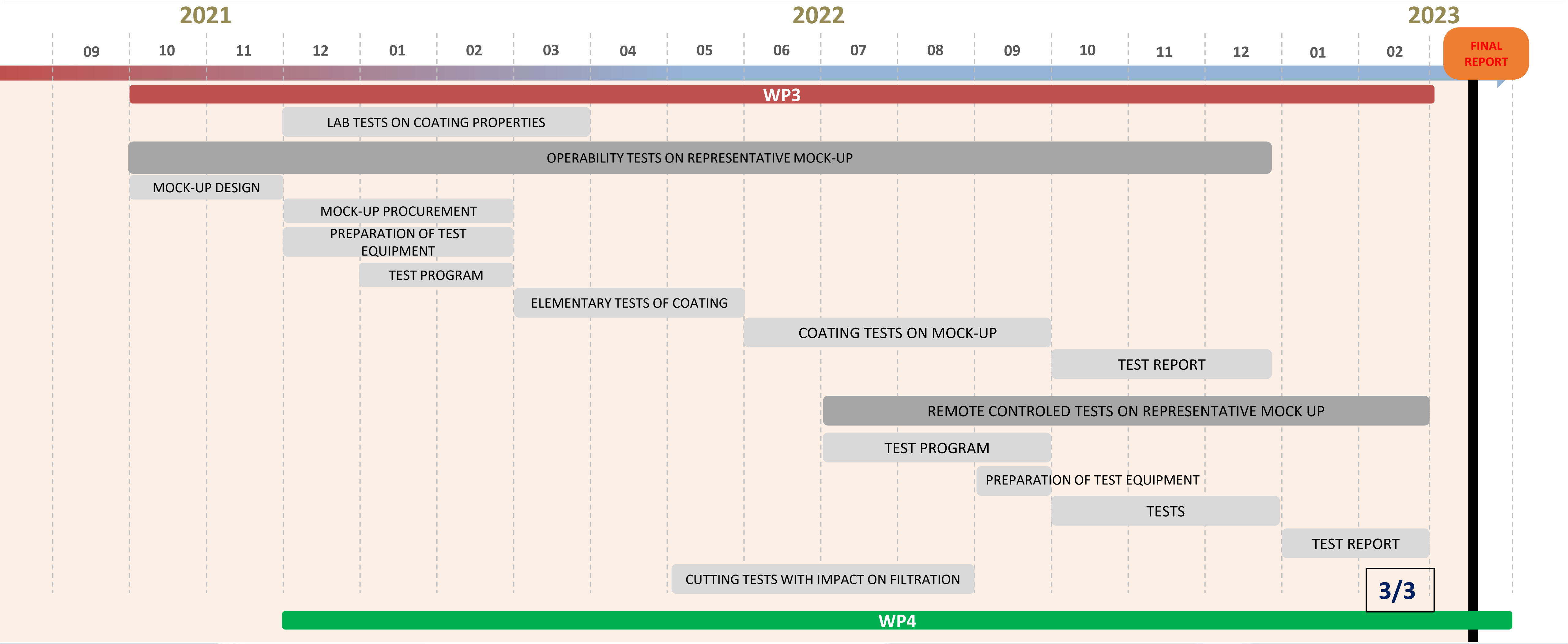
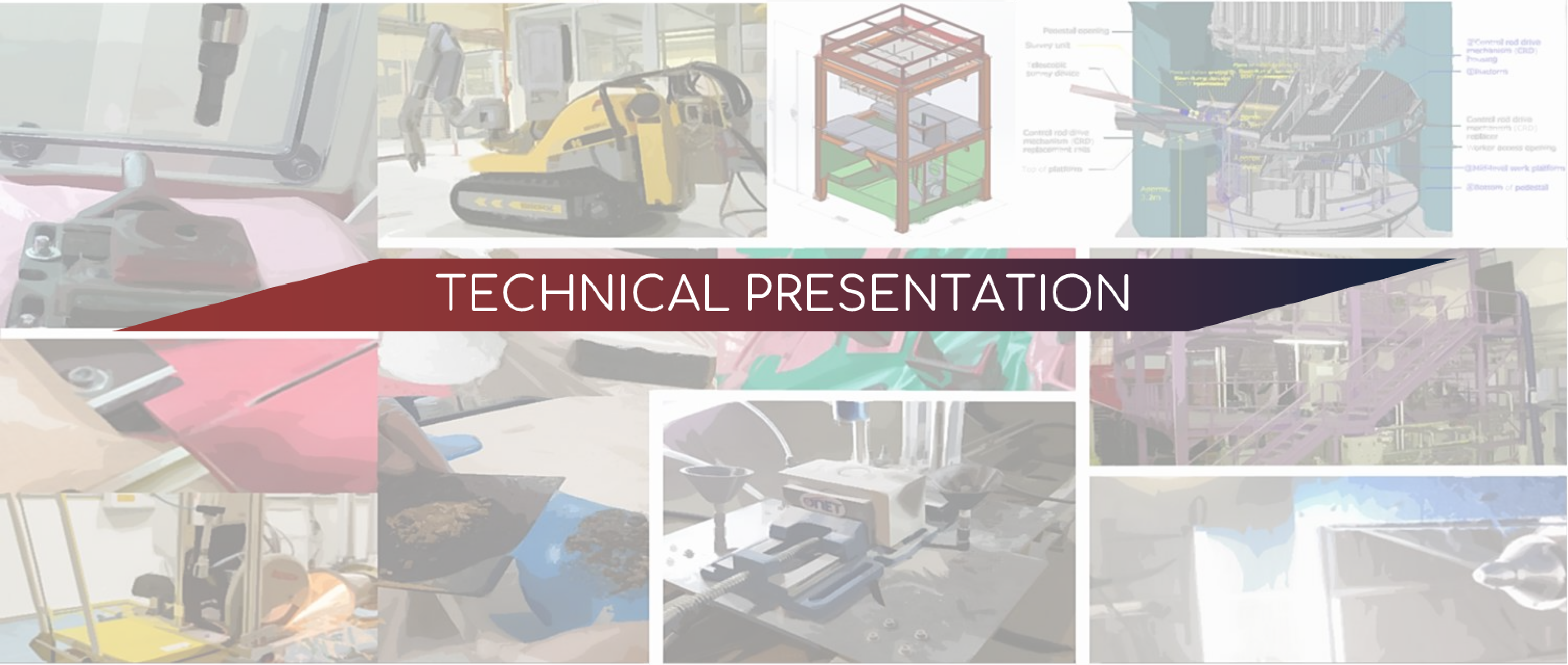
D. SCHEDULE OF THE PROJECT



TECHNICAL PRESENTATION



I. INPUT DATA ANALYSIS, FUNCTIONAL ANALYSIS, DEFINITION OF REQUIREMENTS FOR THE APPLICATION ON SITE

1. 1. GENERALITIES

Before implementing the project, it is very important to determine the characteristics of the needed system. For that, it is mandatory to have input data as reliable as possible. The first task is then to gather all the necessary and available information concerning the situation on site.

Information gathering intends:

- To **identify on-site status** important for the application of coating (like ambient temperature, dose rate, humidity rates, water levels),
- To **present values and data about on-site status** that will be considered as input data for the studies and the tests on coatings,
- To **identity systems, equipment or safety management** items that could be impacted by the application of coating inside the PCV (for example: water filtration system, criticality management equipment, waste management process, filtration systems in air, heat transfer of Fuel Debris). Then, it could be possible to provide accurate and useful data so it is later possible to assess impacts on such systems and equipment,
- To **present data that could be provided**, at the end of the study, in order to establish specifications or suggestions for more specific studies.

In the same time, a functional analysis is carried out: the goal of this study is to fully characterize the requirements of the future system (such as dimensions, lenght of hoses, maintenance service, operability and so on). It is important to carry out the functional analysis alongside with the input data analysis.

The functional analysis and the input data gathering help to determine the tests to be carried out to determine whether a coating can be applicable or not.

GATHERING INFORMATION ABOUT CONDITIONS ON SITE

FUNCTIONAL ANALYSIS TO DETERMINE REQUIREMENTS OF FUTURE SYSTEM

→ **GIVE DIRECTION TO THE PROJECT (DEFINITION OF TEST PROGRAMS, DESIGN AND STUDIES FOR APPLICATION ON SITE)**

I. INPUT DATA ANALYSIS, FUNCTIONAL ANALYSIS, DEFINITION OF REQUIREMENTS FOR THE APPLICATION ON SITE

1. 2. INFORMATION GATHERING ABOUT SITUATION ON SITE

1. 2. 1. 1F Status

Important data about 1F status that have been used during this projects are available in the following documents:

- Upgrading of the Comprehensive Identification of Conditions inside Reactor – Accomplishment Report for FY2017 – International Research Institute for Nuclear Decommissioning (IRID) , The Institute of Applied Energy (IAE) - June 2018 (https://irid.or.jp/_pdf/3_Upgrading%20of%20Comprehensive%20Identification%20of%20Conditions%20inside%20Reactor_IRID_2019.pdf)

- Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Internal Structures - Research Report for FY2019 (https://irid.or.jp/wp-content/uploads/2021/01/2019002entoridasikibonosaranarukakudaif.pdf)

- TEPCO transportation calculation and Development of Technology for Containing, Transfer and Storage of Fuel Debris – research report for FY2019 (https://irid.or.jp/wp-content/uploads/2021/01/2019001ensyuunouisouhokanf.pdf)

Main information used during the project:

- Range of temperature: 0° C to 40° C
- Humidity rate up to 100%
- Water level depends on the considered unit
- Localization of Fuel Debris, estimated composition and hydrogen generation as described in the references above
- Thermal power of Fuel Debris and composition of cooling water as described in the references above
- Access into the PCV possible through routes A, B & C described in the references above

1. 2. INFORMATION GATHERING ABOUT SITUATION ON SITE

1. 2. 2. Important considerations

Systems and equipment impacted by coating utilization

The Fuel Debris Retrieval project considers some systems or equipment that could be impacted by coating use: the filtration system associated to the cooling water, the filtration system of the ventilation system, the pump used to retrieve fuel debris particles and the drying system.

To take into account impact on identified systems, some data are being collected:

- The impact on filtration systems or the pump is considered by measuring sizes and identifying forms of particles generated by coatings. As far as possible, tests are realized on filtration equipment. These data should be transmitted to the dedicated teams to be capitalized on.
- The impact on the drying system is estimated by heating up to 200 ⁰C the selected coatings and analyzing its behavior (liquefaction or not). As far as possible, the thermal conductivity and the tightness of the resin is also analyzed (https://irid.or.jp/wp-content/uploads/2021/01/2019001ensyuunouisouhokanf.pdf)

Safety consideration

As far as possible in the frame of this project, some safety considerations will be evaluated like:

- The management of the heat released by fuel debris (by analyzing thermal conductivity and thickness),
- The management of the hydrogen produced by fuel debris (by analyzing thickness),
- The management of the criticality like modification of the criticality calculations, impact on countermeasures, etc. (by analyzing hydrogenous quantity, thickness, etc.),
- The management of the fire risk (resins flammability and fire load),
- The management of the corrosion (on covered pieces and about the storage canister in a long term consideration).

Waste management

The waste management will also be impacted. An evaluation of the waste volume added with the resins process will be made.

I. INPUT DATA ANALYSIS, FUNCTIONAL ANALYSIS, DEFINITION OF REQUIREMENTS FOR THE APPLICATION ON SITE

1. 3. FUNCTIONAL ANALYSIS OF THE SYSTEM

The functional analysis concern two sub-systems of the dust resuspension suppression system:

a) The COATING CANDIDATE analysis

b) The IMPLEMENTATION SYSTEM analysis

The functional analysis is carried out in order to

- **Identify and classify** the **CRITERIA** for the coating candidates selection
- **Compare** **INPUT DATA** from 1F with the studied criteria
- **Pre-study** the **IMPACT OF THE COATING** on waste, safety and security
- **Defined** the **RESEARCH PLAN** in terms of:
  - Efficiency tests
  - Processing tests
  - Coatings tests and innocuity tests

<u>The functional analysis for the future system to be deployed on site concerns:</u>

- Capacity of the system to cover all the areas of interest inside the PCV: on vertical and horizontal surfaces, on gratings, on beams, etc. and for different conditions (in air, under dripping water, underwater)
- Capacity of the system to be deployed inside the PCV and remotely by operators
- Capacity of the system to be maintained
- Capacity of the system to control the quantity of coating injected
- Capacity of the system to resist to the harsh environment
- Capacity of the system to respect the interfaces on site
- Capacitiy of the system not to generate inadequate waste

This functional analysis led to the lab tests described in the following chapter of this report.

II. FUEL DEBRIS SIMULANT MANUFACTURING

2. 1. DEFINITION OF COMPOSITIONS

From the analysis of published data on the fuel debris of 1F and discussions with TEPCO, 3 compositions have been determined to roughly encompass of the possible 1F fuel debris compositions.

1. A metallic debris, in which solid fuel pellets have been entrained corresponding to the metallic liquid phase obtained for the median composition estimated in 1F2 lower head at the time of vessel melt-through.
2. A MCCI (Molten Core Concrete Interation) composition corresponding to median MCCI estimated in 1F1 sump when it was flooded after more than 10 days of dry interaction (average ARC-F benchmark).
3. An in-vessel melt composition (oxide+metal) corresponding to 1F3.

In all these compositions, Uranium is replaced by Hafnium and surrogates are also used for the transuranians. Natural isotopic composition is used for Fission Products.

Composition E estimated in 1F1: median MCCI

OECD/ ARC-F project conducts a benchmark on MCCI in 1F1 sump:

- >10 days of continuing ablation until efficient water flooding arrived,
- Largest possible concrete fraction of 3 units.

	Wt(%)		Wt(%)
SiO_2	51.56%	MoO_2	0.029%
Al_2O_3	12.70%	$CsOH.H_2O$	0.021%
CaO	10.56%	RuO2	0.018%
Fe_2O_3	9.443%	BaO	0.013%
HfO_2	7.04%	La_2O_3	0.0092%
ZrO_2	5.07%	PdO	0.0088%
Cr_2O_3	1.71%	Pr_2O_3	0.0085%
Fe	1.09%	Sm_2O_3	0.0063%
Ni	0.53%	Sr	0.0060%
SnO_2	0.072%	Y_2O_3	0.0040%
CeO_2	0.061%	Te	0.0038%
Nd_2O_3	0.033%		

Composition F estimated in 1F3: in-vessel melt

- In-vessel debris relocated into pedestal
- Average from BSAF benchmark JAEA+IAE (compatible with current knowledge)

	Wt(%)		Wt(%)
HfO_2	42.74%	B_4C	0.218%
ZrO_2	30.14%	$CsOH.H_20$	0.106%
SS 304L	17.84%	BaO	0.064%
Fe_2O_3	3.092%	La_2O_3	0.047%
Zr	2.040%	PdO	0.044%
Inconel 625	1.784%	Pr_2O_3	0.043%
SnO_2	0.460%	Y_2O_3	0.021%
Cr_2O_3	0.447%	TeO_2	0.019%
CeO_2	0.371%	RuO_2	0.0015%
Fe	0.270%	Sm_2O_3	0.0005%
Nd_2O_3	0.258%	SrO	0.0005%

Composition B estimated in 1F2: Metallic debris + solid pellets

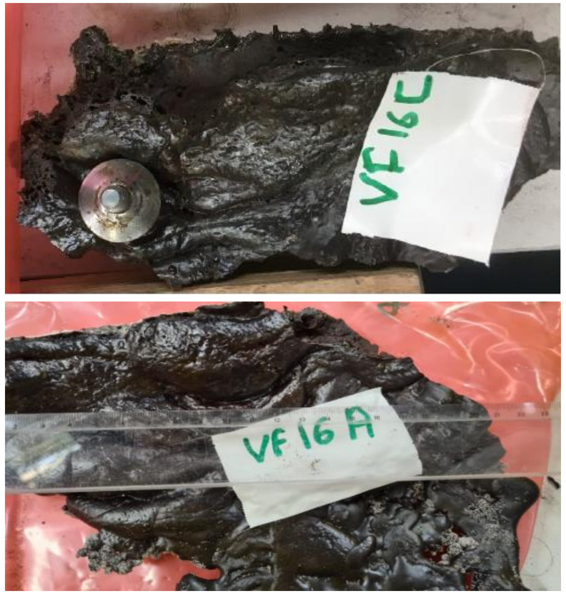
The actual fuel material poured from the vessel lower head to the pedestal in 1F2 are made of fragmented fuel elements entrained by metallic fuel debris melt.
To simulate this type of debris, it is proposed to consider the previously-selected metallic debris in which hafnium oxide pellets, tablets or granules have been inserted : Illy oxidized Zircalloy also included in composition, representative of Lower Head inventory.
Median from SNL/MELCOR - uncertainty analyses

	Wt(%)		Wt(%)
Fe	47.60%	SrO	0.011%
Cr	4.22%	Sm_2O_3	0.007%
Stainless Steel 304L	5.23%	Y2O3	0.007%
Inconel 625	5.23%	B4C	0.493%
Hf	4.70%	Sn	0.085%
Zr	5.73%	Ce	0.042%
H_fO_2 (pellets)	18.72%	Mn	0.002%
ZrO_2	7.50%	Mo	0.012%
SnO_2	0.110%	Ru	0.009%
CeO_2	0.204%	Cs	0.011%
BaO	0.022%	Pd	0.005%
La_2O_3	0.016%	Te	0.002%
PdO	0.015%	Pr	0.005%
Pr_2O_3	0.015%		

II. FUEL DEBRIS SIMULANT MANUFACTURING

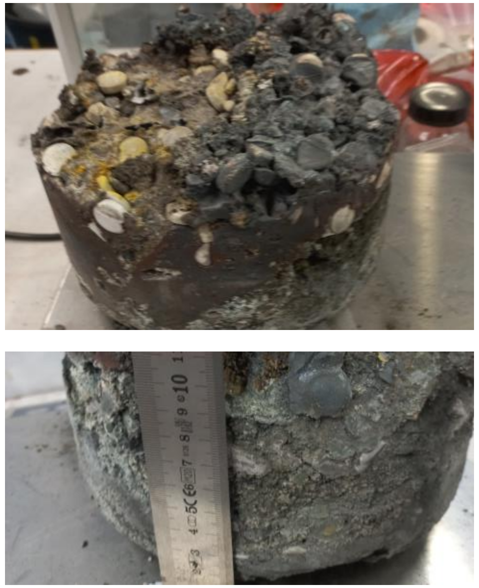
2. 2. RESULTS OF MANUFACTURING

Manufacturing has been achieved (4 melting operations between December 2021 and March 2022). The manufacturing is compliant with the expectations. Overall, about 68 kg of fuel debris simulants have been manufactured and are being transferred to other sites form next phases of experimental activities.



MCCI SAMPLES #1 – First batch
(CEA ref. VF16)

IN-VESSEL SAMPLES #2
(CEA ref. VF15)



METALLIC SAMPLES #3
(CEA ref. VF17)

MCCI SAMPLES #1 – Second batch
(CEA ref. VF16)

III. SELECTION OF COATINGS

3. 1. OVERVIEW OF GLOBAL METHODOLOGY

As already explained, the choice of a coating is driven by the compliance of its characteristics with the requirements for the use on site. The requirements have been determined thanks to the on-site information gathering and the functional analysis.

Here below is explained the global methodology of selection, in 6 steps:

1 + 2 The market survey of coatings gives a first list of coating candidates. Then, the coatings are compared one to each other (technical sheets available + technical discussions with suppliers), a shorter list of coatings is sorted out.

3 Essential tests have been carried out. Priority criteria, identified from input data and functional analysis studies, have been tested. The results give the final pre-selection of coating candidates. These test have allowed the coatings classification regarding on-site materials, area and environment inside PCV.

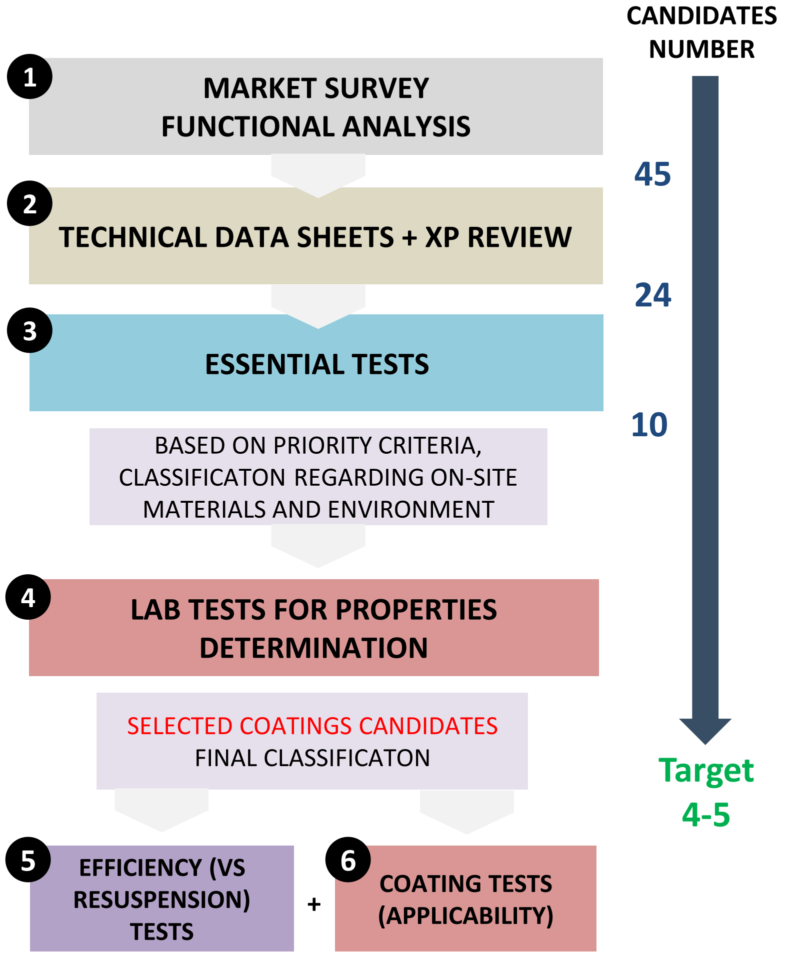
4 Finally, other essential properties are tested on a second campaign (lab tests). Some tests are more complex to implement (such as the irradiation resistance evaluation). By the end of this phase of tests, only 4 to 5 coatings are still in contention

5 Efficiency tests of the coating in terms of dust dispersion suppression is tested.

6 Also, applicability tests will aim at proving that coatings are applicable on site:

- Real size coating tests on mock-ups, at different locations, for several materials,
- Coating tests with remote arm,
- Coating test taking into account the filtration devices on-site.

The WP4 will synthetize the impact of the use of coatings (waste management, safety, criticality, etc.) to ensure the full applicability or not.



III. SELECTION OF COATINGS

3. 2. MARKET SURVEY – FIRST SELECTION

1 The first step has consisted in a worldwide market survey. This market survey targetted coatings already used in the industry (whether it is used in nuclear industry or not). Indeed, no coating development per se was scheduled in this project.

This first selection has been carried out bearing in mind the results of the functional analysis and the information about on-site conditions gathering.
Products from 15 international brands have been studied. At the end of this process, 45 coatings are selected.

Family of products are: Silicone, Polyurethane, Epoxy, Gel, Aqueous base paint, foam, mineralizing coating and Geo-Polymer.

Market Survey - Industrial Feedback

Worldwide Market Survey + Coatings used in the Nuclear Field + Coatings used in non-nuclear activities exposed to particle dispersion

AXSON (SIKA) | BCSN | BHI | DECONGEL | REAL WORLD EPOXY | FEVDI NUCLEAR | HEVADEX | INSTACOTE | JACOBS | JAPAN RESEARCH INSTITUTE | KEMICA | PICCO COATINGS | POLYASIM | PROTECTAPEEL | SICOMIN

Candidate Family Identification and related References

45 COATINGS

SILICONE	POLYURETHANE	EPOXY	GEL	AQUEOUS BASE PAINT	FOAM	MINERALIZING	GEO-POLYMER
RTV FA 878 RTV FA 877 RTV FA 873 FEVDISIL PB	FIXAPRO P02 FIXAPRO P03 PU-FA-879 ML1-ML12 PS413 UR3420 UR5801 KECOR	EPOXYGUARD SCUBAPOXY 1715 SCUBAPOXY 1725 SR 8450 / SD7180 CA 85 / SD 8601 SR 1690 / SD 1213 SR 8500 / SD 860x SR 1126.2 / SD 8205 SR 8200 WARREN 301 UT15	POLYASIM GCP DIAG POLYASIM GCP + ANTI-DUST ASPIGEL 500 ASPIGEL 100	AMISEAL FIRECOAT SINIFIX POLYASIM SECURE + FIXATEUR LP3 ALARA SD STRIPCOAT PROTECTAPEEL BHI STRIPCOAT TLC LIQUIDEX LW BHI PBS STRIPOAT CC STRIP POLYASIM FIX POLYASIM LATEX 1120/1121 SPRAY E105-106	FOAMIX 01	PROTECTION BETON	SIAL
4	8	11	5	14	1	1	1

III. SELECTION OF COATINGS

3. 3. ESSENTIAL AND LAB TESTS – OVERVIEW

2 After the first pre-selection of 45 coatings, a preliminary analysis has been carried out in order to shorten the list of candidates.
The process of this second phase of selection goes through the study of the technical data sheets, the comparison of products between themselves and thanks to discussion with suppliers (OPEX).

Criteria to remove a product from the list of candidates were:

- No formulation research is needed to apply the product
- If two coatings present too many similarities of properties, only one is selected

At the end of this process, the list is shorten to 24 candidates

3 Essential tests are carried out on the 24 remaining coatings. They focus on obvious requirements and tests that are easy to implement (for instance, verification if the coating can be used with water dripping). Each test is noted and coatings are ranked. By the end of this phase, only 10 coatings are still in contention.

4 Lab tests, that are more complex to carry out (such as irradiation tests), are done on the 10 previously selected coatings.
Tests also focus on properties that are a criteria of acceptance for the application on site, or they focus on a data that is needed to assess the impact of the use on site (for instance, gas release)

FIRST PRE-SELECTION BASED ON TECHNICAL DATA SHEETS
(from 45 to 24 coatings)

No Formulation Research (only candidates available on the shelf are selected) + **Physico-chemical similarities** between candidates + **Discussion / Advice** with suppliers

Coating Pre-selection

24 COATINGS

SILICONE	POLYURETHANE	EPOXY	GEL	AQUEOUS BASE PAINT	FOAM	MINERALIZING
RTV FA 878 RTV FA 877 RTV FA 873 FEVDISIL PB	FIXAPRO P02 FIXAPRO P03 PU-FA-879	EPOXYGUARD SCUBAPOXY 1715 SCUBAPOXY 1725 SR 8450 / SD7180 CA 85 / SD 8601	POLYASIM GCP DIAG POLYASIM GCP +	AMISEAL FIRECOAT SINIFIX POLYASIM SECURE + FIXATEUR LP3 ALARA SD STRIPCOAT PROTECTAPEEL BHI STRIPCOAT TLC BHI PBS	FOAMIX 01	PROTECTION BETON
4	3	5	2	8	1	1

ESSENTIAL TESTS
(from 24 to 10 coatings)

First coatings classification in function of tested criteria, location and conditions inside PCV

LAB TESTS
(from 10 to 4-5 final coatings)

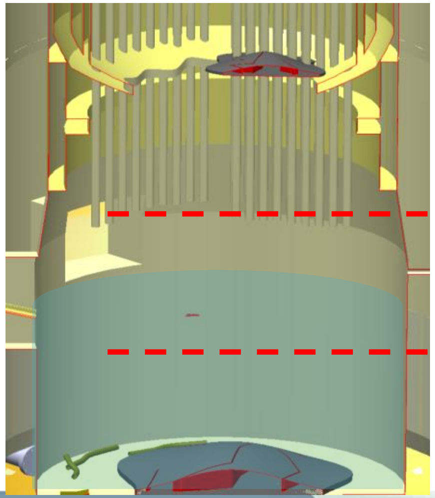
III. SELECTION OF COATINGS

3. 4. ESSENTIAL TESTS

Depending the area of application (whether it is on a metallic surface on the upper part of the pedestal (in the Control Rod Drive Housing (CRDH) area for instance), or it is a metallic surface like a beam or grid, or again the bottom of the pedestal full of fuel debris), criteria of observance may differ.

Indeed, when a coating is applied towards the upper direction on a vertical metallic surface, it needs to be sprayable and it needs to have a short pot life in order not to drip. On the other hand, for the bottom of the pedestal, a coating will need to be injected by gravity and its pot life shall not be too short in order to let the coating cover as much surface as possible. Also, a coating shall have different characteristics whether it is applied in air, under water dripping or underwater.

For these reasons, the pedestal is divided in our study in three areas: upper part (upper than the platform), middle part (platform area) and bottom part (bottom of the pedestal).



UPPER PART

MIDDLE PART

BOTTOM PART

ESSENTIAL TESTS

(from 24 to 10 coatings)

Criteria identification and classification in function of tested criteria, location and conditions inside PCV

UPPER PART OF PCV	MIDDLE PART OF PCV	BOTTOM PART OF PCV
CONDITIONS	**CONDITIONS**	**CONDITIONS**
▪ Humidity 100% & Under rain	▪ Humidity 100% & Under rain	▪ Under water
MATERIALS & SUPPORT	**MATERIALS & SUPPORT**	**MATERIALS & SUPPORT**
▪ Metallic horizontal rusted parts ▪ Hanging metallic bars / Wires	▪ Metallic horizontal rusted parts ▪ Hanging metallic bars / Wires	▪ Pile of gravel (to simulate Fuel Debris) ▪ Pile of metallic rusted pieces / Wires
CRITERIA	**CRITERIA**	**CRITERIA**
▪ Spraying in air conditions & into humidity ▪ Applicability under rain ▪ Capability to be spread on narrow parts ▪ High grip to rusted metallic parts	▪ Spraying in air conditions & into humidity ▪ Applicability under rain ▪ Encapsulation on rusted metallic waste ▪ Vertical application on rusted and no rusted metallic waste	▪ Applicability under water ▪ Encapsulation on sand and gravel ▪ Cross linking under water ▪ Immersion under water

First coatings classification in function of tested criteria, location and conditions inside PCV

10 COATINGS

SILICONE	POLYURETHANE	EPOXY	GEL	AQUEOUS BASE PAINT
RTV FA 878 RTV FA 877 RTV FA 873 FEVDISIL PB	PU-FA-879 FIXAPRO P03	SCUBAPOXY 1725 EPOXYGUARD SR 8450 / SD 7180	POLYASIM GCP DIAG	ALARA SD (not still tested - out of delivery)
4	2	3	1	-

III. SELECTION OF COATINGS

3. 5. LAB TESTS

Objective
The aim of these tests is to determine **final candidates** that can be used on site, and that will be tested for the application tests: spraying tests, resuspension tests, filtration devices tests, remote arm spraying tests.

Description
As the first campaign focused on the most obvious criteria of application, coating locations and conditions; this campaign considers complementary and thorough studies on coatings which:

- Require an external lab for complex tests such as the irradiation resistance tests,
- Need more time (like the aggressive liquid resistance tests or the corrosion on coating surface analysis).

Each test has been carried out individually or by family of coatings (silicon, epoxy…) in order to determine some specific characteristics.
Criteria of tests are determined by the functional analysis. They are divided into the four categories below:

FIRE & TEMPERATURE

- TEMPERATURE BEHAVIOR WITHOUT GAS RELEASE MEASUREMENT
- TEMPERATURE BEHAVIOR WITH GAS RELEASE MEASUREMENT
- FLAME BEHAVIOR WITHOUT GAS RELEASE MEASUREMENT

PHYSICAL PROPERTIES

- VISCOSITY
- SHORE HARDNESS
- POT-LIFE
- THERMAL CONDUCTIVITY
- GAS PERMEABILITY ASSESSMENT)

CHEMICAL PROPERTIES

- RESISTANCE TO AGGRESSIVE LIQUIDS (H_3BO_3 AND SALT)
- WATER ABSORPTION
- CORROSION ON SURFACE
- CHEMICAL CONTENT
- TGA DSC ANALYSIS

RADIOACTIVITY

- RESISTANCE TO IRRADIATION WITH GAS RELEASE MEASUREMENT

ESSENTIAL TESTS

Priority criteria + Coating location inside PCV + Coating conditions inside PCV

First coatings classification currently 8 COATINGS

SILICONE	POLYURETHANE	EPOXY	GEL
RTV FA 878 RTV FA 877 RTV FA 873 FEVDISIL PB	FIXAPRO P03	EPOXYGUARD SR 8450 / SD 7180	POLYASIM GCP DIAG
4	2	2	1

LAB TESTS

Long-term tests + Complex tests in external laboratories + Complex tests in BCSN laboratories

Final coatings classification

As remind, each selected coating must be adapted to the spraying locations (CRD, vertical or horizontal application) and conditions (into humidity, under rain, under water, in air...).

SILICONE	EPOXY
RTV FA 878 RTV FA 877 RTV FA 873	EPOXYGUARD
3	1

III. SELECTION OF COATINGS

3. 5. LAB TESTS

FIRE & TEMPERATURE

TEMPERATURE BEHAVIOR WITHOUT GAS RELEASE MEASUREMENT

TEMPERATURE BEHAVIOR WITH GAS RELEASE MEASUREMENT

FLAME BEHAVIOR WITHOUT GAS RELEASE MEASUREMENT

Coatings may be used on Fuel Debris that generates heat. It is therefore important to determine the behavior of the coatings towards high temperatures. Tests focus on the physical properties of the coatings (does the coating lose its properties when heated?) and on gas release.
Loss of properties can lead to the exclusion of a coating, mas release measurement will give an information about the coating, safety studies will conclude about the applicability of a coating about this parameter.

Content of the tests (overview) :

- Gas release measurement: Hydrogen and VOC release were measured when the coating is heated. The lower the gas release is the better it is for the application on site. Coatings shall be heated on site due to the application to Fuel Debris and during the drying operations for the waste management
- Temperature behavior without gas release measurement: coatings were heated up to 80°C (estimated temperature of Fuel Debris taken for this project as a reference for underwater conditions, see references given in p.127)* 200°C (temperature of heating of drying system of Unit Cans, based on information given in p.15). Chemical properties were looked after. Modifications of consistency (degradation of coating) may imply issues on site
- Flame behavior: tests focused on whether or not a coating will propagate fire

PHYSICAL PROPERTIES

VISCOSITY

SHORE HARDNESS

POT-LIFE

THERMAL CONDUCTIVITY

GAS PERMEABILITY ASSESSMENT

Some physical properties are studied through lab tests. Viscosity, shore hardness and pot life are not criteria that can exclude a coating from the selection. However, depending on the results, it can help sorting them. Indeed, these three parameters are important for the application on site (for instance, it is easier to apply a coating with a low viscosity, etc.).
Thermal conductivity and gas permeability also are criteria that will help sorting the coatings. Indeed, only safety studies can determine whether the thermal conductivity or gas permeability are an important issue. The tests will provide input data for these matters. Nevertheless, it is possible to sort the coating depending on the results of the tests (for instance, a higher thermal conductivity is considered to be better).

Content of the tests (overview) :

- Pot life and viscosity were measured in specific tests at 23°C and 40°C. Both adaptable short pot life and low viscosity are preferred for the application on site.
- The apparent thermal conductivity has been determined by the transient plane heat source (Hot Disk TPS) method ***ISO 22007-2:2008***.

**** Calculations carried out by IRSN and CEA in the frame of another project showed that for the given heat power of Fuel Debris, temperature at the surface of the Fuel debris underwater shall not exceed 80°C. It can be seen on site that temperature is below 100°C since no boiling is observed. This information is true for Fuel Debris underwater, we make no conclusion for Fuel Debris in air.***

III. SELECTION OF COATINGS

3. 5. LAB TESTS

CHEMICAL PROPERTIES

RESISTANCE TO AGGRESSIVE LIQUIDS (H_3BO_3 AND SALT)

WATER ABSORPTION

CORROSION ON SURFACE

CHEMICAL CONTENT

TGA DSC ANALYSIS

These chemical properties are important to determine the applicability of a coating. A coating does not resist to aggressive liquids can not be selected for the application underwater. It is also important, for all the coatings, and for all the situations on site, to test the behavior with water (water absorption that could lead to loss of properties). Corrosion on surfaces is an important criteria for coatings that could be applied on metallic items. Chemical content analysis is important to determine if an element could become radioactive under irradiation. Finally, TGA DSC analysis gives information about the mass loss under different temperatures.

Content of the tests (overview) :

- Resistance to aggressive liquid and water absorption tests have been carried out in small tanks. Weighing and visual control were carried out.
- Corrosion tests have been carried out underwater for 30 days at ambient temperature. Coatings were applied on steel plates.
- Chemical content tests concerned the measurement of concentration in **sulfur / chlorine / bromine / fluorine.** For a classical nuclear application (that means for NPP in exploitation in France) a maximal value concentration of **200 ppm** is considered. Atomic compound concentration has been obtained by: Ionometer, Spectrophotometer UV-vis, ICP-AES & ICP-MS, Ionic Liquids Chromatography.

RADIOACTIVITY

RESISTANCE TO IRRADIATION WITH GAS RELEASE MEASUREMENT

Coatings will face high dose rates on site. It is important to ensure that there will be no loss of properties because of the dose rate. If a coating loses its properties under radiation, it is excluded of the selection.

Content of the tests (overview) :

- Coating samples have been irradiated with a Cobalt 60 irradiation source emitting gamma rays with 1.17MeV and 1.33MeV energies, under partial vacuum. Gas release has been measured and visual control of coatings (modification of properties) have been looked at.

III. SELECTION OF COATINGS

3. 5. LAB TESTS

The table below details the tests grid. Not all the tests have been carried out for all the selected coatings

EVALUATED CRITERIA	LOCATION	RTV878	RTV877	RTV 873	FEVDISIL PB	EPOXYGUARD	SR 8450	FIXAPRO 3	POLYASIM GCP
TEMPERATURE BEHAVIOR WITHOUT GAS RELEASE MEASUREMENT	*Ext. lab*	O	O	O	O	O	O	O	O
TEMPERATURE BEHAVIOR WITH GAS RELEASE MEASUREMENT	*Ext. lab*	O	O	X	X	O	X	O	X
VISCOSITY	*BCSN*	O	O	O	O	O	O	O	O
FIRE BEHAVIOR WITHOUT GAS RELEASE MEASUREMENT	*Ext. Lab*	Avail.	O	O	O	O	O	O	X
RESISTANCE TO IRRADIATION WITH GAS RELEASE MEASUREMENT	*Ext. Lab*	O	O	O	O	O	O	O	X
RESISTANCE TO AGGRESSIVE LIQUIDS (H_3BO_3 AND SALT)	*BCSN*	O	O	O	O	O	O	O	X
THERMAL CONDUCTIVITY	*Ext. Lab*	O	O	O	O	O	O	O	X
WATER ABSORPTION	*BCSN*	O	O	O	O	O	O	O	O
SHORE HARDNESS	*BCSN*	O	O	O	O	O	O	O	X
CORROSION ON SURFACE	*BCSN*	O	O	O	O	O	O	O	O
CHEMICAL CONTENT	*Ext. Lab*	PMUC	PMUC	Avail.	O	O	O	PMUC	O
TGA DSC ANALYSIS	*Ext. Lab*	O	O	O	O	O	O	O	O

O: Tested X: Not tested Avail.: Data already available PMUC: Product and Material Used in nuclear power plant Ext. Lab.: External laboratory

III. SELECTION OF COATINGS

3. 5. LAB TESTS

Finally, in order to sort the candidates still in contention to determine the final selection, results are considered as following:

- Mandatory criteria:
  The test must give a "good" result in order to keep the coating in contention.

  1. Resistance to irradiation: the coating, no matter its area of application, must not lose its properties under irradiation. According to the irradiation tests, only the silicone coatings and epoxy coatings can be selected
  2. No corrosion of metallic parts and maintain of the grip (concerns mainly upper and middle parts): it is important that the coating used do not corrode the metallic parts on which it is used and keeps its grip. Again silicone and epoxy coatings can be selected
  3. No loss of properties with high temperature (concerns mainly the bottom part with the Fuel Debris that generates heat): it is very important that the coating do not lose its properties under high temperatures. Silicone coatings have a very good behavior under high temperatures, epoxy's behavior is a bit under but still acceptable

- Important criteria that help to sort the coatings from one to another:
  1. Limited water absorption (particularly for the bottom part): the coating will have to be efficient even with water. The bottom of the pedestal may be underwater, all the pedestal may be under dripping water. The lesser the coating absorbs water the better it is.
  2. Gas release: to sort coatings that may be equivalent, the amount of gas release under high temperatures and irradiation must be watched. The coating that releases less gas is considered to be better than the others
  3. Pot life: depending the area of application, a short pot life will be an asset. Therefore, a short pot life or a pot life that can be adapted is preferred

→ **For the considered application, inside the pedestal, with high rates of humidity, dripping water, high dose rate, etc. as it has been determined in the input data analysis and in the functional analysis, silicones coatings and epoxy coatings are the most suitable candidates.**

III. SELECTION OF COATINGS

3. 6. FINAL SELECTION OF COATINGS FOR THE APPLICABILITY TESTS

- Among the 10 candidates retained after the essential tests, only 4 are selected for the applicability tests
- The silicone coatings **RTV FA 878** and **RTV FA 877** seem both well adapted for the different areas inside the pedestal and are therefore selected
- The silicone coating **RTV FA 873** is also selected. It is interesting to keep it as well for the applicability tests because it presents a higher hardness which could represent an asset in certain conditions
- Furthermore, **EPOXYGUARD** is also selected because it has shown good results to the different tests especially underwater. Nevertheless, it has to be noted that, for our application, Epoxyguard has shown less assets than the silicone coatings: its behavior under high temperatures and irradation are not as good. Besides, its high viscosity makes it more difficult to use with spray even if it is still manageable.

- **The gas retention must be considered for all coating candidates, especially for hydrogen and methane gases.**

PCV LOCATION

PCV location	Description	Coatings
UPPER	*The coatings in the upper part are spraying in air and under rain conditions.*	RTV FA 878, RTV FA 877, RTV FA 873
MIDDLE	*The coatings in the middle part are encapsulation of metallic waste, vertical application, spraying in air and under rain conditions.*	RTV FA 878, RTV FA 877, RTV FA 873
BOTTOM	*The coatings in the bottom part are encapsulation and cross-linking under water.*	RTV FA 878, RTV FA 877, RTV FA 873, EPOXYGUARD

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

4. 1. GENERALITIES

Objective

Decommissioning operations in 1F could lead to particle resuspension and dispersion due to various stress, such as aeraulic stress (ventilation, gas injection), hydraulic stress for underwater conditions (robots movement, water injection) and mechanical stress (fall of object, vibration). The objective of the tests is to determine the efficiency of the selected coatings in terms of dust resuspension suppression. Different coating scenario are studied, from "perfect" coating to partial coating of a determined area.

Criteria for particles used during the tests

For a given stress intensity level, particle resuspension coefficient is mainly function of particle size distribution. Because of the unknown size of particle deposit inside PCV of 1F, tests are carried out with particles whose size corresponds to the most dispersible one ($d_{resuspension}$) based on aerodynamic diameter considering the particle density which has been determined using CFD numerical simulations (6 µm).

Tests principle

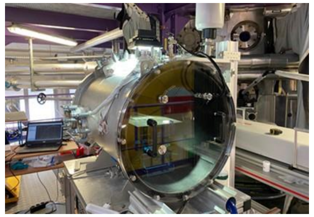
- Various samples (Stainless steel plate or pieces, Fuel Debris simulants) are prepared with well controlled particle deposit ($d_{resuspension}$).
- For air environment tests, the resins efficiencies are evaluated by comparing particle resuspension that may occur between non-coated and coated samples, in measuring the airborne particle concentration.
- Tests will consider perfect coating and also degraded coating to assess its influence on resins efficiency.

Particle resuspension is characterized during various stress for non-coated and coated samples:

Fall of object

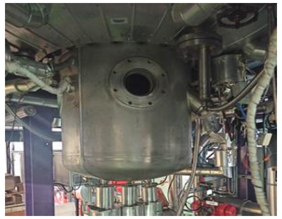
For mechanical stress, the **drop height and the resin coverage ratio** are the main test parameters.

Aeraulic stress



For aeraulic stress, the **air flow velocity and the resin coverage ratio** are the main test parameters.

Water stress



For underwater tests, the **resins efficiencies** are evaluated by measuring the ratio between the particle mass transferred to the water and the initial particle mass deposited on the Fuel Debris.

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

4. 2. AERAULIC STRESS TESTS

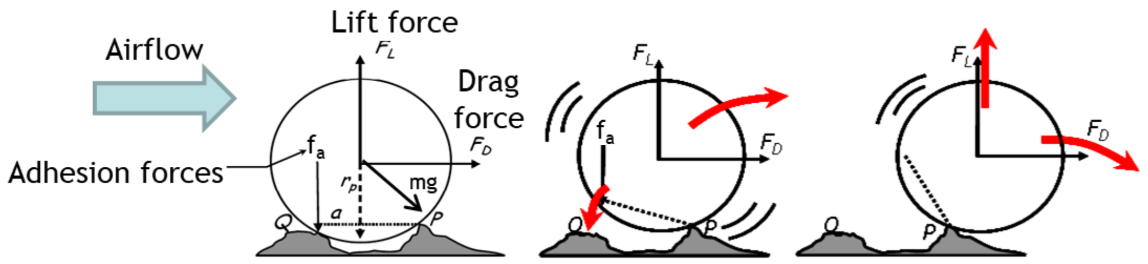
4. 2. 1. Generalities

Objectives of the tests

Tests are meant to determine the efficiency of the coating when it is applied on a surface (whether it is a metallic surface or a Fuel Debris alike surface). Aeraulic stress can be caused by various reasons: airstream due to the global ventilation system, airstream due to the movement of a robot or due to a cutting device such as a disk cutter or a laser cutting head (that will generate important airflows with important velocity).

Therefore, tests have been defined so it is possible to test different air velocities, different angles of airblowing, different surfaces of application and most of all, with different percentage of coverage so it is possible to assess the gain even in incomplete coating situations.

Here below are reminded the physical mechanisms involved in the resuspension of particles. For the tests, calibrated particles that will allow high resuspension rates have been selected.



Physical mechanisms involved in the resuspension of particles

Physical magnitudes of interest for particles resuspension by aeraulics mechanisms are:

- **Particles geometrical diameter**
- **Adhesion forces (function of particles size and roughness of sample)**
- **Gas friction velocity depending on mean airflow velocity**
- **Airflow acceleration (steady or transient states)**

Physical magnitudes for transport of resuspensed particles

- **Particles aerodynamic diameter**
- **Airflow**

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

4. 2. AERAULIC STRESS TESTS

4. 2. 1. Generalities

The main objective of the tests was to evaluate the gain in terms of suppression of dust resuspension, for various conditions, even in a case of a partial coverage. Indeed, if there was no doubt concerning the efficiency of coatings, it shall be difficult to ensure perfect coverage on site due to the complexity of the situation. The idea was therefore to determine in which conditions a partial coverage is beneficial compared to the complexity of the coating operation remotely operated.

The same methodology has been applied for all the tests:

- 2 types of surfaces to be covered have been used: either a stainless steel plate whose dimensions are 150 x 150 x 3 mm or a stainless steel basket, whose dimensions are 150 x 150 x 30 mm (thickness = 3 mm) containing a Fuel Debris simulant bed. These dimensions have been determined to fit inside the experimental set-up while ensuring quantity of particles is enough to carry out conclusive tests.
- On each surface, a deposit of alumina particles Al_2O_3 (particle aerodynamic diameter = 6.4 µm) is carried out. The deposit is implemented on a controlled surface 10 x 110 mm by sieving with a surface mass deposition around 15 mg/cm². Therefore, the quantity of particles is controlled.
- Before each test, it is decided to coat the surface with the deposit of particles or not

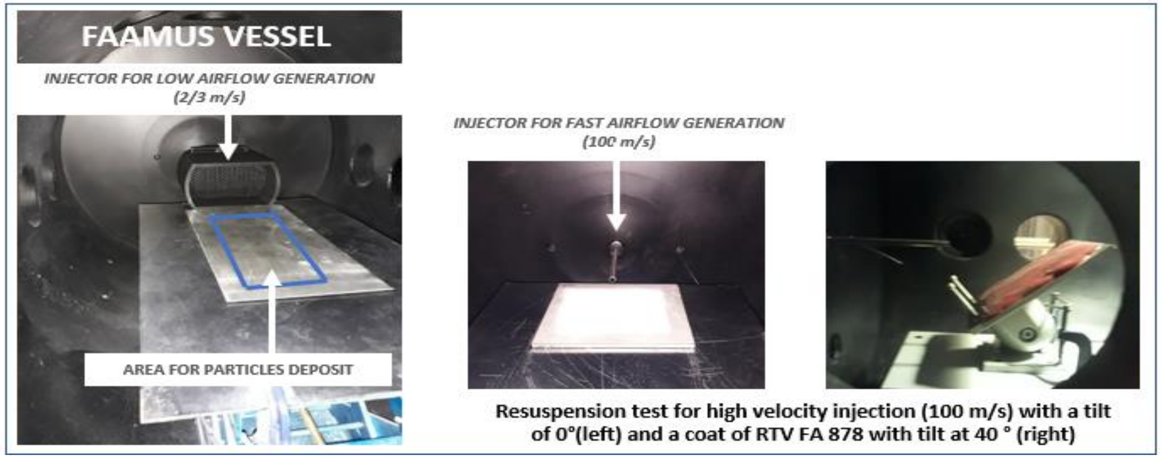
The parameters of the tests are the following:

- Coatings: none (for reference tests), RTV FA 878, RTV FA 873
- Percentage of surface coverage: from 0% coverage (for reference) to 100% (full coverage) with 50% coverage in between to study the case of a partial coating on site
- Sample: stainless steel plate and Fuel Debris simulant bed
- Tilt α: to assess the influence of the angle α between airflow and surface
- Velocity: two flow velocities have been used. 2-3 m/s represents a range of velocity, quite low, such as induced by ventilation or by the movement of a robotic arm (for instance). 100 m/s represents the airflow velocity representative of a cutting tool such as laser cutting.

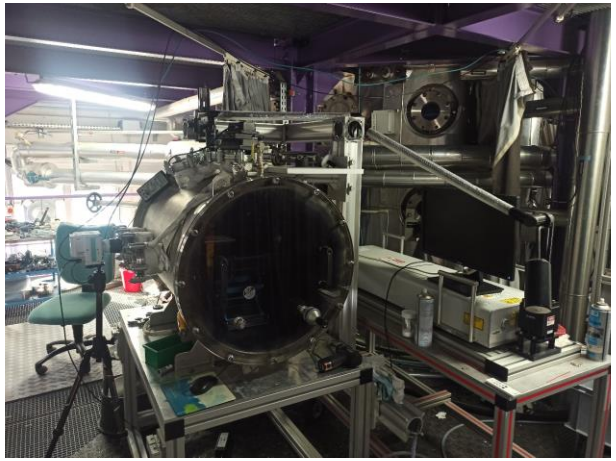
IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

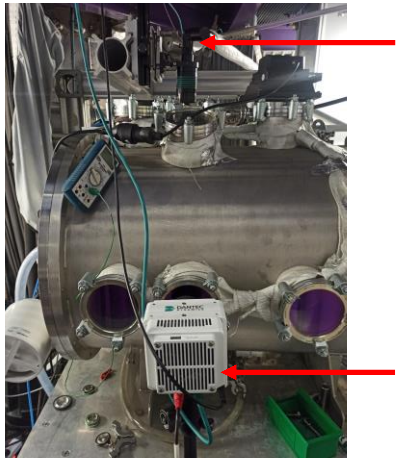
4. 2. AERAULIC STRESS TESTS

4. 2. 2. Tests parameters & overview of the experimental set-up



Resuspension test for high velocity injection (100 m/s) with a tilt of 0°(left) and a coat of RTV FA 878 with tilt at 40 ° (right)





<u>View of FAAMUS enclosure</u>

Two types of air injector are used. The first one (picture on the left) generates a low airflow. The second one (picture in the middle) generates a high velocity airflow that reproduces the laser cutting airflow.

Particles are deposited in front of the air injector. In the pictures, particles are deposited onto metallic plates (pictures in the middle and at right).

The picture on the left shows a metallic plate with deposit of particles and 100% of RTV FA 878 coverage. The metallic plate has been tilted with an angle of 40°.

Mass and number concentrations of particles evolutions are measured inside the enclosure thanks to probes.

The enclosure is cleaned before each test so it prevents the measurements to be distorted.

PIV technique has been used in order to assess the efficiency of coating. Characteristics of the set-up are the following:

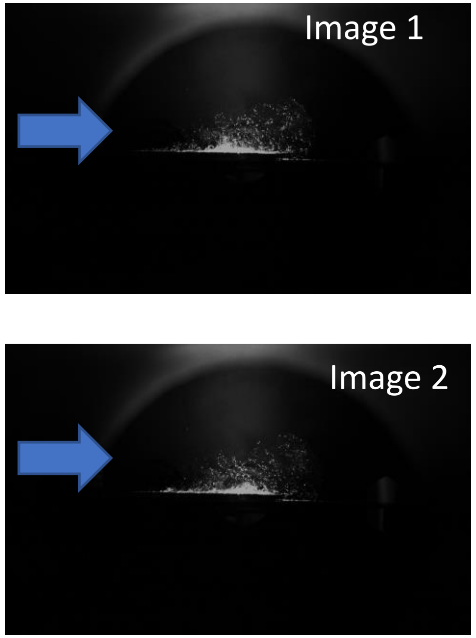
- *Implementation of high speed PIV*
- *Laser 30 mJ at 1 kHz at 527 nm – Camera CCD 1kx1k*
- *Test with particles deposit on horizontal plate with and without resin coating*
- *2 types of airflow are generated:*
    - *Low velocity up to 3 m/s to be representative of natural and forced convection flows due ventilation or robot implementation*
    - *High velocity up to 100 m/s to be representative of gas jet injection through laser cutting head*

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

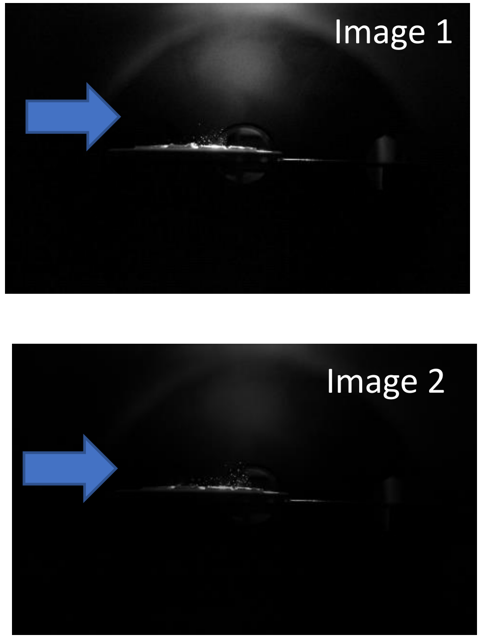
4. 2. AERAULIC STRESS TESTS

4. 2. 3. Results of PIV measurements for particle resuspension visualization for airflow colinear to the plaque (α=0°)

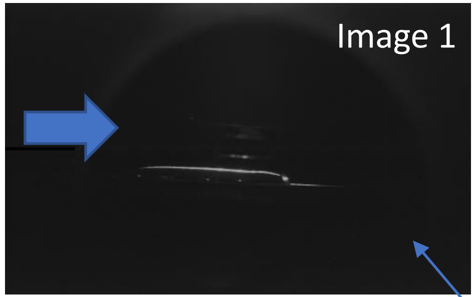
Here are presented the views obtained thanks to the PIV instrumentation for the low and high velocity airflows. It can be seen that 50% of resin coverage is enough to lower the resuspension rate of powder. With a total coverage, no powder is resuspended even at high velocity which can be representative of laser cutting process.



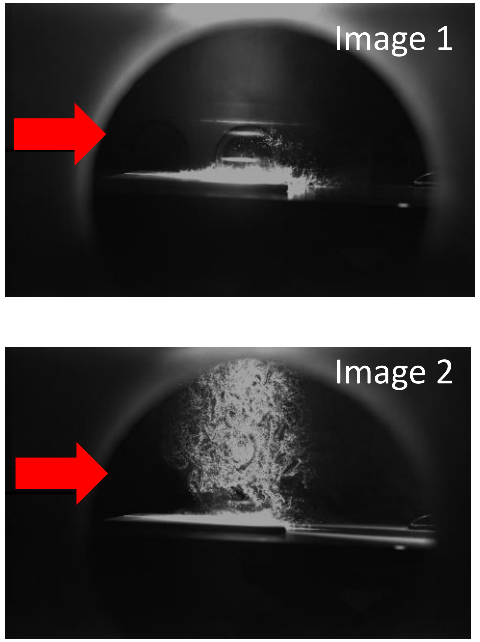
Results for 3 m/s without resin



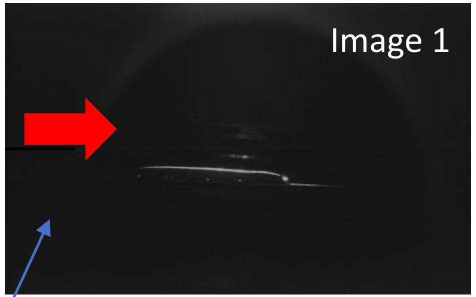
Results for 3 m/s with 50% resin coating (878)



Results for 3 m/s with 100% resin coating (878)



Results for 100 m/s without resin



Results for 100 m/s with 100% resin coating (878)

No particle detected by laser sheet Lighting

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

4. 2. AERAULIC STRESS TESTS

4. 2. 4. General overview of tests results

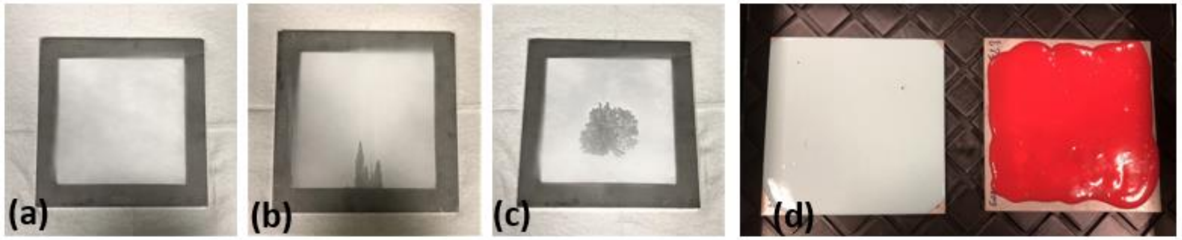
Configurations:

Tests have been successively carried out on a stainless steel plate seeded with particles. It is first tested non-coated with different tilts then coated with RTV FA 873 and RTV FA 878 with half then full coverage. The two velocities (low and high) have been successively tested.

The objective is to evaluate the impact of the coating on the resuspension rate for all configurations.

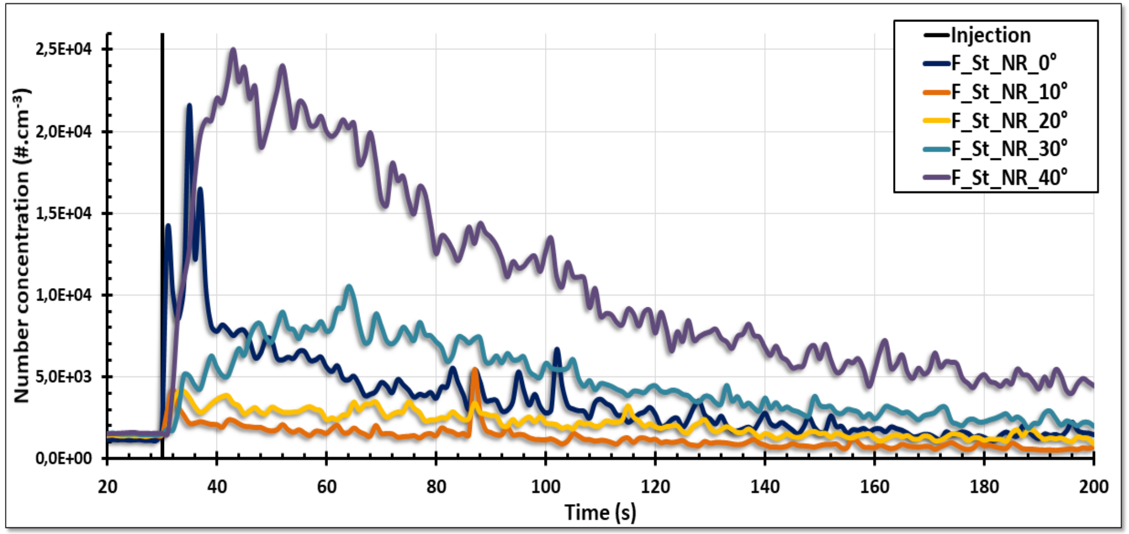
Tests criteria:

Mass concentrations evolution for each test configuration is monitored.



(a) Stainless steel plate with particle deposit before trial (b) after aeraulic stress at 0° (c) after aeraulic stress at 40° (d) stainless steel plate with particle deposit before and after trial at 0° and 40° (no difference)

Example of stainless steel plate seeded with particles and covered with resin



Example of results: evolution of mass concentration of particles inside the enclosure for different angles

Main results:

Efficiency of coating has been evaluated according the formula below:

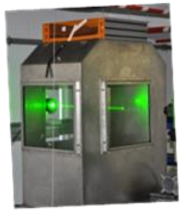
$$Efficiency = 1 - \frac{\sum airborne\ particle\ with\ coating}{\sum airborne\ particle\ without\ coating}$$

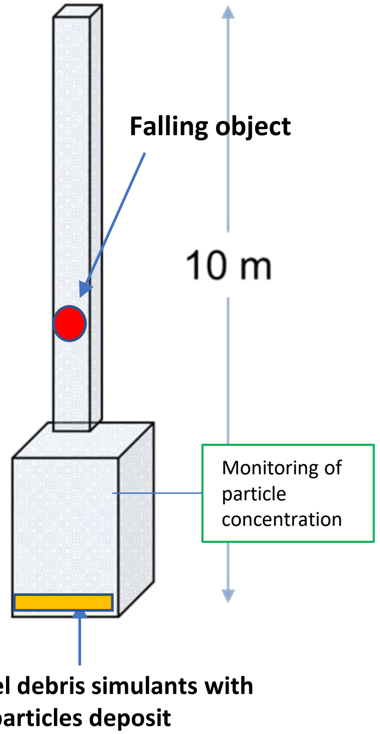
In conclusion, coatings provide a major asset in terms of suppression of dust resuspension. In a case of a resuspension due to a low velocity, partial coating will improve slightly the dust resuspension. However, for high speed velocity, even partial coating is beneficial.

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

4. 3. MECHANICAL STRESS TESTS

4. 3. 1. Experimental set-up – Fall of objects in enclosure

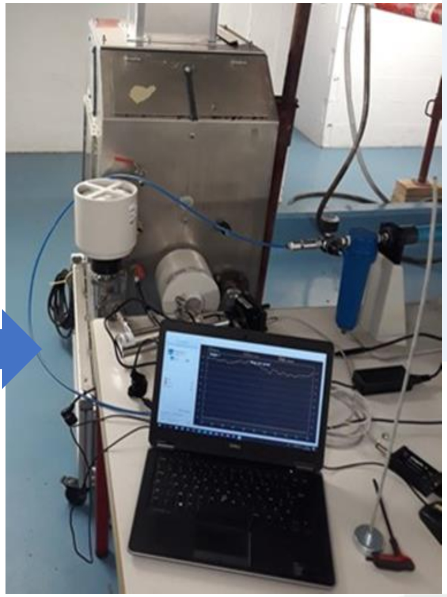




BERGAME facility

The main objective of the mechanical stress tests was to determine the efficiency of the coating, implemented on the Fuel Debris bed, in terms of suppression of dust resuspension due to the fall of an object. Again, the idea was to determine the gain from the use of coatings even with a partial coverage of the Fuel Debris bed.

Tests have been carried in the BERGAME facility of IRSN here described. Particles, with the same characteristics than the ones used for the aeraulic tests, have been seeded successively on stainless steel plates and on a bed of Fuel Debris simulant. Fall of objects were successively a stainless steel ball, then more complex objects. No coverage, partial coverage and full coverage have been tested.



Experimental set-up:

- For the stainless steel ball, a magnetic system for unhooking the metallic sphere has been used, so reproductilibilty of tests was ensured (due also to the metallic sphere itself). The magnetic system for unhooking ensures that the parameters of the fall (height, starting velocity) are also reproductible.
- Mass concentrations are monitored inside the enclosure at the bottom of the tests facily.

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

4. 3. MECHANICAL STRESS TESTS

4. 3. 2. Tests for dust resuspension suppression efficiency measurement

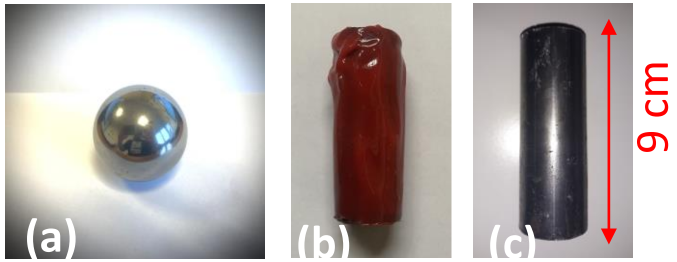
Protocol of the tests:

Tests have been carried out with the following conditions:

- Drop of the stainless-steel ball on a stainless plate alone or Fuel Debris simulant bed (so it is possible to evaluate the blank of the experimental set-up)
- Drop of the stainless-steel ball on a stainless-steel plate or Fuel Debris simulant bed covered with airborne particles deposit (so it is possible to measure the concentration number of particles that are resuspended)
- Drop of the stainless-steel ball on a stainless-steel plate or Fuel Debris simulant bed covered with particles deposit and coated with resin (so it is possible to determine the influence of the coating on the resuspension rate)
- Drop of the stainless-steel ball on a stainless-steel plate covered or Fuel Debris simulant bed with airborne particles deposit and partial coating so it is possible to study the influence of degradation of resin coating

Stainless steel plate with alumina particles deposit (left), with 100% coverage of RTV FA 878 (center) and 90% coverage of RTV FA 873 (right)

Example of stainless steel plates coated with RTV FA 73 resin. Partial coverage is realized as the above.



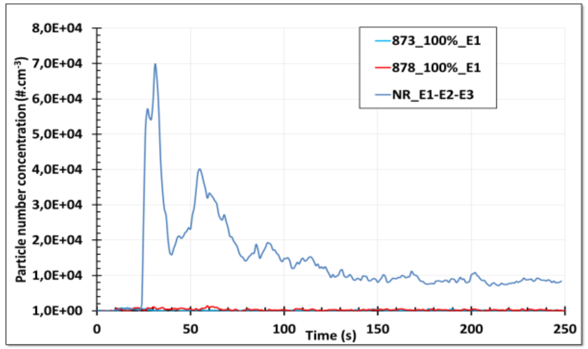
Dropped objects on the stainless steel plates or Fuel Debris simulants bed

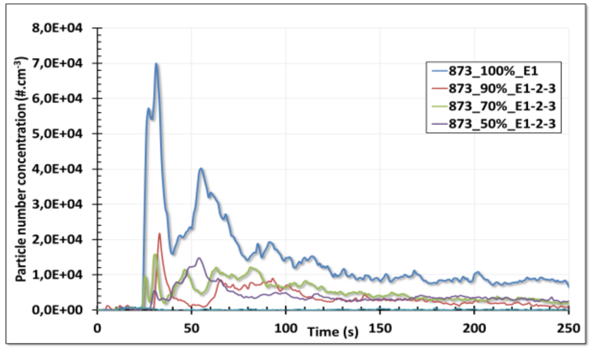
Preparation of Fuel Debris simulant beds. Different coverage can be seen. Weight of coating has been measured in order to simulate the different coverages

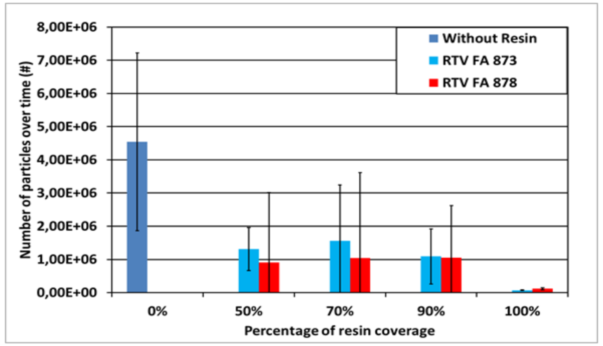
IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

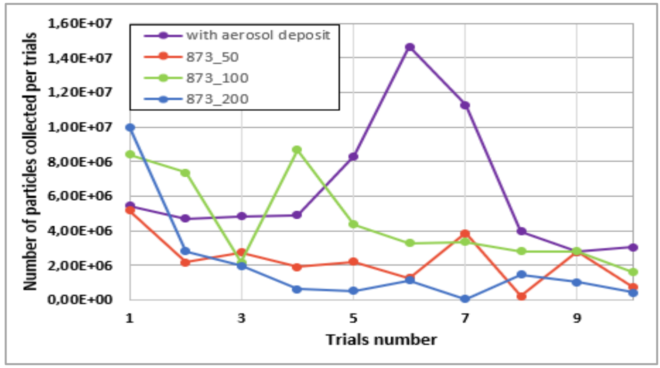
4. 3. MECHANICAL STRESS TESTS

4. 3. 3. Main results & conclusions



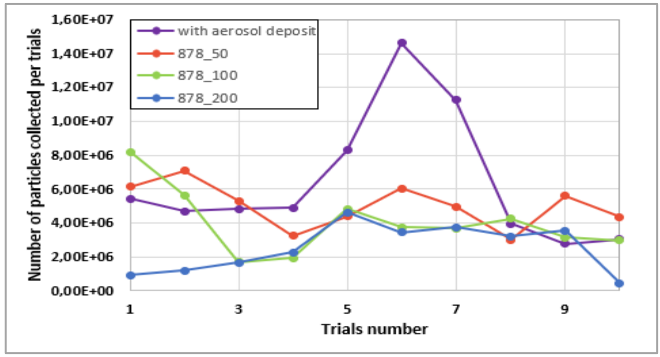


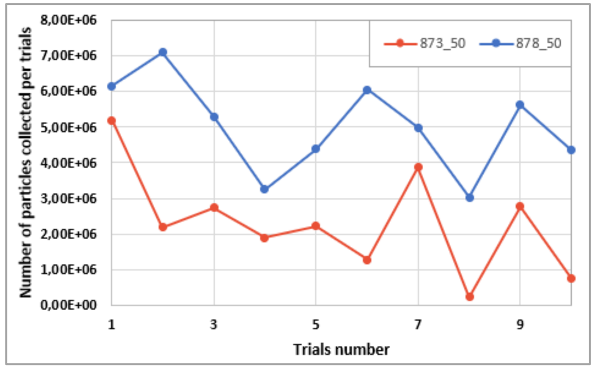


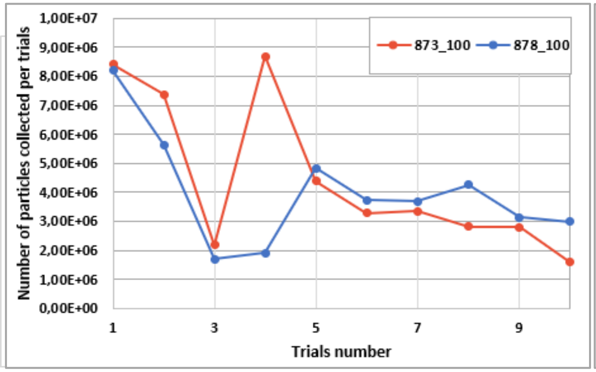


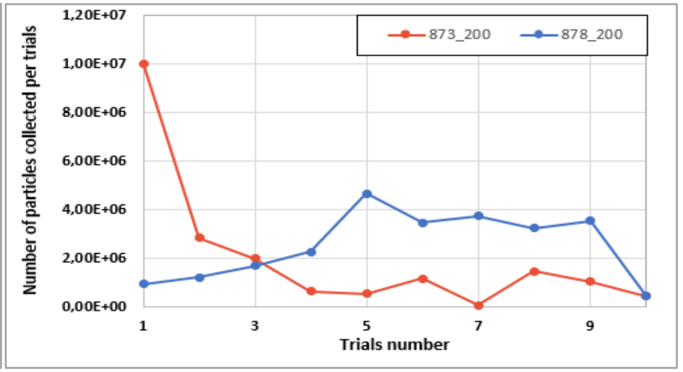
As expected, with a total coverage on stainless steel plates, no dust is resuspended

On the other hand, these results show that suppression of dust resuspension is not linear with the percentage of coverage. (Tests also carried on stainless steel plates with the metallic ball, with stainless steel plates covered with 0%, 50%, 70%, 90% and 100% of their surface.)









Tests on Fuel Debris simulant bed: for one particular coating, as soon as the area of impact is covered with coating, dust resuspension is lowered. (Results for RTV FA 873 (up) and RTV FA 878 (down)

Tests on Fuel Debris bed: both RTV FA 873 and RTV FA 878 are efficient. As long as the area is covered with coating, even with a thin layer, dust resuspension is prevented. Tests showed that RTV FA 783 has a slight benefit compared to RTV FA 878 for Fuel Debris bed stabilization

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

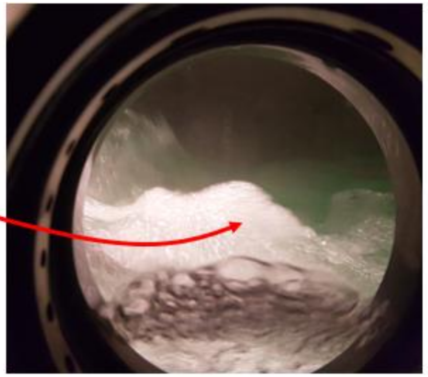
4. 4. HYDRAULIC STRESS TESTS

4. 4. 1. Generalities

Tests were designed to verify the efficiency of coatings underwater, in static conditions or under water stress, by measuring the particle transfer to the water. They took place in TOSQAN facility of IRSN.

TOSQAN facility, IRSN Saclay

TOSQAN sump for under water test



Hydraulic stress by underwater gas jet injection

Samples preparation with FD simulant and coatings

Pieces of FD with fluorescein particles deposit

Coating with resins (RTV FA 878 / RTV FA 873)

Implementation of coated sample with RTV FA 873 resin inside TOSQAN vessel

Definition and qualification of protocol for measurement of particle transfer from the Non Covered / Covered samples to the surrounding water:

- Fluorescein particles are deposited on NC/C samples.
- Particle transfer to water is quantified by fluorimetry measurements which gives the total mass of particle transferred to the water.
- Resin efficiency is determined for each coated sample by comparing the particles mass transferred to the water and the initial particle mass deposited on the coated sample.
- Particle transfer to the water for non coated sample is also considered as reference.

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

4. 4. HYDRAULIC STRESS TESTS

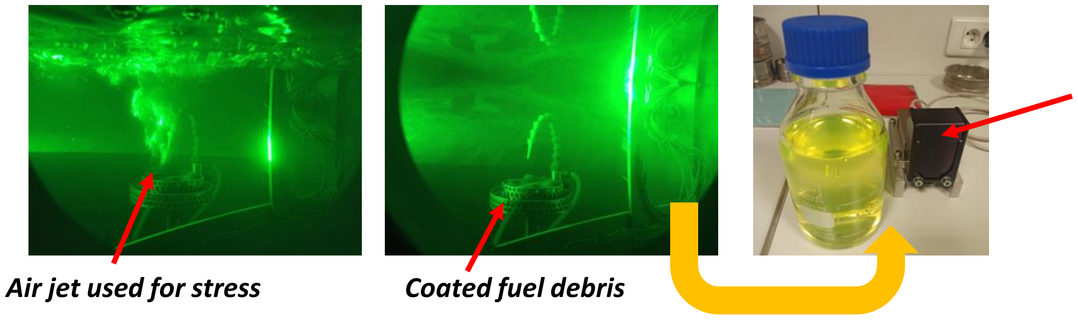
4. 4. 2. Principle of the tests

The fluorimetry technic for determining the aerosol fraction transferred to the water can described as following: Fluorimetry is a very accurate diagnostic leading to a conservative approach to assess resin coating efficiency and to highlight leaks of resin coating.

- Water sampling is performed before and after fuel debris simulant implementation with various scenarios:
  - **Underwater static scenario without stress**
    - Aerosol transfer versus time
  - **Underwater scenario with stresses induced by gas jet**
    - Aerosol transfer due to gas jet interaction with Fuel Debris
  - **Underwater scenario with stresses induced by water jet**
    - Aerosol transfer due to water jet interaction with Fuel Debris

- Fluorimeter signal is function of fluorescein concentration in water.
- Knowing the water volume in the sump, the total mass of fluorescein transferred from the coated Fuel Debris is then determined for each trial.
- Limit of detection is 10^{-10} (g/L).
- Resin efficiency (%) is calculated in considering fluorescein mass transferred to the water and the initial fluorescein mass deposited on Fuel Debris before its coating with resin.

Laser visualization for underwater trial with Fuel Debris coated by resin FA RTV 878



Tests protocol:

- Water sampling is performed before and after fuel debris simulant implementation with successive scenarios:
  - Underwater static scenario without stress during 600 s
  - Underwater scenario with stresses induced by gas jet during 600 s
  - Underwater scenario with stresses induced by water jet during 600 s
  - Underwater static scenario without stress during 7 days

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

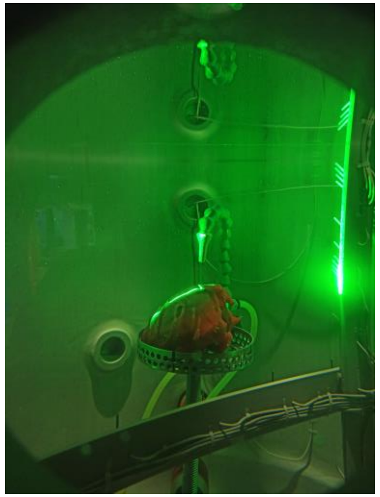
4. 4. HYDRAULIC STRESS TESTS

4. 4. 3. Main results

Test for RTV FA 878

Deposit of 96.4 mg of fluorescein particle of 3 µm on the surface of the fuel debris simulant
100% resin coating is achieved on fuel debris simulant piece

Resin thickness = 5 mm



Static

Aeraulic stress

For all scenarios (TOSQ1_1 to TOSQ1_4) , the resin efficiency to avoid fluorescein transfer to the water was over 99.9%

Deposit of 97.5 mg of fluorescein particle of 3 µm on the surface of the fuel debris simulant
100% resin coating is achieved on fuel debris simulant piece

Resin thickness = 5 mm

Static

Aeraulic stress

For all scenarios (TOSQ2_1 to TOSQ2_4) , the resin efficiency to avoid fluorescein transfer to the water was over 99.8%

IV. PERFORMANCE TESTS, VERIFICATION OF DUST RESUSPENSION SUPPRESSION

4. 5. CONCLUSIONS

- **Efficiency towards dust resuspension with aeraulics stress**
  - Coating with resins is very efficient to avoid particles resuspension due to airflows (low and high velocity)
  - Benefic effect of resins was underlined on fuel debris simulants and stainless-steel plates. Whatever the cause of airflows (ventilation, robot displacement, cutting technics such laser or high-pressure water jet) resin coating will mitigate dust dispersion

- **Efficiency towards dust resuspension following the fall of an object**
  - Resin coating mitigates dust resuspension due to various objects fall with total efficiency if the coating is complete. In case of un-complete resin coating, benefic effect is still underlined due to the stabilization of the fuel debris bed, limiting dust resuspension

- **Efficiency towards dust resuspension underwater**
  - Complete resin coating ensures a total efficiency to avoid aerosols transfer from the fuel debris to the surrounding water

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 1. GENERALITIES

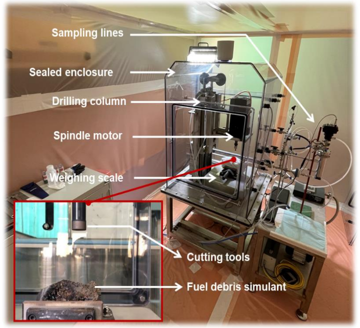
Operations for the retrieval of the Fuel Debris will most certainly go through cutting operations. This is why it is important to determine whether coating could have an impact on such operations. Cutting tests that have been carried out in the frame of this project were meant to:

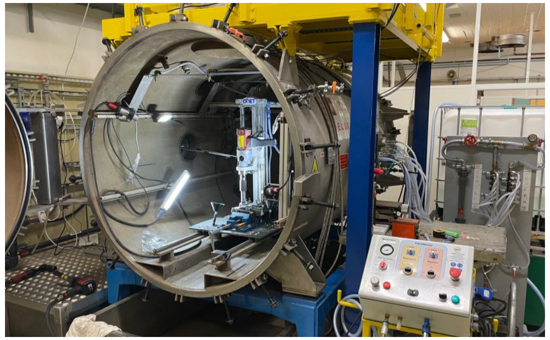
- Assess the impact on airborne particles production. (Does the coating lower or increase the airborne particles production? Does the coating modify the characteristics of the airborne particles that are normally generated?)
- Assess the impact on the cutting performances

Therefore, for these cutting tests, data that are monitored are: number and mass concentrations of airborne particles, morphologies of particles produced, cutting performances

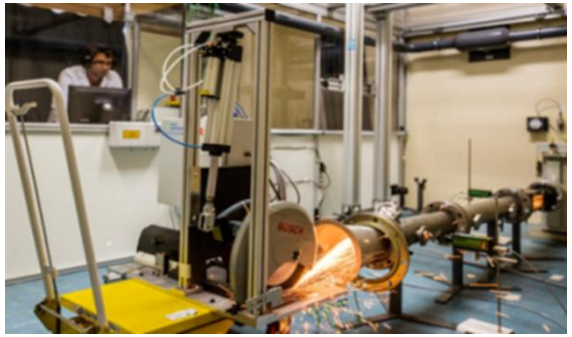
Three cutting tools have been studied:

1. Core boring tool: two phases of tests have been carried out.
   - First phase of tests was implemented in CEA Cadarache's facility FUJISAN at the very beginning of the project. This first phase of tests was meant to get preliminary results for the following steps of the project
   - Second phase of tests was implemented in CEA Saclay's facility DELIA. Tests have been carried out with a more industrial tool with Fuel Debris simulant
2. Disk cutter: tests have been carried out in IRSN's facility CAPIMIF
3. Laser cutting: tests have been carried out in CEA Saclay's facility DELIA

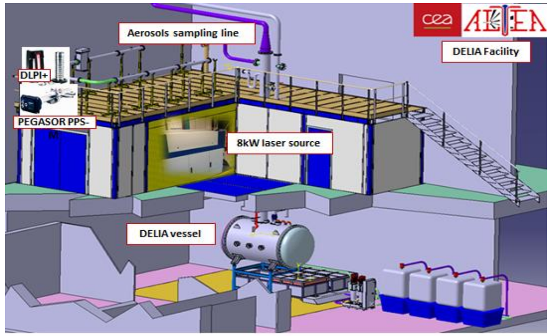




Core boring tests. FUJISAN facility (left) and DELIA facility (right)



Disk cutting tests in CAPIMIF facility



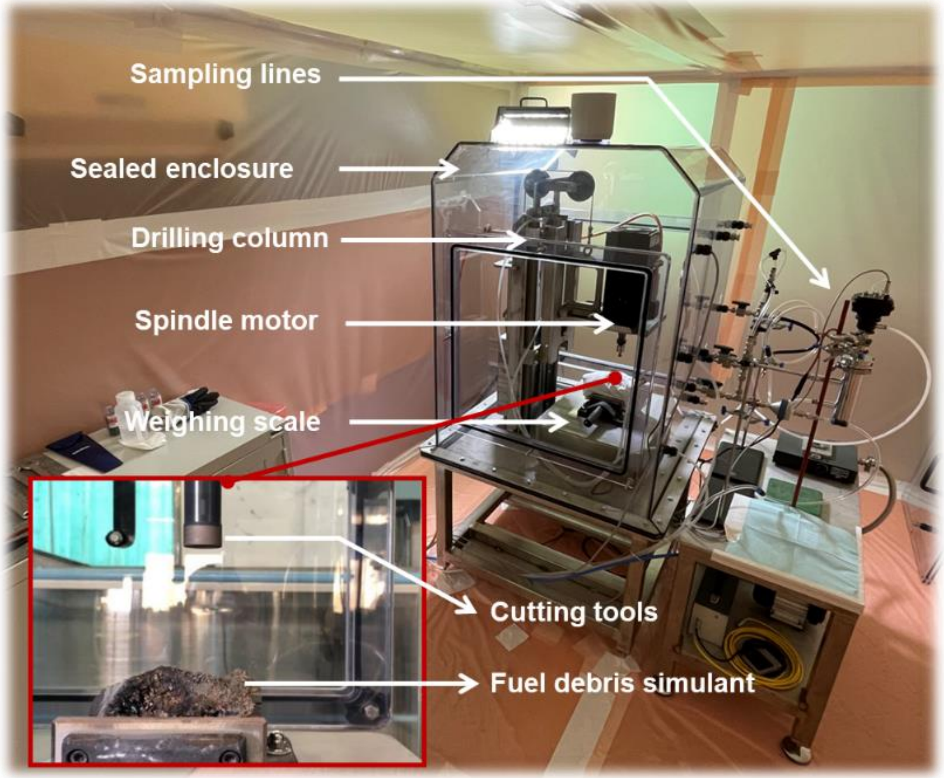
Laser cutting tests in DELIA facility

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 2. CORE BORING TESTS PHASE 1

5. 2. 1. Experimental set-up

Experimental core boring cell used in order to gather input data on the generation of particles during cutting with core boring of Fuel Debris simulant coated with pre-selected coatings:



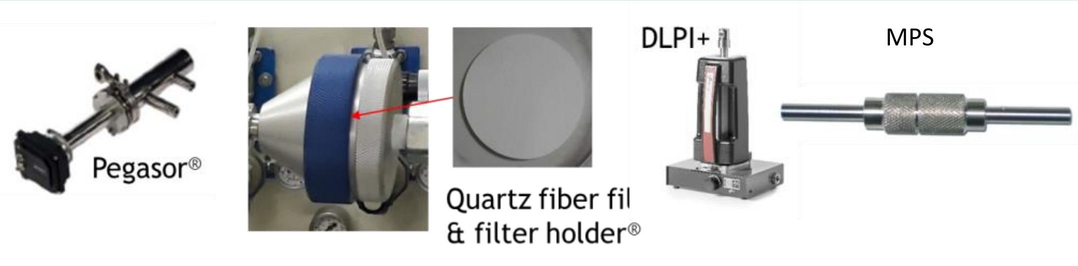
Analyzed criteria

Aerosols characterization has been carried out through:

- Particles size distribution,
- Particles mass and number concentration,
- Morphology for cut particles and their related atomic composition.

To collect particles during cutting, the front wall of the airtight enclosure contains four collection lines. They have been designed to ensure a good aerosol measurement by specific instrumentation:

- **Pegasor® PPS-M** (aerosol number & mass concentration)
- **Filter sampling** (aerosol mass concentration)
- **DLPI+** (aerosol mass size distribution)
- **Mini Particle Sampler (MPS)** (aerosol morphology with post-test TEM analysis)



The **cutting evaluation** has been carried out through the observation of:

- Behavior for block coated with resins during cutting.
- Behavior for the core boring tool in presence of resins.

The **resin efficiency** in term of aerosols mitigation has been evaluated by:

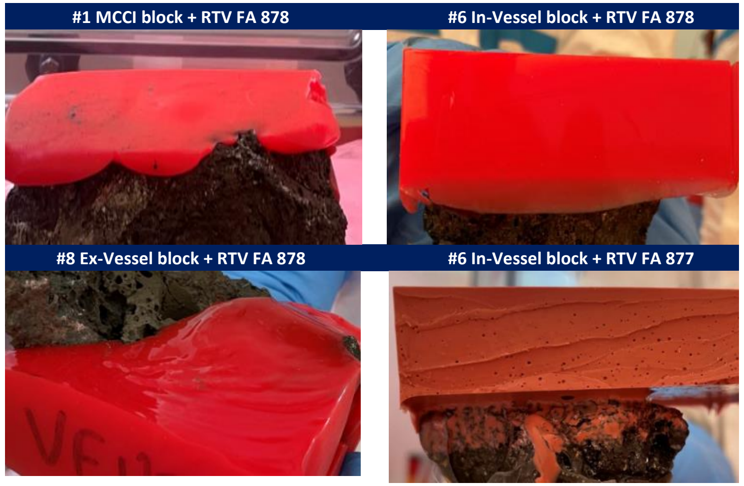
- The airborne particles analysis during and after cutting.
- The removed silicone resins operations after cutting.

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 2. CORE BORING TESTS PHASE 1

5. 2. 2. General overview of the tests

Tests have been carried out in the FUJISAN facility with active prototypical Fuel Debris (with depleted Uranium dioxide) blocks (MCCI, In-Vessel and Ex-Vessel Fuel Debris simulants). This has been possible thanks to URASOL project with JAEA. Results are presented for the tests carried out with two **silicone resins**: RTV FA 877 and RTV FA 878.



Cutting Parameters

The cutting tools is a diamond surface deposit tool with an external diameter to 15 mm.

The cutting force, the rotation speed and the cutting duration are chosen to ensure good aerosols generation without damaging the tool.

Main results:

- Core boring of silicon coating produces a very thin mode of airborne particles (median diameter centered around 400-500 nm)

Aerodynamic median diameter D	MCCI #1	In-Vessel #6	Ex-Vessel #8
With coated resin RTV FA 878	0.6	5.0 (+ 2nd mode at 0.2 µm)	0.5
With coated resin RTV FA 877		4.1 (+ 2nd mode at 0.4 µm)	
With resin RTV FA 878 only	0.4 (+ second mode at 3.5 µm)		

- Airborne particle coefficient expressed by: $$K_A = \frac{m_{airbone}}{\Delta m_{bloc}}$$

The airborne particle coefficients have been determined around 10^{-3}.

K_A (average)	MCCI #1	In-Vessel #6	Ex-Vessel #8	Metallic Ex-Vessel #8
With coated resin	**≈ 4x10^{-4}**	**≈ 7x10^{-4}**	**≈ 8x10^{-4}**	**≈ 3x10^{-4}**
Without coated resin	**≈ 10^{-3}**			

According to URASOL project, the airborne particle coefficient is until **10 times** more important for cutting trials without the use of silicone resin.

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 3. CORE BORING TESTS PHASE 2

5. 3. 1. Overview of the tests

General description:

- Tests take place in **DELIA facility - CEA Saclay**.
- Core boring is carried out in the airtight vessel in which sampling of aerosols is done thanks to specific iso-kinetic probes.
- Data are monitored thanks to Pegasor® PPS-M, filter sampling and DLPI+®.
- Specific airflow is created inside the vessel in order to homogenize the particles concentration inside the vessel.

Analyzed criteria:

For the **aerosols characterization** :

- The particles size distribution thanks to **DLPI®**,
- The particles mass and number concentration with **Pegasor® PPS-M and filter sampling**,
- The morphology for cut particles and their related atomic composition **MPS**.

For the cutting evaluation :

- Behavior for block coated with coatings during cutting.
- Behavior for the core boring tool in presence of coatings.

The coating impact on aerosols generation:

- The airborne particles analysis during and after cutting in the exhaust and in the vessel.
- The influence of a nitrogen atmosphere.

Fuel Debris Simulants:

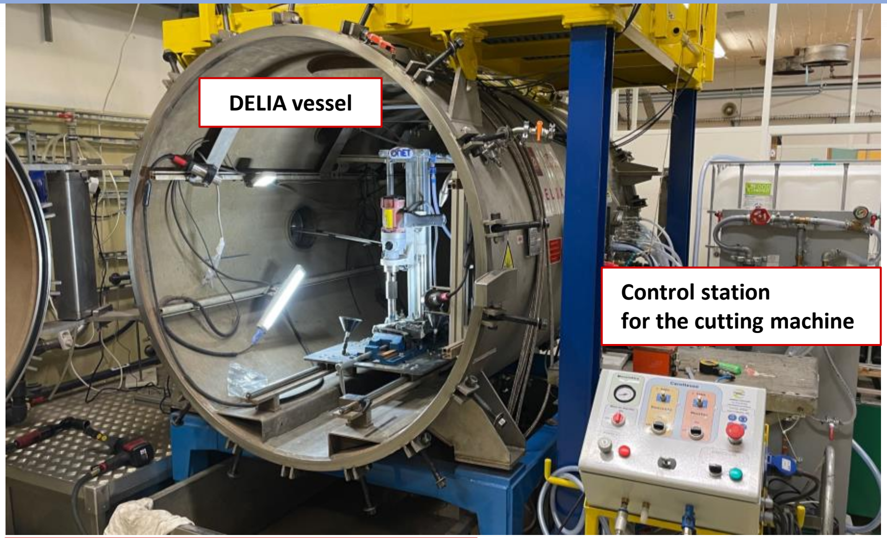
- MCCI sample (partially)
- In-Vessel sample

Selected coatings:

- RTV FA 878 (Silicone)
- RTV FA 873 (Silicone)
- EPOXYGUARD (Epoxy)

Main parameters & Conditions:

- Qualification cutting tests have been carried with Zirconia samples.
- Cutting duration was between 5 and 10 min for Fuel Debris simulant with and without coatings.
- Tests have been performed in air and under nitrogen atmosphere.
- Coatings have been applied previous to the tests in order to comply with the manufacturer's recommendations



Sampling probe connected to airborne monitoring devices, near the cutting point to collect the airborne particles

Core boring tools with sample block positioned *(MCCI/epoxy block)*

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 3. CORE BORING TESTS PHASE 2

5. 3. 2. Tests program

- ✓ 4 Fuel Debris simulants tested (cast fused Zirconia blocks for qualification tests, In-Vessel and MCCI (partially) Fuel Debris simulants),
- ✓ 3 coatings tested (RTV FA 878, RTV FA 873 and EPOXYGUARD,
- ✓ More than 40 cutting tests with various parameters have been carried out.

Tests have been scheduled as follow:

- ✓ Cutting tests on Fuel Debris simulant block <u>without coating</u>
- ✓ Cutting tests on the same Fuel Debris sample with specific coating applied,
- ✓ Cutting tests on specific coating alone (to compare and determine the influence of each coating),
- ✓ Cutting tests on Fuel Debris simulant In-vessel with and without coatings in N_2 conditions,
- ✓ <u>Complementary cutting tests</u> with simulated aerosols on which coating has been applied.

<u>TESTS GRID</u>

STEP 1 : REFERENCE TESTS ON SAMPLES AND ON COATINGS IN AIR

- Fused zirconia block: qualification test to check installation
- Fuel Debris In-vessel #2
- Fuel Debris MCCI #1
- Fuel Debris VF03 with aerosols deposit *(In-vessel Fuel Debris simulant from previous project)*

WITHOUT COATING

- RTV FA 878
- RTV FA 873
- EPOXYGUARD

WITHOUT SAMPLE

STEP 3 : SPECIFIC TESTS IN N_2

- Fuel Debris In-vessel #2
- RTV FA 878

REFERENCE TESTS

STEP 2 : CUTTING TRIALS ON FUEL DEBRIS SAMPLES IN PRESENCE OF COATINGS IN AIR

RTV FA 878			RTV FA 873		EPOXYGUARD	
In-vessel 3 cuts	MCCI 1 cut	VF03 (aerosol) 2 cuts	In-vessel 3 cuts	MCCI 1 cut	In-vessel 3 cuts	MCCI NA

Step 3:

RTV FA 878
In-vessel 3 cuts

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 3. CORE BORING TESTS PHASE 2

5. 3. 3. Tests results – Overview

- For all the tests of the test grid, mass and number concentrations have been monitored
- Morphologies of particles, for some tests, have also been studied

Mass and number concentrations monitoring:

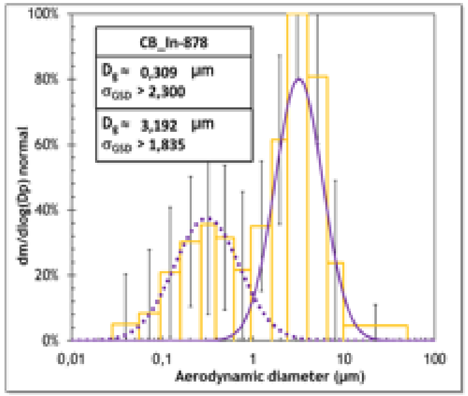
The cutting tools is a diamond surface deposit tool with an external diameter to 15 mm.

The cutting force, the rotation speed and the cutting duration are chosen to ensure good aerosols generation without damaging the tool.

Illustrations of core boring tests:

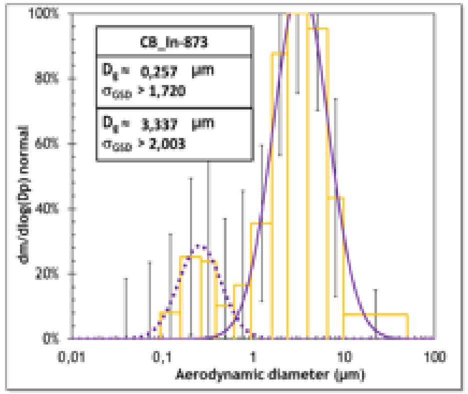
In these pictures, we can see core boring of Fuel Debris simulant "In-Vessel" covered with RTV FA 878 (red coating), RTV FA 873 (grey coating) and Epoxyguard (white coating).

IN-VESSEL #2 WITH RTV FA 878



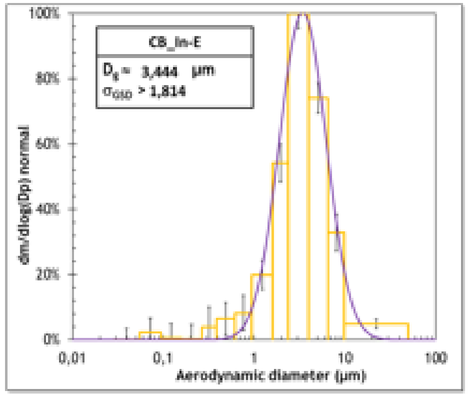
Bi-modal PSD – 0.31 µm / 3.2 µm

IN-VESSEL #2 WITH RTV FA 873



Bi-modal PSD – 0.26 µm / 3.3 µm

IN-VESSEL #2 WITH EPOXYGUARD



Single modal PSD – 3.4 µm

Results on particle size distribution:

As during the first phase of core boring tests, it can be seen that silicone coatings produce a very mode of particles, which is not the case for the Epoxyguard coating.

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 3. CORE BORING TESTS PHASE 2

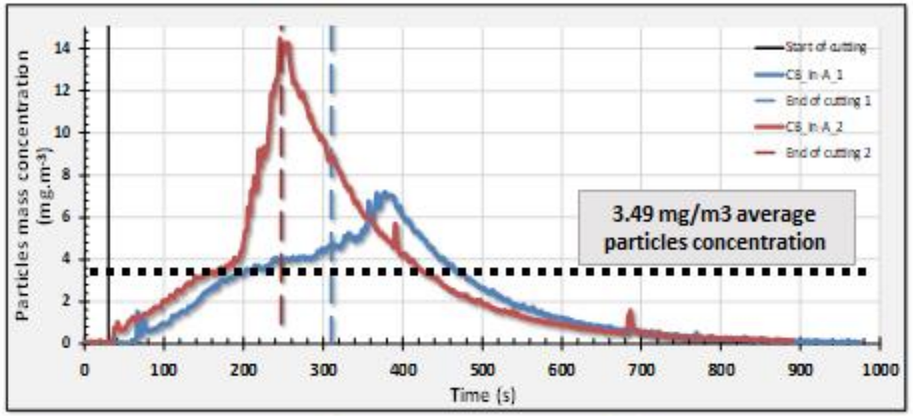
5. 3. 3. Tests results – Overview

Objective: Evaluate the capability of resin coating to mitigate resuspension of already deposited particles close to the cutting area

→ Comparison between Fuel Debris simulant In-vessel VF03 (Fuel Debris manufactured in FY 2018) with particles deposit without and with RESIN coating – RTV FA 878

→ Al_2O_3 particle (6 µm, 3 mg/cm²) have been deposited on Fuel Debris simulant before the cutting with and without resin coating

VF03 + aerosols deposit without coating

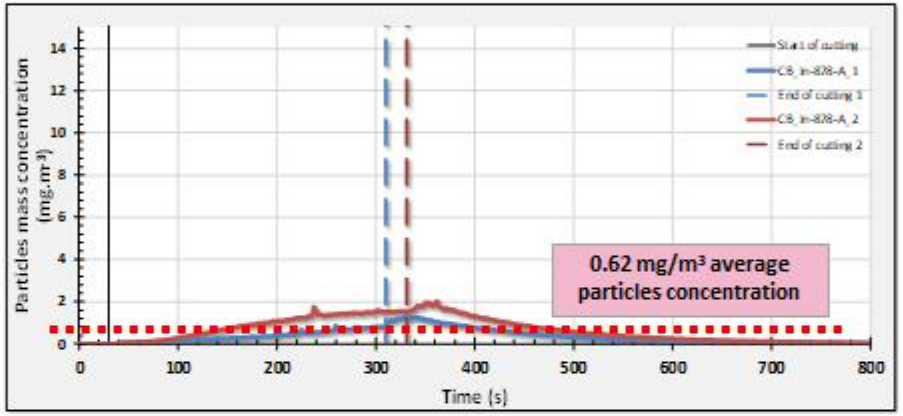


Preparation

Before cutting

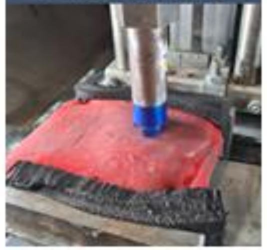
After cutting

VF03 + aerosols deposit with coating RTV FA 878

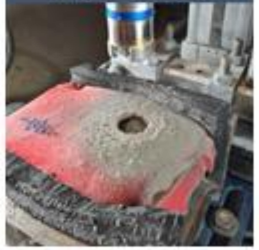


Preparation

Before cutting



After cutting



82% average mass efficiency increase with the coating

Strong decrease of airborne particles generation with resin coating – aeraulic mechanisms involved in particles resuspension are reduced and resin coating limits resuspension du to other mechanism such vibrational one.

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 3. CORE BORING TESTS PHASE 2

5. 3. 4. Conclusions

During FY2021, the core boring tests performed are:

- In air on Fuel Debris simulant In-vessel #2 with and without coating
- In air on Fuel Debris simulant MCCI #1 with and without coating
- In air on Fuel Debris simulant In-vessel VF03 with and without coating + aerosols deposit
- In nitrogen on Fuel Debris simulant In-vessel #2 with and without coating (analysis of results in progress and to be provided at a later date)

The summary of the results obtained is:

AVERAGE MASS EFFICIENCY OF COATING	CONDITIONS	RTV FA 878	RTV FA 873	EPOXYGUARD
Fuel Debris Simulant #2 (In-vessel - VF15)	**Air**	**20%**	**42%**	**-132%**
Fuel Debris Simulant VF03 + aerosol deposit *(In-vessel Fuel Debris simulant from previous project)*	**Air**	**82%**	**NA**	**NA**

During mechanical core cutting in air condition, silicones can reduce aerosol emissions by **20% in mass** on Fuel Debris simulant In-vessel.

With an aerosol deposit, the efficiency of the RTV FA878 silicone coating reaches **82% in mass** → the coating allows to confine a part of the covered aerosols.

On the opposite, the epoxy type coating (EPOXYGUARD) generates an increase in aerosol dispersion of **132% in mass**. This increase is due to the epoxy dust that is generated during the cutting process.

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 4. DISK CUTTING TESTS

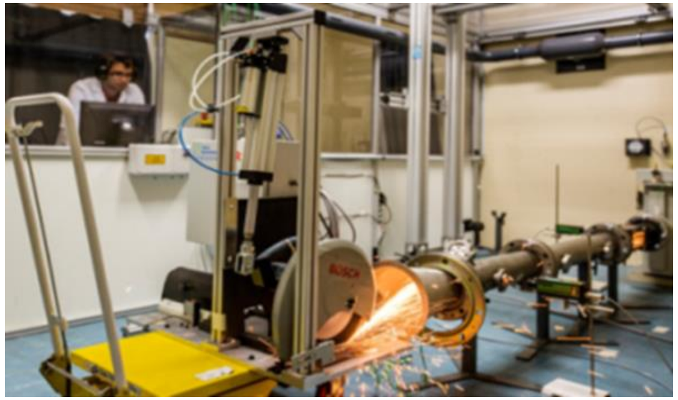
5. 4. 1. CAPIMIF facility overview

The aims of the CAPIMIF preliminary trials are:

- To pre-estimate **resins behavior** on stainless steel plates during Disk cutter cutting (disk diameter 350 mm),
- To evaluate the **resin efficiency** by comparing **during cutting trials with Disk cutter tool for non coated and coated (NC/C) samples.**

The cutting operating parameters are managed through dedicated pneumatic equipment controlled and monitored by operators outside the CAPIMIF enclosure (the applied force on sample during cutting (100 N), the number of cutting).

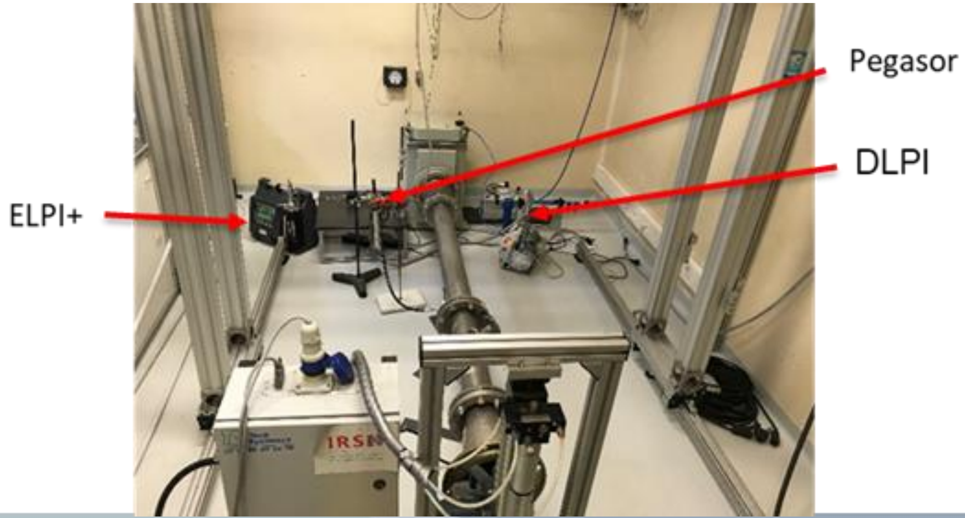
The characterization of generated aerosols is carried out by a dedicated collection line.



Disk cutter test at CAPIMIF

The instrumentations for aerosols characterization are connected to these collection line:

- a **Dekati ELPI+®** to measure the particles size distribution in real time,
- a **HEPA** filter to measure the particles mass concentration,
- a **PEGASOR®** analyzer to measure the particle number concentration in real time,
- a **Mini Particle Sampler** for particle collection and post-analysis by **microscopy** (**TEM)** and **energy-dispersive X-ray spectroscopy (EDS)**,
- Surface temperature measurement of disk and stainless steel plate by infrared sensor

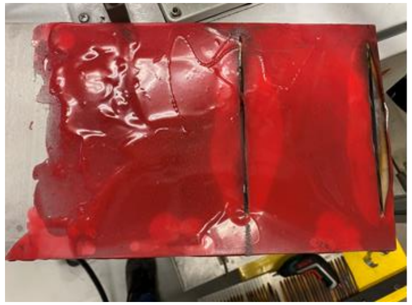


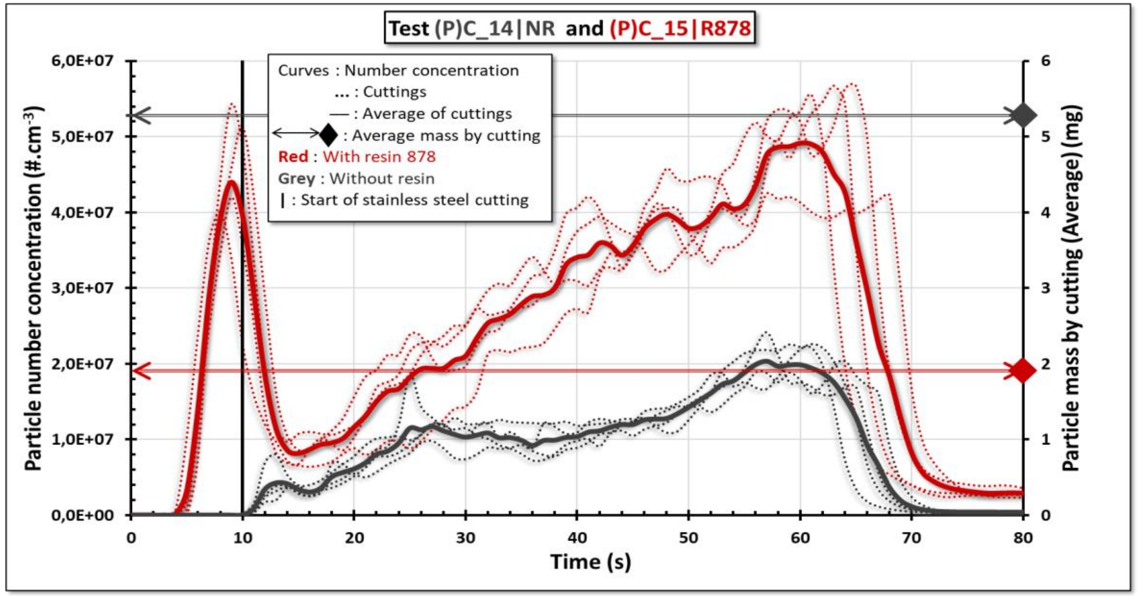
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

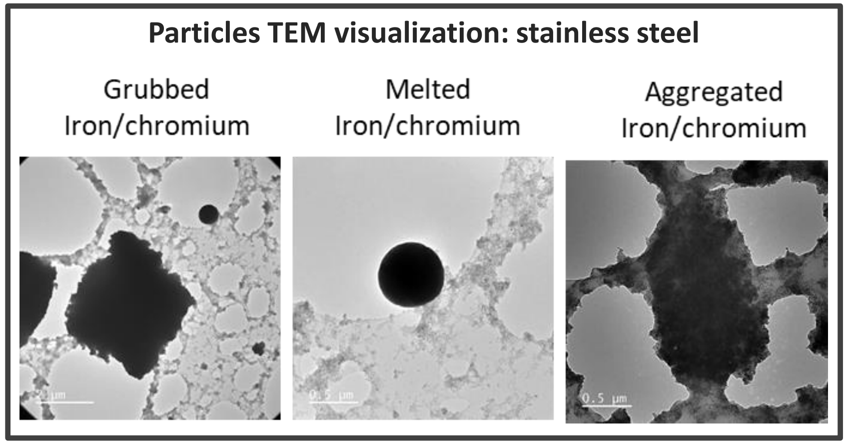
5. 4. DISK CUTTING TESTS

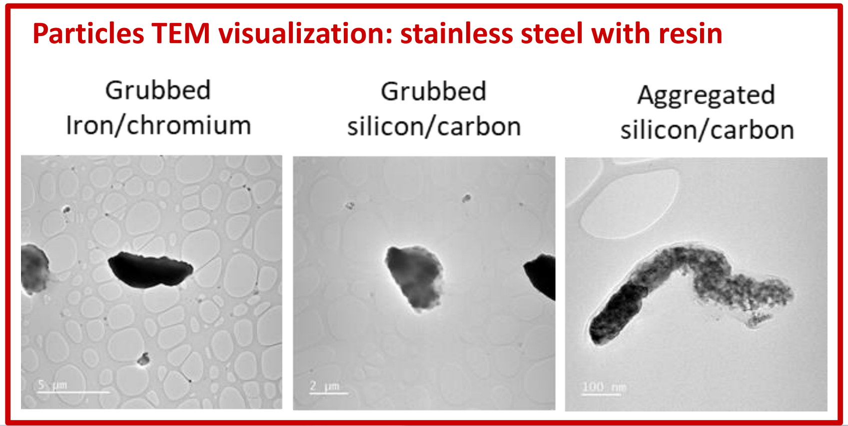
5. 4. 2. Cutting test on a stainless steel plate covered with RTV 878 coating

A 5 mm thick layer of RTV FA 878 has been applied onto the stainless steel plate on its two faces. One stainless steel plate is uncoated so it is possible to compare the results of the two configurations









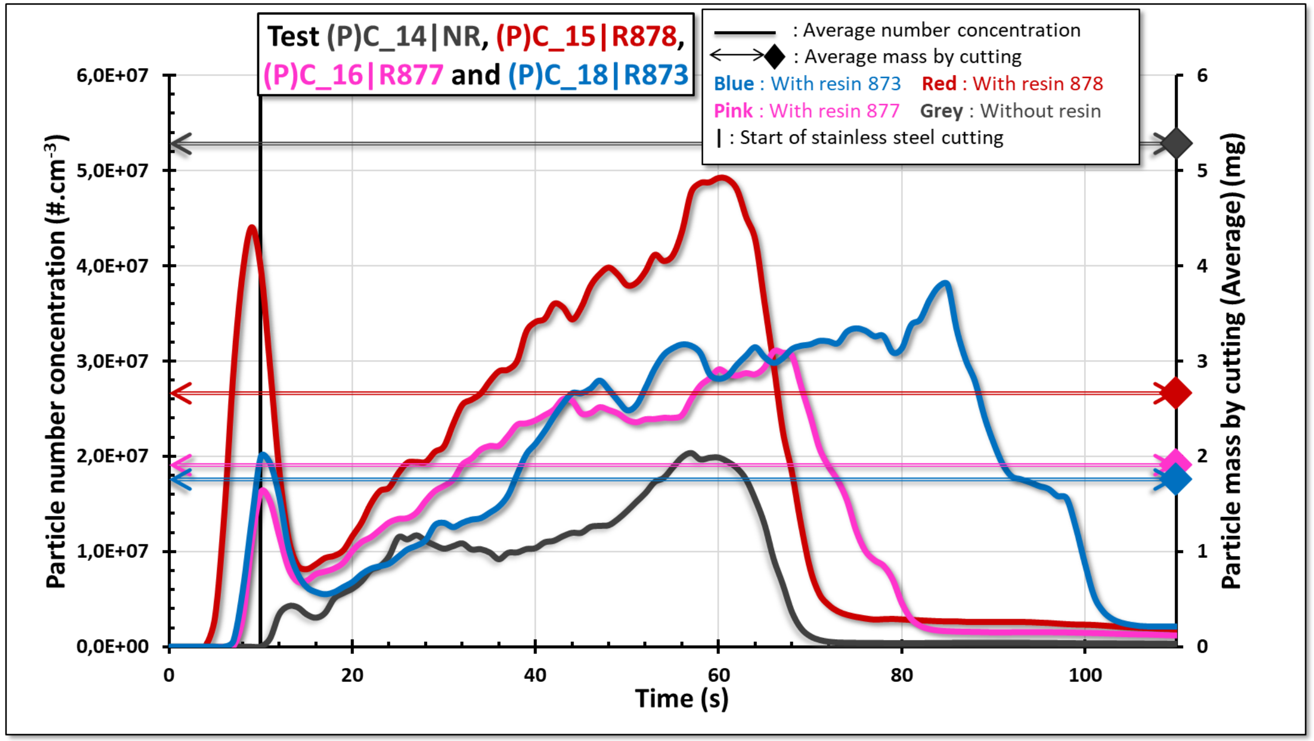
Results show:

- **Higher particle number generation** for coated sample in comparison with non coated sample (by factor 2)
- **Lower particle mass generation** for coated sample in comparison with non coated sample (by factor 3)
- **Good repeatability** in terms of particles generation for consecutive cuttings

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 4. DISK CUTTING TESTS

5. 4. 3. Cutting tests on stainless steel plates covered with RTV 878, RTV 877 and RTV 873 coatings



- **Difference between** resins in terms of **cutting duration (tc)** for a same thickness of stainless steel: $tc_{878} < tc_{877} < tc_{873}$
- **Higher particle generation in number for** coated stainless steel in comparison with non coated sample regardless of the type of coating
- **Lower particle generation in mass** for all coated samples than for non coated samples

RTV FA 873:

- Highest cutting time
- Lowest particle mass generation
- Lowest instant particle number concentration
- ➢ **Efficiency: 67 %**

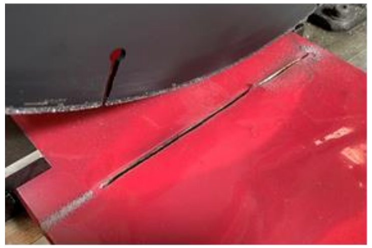
RTV FA 877:

Results between 873 and 878 for:

- Time of cutting
- Mass concentration
- Instant number concentration
- ➢ **Efficiency: 50 %**

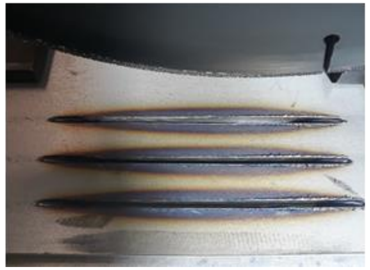
RTV FA 878:

- Lowest cutting duration
- Highest particle mass generation (with coating)
- Highest number concentration
- ➢ **Efficiency: 64 %**



Stainless steel without coating:

- Lowest cutting time
- Highest particle mass generation
- Lowest instant number concentration



V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 4. DISK CUTTING TESTS

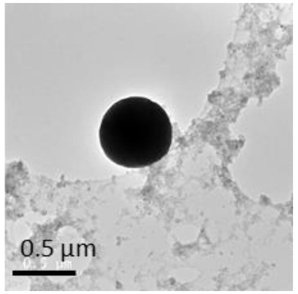
5. 4. 3. Cutting tests on stainless steel plates covered with RTV 878, RTV 877 and RTV 873 coatings

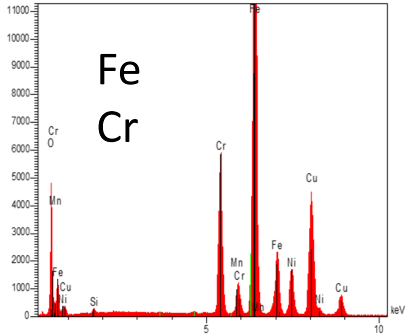
Analysis of resin and metal particles

- TEM and SEM visualizations allow to highlight the interaction between airborne particles and chips particles with resin leading to the impact of resin on particles resuspension during cutting

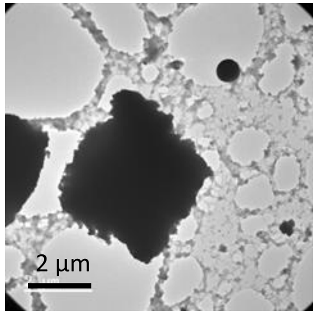
Airborne particles – TEM visualization

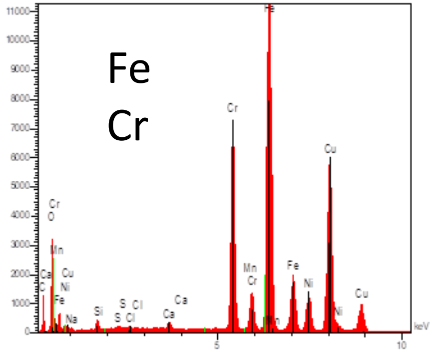
Stainless steel cutting





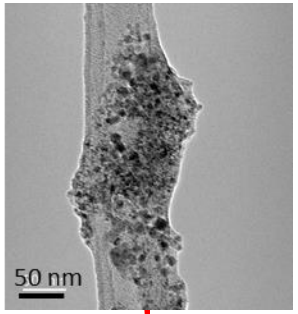
Melted iron ball

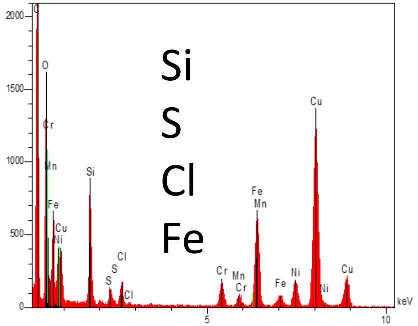




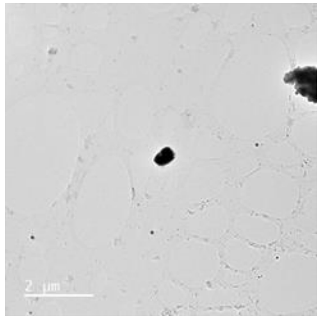
Metal particles with various morphologies (irregular and spherical)

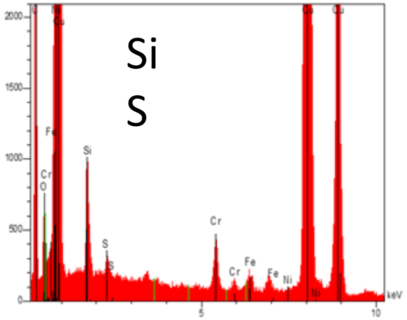
Stainless steel + resin RTV FA 877 cutting



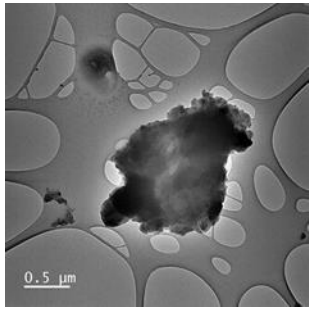


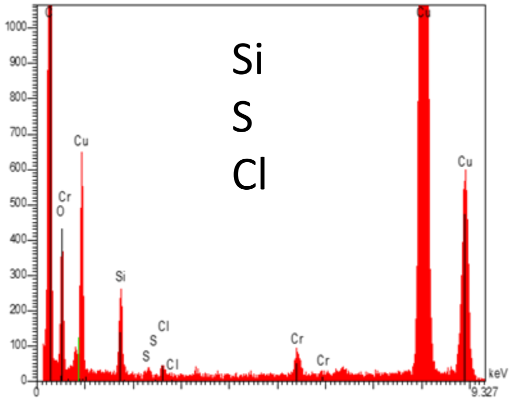
Very fine iron particles are collected with resin





Resin RTV FA 877 cutting only





Resin particles generation, mainly submicronic
Main elementary species of resin RTV FA 877: Si – Cl - S

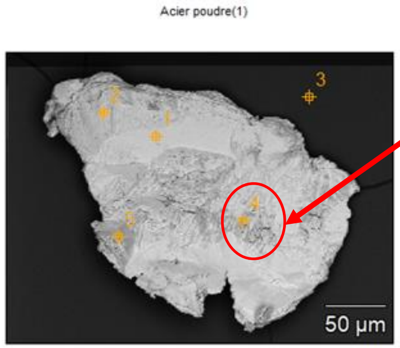
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 4. DISK CUTTING TESTS

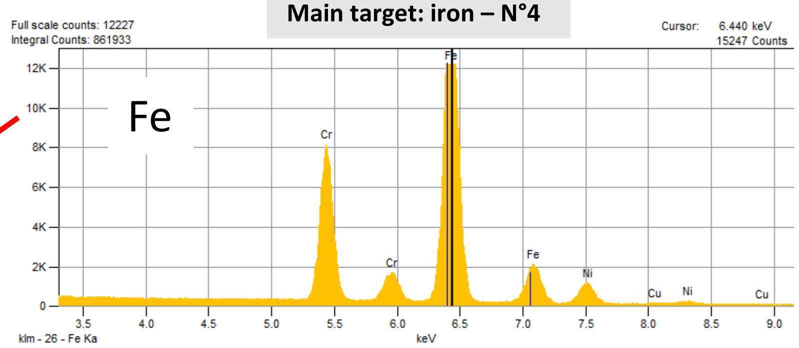
5. 4. 3. Cutting tests on stainless steel plates covered with RTV 878, RTV 877 and RTV 873 coatings

Chips particles (deposited on ground) – SEM visualization and EDS analysis

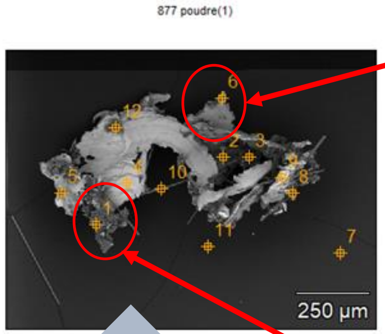
Stainless steel cutting



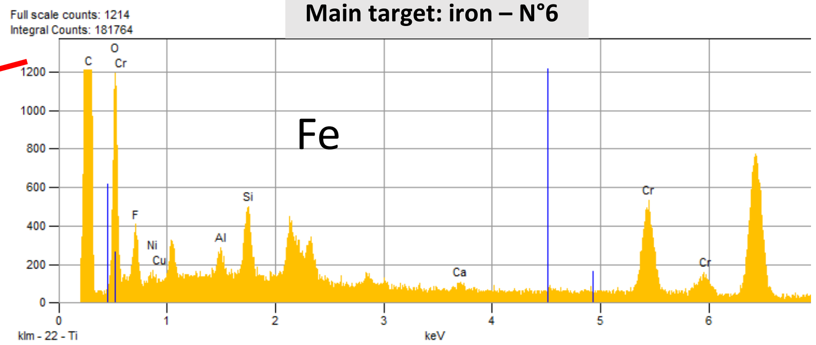
Main target: iron – N°4



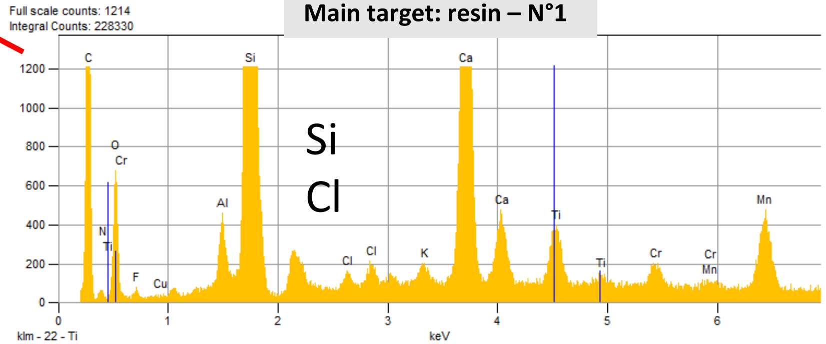
Stainless steel + resin 877 cutting



Main target: iron – N°6



Main target: resin – N°1



Iron chips particles are agglomerated with resin

Resin coating tends to increase the size of chips particles due to agglomeration phenomenon between iron and resin particles.

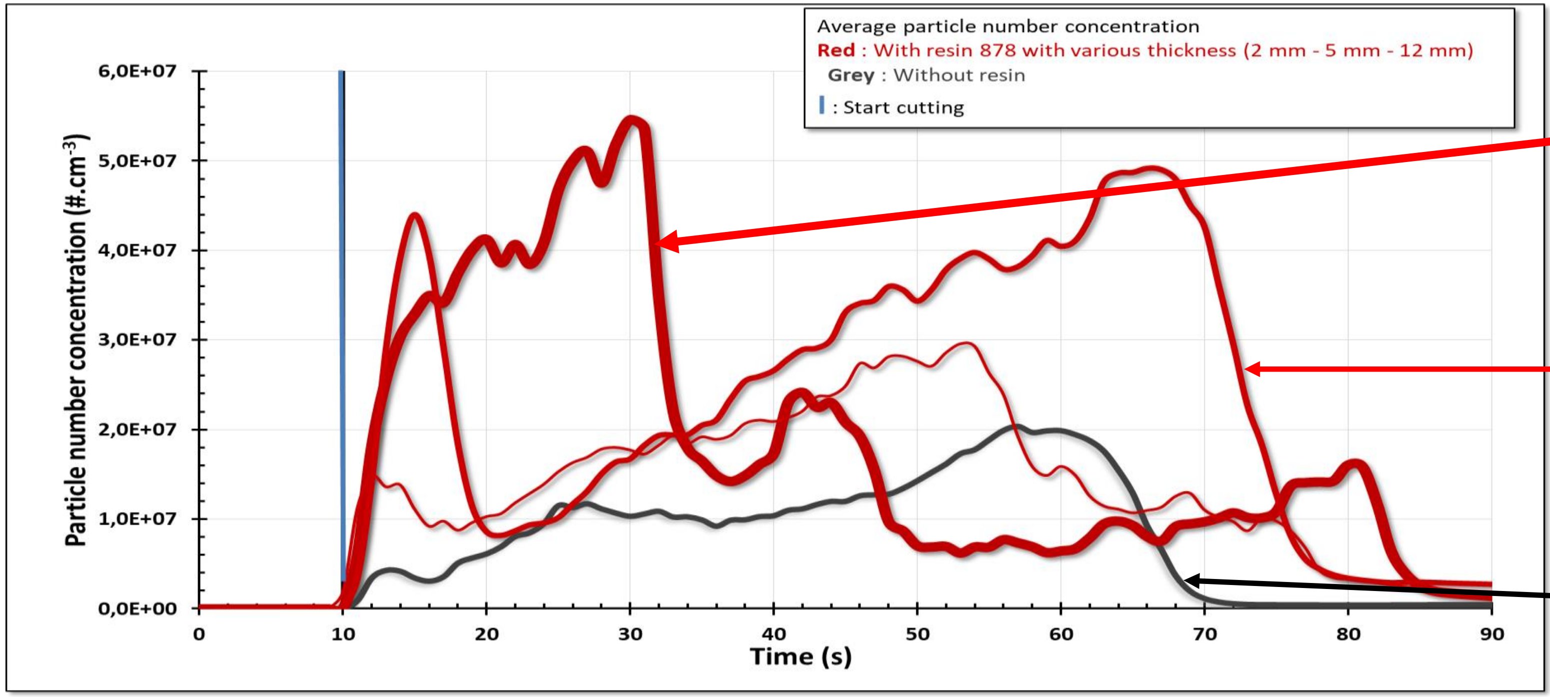
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 4. DISK CUTTING TESTS

5. 4. 3. Cutting tests on stainless steel plates covered with RTV 878, RTV 877 and RTV 873 coatings

Influence of the resin layer thickness on efficiency during cutting

- Efficiency of resin has been tested for various resin layer thicknesses (2 mm – 5 mm – 12 mm) for FA RTV 878.



Resin thickness | **Efficiency**

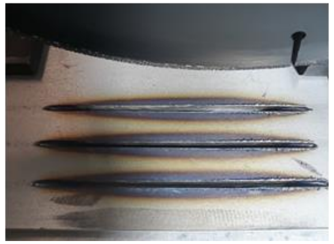
12 mm

68 %

2 mm

77 %

0 mm



The global tendency is that the decrease of resin layer thickness do not degrade the resin efficiency
Cutting issues occurred for the highest thickness due to increase of friction between disk and cut material

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 4. DISK CUTTING TESTS

5. 4. 3. Cutting tests on stainless steel plates covered with RTV 878, RTV 877 and RTV 873 coatings

Synthesis of results of efficiency for various resins and thicknesses

Name of test	Cut material	Resin		Particle number concentration (#.cm^{-3})	Total airborne particle mass (mg) (<10 µm)	Efficiency %
		Type	Layer thickness			
(P)C_14|NR	Stainless steel– 4 mm	NA	NA	1.14E+07	6604	-
(P)C_16|R877	Stainless steel – 4 mm	877	2 mm	2.08E+07	3330	50%
(P)C_18|R873	Stainless steel – 4 mm	873	2 mm	2.37E+07	2199	67%
(P)C_28|R878_LT	Stainless steel – 4 mm	878	2 mm	2.01E+07	1532	77%
(P)C_15|R878	Stainless steel – 4 mm	878	5 mm	2.98E+07	2357	64%
(P)C_29|R878_BT	Stainless steel – 4 mm	878	12 mm	*1.95E+07*	*2121	*68%

* Cutting was not completed due to high friction intensity with resin layer

Resin Efficiency:

E=1-(Airborne particle mass with resin coating / Airborne particle mass without resin coating)

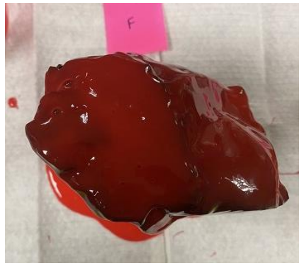
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 4. DISK CUTTING TESTS

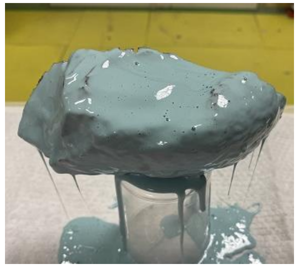
5. 4. 4. Cutting tests on Fuel Debris simulant covered with RTV 878, RTV 877 and RTV 873 coatings

Cutting tests have also been realized on Fuel Debris simulants. The pictures illustrate the coating of MCCI samples

A



B



B'

RTV FA 878: 24h

RTV FA 873: 7 days

C

A: Use of blocks of MCCI simulant (VF19), in total 6 blocks were used, 2 with RTV FA 878, 2 with RTV FA 873 and 2 without coating.

B & B': Application of resin after blending of two components according to their blending ratio. Polymerization of the resin for the recommended time, i.e. 24h for RTV FA 878 and 7 days for RTV FA 873

C: Use of coated samples on CAPIMIF facility with implementation as close as possible to ensure the most stable hold possible of the Fuel Debris simulant block.

For the test, the block of Fuel Debris simulant is held in position by joint clamps. Then the grinder is started and a pneumatic cylinder ensures the contact of the disc with the block during the cutting at a given force of 100N. Stopping and raising the disk cutter is done manually when the block of Fuel Debris simulant is completely cut.

The tests aimed at characterizing :

- The impact on number concentration of particle generate during the cutting of Fuel Debris simulant by disk cutter
- The impact on mass of particle generate during the cutting
- The feasibility of cutting resin-covered Fuel Debris simulant

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

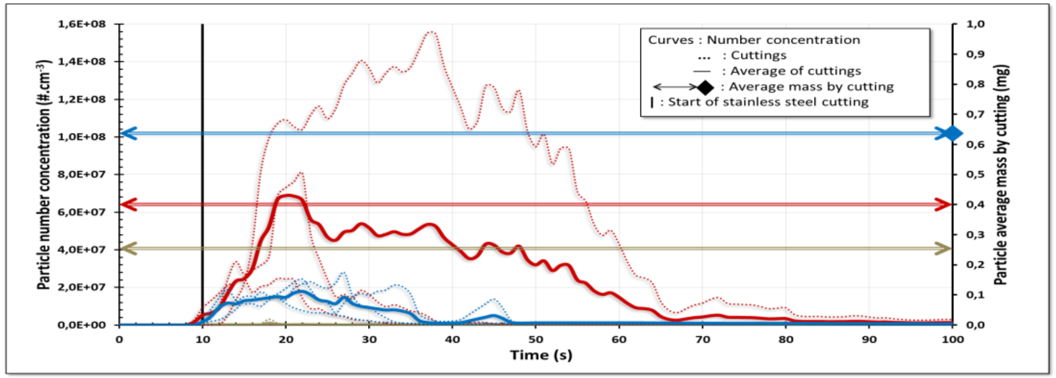
5. 4. DISK CUTTING TESTS

5. 4. 4. Cutting tests on Fuel Debris simulant covered with RTV 878, RTV 877 and RTV 873 coatings

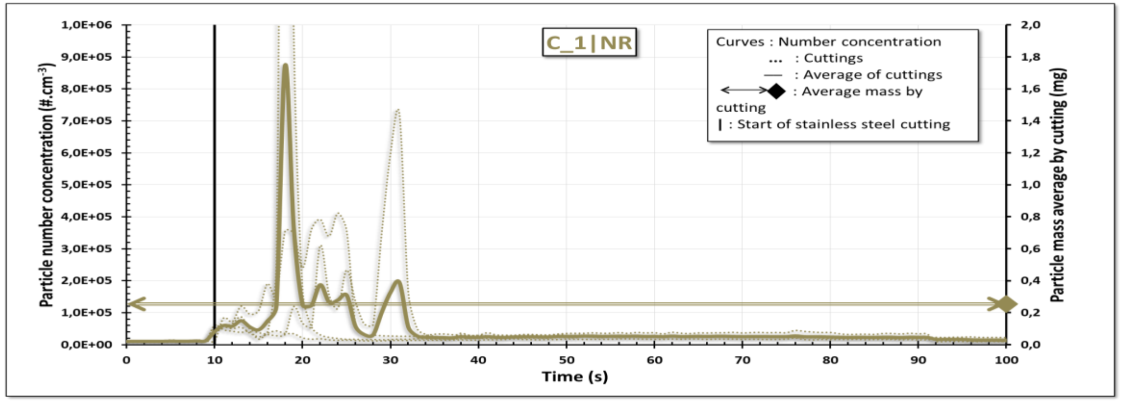
<u>Comparison between trials with and without coat of resin</u>

<u>Results</u>

- The cutting tests with coatings present a numerical concentration of particles 1000 times higher than for the Fuel Debris simulant cutting test without coating. This difference can be explained by the combustion of the coating during cutting (for the RTV FA 878)
- However, in terms of mass they only present a ratio 2 to 3 times greater. We are therefore in the presence of significant generation of particles which would come mainly from resins.



Particle number concentration time evolution - comparison during cutting of between simulant corium without (brown) and with a coat of RTV FA 873 (blue) or RTV FA 878 (red)



Zoom on particle number concentration time evolution during cutting of simulant corium without coat of resin (brown)

Simulant of corium after a cutting by wheel grind without coat (left), with RTV FA 878 coat (middle) and 873 (right)

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 4. DISK CUTTING TESTS

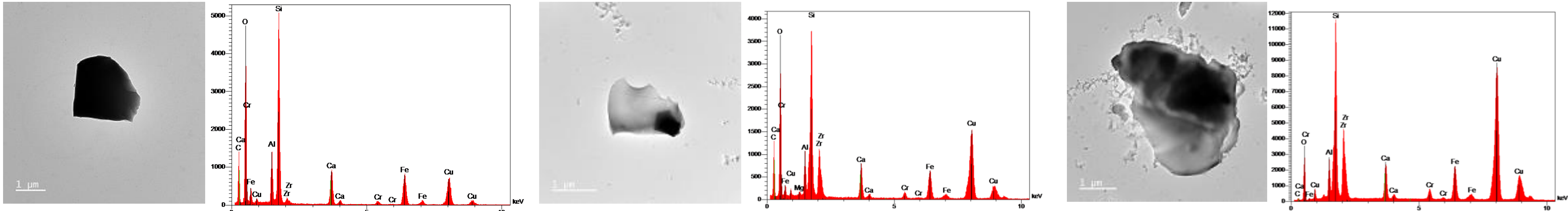
5. 4. 4. Cutting tests on Fuel Debris simulant covered with RTV 878, RTV 877 and RTV 873 coatings

First results of TEM analysis on Fuel Debris simulant with coat of resin

A sample of about ten seconds is taken during a cut in order to analyze the aerosols by TEM analysis.

These TEM analysis aimed at:

- Obtaining keys to understanding the interactions between coatings and Fuel Debris simulant particles during cutting
- Obtaining a qualitative visual of the shape and size of the particles produced



For each set of pictures, TEM picture (left) and spectrum associate (right) of particles generate when cutting with disk cutter with coating, from left to right of RTV FA 877, RTV FA 878 and RTV 873

Observations

- The production of two populations of particles is observed, particles of a size of the order of a micrometer and a second much finer population of particles of a few tens of nanometers
- The second observation that can be made is the encapsulation of large particles by agglomerates of small particles

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 5. GLOBAL ANALYSIS ON RESIN COATING IMPACT ON DUST GENERATION WITH MECHANICAL TOOLS

5.5.1 Report of main conclusions

3 mechanical tools have been considered
- Disk cutter – **CAPIMIF** trials
- Core boring at small scale - **FUJISAN** trials
- Core boring at real scale – **DELIA** trials

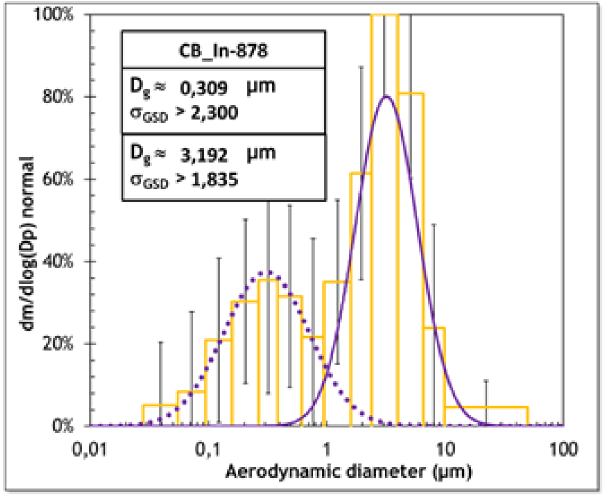
- For each trial, the efficiency of various resins has been characterized in considering the particle generation in terms of mass and number
- The objective is now to bring relevant quantitative elements for characterizing the particle production when resins are implemented, in terms of efficiency and particle source term characterization.

- A reduction of the **airborne particles mass** has been observed for all trials with mechanical cutting when resins coating are used:
  - For disk cutter with stainless steel plates : from 50% to 77%
  - For core boring at small scale for fuel debris simulant: about 90%
  - For core boring at real scale for fuel debris simulant: from 20% to 42%

- Regarding the **airborne particles number**, cuttings with disk cutter and core at small scale **have shown an increase of the generation when resins are used** (decrease for core at real scale)

- Regarding the particle size distribution, all trials with fuel debris simulants have shown that the resin coating generates **a bi-modal size distribution with an additional sub-micronic mode, between 0.2 µm to 0.4 µm**

- The core boring of **the pure resin** (RTV FA 878, core boring trial on FUJISAN) generates a PSD with **a single fine mode at 0.4 µm**



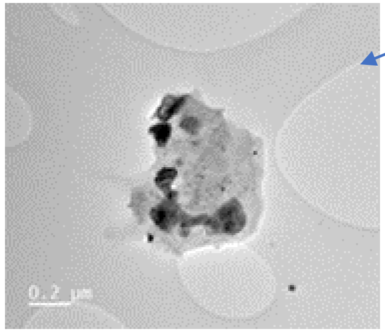
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

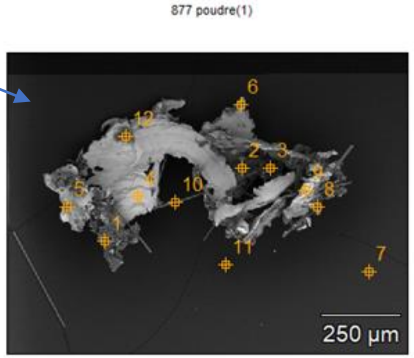
5. 5. GLOBAL ANALYSIS ON RESIN COATING IMPACT ON DUST GENERATION WITH MECHANICAL TOOLS

5.5.2 Analysis of the aerosol composition

The main issue is to demonstrate that the resin do not generate **an additional range of size of radioactive particles** which are critical in terms of safety and radioprotection, according to human inhalation penetration and confinement efficiency. SEM & EDS and TEM & EDS analysis performed on CAPIMIF and DELIA trials have shown that agglomeration occurs between Fuel Debris or stainless-steel large particles (few microns) and resin particles leading to increase the size of particle emission and an increase of particle deposition.

TEM & EDS and SEM & EDS were able to discriminate **qualitatively** the composition between resin and fuel debris simulant or stainless-steel





ICP-MS measurements were performed to try to obtain a **quantitative** value of the content of resin or potential radioactive material in the airborne particle generation

- Current analysis are not concluding due to the poor sensibility of ICP-MS for measuring the carbon which is the tracer element from resin. Further analysis are underway to increase the sensibility of the detection by the laboratory in charge of the analysis.

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 5. GLOBAL ANALYSIS ON RESIN COATING IMPACT ON DUST GENERATION WITH MECHANICAL TOOLS

5.5.3 Phenomenological analysis the cutting process

The phenomenology and the modelling of particle production by mechanical tool was studied by Khettabi, 2009.
The size of generated particle depends on the energy level transmitted by the cutting tools to the material due the friction. This energy level is function of the material characteristics and the tools rugosity.

- Globally, an increase of the energy level tends to reduce the size of the particles. **This energy level can not be modified by the presence of a material layer such resin with a very low hardness and mechanical resistance.**

According to this study, the implementation of a coating with resin can not change the basic process of the initial particle formation by the cutting tool.

The apparition of **a fine mode on the PSD (~0.4 µm in aerodynamic diameter which represents 0.1 µm in terms of geometric diameter)** observed with resin coating is then necessarily associated with the production of resin particles, non-radioactive particles.

In conclusion we can affirm that the resin coating reduces the total mass of airborne particles for all mechanical tools tested in this study, without generating an additional production of submicronic particles whose composition is the same than the cut radioactive material. This mechanism is due to the increase of the particle's deposition and also to the collection of a part of the particle generation by the he edges of the resin layer on either side od the cutting for disk cutter.

The additional production of fine particles is the consequence of the resin coating cutting by the tool which has low consequence in terms of safety even if this amount of particles has to be managed from the point of view of the confinement and waste treatment.

Khettabi, 2009. Thesis from University of Montreal, MODELING OF MICRONIC AND NANOMETRICS PARTICLE EMISSIONS IN MACHINING

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 5. DISK CUTTING TESTS FOR ASSESSMENT OF IMPACT ON FILTRATION DEVICES IN AIR

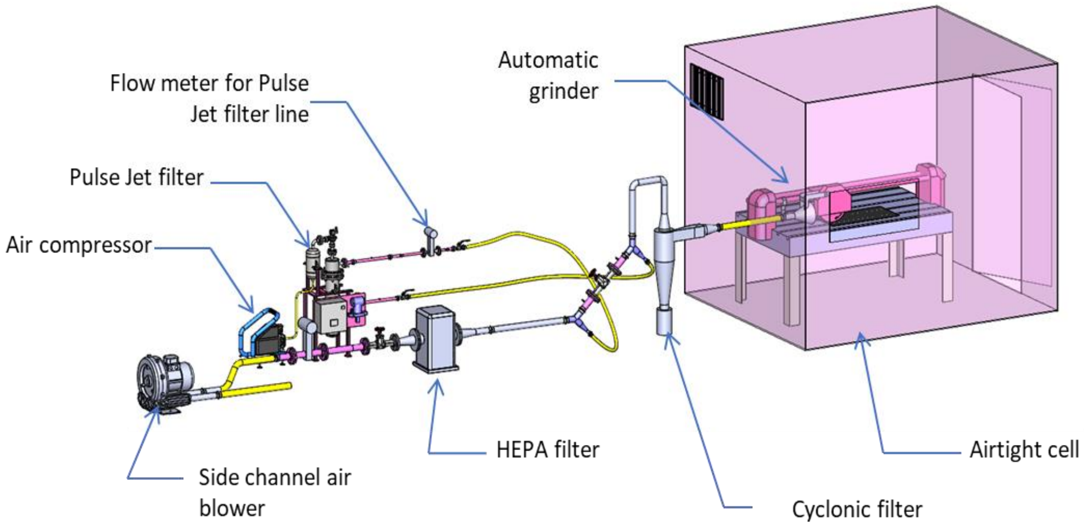
5. 5. 1. General overview

Objective:

The main objective is to observe, to study and to quantify the impact of the use of coatings on filtering devices in air & during cutting operations.

To do so, it is planned to perform cutting tests with an automatic disk cutter.
This cutting technology is closed to the one currently used for the coatings efficiency WP2 tests in CAPIMIF facility.

The cut particles that will be generated by the cutting operations will be collected by an extraction line on which the filtering devices will be implemented.



Description:

This experimental set-up allows to:

- cutting different samples (stainless steel and Fuel Debris simulant samples with or without coatings),
- collect and filter cut particles in specific sampling lines:
  - a line connected to a sized cyclonic filter (the main collection line),
  - a line connected to a standard HEPA filter (media in glass microfiber),
  - a line connected to a pulse jet filter (cartridge made of stainless steel).
- measure the pressure loss for each filtering devices,
- collect cut particle samples to characterize them in specific instrumentations.

Methodology:

It is intended to carry out specific measurement listed below:

- The evaluation of the cut particles total mass deposited in the cyclonic filter's can.
- The determination of the particles number concentration collected upstream from the filtration devices.
- The determination of the mass concentration of cut particles upstream from the filtration devices.
- The acquisition on the pressure loss of filtration devices before, during and after cutting operations.
- The acquisition of the cut particles size distribution up-stream from the filtration devices.
- The determination of the total mass of particles generated during each cutting and trapped inside each filtering devices.

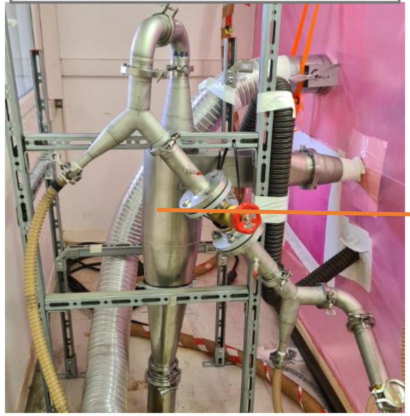
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 5. DISK CUTTING TESTS FOR ASSESSMENT OF IMPACT ON FILTRATION DEVICES IN AIR

5. 5. 1. Experimental set-up

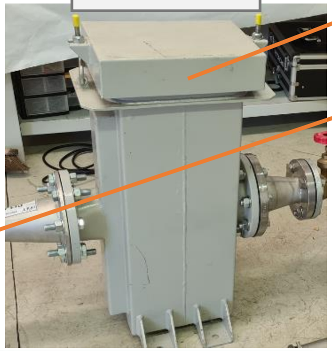
The tests on the effects of coatings on filtration devices (HEPA filter and metallic self cleaning HEPA filter) were conducted in the process laboratory of ONET TECHNOLOGIES in PIERRELATTE.

Cyclonic filter (spark arrestor)



Pulse jet filter

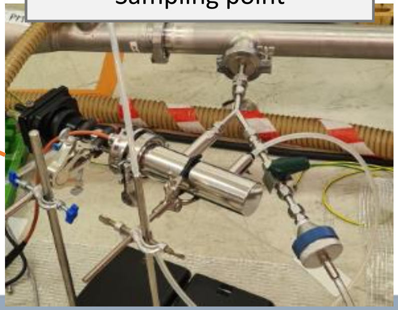
HEPA filter



Disk cutter with collection head

Disk cutter control panel

Sampling point



V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 5. DISK CUTTING TESTS FOR ASSESSMENT OF IMPACT ON FILTRATION DEVICES IN AIR

5. 5. 2. Methodology

Preparation of cutting samples:

- 5 mm stainless steel plate
- 5 mm stainless steel plate with applied coatings by casting:
  - **5 mm RTV FA 878 silicone**
  - **2 mm RTV FA 873 silicone**
  - **5 mm Epoxyguard**
- Fuel Debris simulant metallic VF18

Procedure of the tests:

The coated or uncoated steel plates or the simulant are positioned and fixed on the cutting table then a cut of about 500 mm is made for the plates and 80 mm for the simulant. The cutting aerosols are collected by a specific collection line with a flow rate of 200 m^3/h.

The aerosols are filtered on 3 filtration systems, a cyclonic filter with a cut-off of 3 µm, a HEPA filter and a PORVAIR filter (HEPA filter composed of a flushable metallic cartridge).

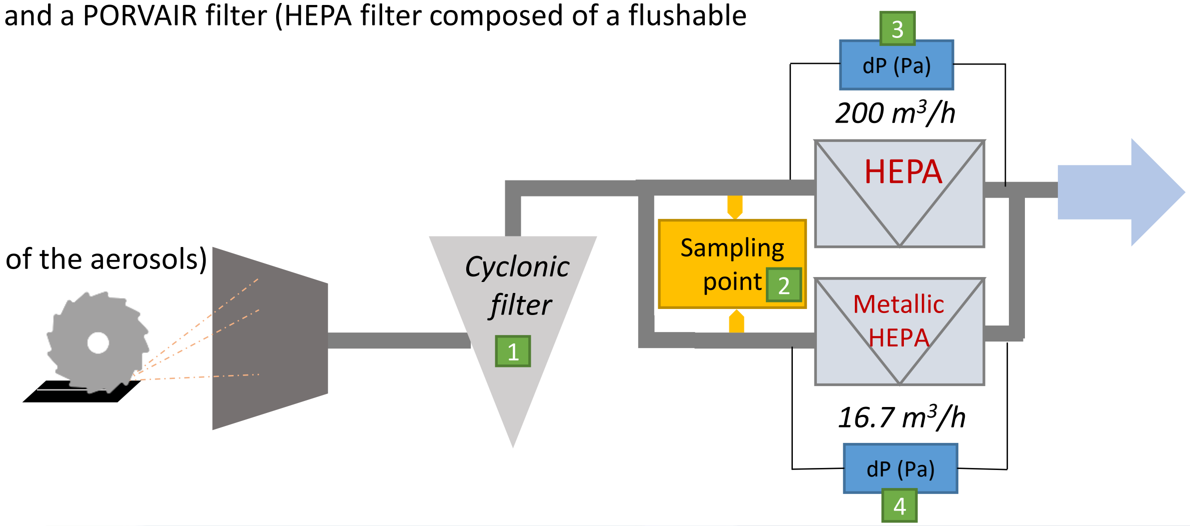
The collection line is instrumented for test monitoring:

1 Weight of the particles collected in the cyclonic filter

2 Analysis of the particles at the inlet of the HEPA filters (mass concentration and size distribution of the aerosols)

3 Measurement of the pressure drop of the HEPA filter

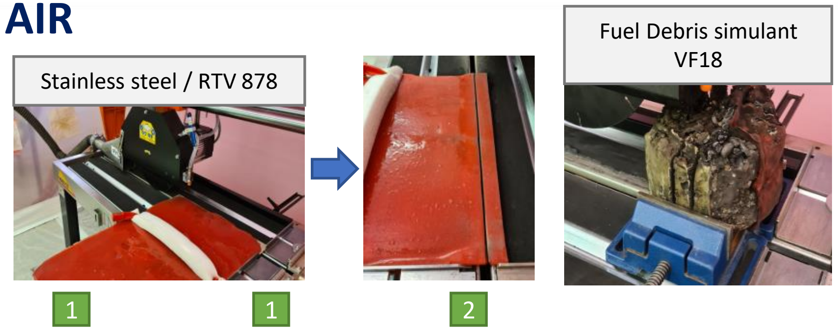
4 Measurement of the pressure drop of the metallic HEPA filter



V. CUTTING TESTS – MEASUREMENT OF IMPACTS

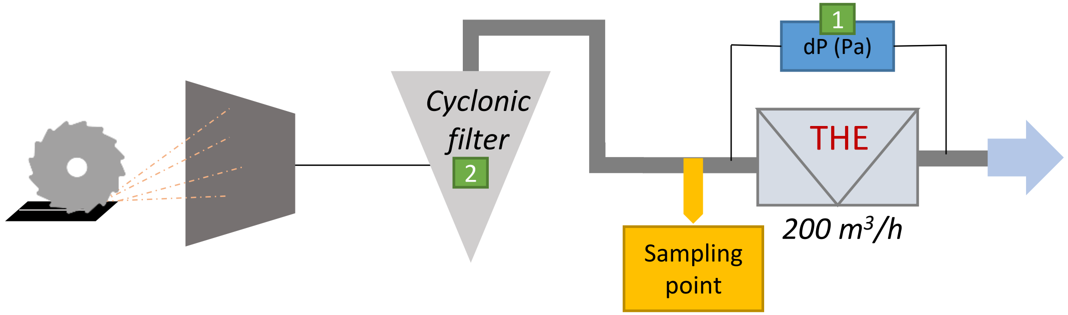
5. 5. DISK CUTTING TESTS FOR ASSESSMENT OF IMPACT ON FILTRATION DEVICES IN AIR

5. 5. 3. Results on main line with cyclonic filter – Evolution of drop pressure



Configuration

- Cutting of 5 mm thick stainless steel plate or 20 to 40 mm thick Fuel Debris simulant VF18
- **5 mm coating with silicone RTV FA 878**
- **2 mm coating with silicone RTV FA 873**
- **5 mm coating with EPOXYGUARD**
- **=> About 50 cuts carried out**



Results

Configuration		Flowrate (m3/h)	Pressure drop on THE filtre (Pa)	Average dP variation/ distance of cutting (Pa/m)	Average dP variation/mass on filter (Pa/g)	Mass particles collected in cyclone / cutting (g)
Steel plate	Without coating	200	dP < 300 Pa	14	0,30	14
			300 Pa < dP < 700 Pa	32	0,55	
			dP > 700 Pa	201	-	
	Steel plate with RTV 878	200	dP < 300 Pa	15	0,05	6
			300 Pa < dP < 700 Pa	55	0,15	
			dP > 700 Pa	-	-	
	Steel plate with RTV 873	200	dP < 300 Pa	5	0,05	4
			300 Pa < dP < 700 Pa	-	-	
			dP > 700 Pa	113	0,75	
	Steel plate with EPOXYGUARD	200	dP < 300 Pa	5	-	7
			300 Pa < dP < 700 Pa	87	0,25	
			dP > 700 Pa	178	0,30	
FD simulant VF18 Metallic	Without coating	200	dP < 300 Pa	42	0,05	11
	FD simulant VF18 Metallic with RTV 878	200	dP < 300 Pa	23	0,05	3

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 5. DISK CUTTING TESTS FOR ASSESSMENT OF IMPACT ON FILTRATION DEVICES IN AIR

5. 5. 3. Results on main line with cyclonic filter – Evolution of drop pressure

Results

On **STAINLESS STEEL plates**, the pressure drop on THE filter per meter of cut increases **similarly** for plates with and without **RTV FA 878**.

With **RTV FA 873**, the pressure drop evolution per meter is **between 2 and 3 times lower** than for uncoated plates.

→It seems none or positive impact of coating on pressure drop per cutting length (dp/L)

Note: Differences in the evolution of the pressure drop are observed depending on the initial pressure drop of the filter. This is the reason why the results are presented by pressure drop range of the THE filter at the beginning of the test.

Moreover, in **the presence of resin**, the results show that the pressure drop of the THE filter per mass of filtered particles increases less rapidly (**from 2 to 6 times lower**)

→ It seems a positive impact of coating on pressure drop per mass of filtered particles (dp/m)

With **Fuel Debris SIMULANT VF18**, we observe that **the pressure** drop per meter of cutting is **divided by 2**. The coating seems to have therefore an effect on the clogging limitation of the HEPA filter.

It is observed that with resin, the quantity of aerosols collected in the cyclone is lower (up to 3 times less with the resin RTV FA 873). This phenomenon is due to the fact that with the coating, the cutting aerosols are smaller and are mainly below the cut-off of the cyclone filter (cut-off at 3 µm).

These results were performed on 2 HEPA cartridges. To confirm these preliminary results, a campaign with more cuttings should be carried out using 1 cartridge per configuration.

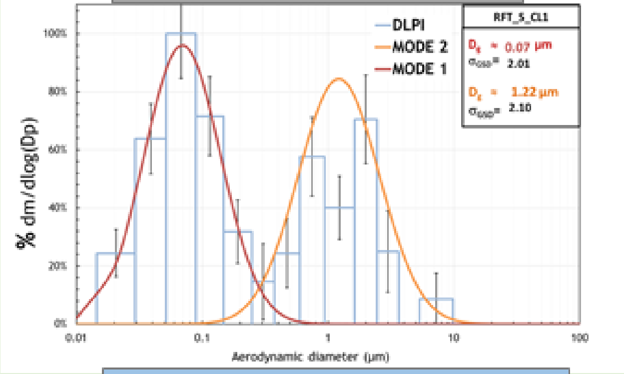
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 5. DISK CUTTING TESTS FOR ASSESSMENT OF IMPACT ON FILTRATION DEVICES IN AIR

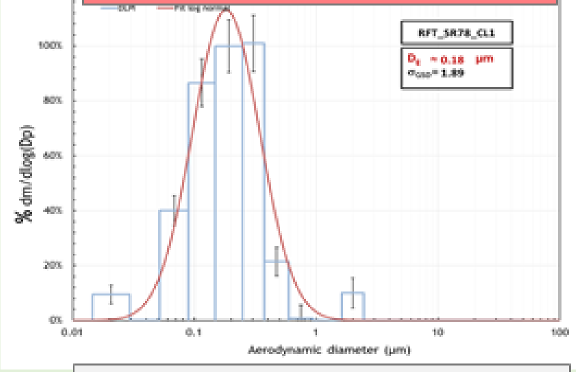
5. 5. 4. Results on main line with cyclonic filter – Particle size distribution

Stainless Steel

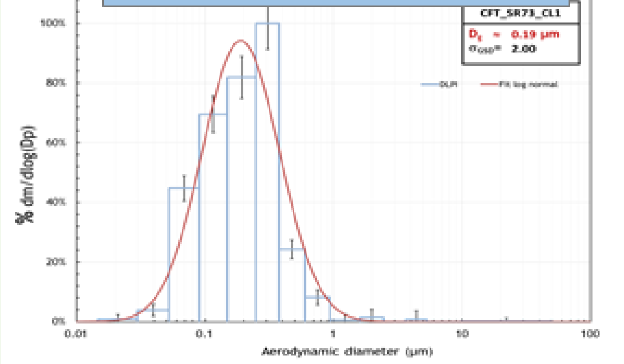
Stainless steel with cyclonic filter



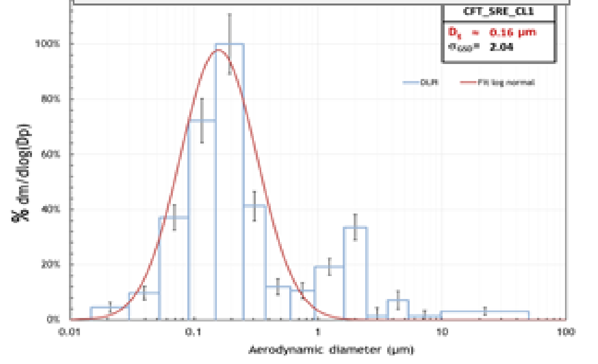
Stainless steel + RTV 878 with cyclonic filter



Stainless steel + RTV 873 with cyclonic filter

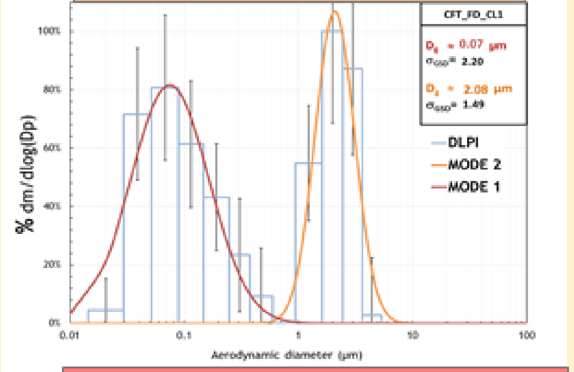


Stainless steel + Epoxyguard with cyclonic filter

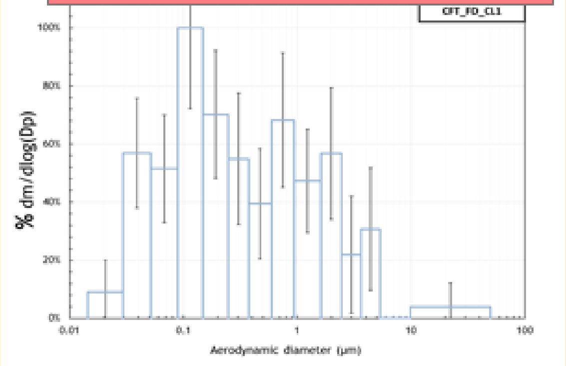


FD simulant VF18

FD simulant VF18 with cyclonic filter



FD simulant VF18 + RTV 878 with cyclonic filter



Without coating, on the stainless steel and on the Fuel Debris simulant VF18, the particle size distribution shows a distribution with 2 modes (around 0.10 µm and between 1 and 2 µm).
With the application of a coating, the larger diameter particles do not appear in the collected aerosols (>1 µm). These particles are either deposited in the cutting chamber because they are too heavy to be collected, or collected in the cyclone. However, the coatings generate finer particles of the order of 0.2 µm.

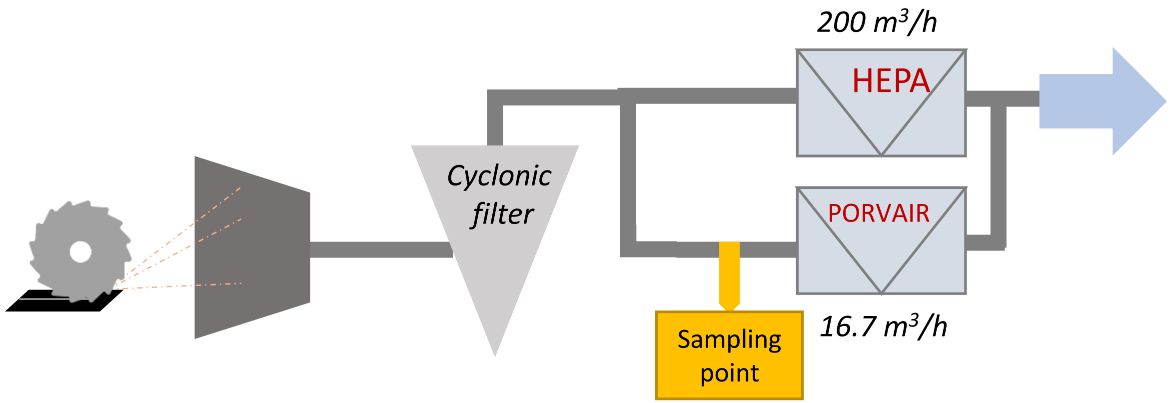
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 5. DISK CUTTING TESTS FOR ASSESSMENT OF IMPACT ON FILTRATION DEVICES IN AIR

5. 5. 5. Results on secondary line with cyclonic filter – HEPA filter with stainless steel cartridges

Configuration

- Cutting of 5 mm thick stainless steel plate + various coatings
- Use of the cyclonic filter



Tests

- 16 cuttings in emerging configuration on stainless steel plate
- 10 cuttings in emerging configuration on stainless steel plate **+ 5 mm RTV878**
- 11 cuttings in emerging configuration on stainless steel plate **+ 2 mm RTV873**
- 8 cuttings in emerging configuration on stainless steel plate **+ 5 mm Epoxyguard**

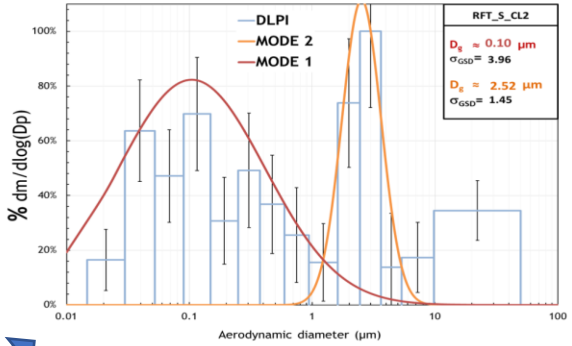
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

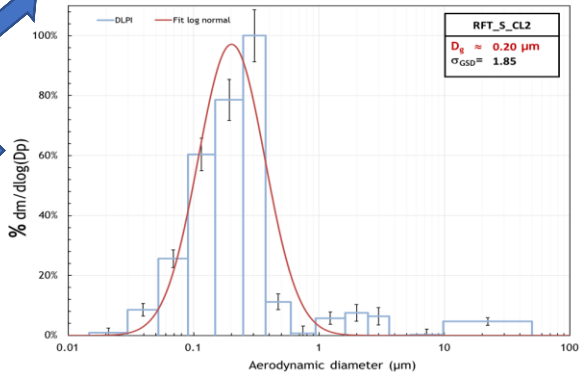
5. 5. DISK CUTTING TESTS FOR ASSESSMENT OF IMPACT ON FILTRATION DEVICES IN AIR

5. 5. 5. Results on secondary line with cyclonic filter – HEPA filter with stainless steel cartridges

Results

			Secondary line with filter PORVAIR	
Configuration	Reference	Number of cuttings	Flowrate (m3/h)	dP variation (mbar/m of cutting)
Steel plate with cyclonic filter	QFT-S-P-CL2 --> CL4 (emerging)	3	16,7	0,47
	RFT-S-P-CL1 --> CL3 (emerging)	3	16,7	0,07
	RFT-S-P-CL4 --> CL13 (emerging)	10	16,7	0,04
Steel plate with RTV 878 and cyclonic filter	CFT-SR878-P-CL1 --> CL3 (emerging)	3	16,7	0,13
	CFT-SR878-P-CL4 --> CL10 (emerging)	7	16,7	0,06
Steel plate with RTV 873 and cyclonic filter	CFT-SR873-P-CL1 --> CL11 (emerging)	11	16,7	0,04
Steel plate with EPOXYGUARD and cyclonic filter	CFT-SEpoxy-P-CL1 --> CL8 (emerging)	8	16,7	0,08





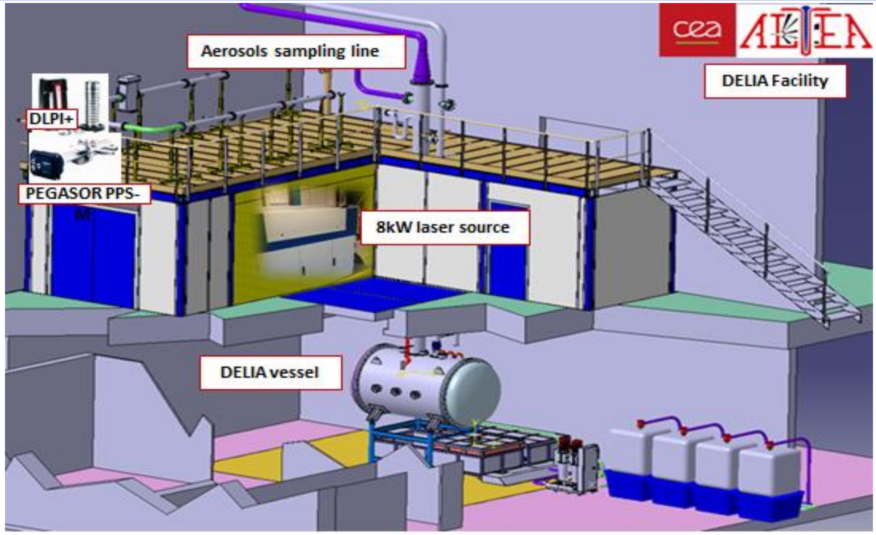
On the metallic HEPA filter, the evolution of the pressure drop is very low for all configurations.
The evolutions of P for each resin are not significant and do not show a different impact on the metal filter cartridge.

For particle size, similar as on the main line, the coating application shows **a single mode around an aerodynamic diameter (dg) of 0.20 µm** and removes the peak observed of particles around 2.5 µm.

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

5. 6. 1. Overview of the tests



Objectives:

1. Assessment of coatings impact on laser cutting process in term of performances
2. Implementation of aerosols characteristics measurements in order to observe the impacts on the production of airborne particles

General description:

- Tests take place in **DELIA facility - CEA Saclay**
- Laser cutting tests are carried out in an airtight vessel. The aerosols sampling line integrates iso-kinetic probes.
- Data are monitored with Pegasor® PPS-M, filter sampling and DLPI+®
- Specific airflow is created inside the vessel in order to homogenize the particles concentration inside the vessel

Analyzed criteria:

Laser cutting process evaluation:

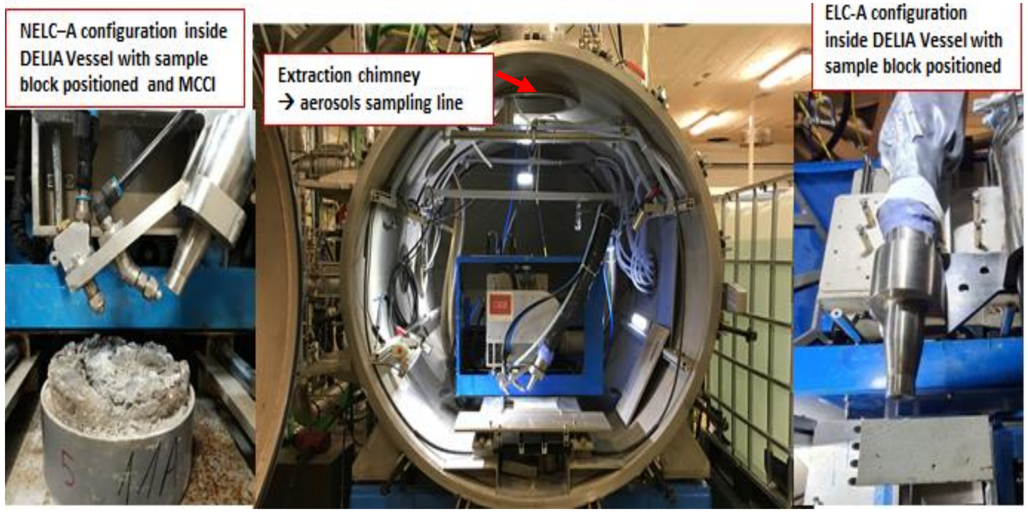
- Kerf depth variation in NELC-A* configuration for zirconia blocks coated
- Variation of the cutting limit speed in ELC-A** configuration for stainless steel coated plates
- Behavior coatings during and after laser cutting

Aerosols characterization (impact of coatings):

- Particles size distribution (**DLPI®)**
- Particles mass and number concentration (**Pegasor® PPS-M and filter sampling)**
- Morphology of the cut particles and their related atomic composition **MPS**

Other parameters of cutting for the assessment of impact of the use of coatings:

- Influence of nitrogen atmosphere
- Influence of humidity



** NELC-A: Non-Emerging Laser Cutting in Air* *** ELC-A: Emerging Laser Cutting in Air*

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

5. 6. 2. Tests program

Tests campaign was held from **01/06/2022** to **30/06/2022**:

- ✓ Samples : fused cast zirconia blocks, stainless steel plates and Fuel Debris simulant VF18,
- ✓ 3 coatings tested (RTV FA 878, RTV FA 873 and EPOXYGUARD,
- ✓ 34 types of cutting tests with various parameters have been carried out in DELIA Facility with or without aerosols characterization

**Phase 1 : LASER CUTTING PROCESS EVALUATION
IMPACT OF 3 SELECTED COATINGS**

Evaluation of coating impact on laser deep gouging process (NELC)		
1	Fused cast zirconia	Uncoated
2		RTV FA 878
3		RTV FA 873
4		EPOXYGUARD
Evaluation of coating impact on laser cutting process (ELC)		
5	40 mm stainless steel (304L)	Uncoated
6		RTV FA 878
7		RTV FA 873
8		EPOXYGUARD

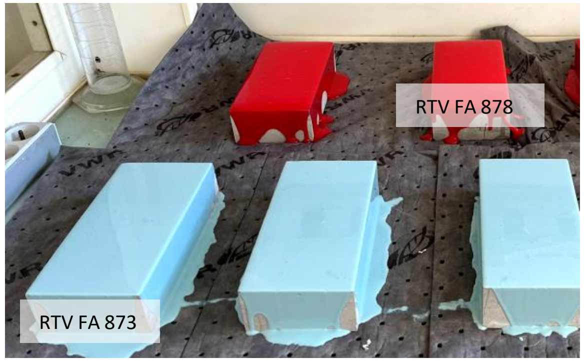
Phase 2 : AEROSOLS SUPPRESSION EFFICIENCY TESTS DURING LASER CUTTING

No.	Configuration	Sample(material)	Type of coating	Environment	Gas flow rate inside DELIA vessel
1	NELC	Fuel debris simulant VF18	Uncoated	Dry Air	180 m^3/h
2				N_2 & Humidity	
3				Air & Water Spray	
4				N_2 & Water spray	
5			RTV FA 878	Dry Air	
6				Air & Humidity	
7			RTV FA 873	Dry Air	
8				N_2 & Humidity	
9	ELC	40 mm stainless steel (304L)	Uncoated	Dry Air	120 m^3/h
10				Air & Water Spray	
11				Dry N_2	
12				N_2 & Water spray	
13				N_2 & Humidity	
14			RTV FA 878	Dry Air	120 m^3/h
15				Air & Water spray	
16				Dry N_2	
17				N_2 & Water spray	
18				N_2 & Humidity	
19				Dry Air (7 % O_2)	48 m^3/h Air & 72 m^3/h N_2
20				Air (7% O_2) & Water Spray	
21				Dry Air (13 % O_2)	48 m^3/h Air & 24 m^3/h N_2
22				Dry Air (13 % O_2) & Water Spray	
23			RTV FA 873	Dry Air	120 m^3/h
24				Dry N_2	
25			EPOXYGUARD	Dry Air	120 m^3/h
26				Dry N_2	

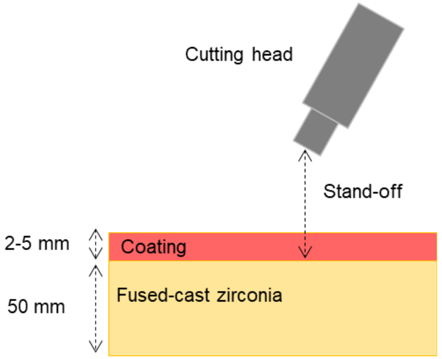
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

5. 6. 3. Cutting process evaluation – NELC (laser deep gouging)



Picture of cast fused Zirconia block coated



Configuration of cutting

Analyzed criteria:

- Kerf depth variation in NELC-A configuration for zirconia blocks coated
- Behavior coatings during and after laser cutting

Experimental conditions:

- The distance between the cutting head and the zirconia surface (stand-off) is set at its nominal value of 52 mm,
- Samples: fused cast zirconia blocks of 50 mm thickness, 100 mm large and 200 mm long with only one face coated,
- Three coatings are evaluated: RTV FA 878(c), RTV FA 873(a), EPOXYGUARD(b). They have been applied accordingly to the recommandations and self-levelling method has been applied. Their thickness is between 2 and 5 mm depending the sample of test,
- Laser power: 8 kW, cutting speed 10 cm/min . Assist gas : dry air.

Pcitures of the tests: three cuts with the RTV FA 873, 2 cuts with Epoxyguard and 1 cuts with RTV FA FA. Trace of calcination is visible on Epoxyguard

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

5. 6. 3. Cutting process evaluation – NELC (laser deep gouging)

For each coating, 3 laser cutting have been carried out. Kerf depths have been measured after each cutting operation. The table below shows the results and the kerf depth average for each configuration:

Coating	Uncoated	RTV FA 873	RTV FA 878	EPOXYGUARD
Kerf depth (mm)		39	34	39
	41	30	39	40
	39.5	38	13.5	37
	39	38	42	40
Average (mm)	39.8	36.3	32.1	39.0
Δ (mm)	0	-3.6	-7.7	-0.8

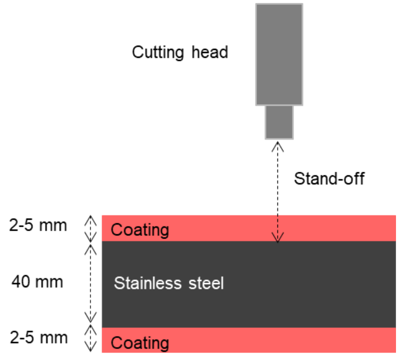
Results:

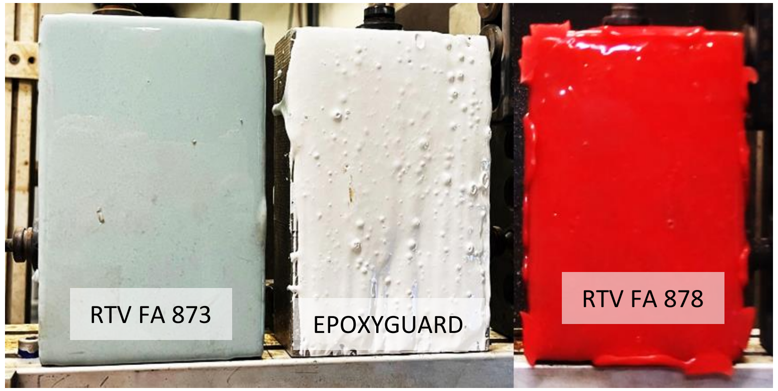
- These three coatings affect more or less the cutting performances.
- The best performance was achieved for EPOXYGUARD (average kerf depth of 39.0 mm).
- RTV FA 878 coating gave mixed results (average value of the kerf depth of 32.1 mm), has lower adhesion because of the smooth surface of fused cast zirconia and peels off. This phenomenon seems to interfere with the ejection of the molten material. Nevertheless a very good adhesion was observed for Fuel Debris simulant.
- RTV FA 873 and EPOXYGUARD have good adhesion to zirconia blocks, even after multiple cuttings on the same work piece.
- All three coatings exhibited traces of local calcination.

V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

5. 6. 4. Cutting process evaluation – ELC





Tests presented here have been carried out on cast fused Zirconia blocks

Analyzed criteria:

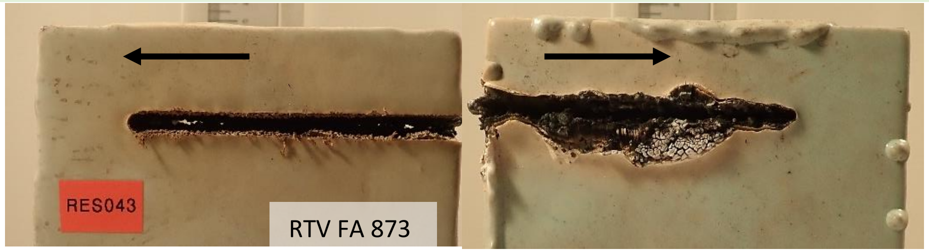
- Variation of the cutting limit speed in ELC-A configuration for stainless steel coated plates
- Behavior coatings during and after laser cutting

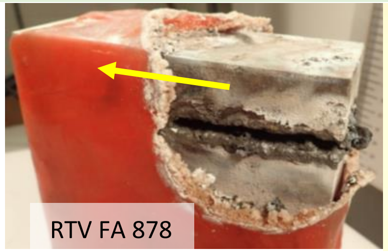
Experimental conditions:

- Three coatings tested : RTV FA 878, RTV FA 873 and EPOXYGUARD,
- Assist gas: 78 m^3/h (dry air and nitrogen only for coating behaviour),
- Laser power: 8 kW,
- Samples: stainless steel plates uncoated (100x150x41 mm^3) and coated of thickness 44.8 mm (RTV FA 873), 52.5 mm (RTV FA 878), 48.3 to 50.9 mm (EPOXYGUARD)

Results:

- Local coating combustion mainly due to the significant heat accumulation and dissipation in a relatively small volume of stainless steel were observed on some tests in air with assist gas in air. Local flames were visible on camera installed in DELIA vessel even after switching off the laser beam. Flammes stop by themselves after seconds.
- Adherence of coatings RTV FA 873 and RTV FA 878 on 304L stainless steel surface is very low in comparison to EPOXYGUARD, which has a very strong adhesion to the same surface.
- Local flames occurred to a lesser degree for RTV FA 873 coating, limit-cutting speed was searched only for this resin. A loss of performance was observed: the limit speed value find is 7.5 cm/min, which is 16.7% slower, compared to the limit speed of a 40 mm thick 304L stainless steel plate. An intermittent cut was obtained at 9 cm/min for samples coated with RTV FA 878 that led us to estimate that after all, this coating has maybe the lowest impact on laser cutting performance.





V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

5. 6. 4. Cutting process evaluation – ELC

Tests presented here have been carried out on stainless steel plates (40 mm thick)

Results:

Laser cutting tests with N2 assist gas and in nitrogen atmosphere or in air with O_2 concentration of 7.6%, and 13% showed no evidence of coatings degradation, combustion or ashes in the vicinity of the laser kerf.

Deep gouging tests were carried out on metallic corium simulant coated with RTV FA 873 and RTV FA 878. Good adhesion of coating to the surface due to roughness of corium was observed, as well as no combustion of the coatings, even during in air tests, nevertheless a black layer of residues and dust it is to be noticed on the sample surface.

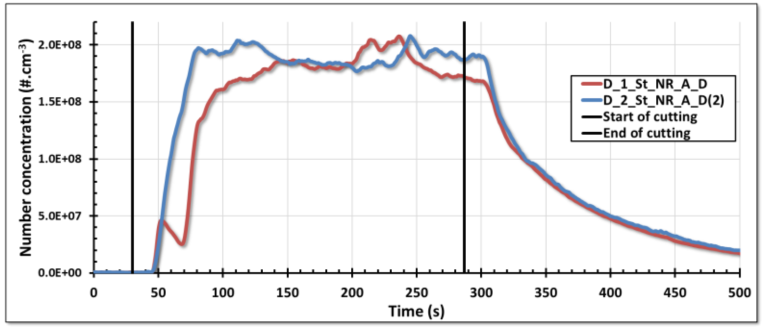
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

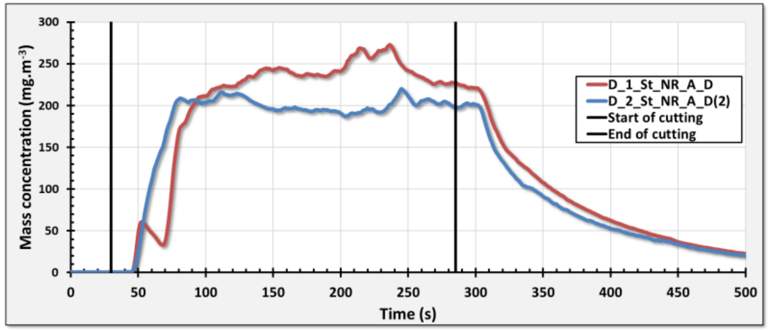
5. 6. LASER CUTTING TESTS

5. 6. 5. Aerosols metrology

Laser cutting tests have been carried out on 40 mm thick stainless steel plates

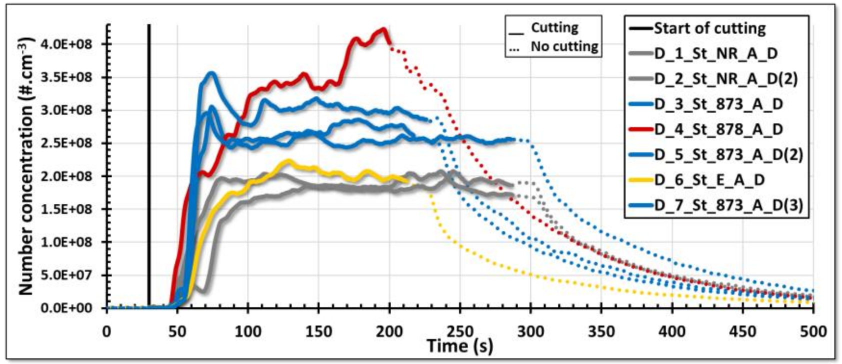
Repeatability tests on stainless steel plates

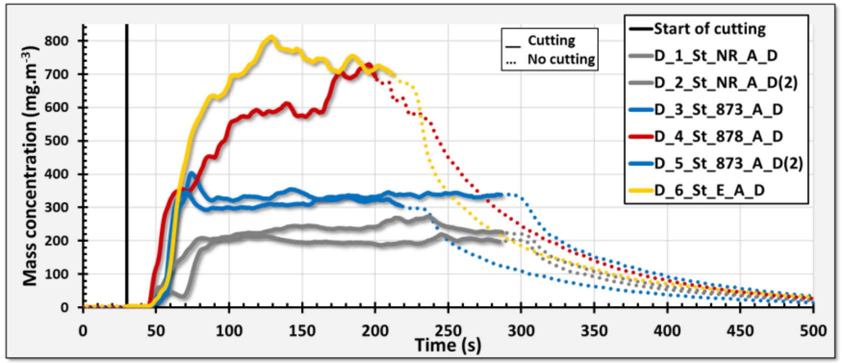




- Good repeatability of the aerosol generation in terms of number and mass particle concentration
- Stability of the concentration level during the cutting phase

Cutting tests on stainless steel plates with coatings in air and dry conditions





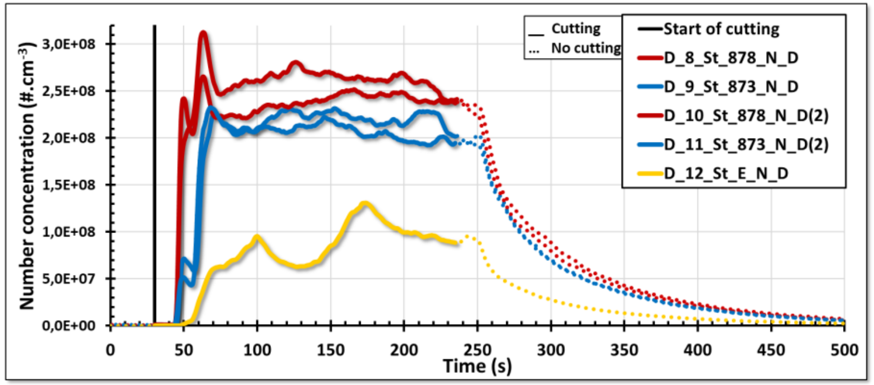
- 3 coatings have been tested: **RTV FA 878, RTV FA 873, Epoxyguard**
- In terms of number concentration
  - Globally, resins coating induces an increase of particle generation except for Epoxy (Epo<873<878)
  - Repeatability for RTV FA 873 coating is underlined
- In terms of mass concentration
  - Strong increase of the mass generation, especially for epoxy and 878 (873<878<Epo) compared to non-coated stainless steel

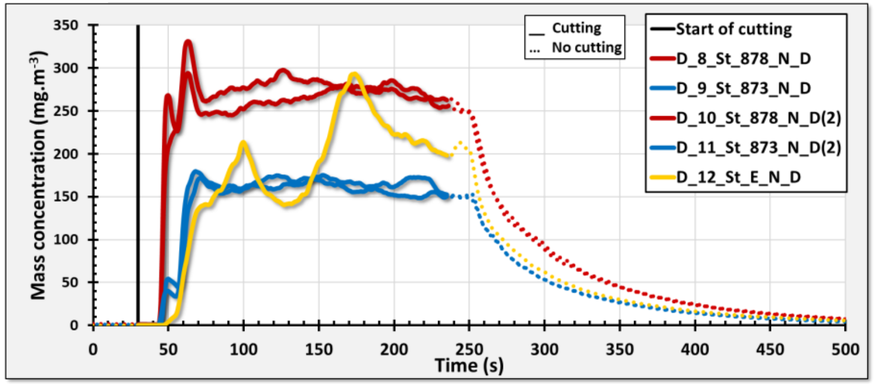
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

5. 6. 5. Aerosols metrology

Cutting tests on stainless steel plates with coatings with Nitrogen and dry conditions





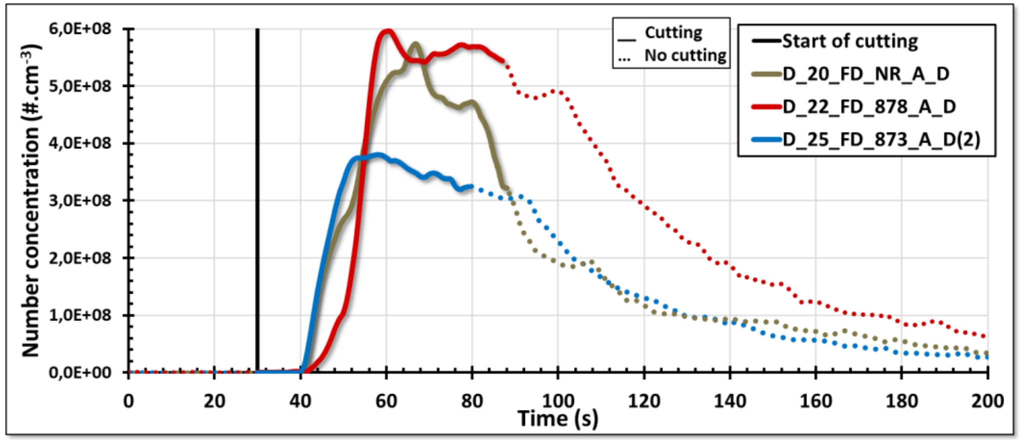
- 3 coatings have been tested: RTV FA 878, RTV FA 873, Epoxyguard
- The refence test without resin coating in nitrogen has failed, so only trials with resins coating are compared.
- The ranking of various resins is similar in Nitrogen than for AIR condition for particles number generation
- For the particle mass generation, we can observe a strong reduction of the airborne particles quantities in Nitrogen condition compared to air conditions.

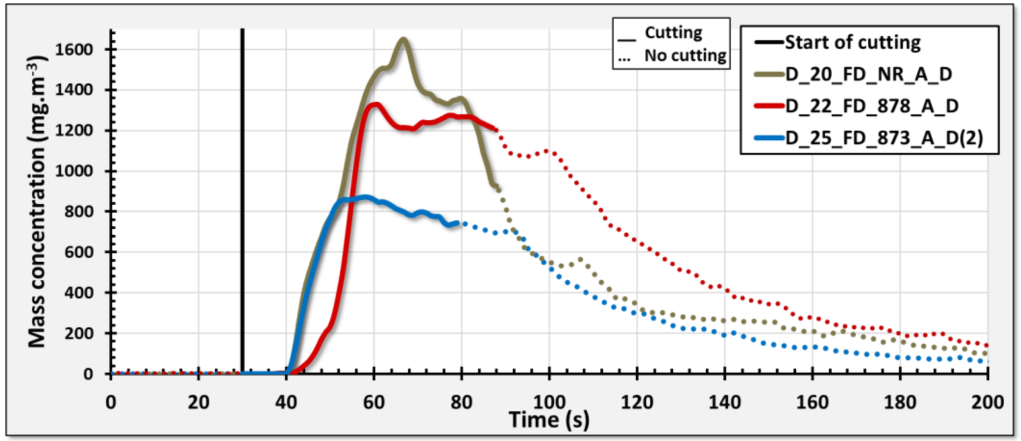
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

5. 6. 5. Aerosols metrology

Cutting tests on Fuel Debris simulant in dry air conditions





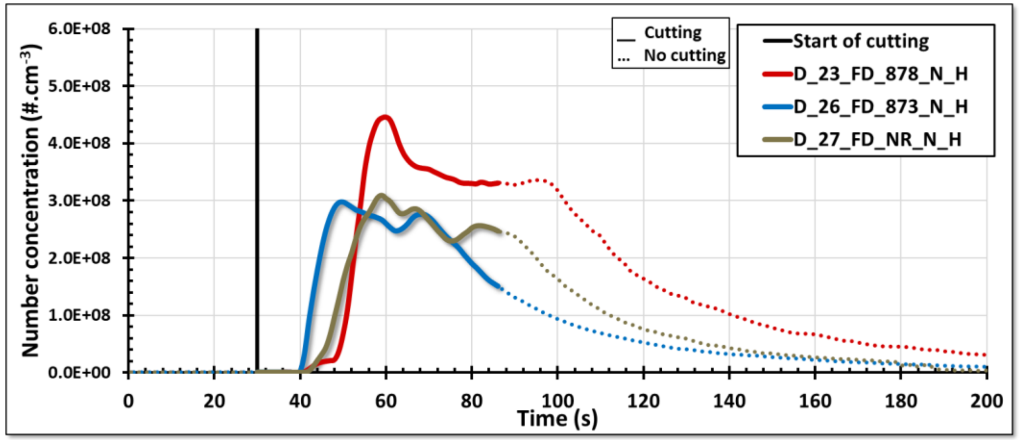
- Similar particle generation between non-coated Fuel Debris and coated Fuel Debris with resin RTV FA 878 during the cutting phase. After, an increase is observed for coated Fuel Debris.
  - ➢ Could be explained by the degradation of the resin RTV FA 878 and the soots production
- Coating with resin RTV FA 873 induces a reduction of the particle generation in terms of mass and number during the cutting phase.
- No increase of particles generation is observed after cutting phase in agreement with the fact that no degradation of the resin RTV FA 873 was observed during the trial

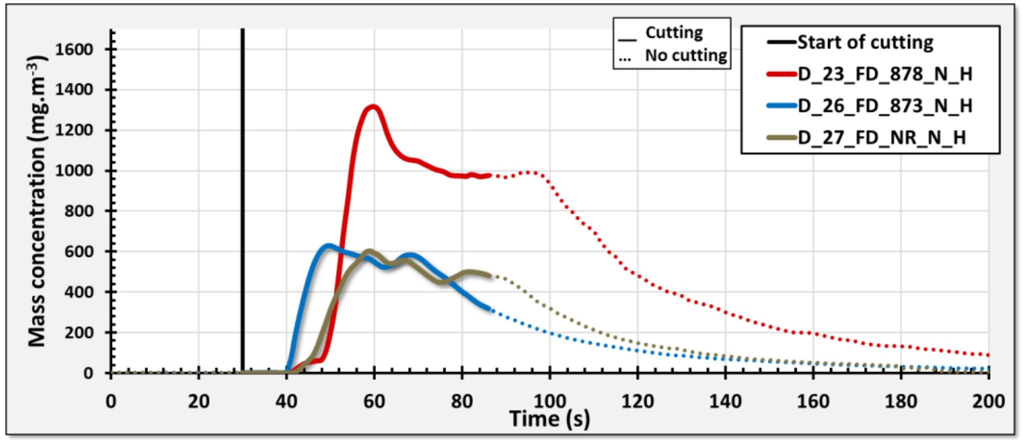
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

5. 6. 5. Aerosols metrology

Cutting tests on Fuel Debris simulant with humidity and Nitrogen





- Similar particle generation between non-coated Fuel Debris and coated Fuel Debris with resin FTV FA 873 during the cutting phase. Reduction of particles generation after for coated Fuel Debris.
- Important increase of particles generation for coated Fuel Debris with resin 878, both in number and mass.
  - Could be explained by the degradation of the resin RTV FA 878 by pyrolysis.

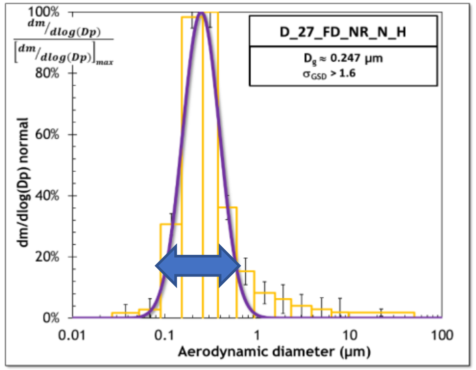
V. CUTTING TESTS – MEASUREMENT OF IMPACTS

5. 6. LASER CUTTING TESTS

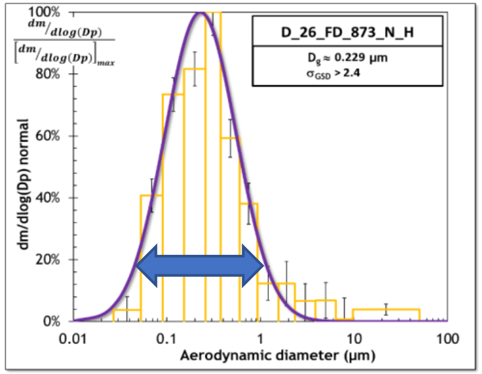
5. 6. 5. Aerosols metrology

Particles size distribution for laser cutting of Fuel Debris simulant with and without coating (humidity + Nitrogen conditions)

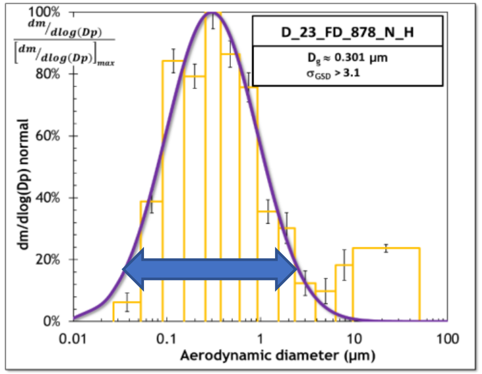
Fuel Debris without resin coating



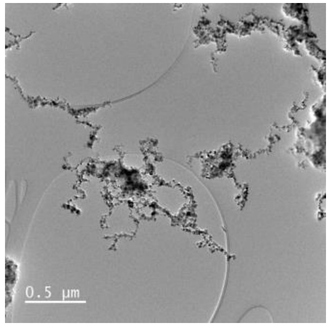
Fuel Debris with resin coating (RTV FA 873)

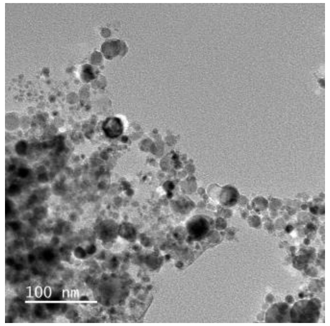


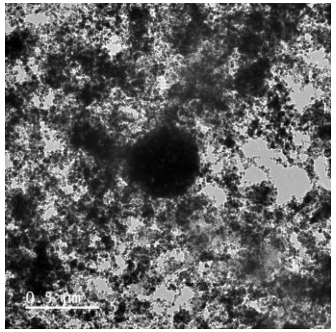
Fuel Debris with resin coating (RTV FA 878)

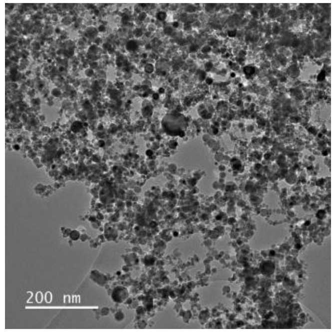


MET analysis for laser cutting of Fuel Debris simulant with and without coating (humidity + Nitrogen conditions









- **No significant evolution of the mass median diameter with resins coating compared to Fuel Debris only.**
- **Spread of the PSD increases with resins coating, especially for RTV FA 878.**
- **Particles morphology seems similar with and without resins.**
- **Resins degradation due to laser interaction may generate particles with same fractal morphology as Fuel Debris.**

VI. APPLICABILITY & OPERABILITY TESTS

6. 1. GENERALITIES

In order to determine whether a coating is suitable for a use on site, it is mandatory to ensure it is applicable under on-site approaching conditions. For that, applicability and operability tests have been scheduled. They are carried out in two separate phases. These two separate phases are meant to focus on the following:

1. Tests in BCSN facilities: tests are realized on a representative mock-up (see below) and with an automatic robotic arm. The objectives of this phase of tests are:
   i. To determine whether the selected coating are applicable and under which conditions of application
   ii. To set the correct parameters of applications depending the area and conditions of application
2. Tests in CEA Marcoule facilities: once the coating parameters have been set, then operability are carried out with a remote controlled robotic arm, with indirect vision. The objectives of the tests are:
   i. To assess the capacity of a remote controled arm to reach different positions
   ii. To assess the feasibility for a remote controled arm to realize a satisfaying coating operation
   iii. To determine the main constraint of operability on site (vision, determination of the quality of the coating, etc.)

PHASE 1: TESTS ON APPLICABILITY AND DETERMINATION OF OPERATIONAL PARAMETERS

PHASE 2: TESTS WITH REMOTE CONTROLED ARM AND UNDIRECT VISION TO DETERMINE THE OPERABILITY CONSTRAINTS

→ **PHASE 1 + PHASE 2 = GENERAL APPROACH FOR THE APPLICABILITY & OPERABILITY ON SITE**

VI. APPLICABILITY & OPERABILITY TESTS

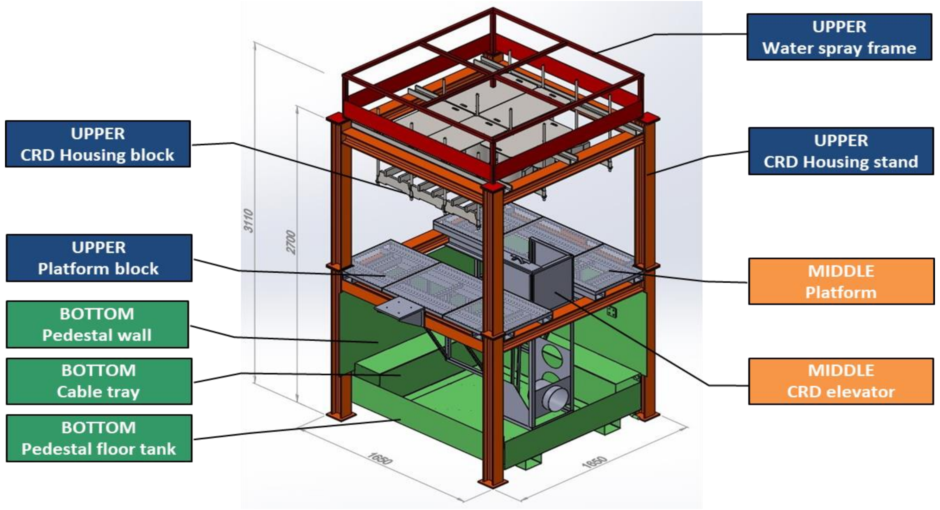
6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 1. Overview of the tests

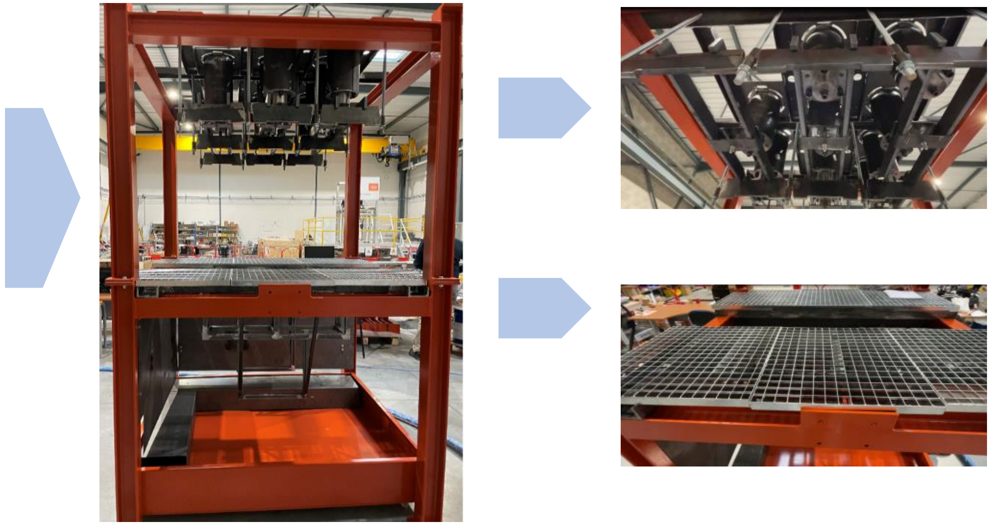
The objectives of the operability tests in BCSN facilities were to:

- Realize representative feasibility tests with selected resins on real size mockup
- Define parameters with a robotic arm to spread resin on each areas with a specific thickness
- Correlate these parameters and results with industrial representative reference tele-operated equipment

In order to carry the tests, a mock-up has been designed, manufactured and mounted into the test facility. In order to make it representative of the on-site environment, geometries and areas of coating application have been reproduced: a few CRD-H have been implemented, so have been gratings, beams, cable tray, etc. The bottom of the mock-up allows water retention, so it is possible to implement material representative of Fuel Debris (such as gravel for instance) and carry out coating tests under water. At the top of the mock-up (upper part), water spray has been implemented so it is possible to carry out spraying tests on upper and middle parts of the mock up with dripping water.



Design of the mock-up with the three identified areas as for the tests on the coating properties: upper, middle and bottom part. Upper and middle parts are in air with dripping water, bottom part can be either in air or underwater



Pictures of the mock implement in the test facility. A few representative elements of CRD-H have been implemented. Tests have also been carried out on gratings

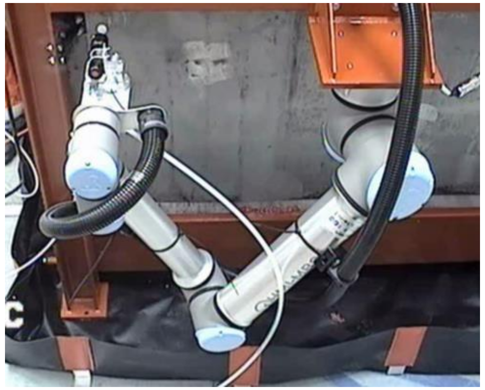
VI. APPLICABILITY & OPERABILITY TESTS

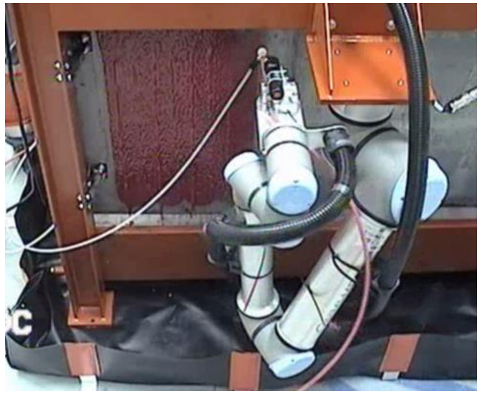
6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 1. Overview of the tests

The test equipment is composed of the following items:

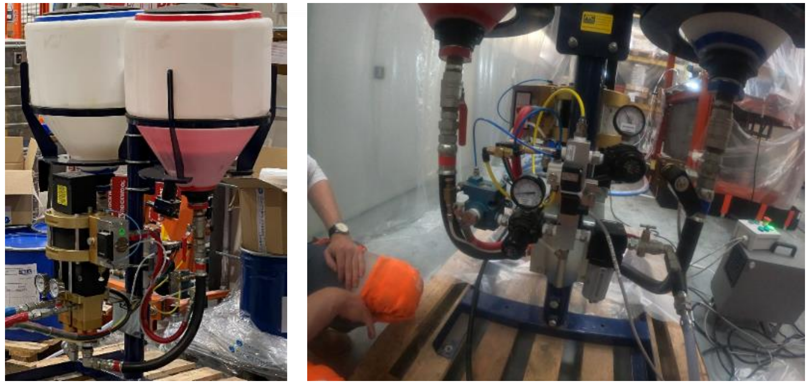
- One machine in which the coating is loaded and that pushes the coating into the spraying/injection system
- Flexible hoses which inner diameter is 13 mm
- One « gun » which purpose is to spray the coating after it has mixed the components (in the case the coating is a bi-component such as RTV FA 878)
- In order to properly determine and reproduce parameters of tests, spraying tests are carried out with the help of a robotic arm. In this way, it is possible to reproduce spraying movements (trajectories, speed)



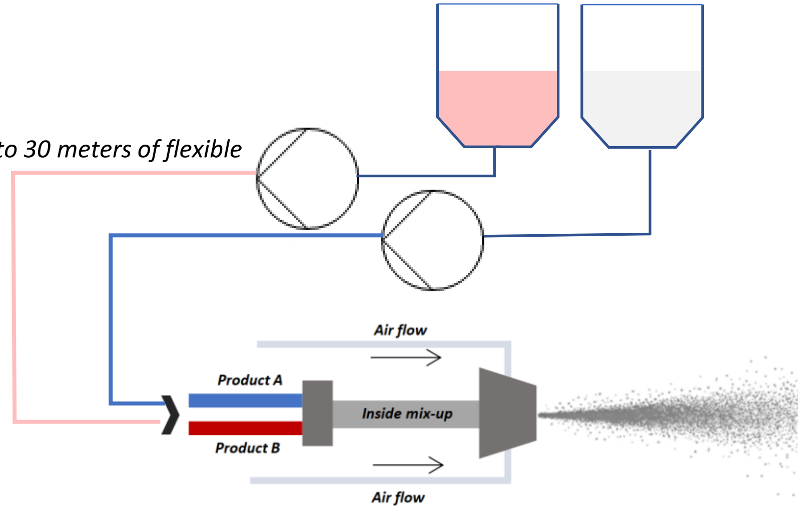


The objective of the tests can be summarized as following:

- Among the four coatings already selected for the tests, determine which one is more suited for each area/configuration of test
- Determine the most suitable manner to apply the coating depending on the different areas (injection vs spraying)
- Determine the best parameters of application for area/configuration of test: distance of application, application speed, number of necessary layers. **The main criteria to respect is to obtain a 2 mm thickness of coating**



View of the "Matrasur" spraying machine. The coating RTV FA 878 is composed of two components that are mixed together just before the spraying/injection



Principle of test equipment. The components are loaded and transported throught flexible hoses (up to 30 meters length). Spraying system needs compressed air

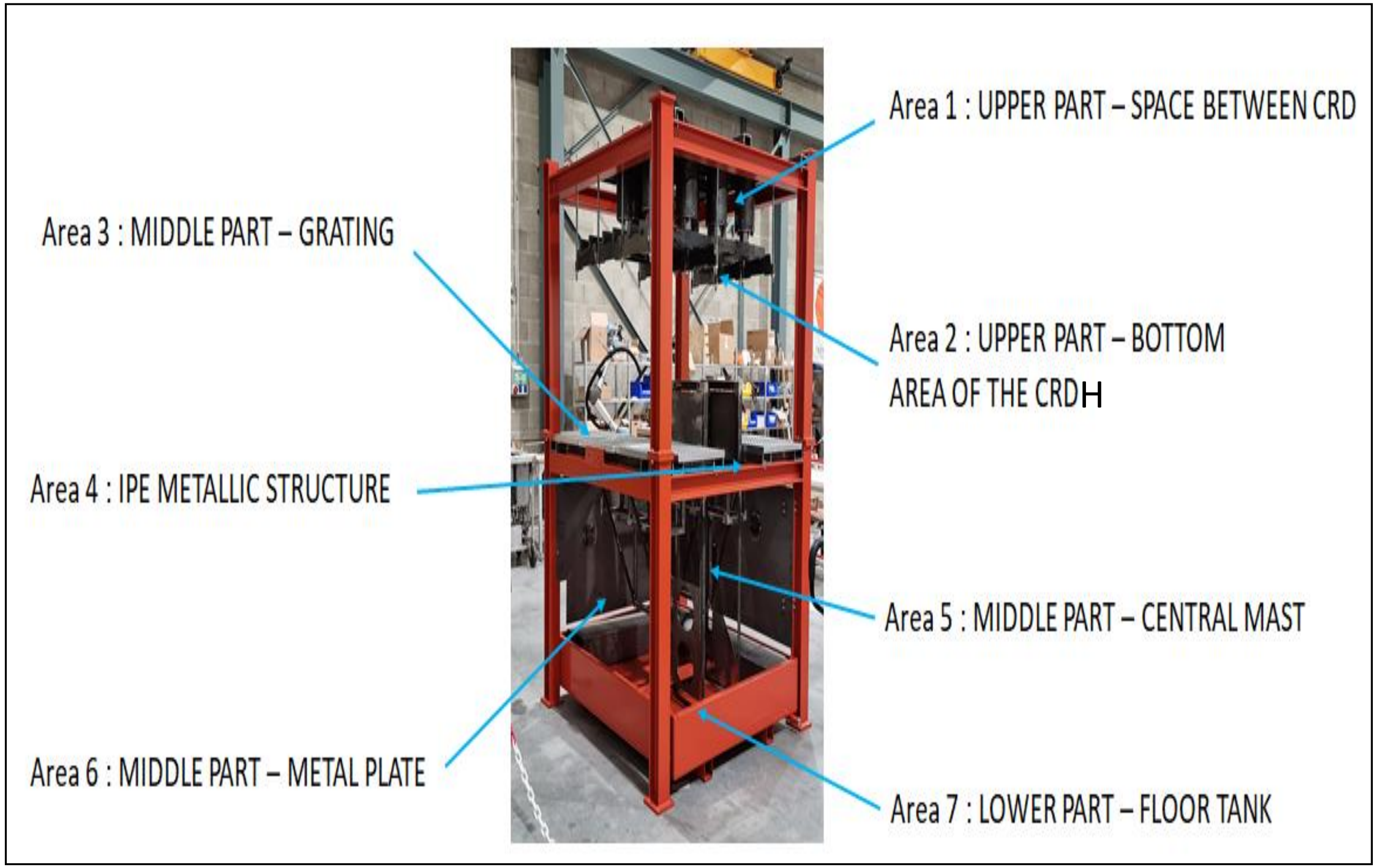
VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 2. Definition of the areas for operability tests – 7 mains areas tested

The mock-up present several elements whose characteristics are different. It has been divided in 7 areas. Indeed, coating parameters are different depending on the different areas:

- Area 1: Upper part – Space between CRDH. This area is composed of metallic and round items. This area needs to be sprayed, movement of the robotic arm must be circular
- Area 2: Upper part – Bottom area of the CRDH. This area is composed of metallic bars. It must be sprayed from below and above
- Area 3: Middle part – Grating. This area is very specific. Coating of gratings is specifically studied
- Area 4: I Beam (IPE) metallic structure. This part concerns all the metallic structures of the mock-up
- Area 5: Middle Part – Central mast. This area concerns a vertical metallic item with a complex geometry. Robotic arm movements have to be set accordingly
- Area 6: Middle Part – Metal plate. This area concerns a vertical metallic plate
- Area 7: Lower Part – Floor tank. This area represents the bottom of the pedestal. It can be filled with water to carry out underwater tests



VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 3. Preselection of coating depending on the area

At the end of the lab tests phase, 4 coatings were considered for the operability tests: the silicon coatings RTV FA 878, RTV FA 877 and RTV FA 873 for the upper and middle parts. They were also candidates for the bottom part alongside with the Epoxyguard coating.

Preliminary tests have been carried out on each coating and for each of the 7 areas described in section 6.2.2. The objective of these preliminary tests was to determine whether all the coatings are equally applicable or if one of them is better suitable compared to the others.

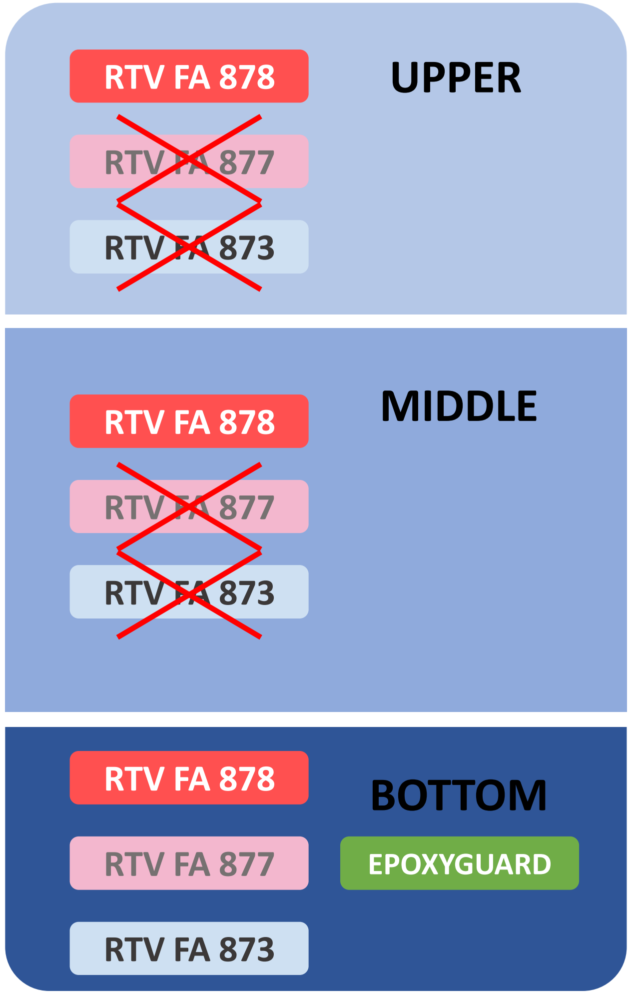
Spraying tests have been carried out on area 1 to area 6: many items of these areas are metallic and vertical. The parameters that were looked after were the following: capacity for a coating to be applied and realize a 2 mm thick coating, with viscosity and time of cross linking compatible with the application (in other words, preliminary tests to ensure that the coating can be applied on vertical surfaces, with effective parameters that will lead to a well covered surface. A bad result is a coating that continues to pour leading to poorly coated areas).

<u>Results of the preliminary tests:</u>

It is much more difficult to obtain satisfaying coating operations with the RTV FA 877 and RTV FA 873 compared to the RTV FA 878. Indeed, due to their viscosity, density, lack of grip and high pot life, when applied on vertical elements, RTV FA 877 and RTV FA 873 continued to pour. It was not possible to obtain an uniform coating. In order to make them efficient, it should have proceeded to modify their characteristices.

Therefore it has been decided, for areas 1 to 6, to focus the tests with RTV FA 878: this coating is the most appropriate because it has a short pot life (which is very convenient for this application) and has a natural high grip, for this application, there is no need to modify its characteristics.

For the lower part (area 7), all the 4 selected coatings have been tested and results are satisfying for all of them.



VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 4. Test results of Area 1: Upper Part – Space between CRD

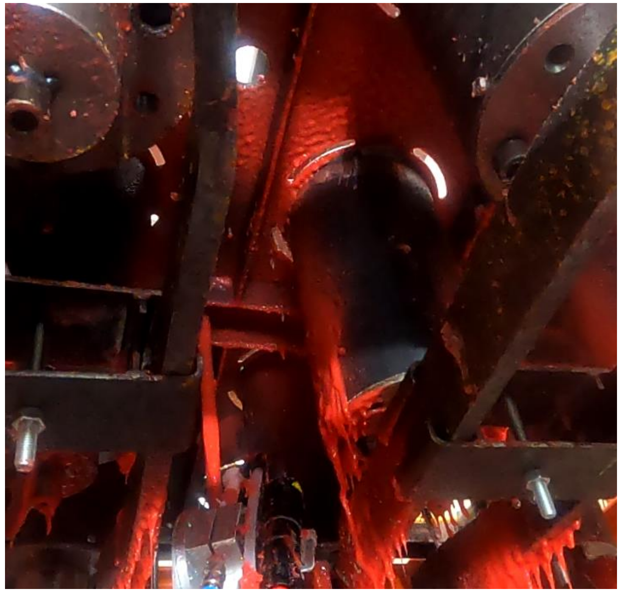
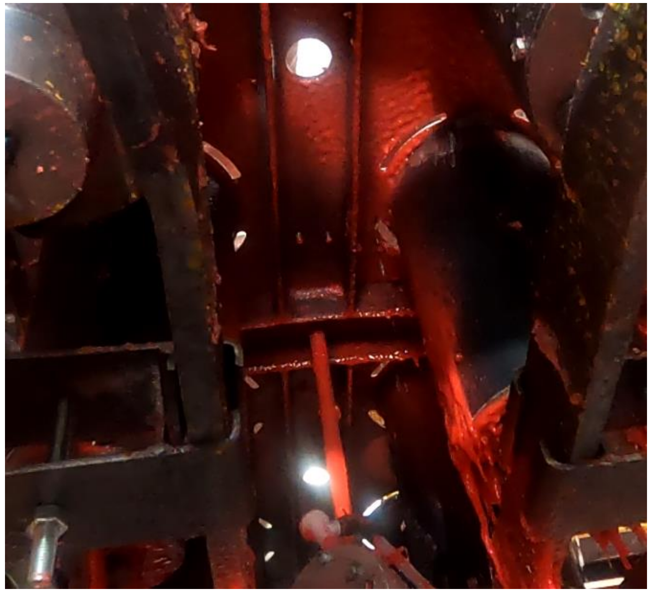
Configuration of tests:

- Coating: RTV FA 878
- Type of application: spraying
- Equipment: Spraying equipment + remote arm
- Machine used: Matrasur
- Distance between machine and spraying nozzle : 30 meters
- Environment: under dripping water

Characteristics of the area 1:

- Narrow space between CRD Housing
- Cylindrical shapes + specific elements: cables, threaded bars



Pictures illutrate the robotic arm was able to spray coating between the CRD-H and that all the surfaces are correctly coated with a 2 mm layer.

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

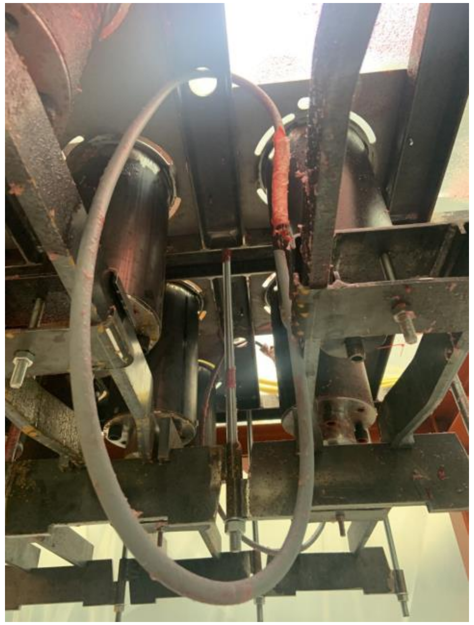
6. 2. 4. Test results of Area 1: Upper Part – Space between CRD

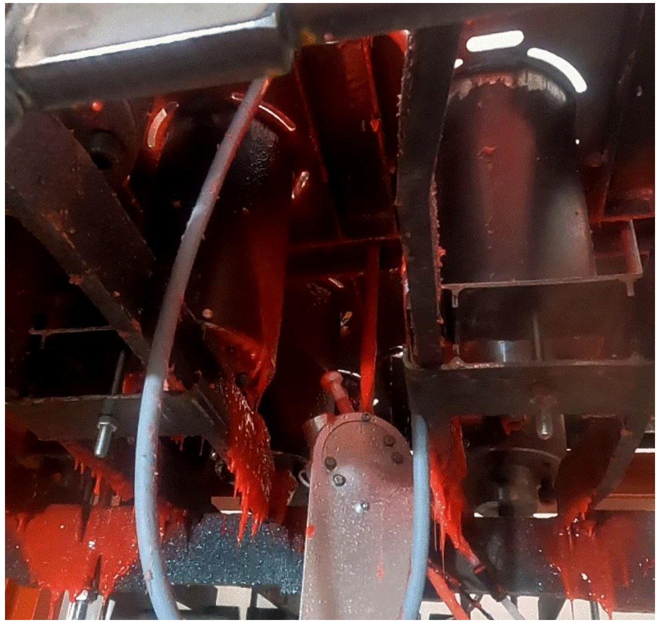
Main results for area 1:

- The full covering of cylindrical elements of the CRD has been achieved
- The coating covering is reproducible: it has been carried out for two different areas of area 1
- The full covering of the top metallic structure has been achieved
- The full covering of specific items such as cables and threaded bar has been achieved

Main parameters of the coating tests:

- Coating has been carried out with the RTV FA 878
- In order to ensure an effective coating, distance between spraying nozzle and the area to be coated must be between 5 cm and 15 cm
- Speed of application must be lower than 10 cm/s
- Number of layers = 3
- The average thickness measured is about 4.5 mm





Cable and threaded bar have also been coated

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

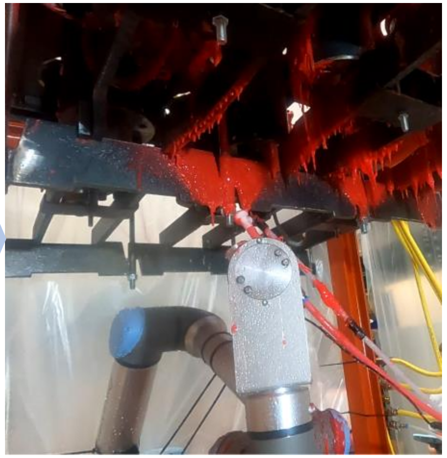
6. 2. 5. Test results of Area 2: Upper Part – Bottom Area of the CRD

Configuration of tests:

- Coating: RTV FA 878
- Type of application: spraying
- Equipment: Spraying equipment + remote arm
- Machine used: Matrasur
- Distance between machine and spraying nozzle : 30 meters
- Environment: under dripping water

Characteristics of the area 2:

- Flat vertical metallic part
- Horizontal suspended metallic parts
- Cylindrical shapes with screw (bottom of CRD-H)
- Specific elements: threaded bars



Pictures illustrate the robotic arm is able to properly cover vertical and horizontal flat metallic parts, the cylinders and the screw of the CRD bottom

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

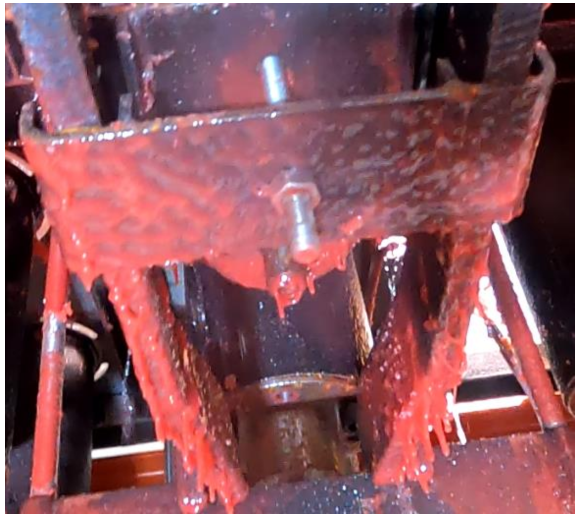
6. 2. 5. Test results of Area 2: Upper Part – Bottom Area of the CRD

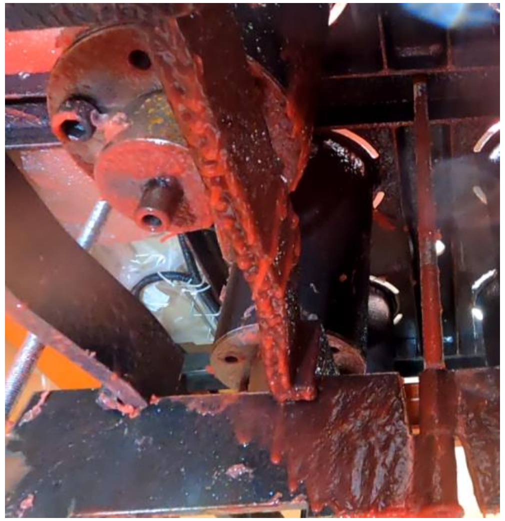
Main results for area 1:

- The full covering of flat metallic parts have been achieved
- The coating covering is reproducible: it has been carried out for two different areas of area 1
- The full covering of the cylindrical elements and screws have been achieved
- The full covering of specific items such as cables and threaded bar has been achieved

Main parameters of the coating tests:

- Coating has been carried out with the RTV FA 878
- In order to ensure an effective coating, distance between spraying nozzle and the area to be coated must be between 15 cm and 20 cm
- Speed of application must be lower than 10 cm/s
- Number of layers = 3
- The average thickness measured is about 3.5 mm





VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 6. Test results of Area 3: Middle Part – Grating

Configuration of tests:

- Coating: RTV FA 878
- Type of application: spraying
- Equipment: Spraying equipment + remote arm
- Machine used: Matrasur
- Distance between machine and spraying nozzle : 30 meters
- Environment: under dripping water

Characteristics of the area 1:

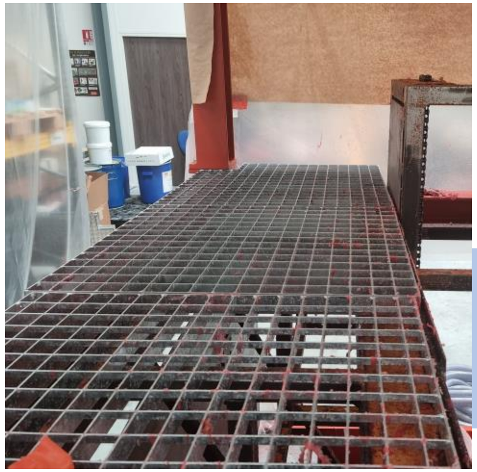
- Thin metallic structure
- Complex shape

Main results for area 1:

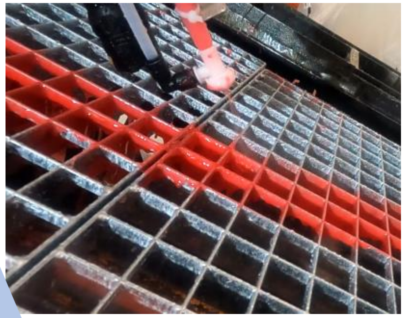
- All thin metallic parts are coated
- In order to cover all the gratings, it is necessary to carry out 3 layers of coating with different angles of application (+45°, 90° and -45°)
- 2 mm thickness of coating has not been reached

Main parameters of the coating tests:

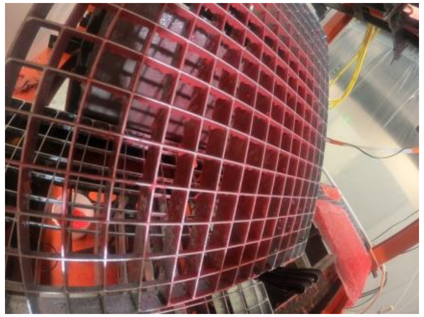
- Coating has been carried out with the RTV FA 878
- In order to ensure an effective coating, distance between spraying nozzle and the area to be coated must be between 15 cm and 20 cm
- Speed of application must be lower than 10 cm/s
- Number of layers = 3
- The average thickness measured is about 0.8 mm horizontally and 1.2 mm vertically



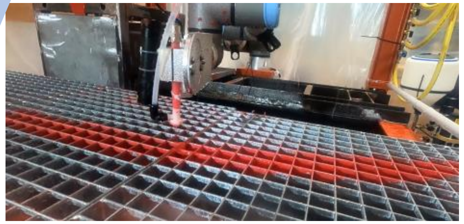
View before the tests start



Coating in progress



Global view after spraying



Coating in progress

Elementary shape after peeling

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

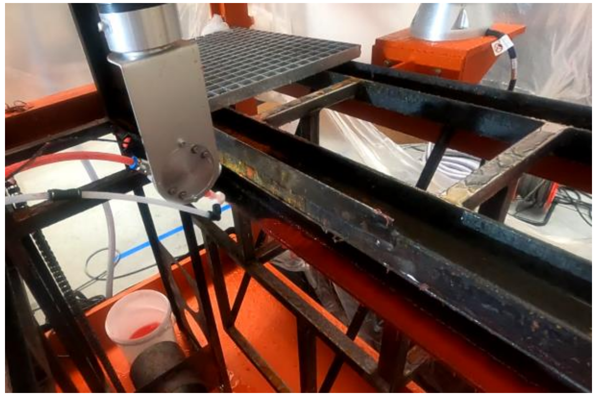
6. 2. 7. Test results of Area 4: Middle Part – I Beam Metallic Structure

Configuration of tests:

- Coating: RTV FA 878
- Type of application: spraying
- Equipment: Spraying equipment + remote arm
- Machine used: Matrasur
- Distance between machine and spraying nozzle : 30 meters
- Environment: under dripping water

Characteristics of the area 4:

- Horizontal metallic part with specific shape
- Geometrical shape presenting a retention of water (due to dripping water)
- Corroded items



View before the tests start

Main results for area 4:

- All metallic shape is covered
- Coating is effective not only on metallic parts but also with corroded items and IPE bars filled with water (retentions)

Main parameters of the coating tests:

- Coating has been carried out with the RTV FA 878
- In order to ensure an effective coating, distance between spraying nozzle and the area to be coated is about 5 cm
- Speed of application must be lower than 5 cm/s, Number of layers = 2
- The average thickness measured is about 3.2 mm

View after spraying

Coating after it has been pealed

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 8. Test results of Area 5: Middle Part – Central Mast

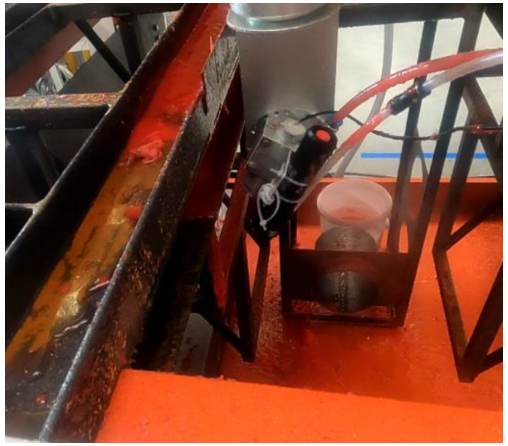
Configuration of tests:

- Coating: RTV FA 878
- Type of application: spraying
- Equipment: Spraying equipment + remote arm
- Machine used: Matrasur
- Distance between machine and spraying nozzle : 30 meters
- Environment: under dripping water

Characteristics of the area 5:

- Thin welded metallic structure
- Narrow space between metallic parts
- Complex element like mechanical chain

View before the tests start



With the remote arm, it is possible to spray entirely the area: it is capable to spray between narrow space and to cover all the faces of the structure

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 8. Test results of Area 5: Middle Part – Central Mast

On the main frame, all the faces are totally are covered

It is more complicated to cover such complex elements like vertical mechanical chain. However, because the coating pot life is short, it is still possible to encapsulate it

<u>Main results for area 5:</u>

- It is possible to coat all the items of the area (thin welded structure) as long as the robotic arm is capable to position the spraying nozzle

<u>Main parameters of the coating tests:</u>

- Coating has been carried out with the RTV FA 878
- In order to ensure an effective coating, distance between spraying nozzle and the area to be coated must be between 15 cm and 20 cm
- Speed of application must be lower than 10 cm/s,
- Number of layers = 2
- The average thickness measured is about 3 mm

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 9. Test results of Area 6: Middle Part – Metal Plate

Configuration of tests:

- Coating: RTV FA 878
- Type of application: spraying
- Equipment: Spraying equipment + remote arm
- Machine used: Matrasur
- Distance between machine and spraying nozzle : 30 meters
- Environment: without dripping water

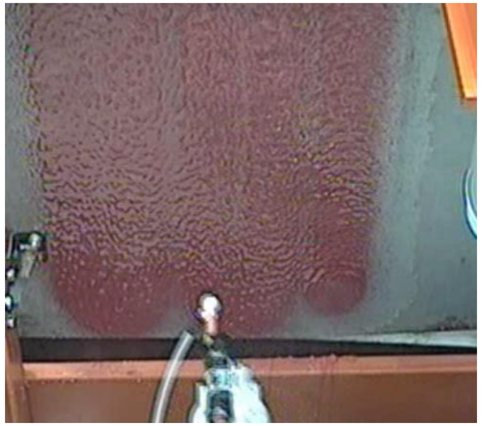
Characteristics of the area 6:

- Vertical wide metallic plate

Main results for area 6:

- The metallic plate is entirely coated. With this kind of geometry, it is possible to obtain an uniform thickness of coating

View of the area before the test start



Coating in progress – first layer

Coating in progress – second layer

Easily peeling after coating

Main parameters of the coating tests:

- Coating has been carried out with the RTV FA 878
- Distance between spraying nozzle and the area to be coated must be about 20 cm
- Speed of application must be lower than 10 cm/s, Number of layers = 2
- The average thickness measured is about 2.5 mm

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 10. Test results of Area 7: Lower Part – Floor Tank – RESIN RTV FA 878

Tests on the area 7 are representative of the bottom of the pedestal where many items may be found in addition to the molten Fuel Debris.
Also, the bottom of the pedestal is most likely to be filled with water.

Therefore, the specificities of the area can be described as following:

- The application of coating is carried out underwater. Water level is about 15 cm
- The application of coating is carried out and evaluated on 5 different types of debris:
    1. Concrete bloc: it is representative of molten Fuel Debris or concrete that could be encountered at the bottom of the pedestal
    2. Metallic parts: it is representative of items that could have fallen
    3. Sand: it is representative of sediments that be present at the bottom of the pedestal
    4. Gravel: it is representative of potential pieces of molten Fuel Debris
    5. Concrete pieces: it is also representative of concrete pieces that my be encountered at the bottom of the pedestal

4 coatings have been tested: RTV FA 873, RTV FA 877, RTV FA 878 and the Epoxyguard.

Criteria that are observed to determine whether the coating is efficient or not is its capacity of cross-link and encapsulate efficiently the different items. One effective coating must become solid and maintain the debris.
Coating is injected by pouring (using gravity) either with an injection machine or by hand. Each tests lasts 24 hours: it is the maximum time to consider the characteristics of the coating.

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 10. Test results of Area 7: Lower Part – Floor Tank – RESIN RTV FA 878

Illustrations of coating tests underwater with RTV FA 878 are given below (pouring by gravity with an injection machine, distance injection nozzle – debris around 5 cm):


Injection on concrete block

After 24h

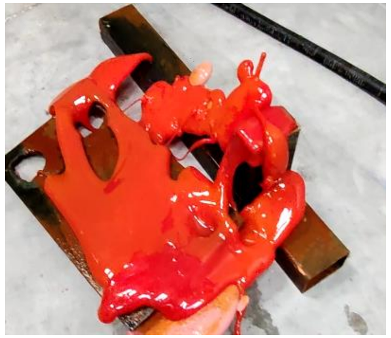
View of the coating

Observations:

The covering of the concrete block with RTV FA 878 is efficient. The resin does not pour too much, it grips properly.

It is possible to peel the coating. Small pieces are caught in the coating.


Injection on metallic parts



View of the coating

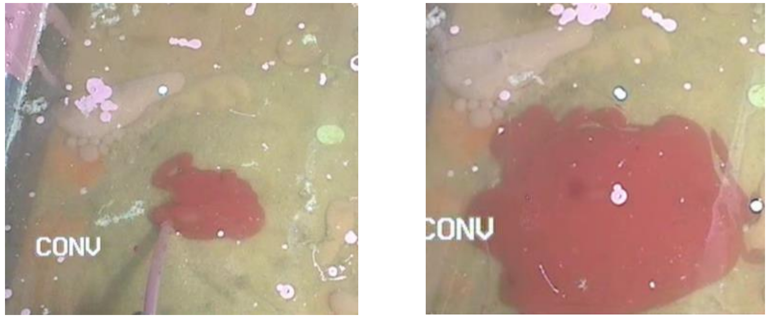
Observations:

The coating onto metallic surfaces is also satisfactory. The resin does not pour, the surface is covered

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 10. Test results of Area 7: Lower Part – Floor Tank – RESIN RTV FA 878



Injection on sand

View of the coating

Observations:
The coating of sand is efficient. When the coating is peeled, it can be seen that sand has been trapped.

Injection on gravels

View of the coating

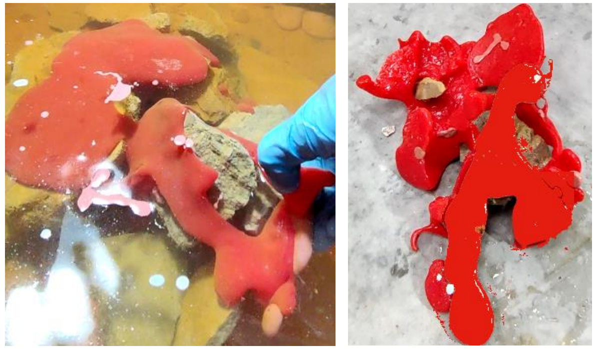
Observations:
The coating onto gravels is efficient. The surface is properly covered. Small pieces are trapped into the coating

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 10. Test results of Area 7: Lower Part – Floor Tank – RESIN RTV FA 878

Injection on concrete pieces



View of the coating

Observations:
The coating of sand is efficient on concrete pieces.

Conclusions about the RTV FA 878:

During the tests, it has been observed for RTV FA 878:

- The RTV FA 878 has a density near 1 (= water density). Nevertheless, when used with an injection gun and because it has a high and a short pot life, coating is efficient for all the items that represent debris
- Thanks to its viscosity (between the viscosities of RTV FA 877 and RTV FA 873) and its grip, the coating is effective and uniform with a ticjkness aournd 7 mm
- The RTV FA 878 capturs the little pieces of gravels

Applicability is considered for: 1) Concrete blocks, 2) Metallic parts, 3) Sand, 4) Gravel, 5) Concrete pieces

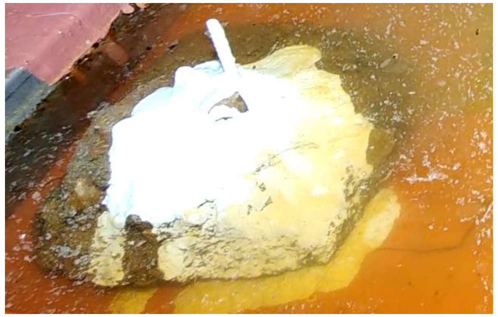
VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 10. Test results of Area 7: Lower Part – Floor Tank – RESIN EPOXYGUARD

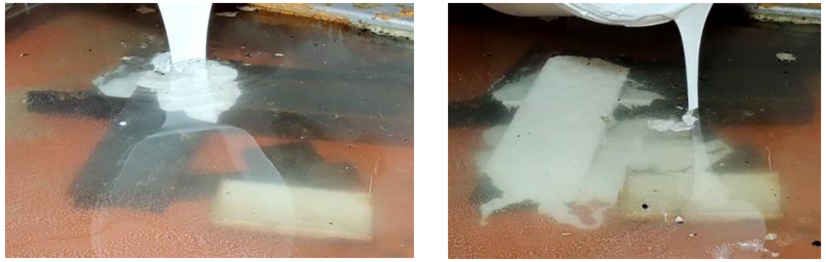
Illustrations of coating tests underwater with Epoxyguard are given below (manual pouring):

Pouring on concrete



View of coating

Observations:
The coating is effective, all the surface is easily covered. The Epoxyguard do not pour too much, it reticulates properly on the surface of the concrete block.



Pouring on metallic parts

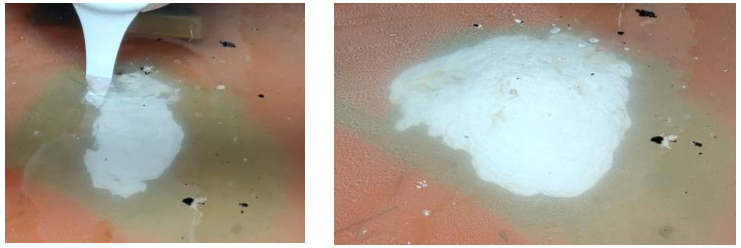
View of coating

Observations:
Same result is observed for the metallic surfaces.
However, the Epoxyguard solidifies, it is not possible to peel it after reticulation. The metallic parts are stuck together.

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

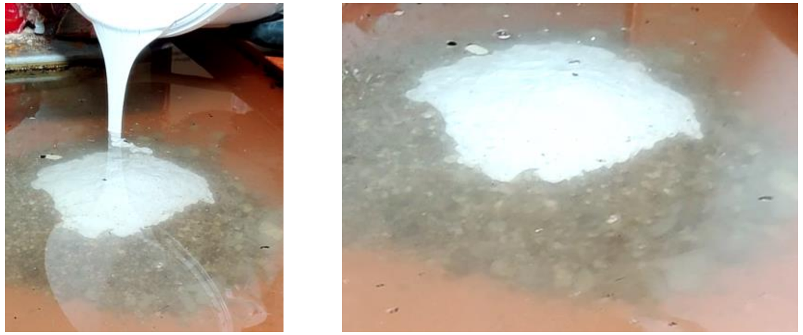
6. 2. 10. Test results of Area 7: Lower Part – Floor Tank – RESIN EPOXYGUARD



Pouring on sand

View of the coating

Observations:
The coating is effective. Sand in contact with the Epoxyguard is trapped in the coating.



Pouring on gravels

View of the coating

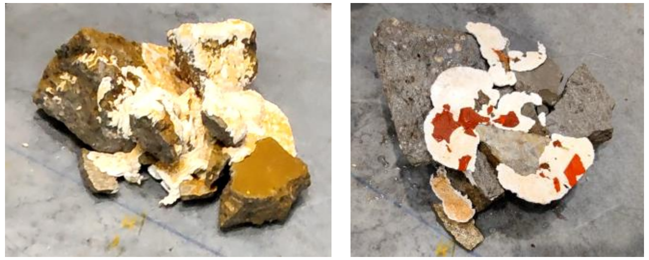
Observations:
Again, the coating is effective and the gravels are stuck into the coating.
The final coating is a solid block.

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 10. Test results of Area 7: Lower Part – Floor Tank – RESIN EPOXYGUARD

Pouring on concrete pieces



View of the coating

Observations:

The coating is effective. All the concrete pieces are tight together because of the coating.

Conclusions about the Epoxyguard:

During the tests, it has been observed for RTV FA 878:

- Epoxyguard has a high density, therefore it pours easily underwater
- It has a high grip and a high viscosity and therefore, the coating is effective for every kind of items representative of the debris
- The thickness of coating obtained is around 3 mm
- Epoxyguard capturs many little pices of gravels
- It is not possible to peal the coating after cross-linking, all the debris become compact and tight together by the resin

Applicability is considered for: 1) Concrete blocks, 2) Metallic parts, 3) Sand, 4) Gravel, 5) Concrete pieces

VI. APPLICABILITY & OPERABILITY TESTS

6. 2. APPLICABILITY TESTS IN BCSN FACILITIES

6. 2. 11. Main conclusions

At the end of this phase of tests, it is possible to present the following conclusions:

- Coating operations have been effective for all the areas with the RTV FA 878 which is a silicone coating and also with the Epoxyguard underwater
- It does not mean that this is the only product that has worked, but it clearly showed the best results
- Tests prove that with the correct spraying parameters and a good positioning of the spraying nozzle, coating can be done efficiently on all the considered surfaces of the pedestal

Concerning the applicability of the system, tests have proven that:

- An efficient coating can be carried out with an industrial machine such as Matrasur
- Diameters of flexible hoses remain thin, which means that their implementation on a robotic arm on site can be done without too much difficulties
- Tests have been carried out with a 30 meters length of flexible hoses. Tests have also been carried out with 50 meters of flexible hoses. Results were conclusive.

⇒ From these results, we can conclude that the applicability of the solution is proven

The next phase of tests (operability tests) will now focus on the functions that concern the remote controlled operations on site with undirect vision such as the vision, the verification of the effective coating, etc.

VI. APPLICABILITY & OPERABILITY TESTS

6. 3. OPERABILITY TESTS IN CEA MARCOULE FACILITY

6. 3. 1. General overview

Objective

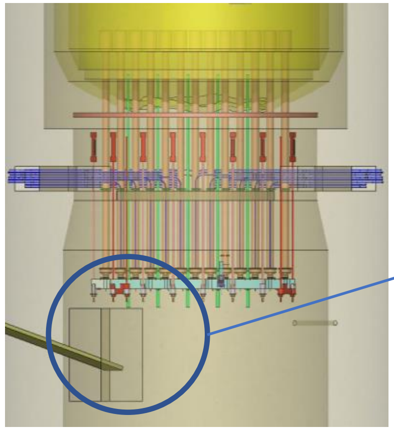
Objective is to perform coating spraying with industrial tele-operated equipment on a representative mock-up of the pedestal in order to evaluate performances and operational constraints. At the end of the tests, it shall be possible to give conclusions and leads for the design of an operational prototype.

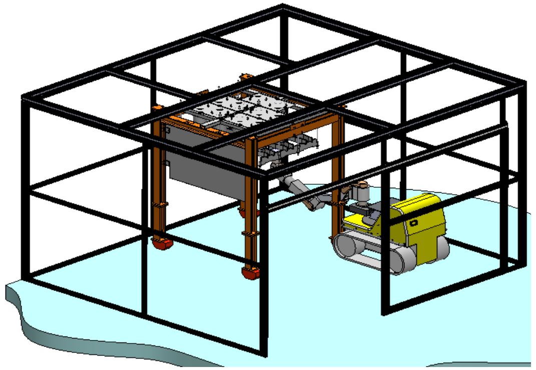
These tests have been carried out in LSTD CEA facilities at Marcoule site. They made it possible to:

- Verify the **operational implementation** of the spraying system with the **coverage rate**,
- Evaluate the **accessibility** of tele-operated and coating equipment inside PCV,
- Identify the **necessary technical improvements** for an **operational and remote implementation** of this process.

Experimental set-up: mock-up

The mock-up used for the tests is the bottom part already used for the first applicability tests in BCSN facilities. It has been implemented in an enclosure, made up of transparent walls which can be made opaque using curtains and whose dimensions are 4.5 x 4 x 2.5 m (L, W, H)





Overview of the test enclosure, meant to be representative of a part of the pedestal, under the CRD-H. Picture on the right shows it is possible to darken the walls with curtains

VI. APPLICABILITY & OPERABILITY TESTS

6. 3. OPERABILITY TESTS IN CEA MARCOULE FACILITY

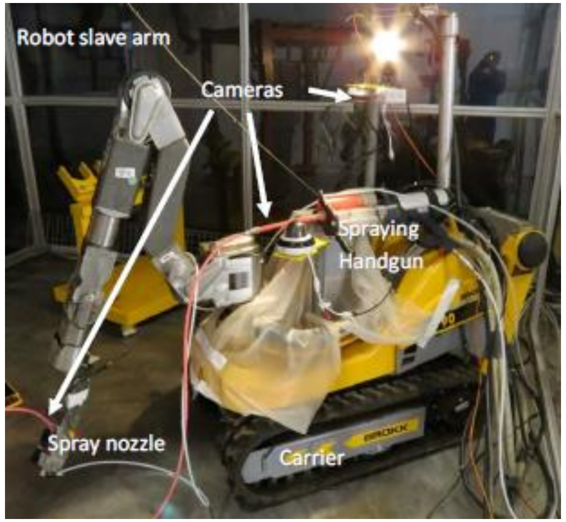
6. 3. 1. General overview

Experimental set-up: carrier, arm and operating equipment

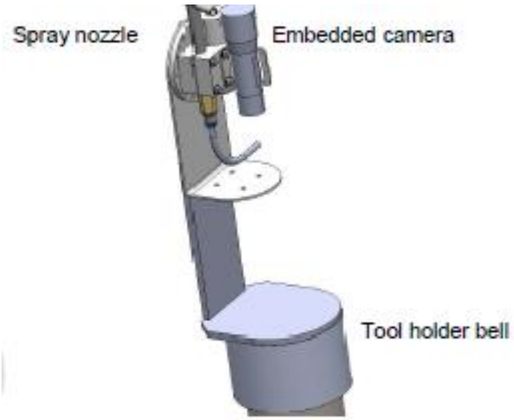
The carrier is a Brokk 90 mobile used for decommissioning work. It is remotely controlled by wire and moves on rubber tracks. A Maestro slave arm is implemented on the carrier: it is an hydraulic remotely operated robot arm with bilateral control allowing force feedback and with 6 degrees of freedom.

The spraying nozzle is implemented on the tool handler of the Maestro arm. Cameras are also implemented: two are implemented on the carrier Brokk, one is implemented close to the spraying nozzle. This set-up is considered to be representative of what could be implemented on site.

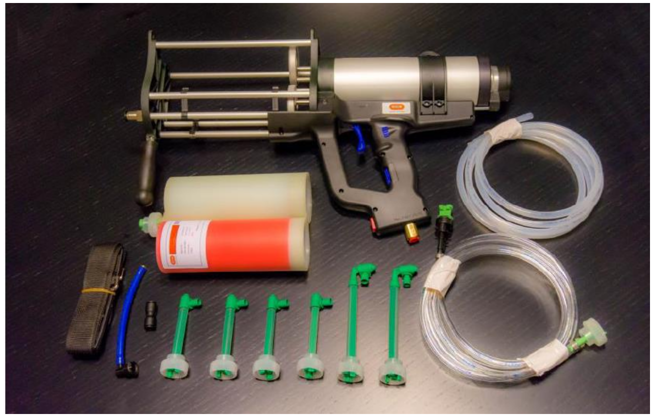
The spraying system has been simplified: it is composed of a spray gun implemented on the carrier. The mixing of the products A and B that compose the RTV FA 878 coating (coating that is used for these tests) is therefore done a few meters before the spraying nozzle.



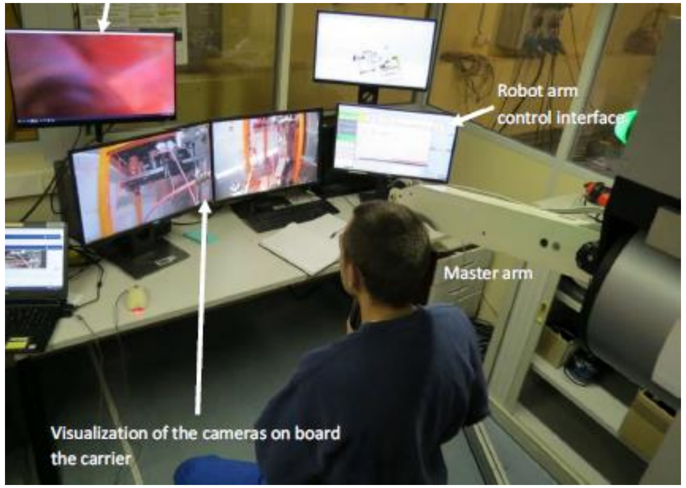
Carrier Brokk 90 mobile with implementation of Maestro slave arm, spraying handgun and cameras



Implementation of spray nozzle and camera on the tool handler bell of the Maestro arm



Spraying Handgun and accessories



Control room from which the operator drives the spraying equipment. Cameras and screens help him

VI. APPLICABILITY & OPERABILITY TESTS

6. 3. OPERABILITY TESTS IN CEA MARCOULE FACILITY

6. 3. 2. Methodology and tests program

Operating conditions:

- Tests have been carried out in the dark with undirect vision
- After each test, the performance criteria were quantified
- Tests are recorded in video camera
- Each test has been carried out in two phases: a first phase was performed to see which area is easy to reach, the second phase focus to the more difficult areas to reach

Preparatory phases:

- Setting up of the mock-up in the enclosure
- Preparation of cartridges (resin part A and part B + retardant)
- Setting a temperature of 12°C in an air conditioned chamber
- Implementation of cartridges on the remote controlled robot

Tests:

- Before each test starts, video recording is launched
- Test is carried out on the targeted areas, after compressed air has been opened for the spraying nozzle and for the cartridges
- Tests are stopped when a surface is fully covered or if the cartridge of coating is empty

Experimental set-up removal:

- After each test, coating is removed carefully from the mock-up. Percentage of coverage is evaluated, the thickness is measured

Tests program

- Preliminary tests are first carried out in order to determine most efficient parameters for the spraying
- Tests on determined areas of the mock-up are carried out with the determined parameters

VI. APPLICABILITY & OPERABILITY TESTS

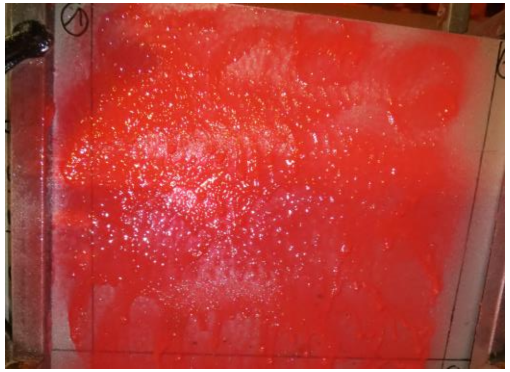
6. 3. OPERABILITY TESTS IN CEA MARCOULE FACILITY

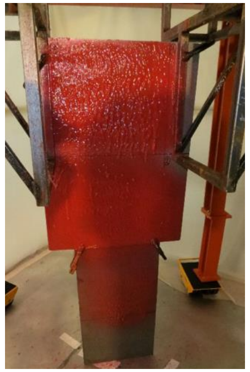
6. 3. 3. Tests results

1) Preliminary tests on a simplified mock-up

The first step has consisted in tests on a simplified mock-up (metallic plate). The objective of these preliminary tests was to determine the best parameters for the spraying operation with the tele-operated equipment. Spraying parameters are: displacement ratio, control assistance and moving speed of the slave arm, compressed air pressure, distance between the spraying nozzle and the mock-up. For that, after each test several measurements have been done: thickness of coating deposited (mm), behavior of coating after dying (???), percentage of surface covered with a minimum of 2 mm thickness (measurements have been done with a digital thickness gauge after the coating has dried). Preliminary tests also aimed at verifying that the vision system is sufficient and effective.

Mock-up with remote controlled arm with spraying nozzle implemented





View of the coated metallic plate

Coating removed from mock-up for thickness measurement

__Conditions of most successful tests:__
- *Temperature of RTV FA 878 coating maintained at 12°C before use*
- *Hose diameter = 10 mm*
- *Compressed air for pneumatic spray handgun (for pushing the coating through hose) = 6/7 bars*
- *Compressed air for spray nozzle (air injection for spraying) = 3 to 5 bars*

Tests results:

A thickness not less than 2 mm on the totality of the vertical metallic plate has been obtained with the following parameters (average of coating thickness = 3.7 mm):
- Linear motion speed lower than 2 cm/s
- Spray distance between 20 and 30 cm (control assistance of robotic arm has been used in order to block degrees of freedom and therefore ensure flat movement)
- 3 passes of coating are needed
- Displacement ratio of 0.5 (meaning that when the operator moves the master arm by 10 cm, the slave arm moves by 20 cm)

VI. APPLICABILITY & OPERABILITY TESTS

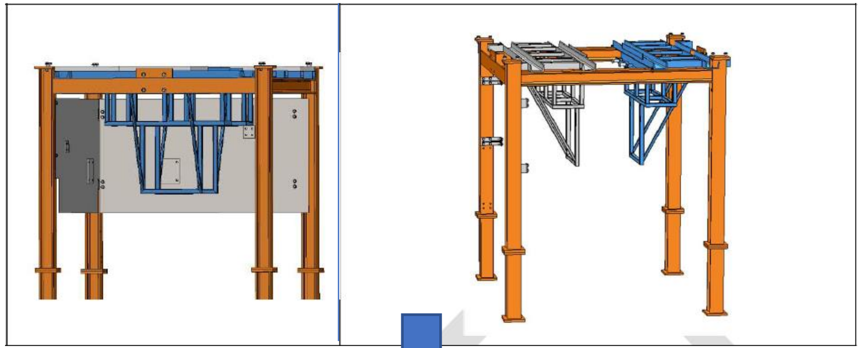
6. 3. OPERABILITY TESTS IN CEA MARCOULE FACILITY

6. 3. 3. Tests results

2) Spray tests on a representative mock-up

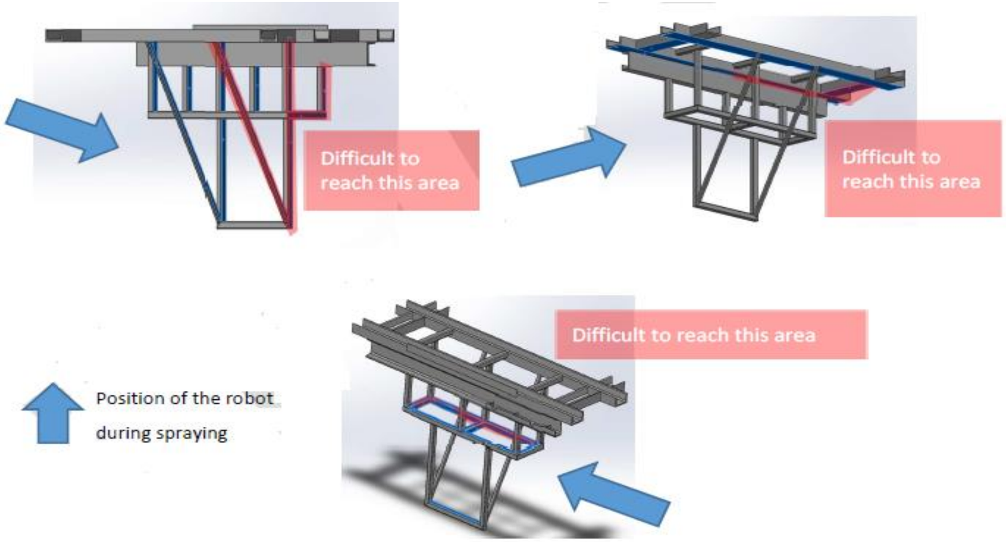
Spraying tests have been achieved on representative parts of the mock-up. Following slides illustrate the tests. Here are presented the tests on the mast supporting structure.
Parts that are targetted are highlighted in blue.

Mast supporting structure



Tests results:

Spraying test has been carried out two times. Percentage of covered area (target) was about 67% and 57%.
Average thickness was 1.12 mm and 1.74 mm.
Front surfaces have all been reached. However, surfaces at the rear faces were not. Indeed, it is difficult these areas with the experimental set-up (robotic arm with three articulations)



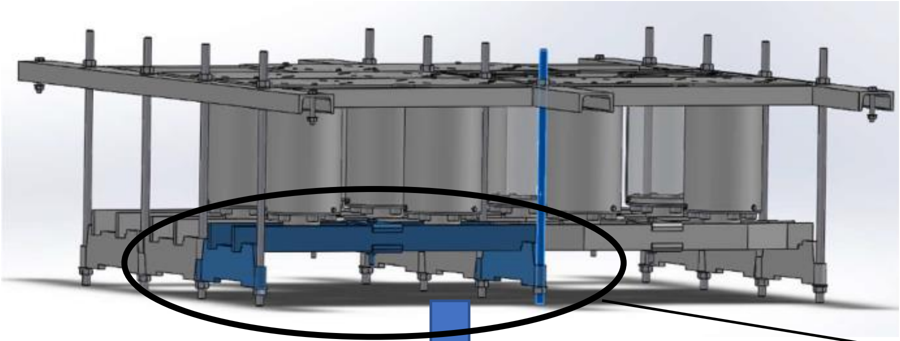
VI. APPLICABILITY & OPERABILITY TESTS

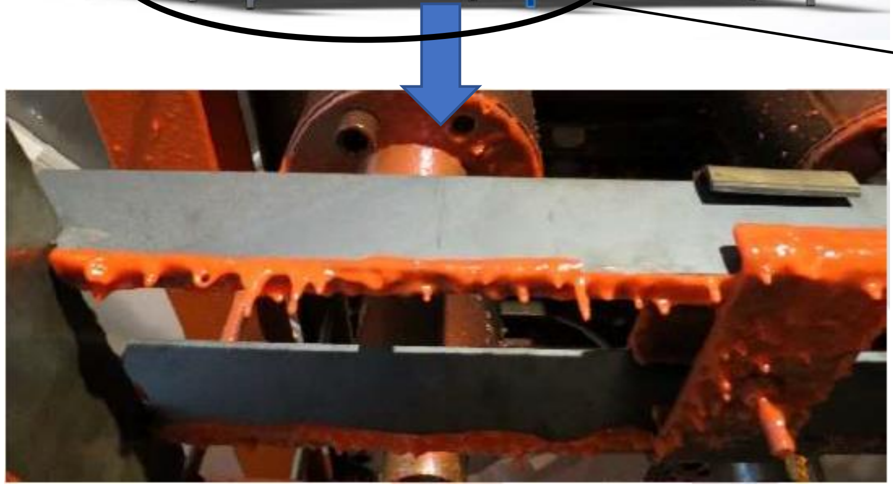
6. 3. OPERABILITY TESTS IN CEA MARCOULE FACILITY

6. 3. 3. Tests results

2) Spray tests on a representative mock-up

Lower part of CRD-H

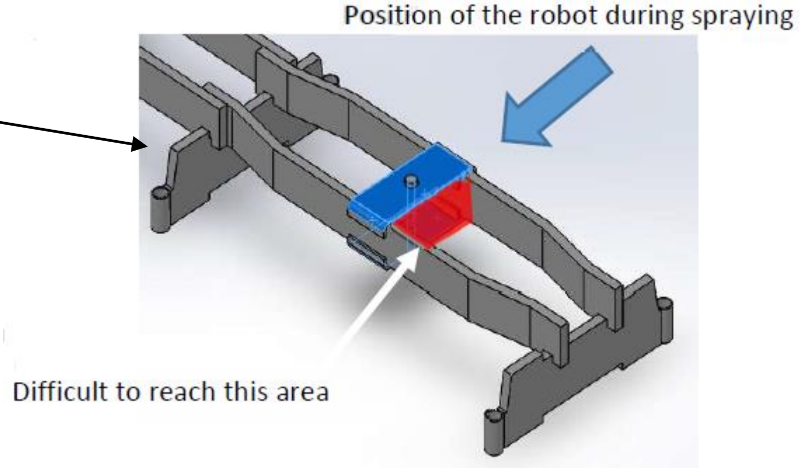




Tests results:

Spraying test has been carried out two times. First test targeted reached 60% coverage with a full coverage of front faces. Average thickness was 1.5 mm and 1.35 mm. Second test focused more on the rear surfaces and inner and upper surfaces. Percentage of coverage reached 84% with an average thickness of 1.35 mm.

Again, some surfaces were difficult to reach:



Lower part of the representative mockup of Control Rod Drives area

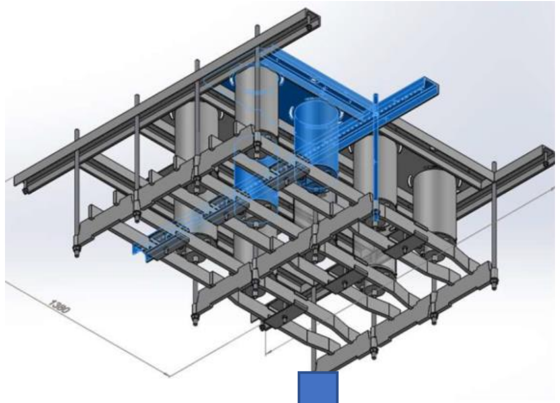
VI. APPLICABILITY & OPERABILITY TESTS

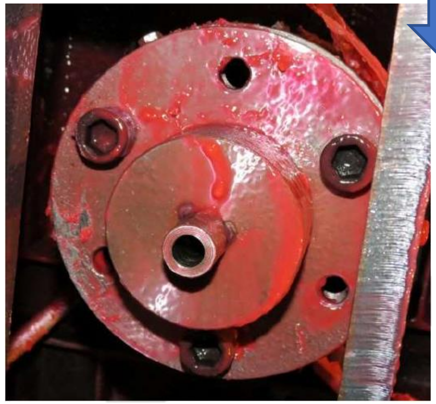
6. 3. OPERABILITY TESTS IN CEA MARCOULE FACILITY

6. 3. 3. Tests results

2) Spray tests on a representative mock-up

Cylindric part of CRD-H:





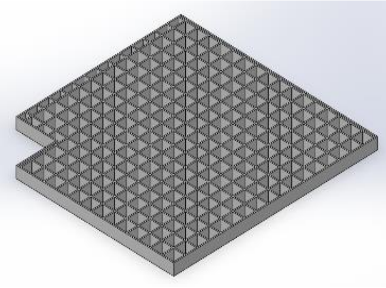
Tests results:

It was carried out 4 tests for the cylindrical part of CRD:

- The first two tests did not give satisfactory results on spray thicknesses because there has been a premature cross-linking in the hoses.
- The last two tests really worked correctly with a spray that lasted over 40 minutes and 100% of the mock-up could be covered with the average thickness of 1.5 mm. For the last test, 3 cartridges were used, i.e about 4.2 L of resin.

The parts between the cylindrical part of CRD are more difficult to access but it is still feasible. To obtain these results, the robot arm came into contact several times with the mock-up.

Grating:



Tests results:

It was carried out 2 tests :

- For the first test, the spraying of the resin was made in several passes with first a vertical position of the nozzle, then an inclination to the left, to the right, forwards and finally backwards. Two thirds cartridges were used. 100% of the mock-up was covered with an average thickness of 0.98 mm.
- For the second test, the area was reduced which has improved the average thickness (100% for 1.3mm).

VI. APPLICABILITY & OPERABILITY TESTS

6. 3. OPERABILITY TESTS IN CEA MARCOULE FACILITY

6. 3. 3. Tests results

2) Spray tests on a representative mock-up

Summary of results

The table below summarizes the results of the tests in terms of coating performances (surface covered and average thickness reached)

Mock-up	Surface covered (%)	Average thickness (mm)	Comments
Cylindrical part of CRD	100	1,52	Difficult access to the rear of the cylindrical part of the CRD but feasible
Lower part of CRD	84	1,35	Part between the two metal blades is difficult to access but seems to be feasible with a lot of resin
Mast supporting structure	67	1,12	Parts at the back of the mock-up are inaccessible with the robot arm used
Grating	100	1,3	No difficulties noted
Bottom and side wall	100	3,11	No difficulties estimated

VI. APPLICABILITY & OPERABILITY TESTS

6. 3. OPERABILITY TESTS IN CEA MARCOULE FACILITY

6. 3. 4. Advice for the implementation of the resin process with remotely operated equipment

Sub-set	Advices
Nozzle spray	Add a motorization operated from the cockpit to ensure a change of spray angle to improve coverage and accessibility of the resin spray Use of a nozzle with either very rigid materials to resist to accidental contact with the robot arm and the mock-up or elastic to absorb shocks Develop an all-in-one nozzle with support, camera and air supply.
Flexible tubes	Integrate the hoses into the robot arm or to provide a flexible sleeve adapted to the robot arm and to these hoses.
Spray Handgun	Have control of the spray handgun in the cockpit Lower the distance between mixer of products A and B and the spraying nozzle. Study solutions to make cartridge replacement teleoperable
Arm robot	Select an arm that has a payload 5kg with a small footprint, with good force feedback sensitivity, with a minimum extension of 1.8m, that is easily decontaminated or protected by a sealing sleeve
Carrier	Have control of carrier in the cockpit
Supervision/camera	Investigate solutions for remote cleaning of camera lenses Add an ambient camera to avoid shadow areas or interpretation problems Improve steering aids to ensure the correct thickness of resin coverage
Control-command	Use a Cartesian control or have an isokinetic master and slave arm system with an articular control Improve the management of resin thickness and coverage, control laws must be implemented by adding external sensors.
Operating Mode for the resin elaboration	Make the resin preparation phases more reliable and adapt it to the quantities required to cover the mock-ups correctly.

VII. ASSESSMENT OF IMPACTS

7. 1. GENERALITIES

Objective
Global assessment study of coating including impact on systems and equipment, safety analysis and waste management .

Description
The impact study will include three kinds of analysis :

- **An analysis for systems and equipment identified as IMPACTED BY COATING (7.2) like**:
  - ❑ AIR FILTRATION SYSTEM
  - ❑ LIQUID FILTRATION SYSTEM
  - ❑ PUMP USED TO RETRIEVE FUEL DEBRIS PARTICLES
  - ❑ DRYING SYSTEM
- **A SAFETY ANALYSIS (7.3) and careful consideration about**:
  - ❑ CRITICALITY
  - ❑ GASES EMISSION
  - ❑ FIRE RISK
  - ❑ HEAT MANAGEMENT
- **A WASTE MANAGEMENT ANALYSIS (7.4)**

Methodology about systems and equipment identified as IMPACTED BY COATING:
- ❑ Identification of the possible impact on the equipment
- ❑ Reminder of results from tests about each possible impact
- ❑ Analysis about the real impact expected

Methodology about SAFETY ANALYSIS:
- ❑ Identification of the origin of the risk
- ❑ Reminder of results from tests about
- ❑ Analysis about the level and the management of the risk

Methodology about the WASTE MANAGEMENT:
- ❑ Identification of waste classification for coating depending on threshold values about radiological activity coming from contamination.
- ❑ Analysis of coating impact in the waste for mid- and long-term disposal based on French experience.

This assessment is based on some assumptions and limited by the current stage of other studies. For each case where the assessment could not conclude, some possibilities are proposed to be studied at a later stage.

VII. ASSESSMENT OF IMPACTS

7. 2 IMPACTS ON SYSTEMS AND EQUIPMENT

4 identified systems

In the frame of the project, 4 systems and equipment have been identified to be potentially impacted by the use of coating inside the PCV:

- Air filtration system: due to the spraying of coating, and the cutting of coated equipment, airborne particles could affect the filtration systems in air
- Liquid filtration system: when applied underwater, coating may generate particles that could impact the liquid filtration system
- Pump used to retrieve Fuel Debris particles in water: same as for the liquid filtration system
- Drying system of Unit cans: because the process of heating could modify the chemical structure of the coating and lead to gas release

⇒ **Studies and tests carried out in the frame of the project proved that, for the three first points above, the system and equipment identified are not affected by the use of coating**
⇒ **However, concerning the drying system of Unit cans, further tests have been carried out**

Drying system & gas release under high temperature

The drying system is based on a temperature rise to 200°C and blowing or vacuuming for several hours. The risks identified are related to a modification of the physical characteristics of the resin (softening and melting, liquefaction) and to the emission of gases potentially caused by this treatment. The risks associated with the drying system are:

- Reduction in drying efficiency,
- The release of gases not foreseen by the gas treatment process (type of gas or quantity too high)
- The creation of an airtight barrier preventing the escape of the gases produced over time.

The data needed to analyse these risks is related to the behaviour of the resin at 200°C: observation of the physical changes of the resin (visual and viscosity measurement) as well as an analysis of the gases released by the resin.

Tests were carried out so it has been possible to assess the behavior of the resin under high temperature and irradiation. (See « Physical proprieties » in chapter 3: Selection of coatings). Results showed no softening and melting or liquefaction for RTV 878 and epoxyguard coating. Coatings seem to be harder with the rising of the temperature.

The gas released analysis is presented in the following pages. Several tests were carried out and gases are emitted from the coating under heat rising or irradiation

Conclusion:

Resins have a low impact on the drying system. As the resin becomes harder as it dries, there will be no formation of a waterproof barrier as a result of softening or liquefaction. Furthermore, this behavior should not reduce the drying efficiency. However, the gases emitted by the resin during the drying process must be taken into account for the sizing of the equipment.

VII. ASSESSMENT OF IMPACTS

7. 3 SAFETY ANALYSIS

7. 3. 1. Gases emission

Origine:

Preliminary tests showed that resins generate gases under high temperature and irradiation.
The gases come from the degradation of the resins components.
Depending on the kind of gases, the emission could lead to different kind of risk:

- An explosion risk for explosive gases,
- A risk of toxic gas spread
- A risk of overpressure when the waste is in a tight container

The results of the analysis must be taken into account for all equipment related to the gas emitted by waste (for instance: gas filter size, ventilation of PCV and all room where waste could be stored, assessment of overpressure for the transport step)

To analyze the gas rate, resins (RTV 878 and Epoxy guard) were heated or irradiated.

Tests realized:

- Measurement of the following gas rate under heating at 200°C : Hydrogen (H2), methane (CH4), carbon dioxide (CO2), and main Volatil Organic Component (VOC).
- Measurement of COV and H2 gas rate under irradiation (1 kGy/h for a cumulated dose of 1 MGy)

Methodology:

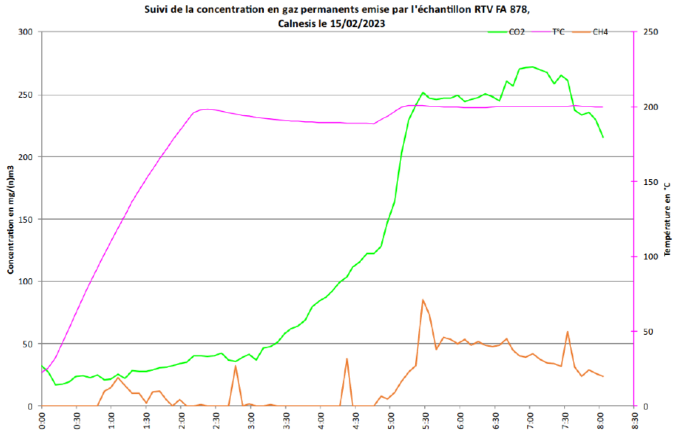
- Samples are implemented in a thermo degration vessel of a tubular furnace.
- Thermal programmation of the furnace is: heating ramp from 20°C to 200°C during 3 hours (1°C/min) then 5 hours of heating at 200°C leading to 8 hours of analysis.
- An air flow goes through the vessel continously, 1 analyse of gas composition inside the vessel is carried out every 6 minutes.

VII. ASSESSMENT OF IMPACTS

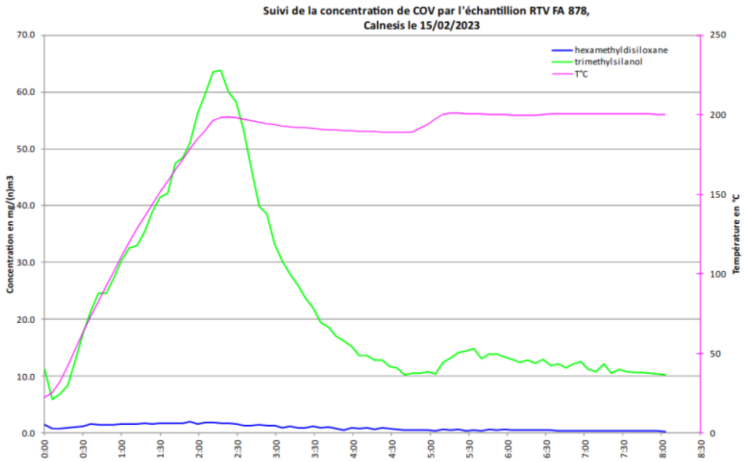
7. 3 SAFETY ANALYSIS

7. 3. 1. Gases emission under 200°C heating

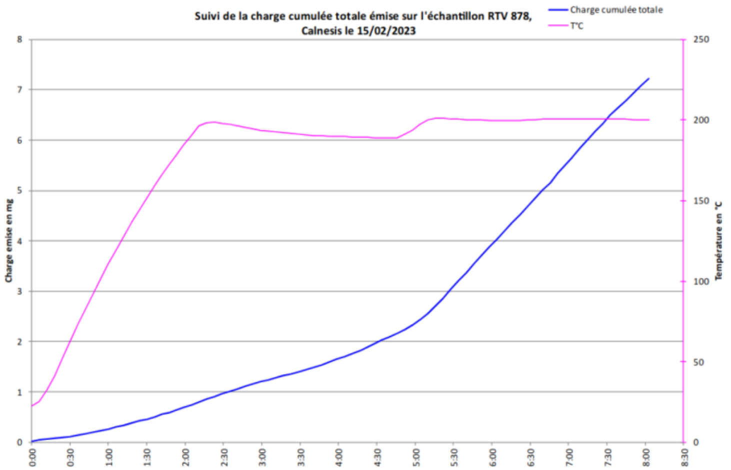
Results of measurement for **RTV FA 878** of the following gas rate under heating at 200°C (8 hours with a ramp up) : Hydrogen (H2), methane (CH4), carbon dioxide (CO2), and main Volatil Organic Component (VOC)



CO2 and CH4 generation over the time



VOC generation over the time



Global mass flow over the time

Synthesis:

Composé	Charge émise *mg*	*mg/g d'ech.*	*% massique de la charge %*
CO2	5,51	0,49	76 %
CH4	0,67	0,06	9 %
H2	<0,01	<0,001	<0.1%
Trimethylsilanol	0,99	0,09	13,7%
Hexamethyldisiloxane	0,04	0,004	0,6%
Total	7,21	0,63	100 %

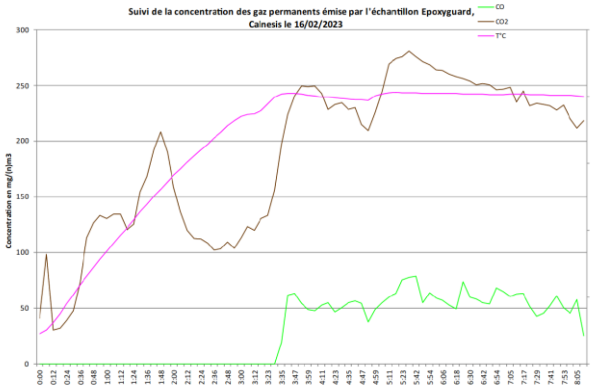
Measurements show that the gases emission of the resin is very low. The most part is coming from CO2. A little amount of CH4 is emitted an no hydrogen is detected. For VOC, only two components are detected. We can observe a start of decrease in the mass flow of the cumulated gas production over these 8 hours of test.
Thes data represent a starting point regarding gas emission during storage. It would be interesting to perform such kind of tests but on a longer period to confirm gas emission from resin addition should not be an issue for storage and even more for disposal phase.

VII. ASSESSMENT OF IMPACTS

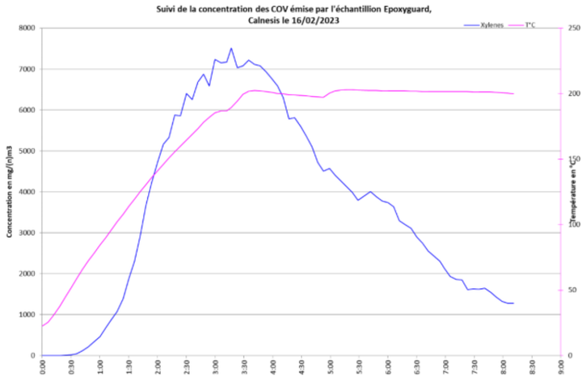
7. 3 SAFETY ANALYSIS

7. 3. 1. Gases emission under 200° C heating

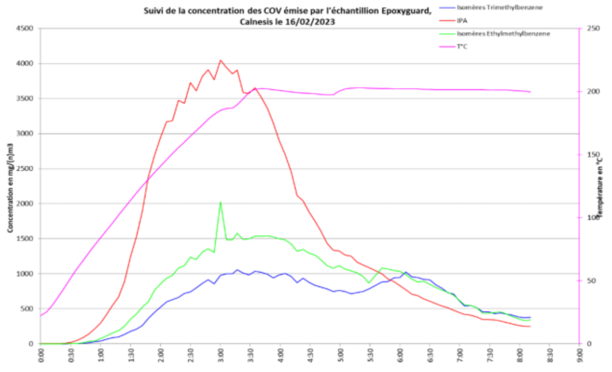
Results of measurement for **Epoxy coating** of the following gas rate under heating at 200°C : Hydrogen (H2), methane (CH4), carbon dioxide (CO2), and main Volatil Organic Components (VOC)



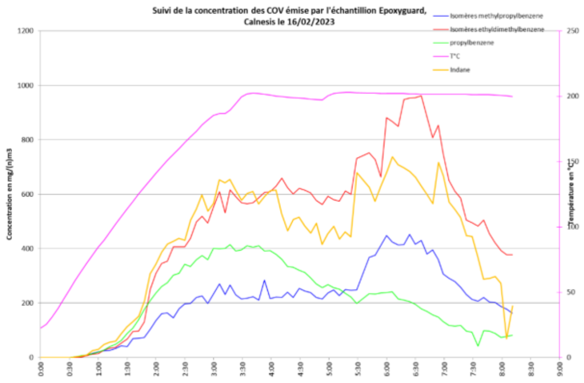
CO2 and CH4 generation over the time



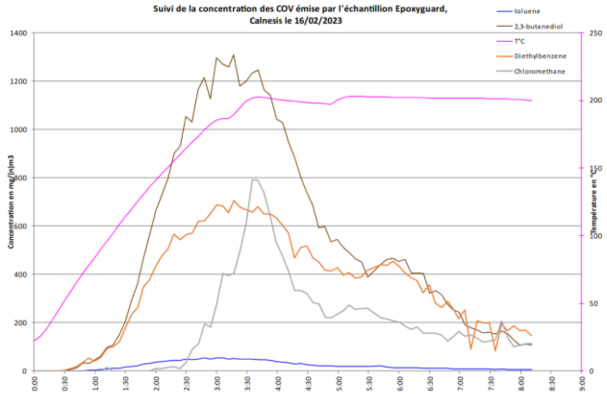
VOC generation over the time



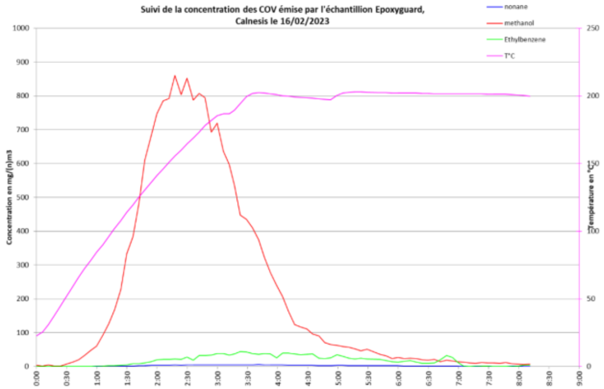
Global mass flow over the time



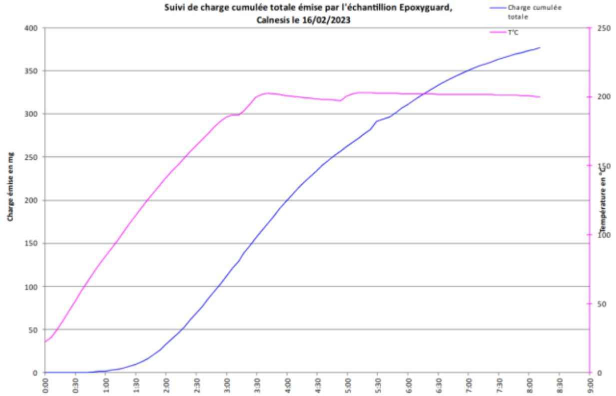
VOC generation over the time



VOC generation over the time



VOC generation over the time



Global mass flow over the time

VII. ASSESSMENT OF IMPACTS

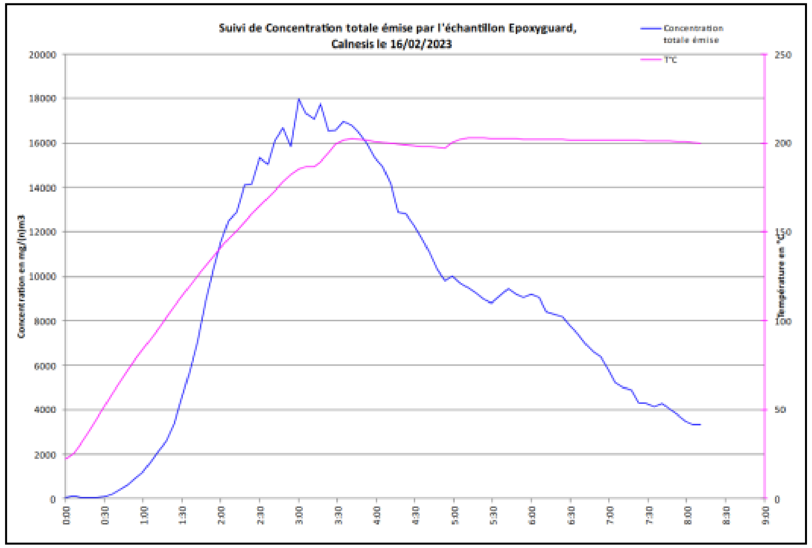
7. 3 SAFETY ANALYSIS

7. 3. 1. Gases emission under 200° C heating

<u>Synthesis for Epoxy Guard:</u>

- Measurements show that the gases emission of the resin is very important. The most part is coming from VOC.
- A little amount of CO_2 and CH_4 is emitted an no hydrogen is detected. For VOC, many components are detected, especially xylenes.
- A strong decrease in the global mass flow is observed after a few hours (even if the value remains quite high after 8h – around 3500 mg/m3)

Composé	Charge émise *mg*	*mg/g d'ech.*	*% massique de la charge %*
CO	1,39	0,13	0,40 %
CO2	8,28	0,8	2,20 %
H2	<0,01	<0,001	<0,1%
Xylenes	157,74	15,31	41,90 %
IPA	66,66	6,47	17,70 %
Isomères Ethylmethylbenzene	35,91	3,49	9,50 %
Isomères trimethylbenzene	26,74	2,6	7,10 %
2,3-butanediol	22,32	2,17	5,90 %
Isomères ethyldimethylbenzene	20,56	2	5,50 %
Methanol	9,48	0,92	2,50 %
propylbenzene	8,9	0,86	2,40 %
Isomères methylpropylbenzene	8,84	0,86	2,30 %
Indane	3,7	0,36	1,00 %
Isomères diethylbenzene	2,73	0,27	0,70 %
Chloromethane	1,45	0,14	0,40 %
Toluene	0,94	0,09	0,20 %
Ethylbenzene	0,75	0,07	0,20 %
Nonane	0,10	0,01	0,03 %
Total	376,58	36,56	100,00 %



GLOBAL GAS MASS FLOW over the time

VII. ASSESSMENT OF IMPACTS

7. 3 SAFETY ANALYSIS

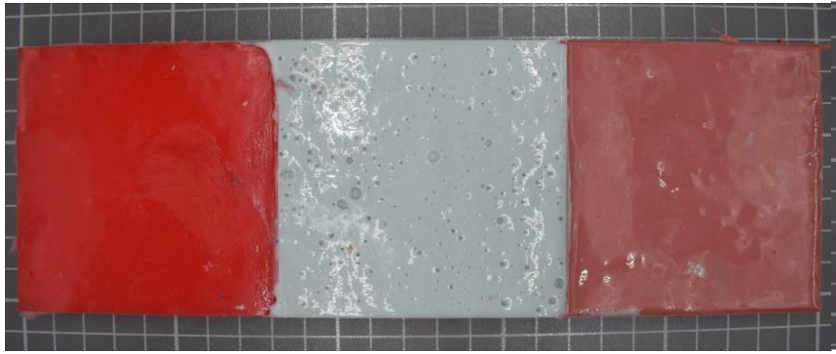
7. 3. 2. Gases emission under irradiation

3 resin samples were submitted to a dose rate of 1 000Gy/h for a cumulative dose of 1 000 kGy (gas measurements were performed once at the end of the test). Considering constraints for this test to be performed, there were performed by family (3 kinds of silicone and 3 kinds of epoxy) :

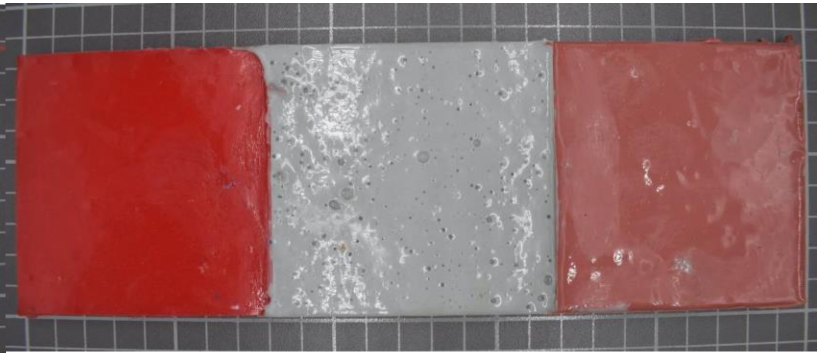
- Measurements presented H2 and COV gases emission (values are after irradiation and cumulative for thes 3 silicone samples : RTV878, 873 and 877)

Gas identification	Gas measurements in the enclosure (ppm)
H2	782
VOC	22

- Rk : values regarding Epoxy family showed global values higher for H2 (>2000ppm - limit of detection of the probe) and 105 ppm for COV.
- Pictures before and after irradiation for silicones are presented below => no significative structural modification observed :



Silicones (RTV 878/873/877) before irradiation



Silicones after irradiation (1 MGy)

VII. ASSESSMENT OF IMPACTS

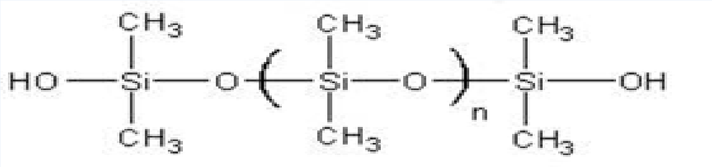
7. 3. SAFETY ANALYSIS

7. 3. 2. Criticality

Objective:
The main objective is to analyze the impact of coating about criticality.

To do so, two different studies are carried out:
- The first study concerns the impact of the coating inside the PCV.
- The second study concerns the impact of the coating in storage canisters for a storage configuration

Global Hypothesis:
Studied coatings have a silicone base:



Silicone base coating

- To be conservative, simulations will take **methylene molecule (CH_2)** as coating. This molecule is a standard used for plastic and synthetic components in criticality simulations.
- Simulations take a conservative fissile environment: UO_2 with 5% enrichment with optimum on moderation.

Methodology:
Studies are made with CRITSTAL V2.0.2 formulary based on the CEAV5.1.2 library.
All calculations are made in two steps :
- The study of the fissile environment by the APOLLO2 code,
- The study of the k_{eff} by Monte-Carlo code

For the analysis of the **coating impact inside the PCV**, 3 types of calculation are considered :
- An infinite plate of fuel debris and one layer of water and on layer of concrete (to be conservative)
- A 7m diameter cylinder of concrete with 1 m thickness (similar but conservative to the pedestal)
- A concentric spherical geometry, a usual geometry for criticality study used as the most conservative case

The parameter studied is the thickness or amount of resin. For each calculation, **the objective is to find the limit of reactivity (k_{eff}). The criteria about k_{eff} is: $k_{eff} + 3\sigma$ ($\sigma \leq 0{,}001$) = 0,950.**
[0, 95 is the usual threshold considered for subcritical system in the preliminary criticality studies].
To reach this limit, one thickness or amount of resin is chosen and the amount of fissile mass is adapted to find the limit of reactivity.

For the **coating impact analysis in storage canisters for a storage configuration**, 2 types of calculation are considered :
- A 10*10 array of storage canisters with a distance of 33 cm between two storage canisters centers (similar to IRID's criticality study).
- An infinite array of storage canisters with a distance of 33 cm between two storage canisters centers (to be conservative).

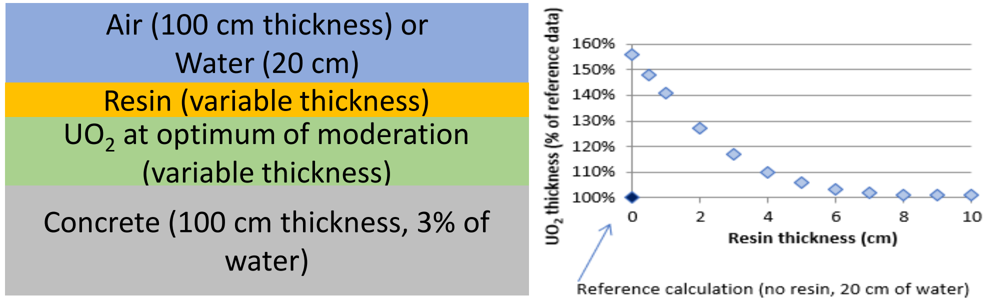
The parameter studied is the k_{eff} depending on the amount of resin inside canisters for the different volumetric humidity rate inside the Fuel Debris (20 %, 10% and 1%).

VII. ASSESSMENT OF IMPACTS

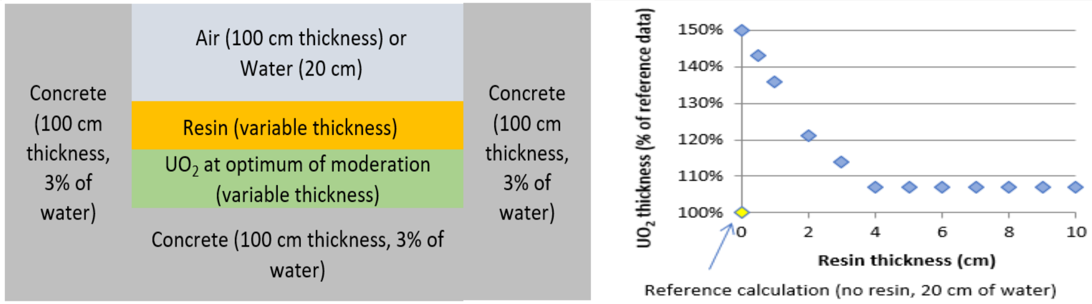
7. 3. SAFETY ANALYSIS

7. 3. 2. Criticality

Coating impact inside the PCV – Calculations models and main results



First model: Infinite plate model

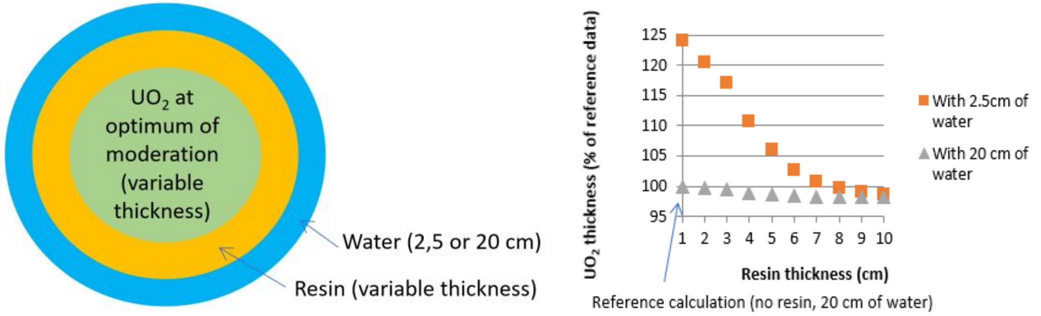


Second model: Simulation of PCV

Hypothesis for the calculations:

Parameters for the calculations are the following:

- Variable thickness of UO_2 moderate by water
- Variable thickness of resin (0,5 cm and from 0 cm to 10 cm with a pitch of 1 cm)
- Calculations are carried out in air and underwater: 100 cm air thickness or layer of 20 cm of water except for spherical model (2,5 cm or 20 cm of water)
- Concrete is considered to be 3% of water and 100 cm thickness



Third model: Spherical model

Main results

For each model of calculation, results show that coating has a limited impacts on the criticalilty:

- No impact with a 20 cm layer of water
- Limited impact of coating in air (from 4-8% with 0.5 cm thickness of coating)
- **About the pedestal, results show that the resin should have no impact on the current criticality state**

VII. ASSESSMENT OF IMPACTS

7. 3. SAFETY ANALYSIS

7. 3. 2. Criticality

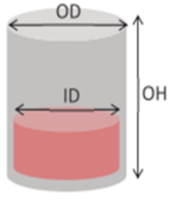
Storage configuration – Hypothesis

- The storage canisters geometry and the storage configuration is based on IRID’s publication. There are two unit cans in a storage canister. The geometry of unit can and storage canister are detailed on the right.
- Each unit can is filled with UO_2 enriched at 5wt% and resin (simulated by CH_2).
- For calculations the volumetric water content in UO_2 is 1%, 10% or 20%.
- The center to center distance between two storage canister is 33 cm.

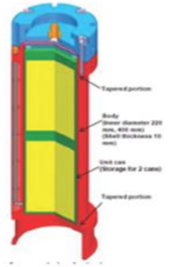
To be conservative, it is important to add some reflective component around the storage canisters:

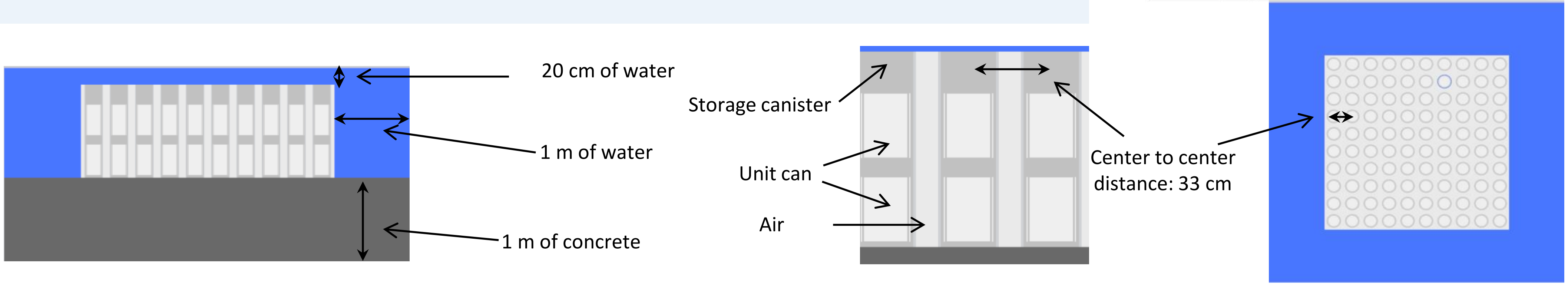
- Storage canisters are stored on a slab of 1m of concrete
- Around the storage canister, there is a wall of 1m of water
- Above the storage canisters, there is a wall of 20 cm of water
- A layer of water of different thickness around each storage canisters has been studied to be the most conservative. The most conservative case is reach with no water layer.

UNIT CAN - Geometry	
ID [mm]	198
IH [mm]	360
OD [mm]	210
OH [mm]	366
Wall/Bottom thickness [mm]	6
Material	SUS316L Stainless Steel
Housing volume [L]	11,1



STORAGE CAN - Geometry	
ID [mm]	220
IH [mm]	840
OD [mm]	240
OH [mm]	1106
Wall thickness [mm]	10
Bottom thickness [mm]	30
Material	SUS316L Stainless Steel
Housing volume [L]	38,0
Cover OD [mm]	300
CoverOH [mm]	236





VII. ASSESSMENT OF IMPACTS

7. 3. SAFETY ANALYSIS

7. 3. 2. Criticality

Storage configuration – 10*10 storage canisters

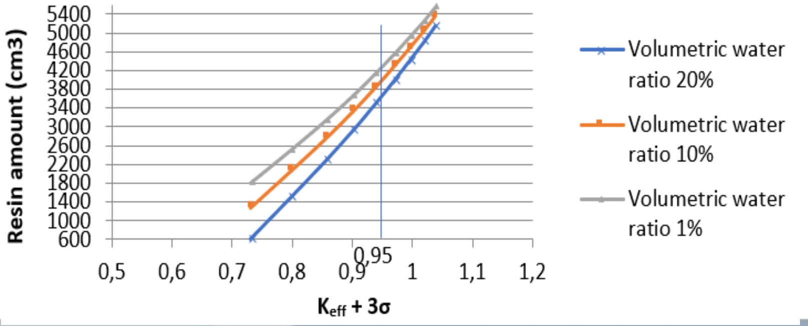
For each volumetric humidity rate (1, 10 and 20%), the impact of the addition of resin in storage canisters is studied by comparison of the effective neutron multiplication factor (k_{eff}).
The variation of the amount of resin in storage canister is chose as the ratio between fissile material volume (UO_2) and moderator volume (resin and water converted in resin equivalent) is from 20% to 100% by step of 10%.

		Volumetric humidity rate in corium : 20%				Volumetric humidity rate in corium : 10%				Volumetric humidity rate in corium : 1%			
Moderator volume / UO_2 volume (%)	$K_{eff} + 3\sigma$	UO_2 (cm^3)	Resin (cm^3)	Water in corium (cm^3)	Resin equivalent of water in corium (cm^3)	UO2 (cm^3)	Resin (cm^3)	Water in corium (cm^3)	Resin equivalent of water in corium (cm^3)	UO2 (cm^3)	Resin (cm^3)	Water in corium (cm^3)	Resin equivalent of water in corium (cm^3)
20	0,731	10527	620	2105,3	1485,6	9869	1277	986,9	696,4	9343	1803	93,4	65,9
30	0,800	9618	1528	1923,6	1357,4	9066	2080	906,6	639,8	8621	2525	86,2	60,8
40	0,857	8854	2292	1770,8	1249,6	8384	2762	838,4	591,6	8002	3144	80,0	56,5
50	0,903	8203	2944	1640,5	1157,6	7798	3349	779,8	550,2	7466	3680	74,7	52,7
60	0,940	**7640**	**3506**	1528,1	1078,3	**7288**	**3858**	728,8	514,3	**6997**	**4149**	70,0	49,4
70	**0,971**	7150	3996	1430	1009,1	6841	4306	684,1	482,7	6584	4562	65,8	46,5
80	**0,997**	6719	4427	1343,8	948,3	6445	4701	644,5	454,8	6217	4930	62,2	43,9
90	**1,020**	6337	4809	1267,4	894,4	6093	5054	609,3	429,9	5888	5258	58,9	41,6
100	**1,039**	5996	5150	1199,3	846,3	5777	5369	577,7	407,7	5593	5553	55,9	39,5

Results show that the K_{eff} increase with the amount of resin. The limitation ($K_{eff} + 3\sigma = 0,95$) is reached for:

- 3506 cm3 of resin (31% of the storage canister usefull volume) for a volumetric humidity rate in corium of 20%, for a UO_2 volume of 7640 cm3
- 3858 cm3 of resin (35% of the storage canister usefull volume) for a volumetric humidity rate in corium of 10%, for a UO_2 volume of 7288 cm3
- 4149 cm3 of resin (37% of the storage canister usefull volume) for a volumetric humidity rate in corium of 1%, for a UO_2 volume of 6997 cm3

To conclude these preliminary calculations, **it seems important to not reach more than 30% of resin in a storage canister.**



VII. ASSESSMENT OF IMPACTS

7. 3. SAFETY ANALYSIS

7. 3. 2. Criticality

Storage configuration – Infinite array of storage canisters

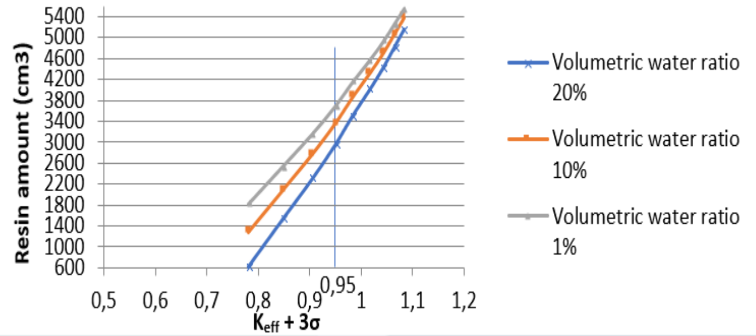
As for the 10*10 storage configuration, for each volumetric humidity rate (1, 10 and 20%), the impact of the addition of resin in storage canisters is studied by comparison of the effective neutron multiplication factor (k_{eff}). The variation of the amount of resin in storage canister is chose as the ratio between fissile material volume (UO_2) and moderator volume (resin and water converted in resin equivalent) is from 20% to 100% by step of 10%.

		Volumetric humidity rate in corium : 20%				Volumetric humidity rate in corium : 10%				Volumetric humidity rate in corium : 1%			
Moderator volume / UO_2 volume (%)	$K_{eff} + 3\sigma$	UO_2 (cm^3)	Resin (cm^3)	Water in corium (cm^3)	Resin equivalent of water in corium (cm^3)	UO2 (cm^3)	Resin (cm^3)	Water in corium (cm^3)	Resin equivalent of water in corium (cm^3)	UO2 (cm^3)	Resin (cm^3)	Water in corium (cm^3)	Resin equivalent of water in corium (cm^3)
20	0,781	10527	620	2105,3	1485,6	9869	1277	986,9	696,4	9343	1803	93,4	65,9
30	0,848	9618	1528	1923,6	1357,4	9066	2080	906,6	639,8	8621	2525	86,2	60,8
40	0,905	8854	2292	1770,8	1249,6	8384	2762	838,4	591,6	8002	3144	80,0	56,5
50	0,950	**8203**	**2944**	1640,5	1157,6	**7798**	**3349**	779,8	550,2	**7466**	**3680**	74,7	52,7
60	0,984	7640	3506	1528,1	1078,3	7288	3858	728,8	514,3	6997	4149	70,0	49,4
70	1,017	7150	3996	1430,0	1009,1	6841	4306	684,1	482,7	6584	4562	65,8	46,5
80	1,044	6719	4427	1343,8	948,3	6445	4701	644,5	454,8	6217	4930	62,2	43,9
90	1,065	6337	4809	1267,4	894,4	6093	5054	609,3	429,9	5888	5258	58,9	41,6
100	1,084	5996	5150	1199,3	846,3	5777	5369	577,7	407,7	5593	5553	55,9	39,5

As for the 10*10 storage configuration, results show that the K_{eff} increase with the amount of resin. The limitation ($K_{eff} + 3\sigma = 0,95$) is reached for:

- 2944 cm3 of resin (26% of the storage canister usefull volume) for a volumetric humidity rate in corium of 20%, for a UO_2 volume of 8203 cm3
- 3349 cm3 of resin (30% of the storage canister usefull volume) for a volumetric humidity rate in corium of 10%, for a UO_2 volume of 7798 cm3
- 3680 cm3 of resin (33% of the storage canister usefull volume) for a volumetric humidity rate in corium of 1%, for a UO_2 volume of 7466 cm3

To conclude these preliminary calculations, **it seems important to not reach more than 26% of resin in a storage canister.**



VII. ASSESSMENT OF IMPACTS

7. 3. SAFETY ANALYSIS

7. 3. 2. Criticality

Conclusion

Three calculations have been made to study the impact of a resin layer in the pedestal :

- An infinite plate model
- A more realistic pedestal geometry
- A spherical geometry, the most conservative model and usual geometry for criticality study.

The three calculations leads to the same conclusion :

- The resin have an impact lower than 20 cm of water. Moreover, the addition of resin to this 20 cm layer of water do note modify the criticality state in the pedestal.
- Without water, calculations show that a layer of 0,5 mm of resin have an slight impact on the criticality state of the pedestal (between 5 and 8 %). A 2 cm layer of resin have a bit more impact, between 13 and 29%.

These results show that the resin should have **no impact on the current criticality state in the pedestal.**

Two calculations have been made to study the impact of resins in storage canister for a storage configuration:

- A 10*10 storage configuration
- An infinite array

The two calculations lead to the same conclusion :

- The reactivity of the system increase with the amount of resin in storage canisters.
- In the most conservative case, the limit ($K_{eff} + 3\sigma = 0,95$) is reached for 26% of resin in storage canisters and in the best case, the limit is reached for 37%.

It is important to keep in mind that these calculations are very conservative**. The resin have an impact on the storage step and this impact should be studied in future study** with a more realistic composition for instance. The value of 26% of resin in a storage canister will be compared to resins coating test and retrieval operations considered.

VII. ASSESSMENT OF IMPACTS

7. 3 SAFETY ANALYSIS

7. 3. 3. Fire risk

Origin of the risk:
Resin is an organic compound which under certain conditions could ignite or burn.

In some tests, the high temperature rise (when the force applied to the disc is very high or at the laser beam) showed that the resin could be locally consumed.
It is therefore necessary to analyse the conditions under which these situations can occur and what the potential consequences are.

Tests realized:

- Selection of coating not flammable (from sheet data) (chapter 3.2)
- Flammability resistance tests for coating (chapter 3.4)

The aim of these tests is to evaluate the flammability resistance for coating candidates.
Flammability is an important criteria of tests: if a coating presents a risk toward the fire risk, it is excluded of the selection. Criteria of successfully passed test is that the coating is not flammable.

- Core boring tests (Chapter 5)
- Disc cutting tests (Chapter 5)
- Laser cutting tests under air (Chapter 5)
- Laser cutting test under nitrogen (Chapter 5)

Analysis and conclusion:
To limit the risk of fire propagation, the selected resins have to present a strong resistance to flammability. The tests carried out, which are standardized, do however have their limits. The resin is still an organic compound and in some cases that exceed the test standards, it is possible for it to burn. Flame tests have shown that if the resin burns, the reaction stops by itself when the heat source that caused the hazard is no longer present.

During cutting tests, under particular conditions (high pressure of the mechanical cutting tool during cutting or at the melting point of the material for air laser cutting), resin was consumed locally but the reaction, located at the cutting point, stopped as soon as the cutting sequence was stopped.

- In the case of the disc cutter (grinder), if the pressure applied is within a controlled range, the resin does not burn. The cutting speed when using the grinder should therefore be considered and potentially limited
- In the case of the laser, when nitrogen is used instead of air as assist gas, the resin does not burn. The use of nitrogen is recommended for laser cutting. If air is used, the resin could burn up locally.
- The core boring tests carried out have never resulted in burning resin.

VII. ASSESSMENT OF IMPACTS

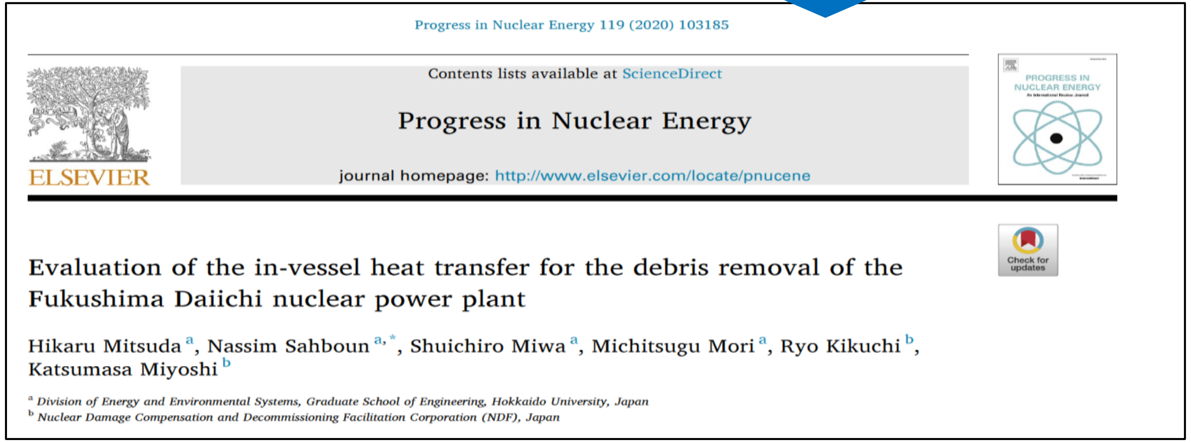
7. 4 IMPACT ON HEAT TRANSFER FROM FUEL DEBRIS

Objective:

- Assessment of the influence of resin coating on the cooling of fuel debris bed
- Assessment of the potential temperature to which the resin coating is subjected

⇒ Proposal of a Computational Fluid Dynamics (CFD) study aiming to evaluate the temperature that resin may reach close to fuel debris and depending on the location on the pedestal floor (above or out of sumps)

- Presentation of the setup of CFD simulations with ANSYS CFX code for advice and discussion with given initial and boundary conditions
- Most of initial conditions in relation to 1F site have been provided by the publication of **Mitsuda et al. 2020, *Progess in Nuclear Energy***



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ELSEVIER

Evaluation of the in-vessel heat transfer for the debris removal of the Fukushima Daiichi nuclear power plant

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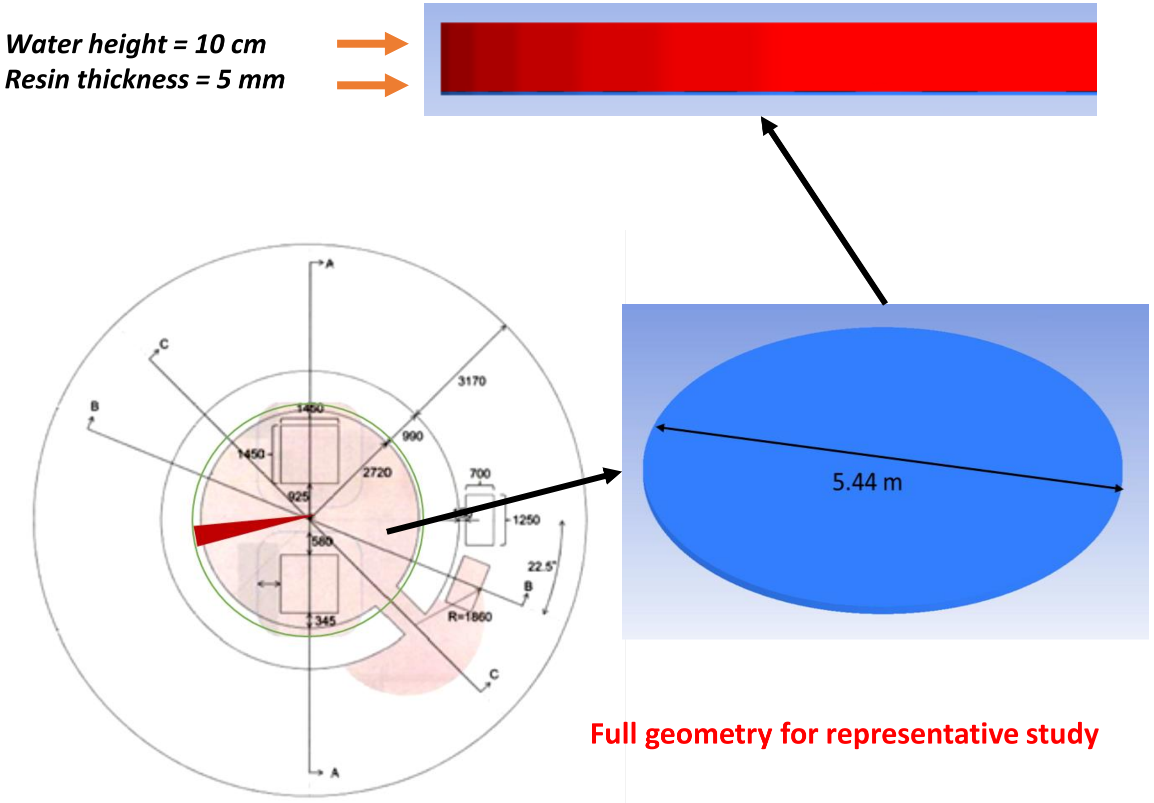
Definition of calculation domain:

- Definition of pedestal floor geometry based on Mitsuda[1] publication

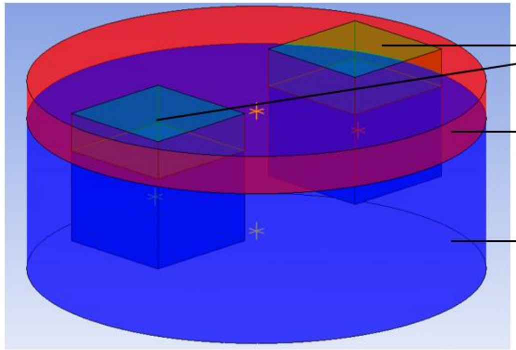


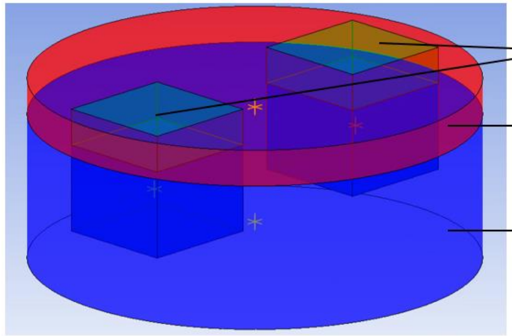
VII. ASSESSMENT OF IMPACTS

7. 4 IMPACT ON HEAT TRANSFER FROM FUEL DEBRIS

Calculation description

- Calculation of thermal diffusion inside the sumps and the concrete taking into account the heat flux of each sump of around 7 kW/m²
- Heat transfers with the water and the air of the pedestal are taken into account without resin to get a reference state before covering the fuel debris
- Boundary conditions for each part of the computational domain are presented below



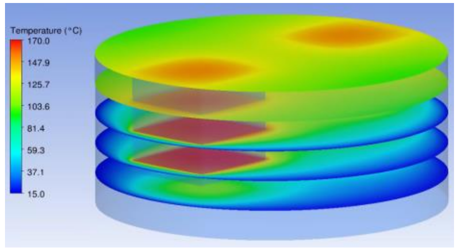


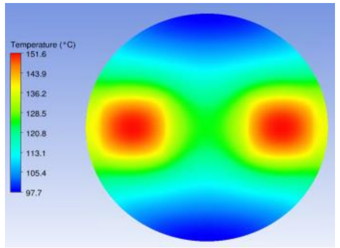
- Heat fluxes applied to Fuel Debris distributed above the ground and inside the sumps
- Boundary condition of water flow above fuel debris (10 cm height) with a flowrate of 1.7 m3/h, allowing to evaluate the convective heat transfer coefficient with water <u>HTCw =18 $W.m^{-2}.K^{-1}$</u>

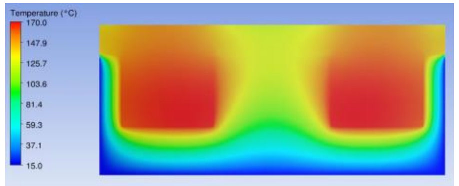
VII. ASSESSMENT OF IMPACTS

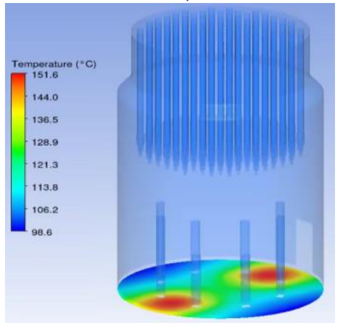
7. 4 IMPACT ON HEAT TRANSFER FROM FUEL DEBRIS

Here below are presented the calculation results for water with HTC = 18 $W.m^{-2}.K^{-1}$ (penalizing configuration)

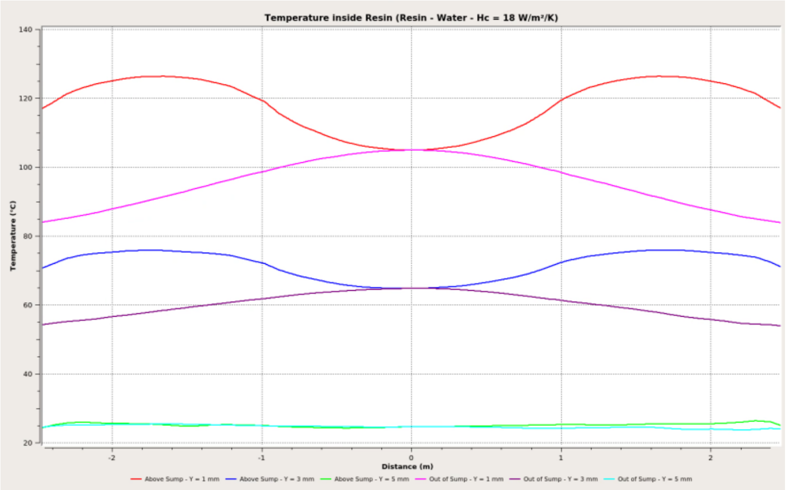


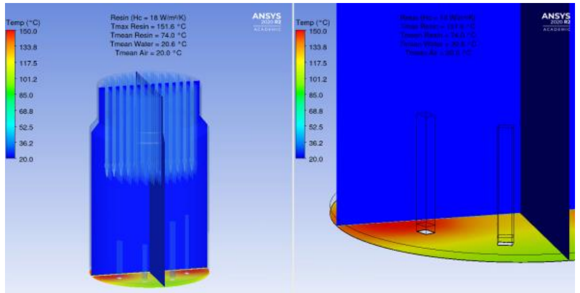






Application of the top temperature field as an initial condition for a calculation with a resin layer of 5 mm in the 1F2 pedestal





<u>Results:</u>

Resin temperature ranges between 25 °C and 151.6 °C with a mean value of 74 °C

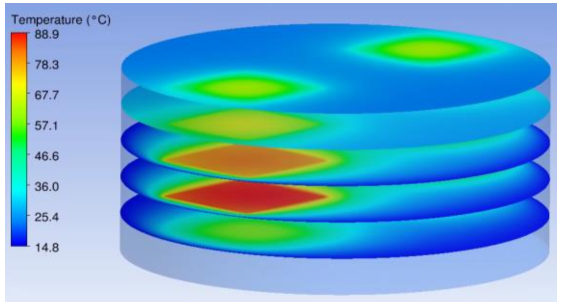
This result is obtained with a very penalizing condition of water velocity above the ground which limits the heat tranfer with the fuel debris ($V_w = 2.10^{-5}$ m/s)

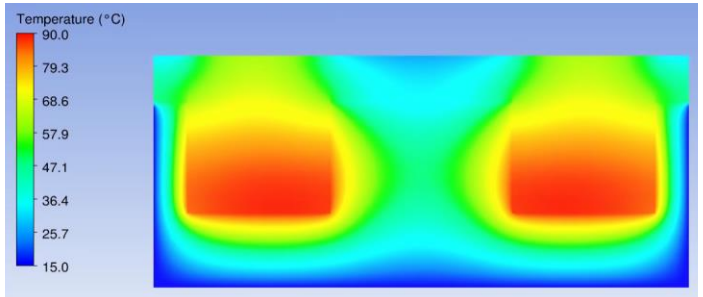
⇒ By considering a higher velocity due to the fall of water droplet on the ground (V_w = 0.13 m/s), the convective heat transfer coefficient grows up to 400 $W.m^{-2}.K^{-1}$

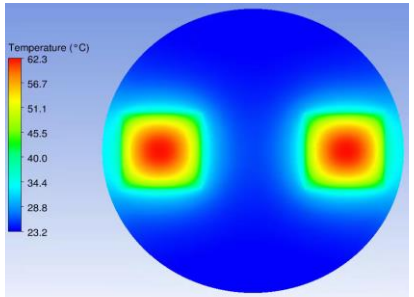
VII. ASSESSMENT OF IMPACTS

7. 4 IMPACT ON HEAT TRANSFER FROM FUEL DEBRIS

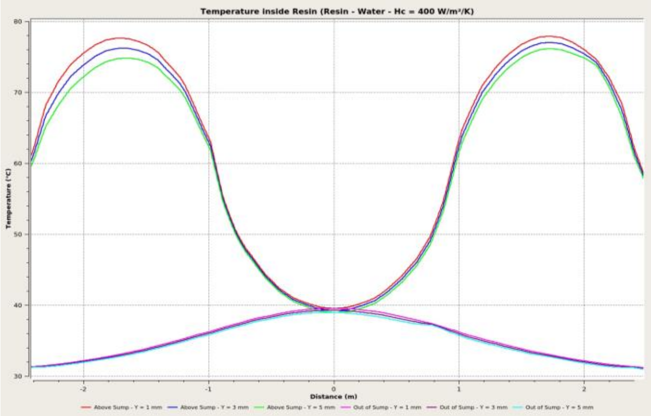
In the case of htc = 400 $W.m^{-2}.K^{-1}$ corresponding to a velocity of water induced by droplet falling down to the floor, the temperature at the surface of fuel debris is lower than for htc = 18 $W.m^{-2}.K^{-1}$ and heat exchanges with water are better

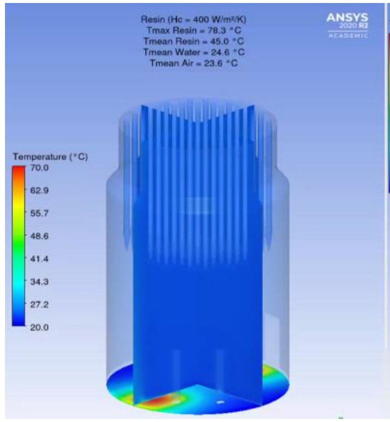


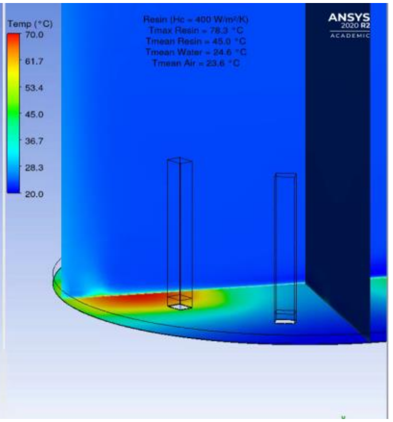




The use of this temperature field as an initial condition for a calculation with a resin layer of 5 mm in the 1F2 pedestal allows to produce the results presented after:







Resin temperature ranges between 30 °C and 78 °C with a mean value of 45 °C

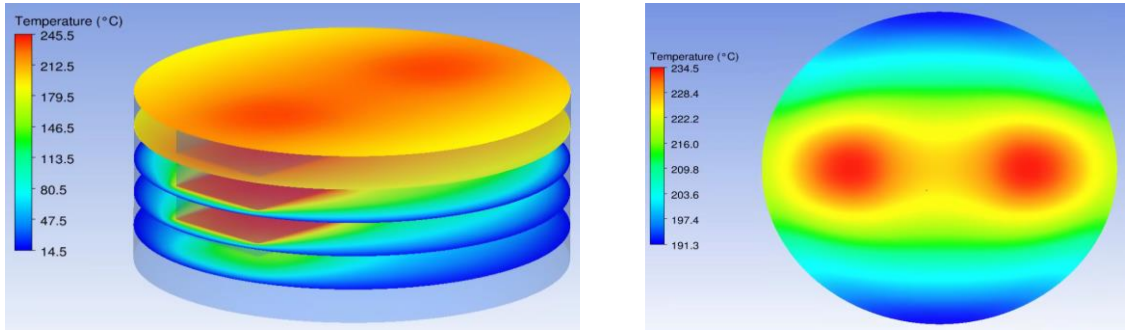
- ⇒ In conclusion of these calculations with a resin layer of 5 mm and a water layer of 10 cm, it appears that the temperature of resin does not reach levels which could call into question its integrity even for penalizing configurations

- ⇒ In order to evaluate the consequences of water absence above the resin, a calculation was done with air conditions and without water and the results are presented after

VII. ASSESSMENT OF IMPACTS

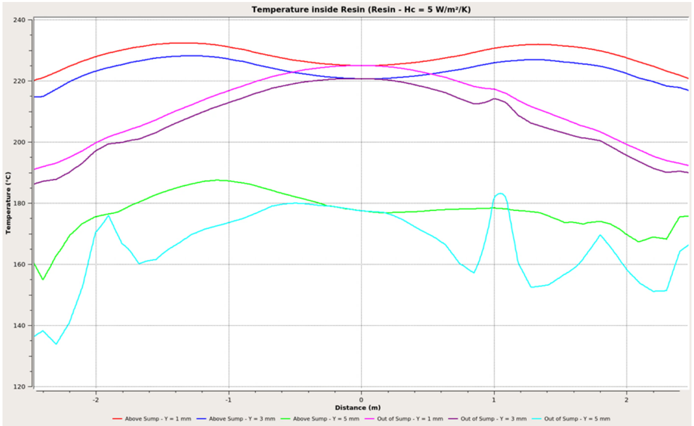
7. 4 IMPACT ON HEAT TRANSFER FROM FUEL DEBRIS

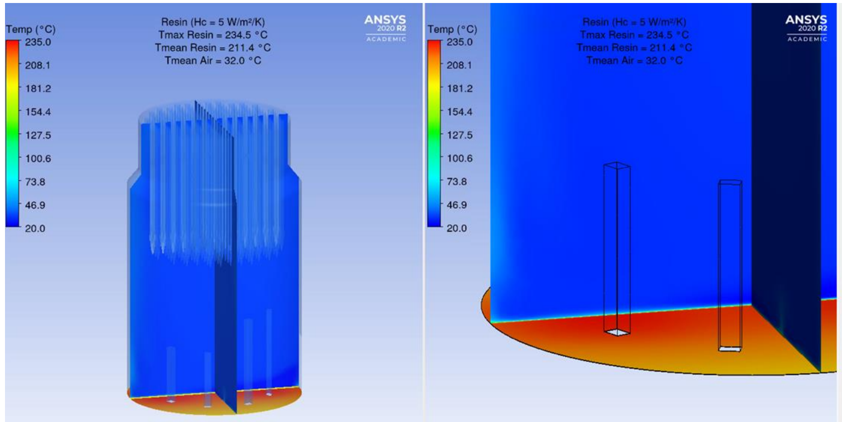
The main issue with air is that the heat transfers are very bad and consequently the htc is very low. In the case of water absence (only air), htc = 5 $W.m^{-2}.K$ corresponding to a velocity of air arbitrarily evaluated to 0.1 m/s



Calculation results for air with htc = 5 $W.m^{-2}.K^{-1}$ (penalizing configuration)

The use of this temperature field as an initial condition for a calculation with a resin layer of 5 mm in the 1F2 pedestal allows to produce the results presented after:





⇒ For these penalizing conditions, resin temperature ranges between 140 °C and 235 °C with a mean value of 211 °C

⇒ These results shows a temperature level very high regarding the integrity of resins. However, we do not have any information about the ventilation of 1F2 pedestal and thus about the airflows close to the floor. It has strong consequences on the results because the htc for air is closely linked to the air velocity. An increase of the velocity from 0.1 m/s to 1 m/s may grow up the htc from 5 to 18 $W.m^{-2}.K^{-1}$ and involve the conservation of the integrity of the resin.

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.1 Waste classification of coating

Methodology:

- Identification of Japanese radioactive waste management regulation (The Reactor Regulation Act).
- Fuel debris analysis based on *JAEA*-Data/*Code* 2018-014.
- Identification of threshold values about radiological activity for coating contamination.

Synthesis about step 1:

The main results are that the fuel debris will be a category 1- TRU waste and the threshold to shift to the category 2-L1 waste is the alpha emitters concentration.
This alpha concentration threshold is **10^5 Bq/g**.
Based on JAEA data about fuel composition, this concentration is reached if **0.5g of fuel is incorporated in 1kg of coating**.

At the sight of this value, it seems reasonable to not further study the possibility to sort coating by a specific treatment. The coating will be sorted as others wastes from inside the PCV (two kinds of storage canisters or a waste storage container)

Details about step 1:

The evaluation of the waste classification for fuel debris is based on the results from JAEA calculations performed for fuel materials (activity per core). For the evaluation of alpha emitters, only activities from major nuclides are considered: U235, U238, Pu238, Pu239, Pu240 and Am241.
In order to evaluate specific activity of waste in Bq/g, the mass of heavy metals per core is considered (Unit 1 : 68 tHM; Units 2 & 3: 94 tHM).
Results of this preliminary evaluation are detailed in the table below (green: criterion is not exceeded, red: criterion is exceeded). The fuel debris exceeds the limit for the category 2- L1 waste for the alpha emitters concentration. So fuel debris is a category 1 waste.

	Limit categorisation Japan (Bq/g) – Category 2	Core 1		Core 2		Core 3	
	Interm. Depth disposal (L1)	10 years	50 years	10 years	50 years	10 years	50 years
Co60	Unlimited	9,98E+03	5,18E+01	1,03E+04	5,35E+01	9,35E+03	4,85E+01
Sr90	Unlimited	1,73E+09	6,59E+08	1,60E+09	6,08E+08	1,51E+09	5,75E+08
Cs137	Unlimited	2,36E+09	9,39E+08	2,16E+09	8,58E+08	2,04E+09	8,10E+08
C14	1,00E+10	2,97E+03	2,96E+03	2,60E+03	2,59E+03	2,44E+03	2,43E+03
Ni63	Unlimited	1,67E+05	1,24E+05	1,48E+05	1,10E+05	1,38E+05	1,02E+05
Tc99m	1,00E+11	3,99E+05	3,99E+05	3,55E+05	3,55E+05	3,35E+05	3,35E+05
Cl36	1,00E+06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
I129	1,00E+06	9,12E+02	9,12E+02	7,99E+02	7,99E+02	7,55E+02	7,55E+02
alpha emitters	1,00E+05	**1,42E+08**	**1,76E+08**	**1,13E+08**	**1,47E+08**	**1,34E+08**	**1,71E+08**

With the maximal value of the alpha emitters concentration identified (1,76x10^8 Bq/g), it is possible to find the maximal amount of fuel debris incorporate in the coating to reach the limit (10^5 Bq/g). The value is 0.5 g of fuel debris per kilogram of coating.

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.2 Methodology to study the impact of coating added to the waste for storage and long-term disposal

The global approach consists of verifying that the resins (compositions) and their evolution over time (degradation under the effect of irradiation, temperature, humidity, a.s.o.) do not induce risks for the management of the waste that could impact the safety of the storage.

Methodology:

- Listing of General Waste Acceptance Criteria that could be used based on French example
- Identification of those that could be impacted by adding coating in waste
- Description of the methodology to study the impact
- Analysis of the impact when it is possible

Explanation of the methodology:

Requirements applicable to waste packages to be stored originating coming from regulatory constraints, safety analysis and operations constraints. These requirements are called Waste Acceptance Criteria. As the storage and disposal facility for fuel debris are currently not defined, a list of general Waste Acceptance Criteria is proposed. This list is based on similar projects and international accepted practices according to waste characteristics.

To be exhaustive, each criterion is analyzed to know if it could be impacted by adding coating to the waste.
For each criterion impacted, a methodology to analyze the impact is defined.

Depending on the criterion and methodology, there may be several possibilities:

- There is no impact
- There is an impact and the analysis is possible through test realized previously in the project.
- There is an impact and the analysis will need to carry out additional and specific tests.
- There is an impact that needs more data about the storage or disposal to be analyzed. In this case, the methodology will provide data to take into account potential constraints on the future storage / disposal facility.

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.3 General requirements about waste

Main related functions	Criteria	Requirements to be fulfilled considering constraint functions
Storage phase		
All functions	Radiological inventory	Radiological inventory per waste package should be declared and could be limited (according to facility license or accidental situations).
To contain radioactive substances	Containment of solid substances and aerosols in normal conditions	The primary container should be tight (solid materials and aerosols) in order to contain radioactive substances at a level compatible with the design of the facility during at least the storage phase.
	Surface contamination	Surface contamination of primary packages should be limited at a level compatible with the design of the facility (compliant with regulatory requirements).
	Drop resistance of waste package	The tightness of the primary container following a drop from a specific height should be guaranteed during at least the storage phase (height depending on the installation).
	External thermal loads resistance	In case of thermal loads, the containment of the solids substances and aerosols should be guaranteed.
		In case of thermal loads, the containment of gases and volatiles radionuclides should be guaranteed
	Primary container resistance to overpressure and potential explosion (if leakproof container)	The primary container should be designed to the maximum overpressure due to gas generation within the waste package and its potential explosion (if not excluded).
	Resistance to stacking (if any)	The primary container should resist to stacking position on several levels according to the total height of the pits (consistent with the sizing of the installation)
To limit dose rate in compliance with shielding design	Maximum dose rate at given distance of the waste package	Maximum dose rate at a given distance from the waste package should be compliant with the sizing of the facility (radiological protections).

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.3 General requirements about waste

Main related functions	Criteria	Requirements to be fulfilled considering constraint functions
Storage phase		
To maintain sub-critical conditions	Reference fissile medium and reflection conditions	The compliance of the waste package with the sub-critical conditions (fissile medium and reflections conditions) defined for the sizing of the facility should be guaranteed (fissile materials inventory, moderator quantities or concentration, reflection conditions, neutron absorbers).
	Geometry of primary container	The primary package geometry should be compliant with criticality analysis.
	Primary container resistance to overpressure and potential explosion (if leakproof container)	The primary container should be designed to the maximum overpressure due to gas generation within the waste package and its potential explosion (if not excluded).
	Resistance to stacking (if any)	The primary container should resist to stacking position on several levels according to the total height of the pits (consistent with the sizing of the installation)
To dissipate heat from fuel debris	Heat power at reception	The maximal thermal power at reception per waste package should be compliant with the sizing of the facility (ventilation systems) in order to respect thermal limits (electronic devices, concrete structure, etc.).
To evacuate gases (radiolysis, corrosion, etc.)	Evacuation of gases generated within the waste package (for a non airtight container)	The primary container should include a system to evacuate the gases for the duration for which gases are likely to be generated
	Explosive gases rate	The maximum explosive gases rate per waste package should be compliant with the sizing of the facility.
	Radioactive gases	The maximum radioactive gases rate per radionuclide of all waste packages should be limited according to facility design and authorized release limits

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.3 General requirements about waste

Main related functions	Criteria	Requirements to be fulfilled considering constraint functions
Storage phase		
Operations (To guarantee reception and transfer of waste package)	Identification number	Each waste package should have an identification number (reference) resistant to storage conditions over time.
	Mass of the waste package	The mass of the primary package should be less than the maximum allowable weight specified for the storage facility.
	Geometry of primary container	The primary package should comply with the specified plan for which the storage facility is sized (pits diameter, dimensions of NUHOMS®, etc.) (see also criticality)
	Gripping interface	The gripping interface should be compliant with the sizing of the facility at reception and over time.
Substances (To guarantee compliance with design and safety assessments)	Substances to be declared	Various chemical substances should be declared at the waste package level (aggressive substances for the primary container, sources of radiolysis or corrosion gas, chemical toxic inventory, etc.)
	Special substances (ex. pyrophoric materials)	It should be demonstrated that the waste package with pyrophoric material does not represent a source of danger during the normal situations and accidental conditions.
	Prohibited substances	Absence of prohibited substances (not covered by the design of the facility) should be guaranteed.

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.3 General requirements about waste

Main related functions	Parameters /Requirements for disposal (post-closure) to be fulfilled considering constraint functions
Disposal phase	
To limit radionuclide release	Radiological inventory of the waste packages should be declared with a particular attention to mobile and long-lived radionuclides. Potential gaseous radionuclides should also be declared.
	In addition to the radiological inventory, a toxic inventory should be evaluated for the set of waste packages to be disposed of.
To control degradation products	The quantity of organic materials and salts (forming potentially complexing species) present in fuel debris should be evaluated for the set of waste packages, and limited as much as possible.
To maintain sub-critical conditions	The compliance of the waste package with the sub-critical conditions (fissile medium and reflections conditions) and its evolution over time defined for the disposal should be guaranteed.
	Voids in the waste package, should be limited to limit re-concentration of fissile materials in the disposal cells.
To dissipate heat from fuel debris with respect to radionucleide mobility and migration	The maximal thermal power at reception and the thermal power decay over time per waste package should be limited in a range within which the processes governing changes in the disposal system could be represented and modelled reliably
To limit strains and hydraulic disturbance in the repository system	Voids within the set of waste packages should be limited as much as possible to limit strains and hydraulic disturbance on the repository system (in order to preserve the host rock)
To control dose rate according to overpack and/or repository design	Maximum dose rate at a given distance from the waste package should not impact repository components and be compliant with the overpack design (if any).
To control gas build-up according to overpack and/or repository design	Gases rate per waste package (corrosion, radiolysis, etc.) should be declared to verify its compliance with the repository design (including the overpack if any).
To control overpack internal corrosion (chemical and radiolysis aggressiveness)	Substances favoring internal corrosion of the overpack (if any) should be declared at the waste package level and limited as much as possible.

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.4 Identification of criteria or requirements impacted by adding coating in waste

Main related functions	Criteria	Potentially impacted by addition of resin in the waste package	Remarks and justification
Storage phase			
All functions	Radiological inventory	No	The coating does not include any radiological component
To contain radioactive substances	Containment of solid substances and aerosols in normal conditions	No	In normal conditions the containment will not be modified
	Surface contamination	No	The external surface of the container is not impacted
	Drop resistance of waste package	No	The drop resistance is not impacted
	External thermal loads resistance	No	The external thermal loads resistance is not impacted
	Primary container resistance to overpressure and potential explosion	No	The primary resistance to overpressure is not impacted
	Resistance to stacking	No	The resistance to stacking of the container is not impacted
To limit dose rate in compliance with shielding design	Maximum dose rate at given distance of the waste package	Yes	The addition of coating in the waste could lead to lower the maximum dose rate by shielding or by the limitation of the amount of radioactive material in the waste
To maintain sub-critical conditions	Reference fissile medium and reflection conditions	Yes	Depending on the composition of coating, the reference fissile medium and reflection conditions could be modified
	Geometry of primary container	No	The geometry of the container is not impacted
	Primary container resistance to overpressure and potential explosion	No	The primary resistance to overpressure is not impacted
	Resistance to stacking	No	The resistance to stacking of the container is not impacted

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.4 Identification of criteria or requirements impacted by adding coating in waste

Main related functions	Criteria	Potentially impacted by addition of resin in the waste package	Remarks and justification
Storage phase			
To dissipate heat from fuel debris	Heat power at reception	Yes	The coating could modified the heat transfer, and the irradiation of the resin could increase the heat power of the waste.
To evacuate gases (radiolysis, corrosion, etc.)	Evacuation of gases generated within the waste package	Yes	Depending on the gases rate generation, it could be possible to impact the sizing of the filter (low probability)
	Explosive gases rate	Yes	
	Radioactive gases	No	The coating does not generate radioactive gases
Operations (To guarantee reception and transfer of waste package)	Identification number	No	The coating has no impact on the identification number of the container
	Mass of the waste package	No	The coating will have no impact on the mass of the waste package, only on the mass composition inside the waste package
	Geometry of primary container	No	The geometry of the waste package is not modified
	Gripping interface	No	The coating has no impact on the gripping interface
Substances (To guarantee compliance with design and safety assessments)	Substances to be declared	Yes	Depending on composition and degradation products, some substances could have an impact
	Special substances (ex. pyrophoric materials)	Yes	
	Prohibited substances	Yes	

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.4 Identification of criteria or requirements impacted by adding coating in waste

Main related functions	Parameters /Requirements for disposal (post-closure) to be fulfilled considering constraint functions	Potentially impacted by addition of resin in the waste package	Remarks and justification
Disposal phase			
To limit radionuclide release	Radiological inventory of the waste packages should be declared with a particular attention to mobile and long-lived radionuclides. Potential gaseous radionuclides should also be declared.	No	The radiological inventory is not modified by adding coating in the waste.
	In addition to the radiological inventory, a toxic inventory should be evaluated for the set of waste packages to be disposed of.	Yes	Depending on composition and degradation products, some substances could have an impact.
To control degradation products	The quantity of organic materials and salts (forming potentially complexing species) present in fuel debris should be evaluated for the set of waste packages, and limited as much as possible.	Yes	
To maintain sub-critical conditions	The compliance of the waste package with the sub-critical conditions (fissile medium and reflections conditions) and its evolution over time defined for the disposal should be guaranteed.	Yes	Our preliminary criticality studies within canisters presented a potential impact of the resin.
	Voids in the waste package, should be limited to limit re-concentration of fissile materials in the disposal cells.	Yes	The addition of coating in the waste could have an impact on voids in the waste package at a long time scale according to time of degradation between resin and other materials (will depend of the conditioning form of the waste)
To dissipate heat from fuel debris with respect to the integrity of buffer material and near field host formation	The maximal thermal power at reception and the thermal power decay over time per waste package should be compliant with the disposal facility in order to preserve the integrity of buffer material and the host rock formation.	Yes	The coating could modified the heat transfer, and the irradiation reaction could increase the heat power of the waste (low probability).
To dissipate heat from fuel debris with respect to radionuclide mobility and migration	The disposal system evolution in time has to be modelled reliably. For this, the maximal thermal power at reception and the thermal power decay over time per waste package should be limited.	Yes	

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.4 Identification of criteria or requirements impacted by adding coating in waste

Main related functions	Parameters /Requirements for disposal (post-closure) to be fulfilled considering constraint functions	Potentially impacted by addition of resin in the waste package	Remarks and justification
Disposal phase			
To limit strains and hydraulic disturbance in the repository system	Voids within the set of waste packages should be limited as much as possible to limit strains and hydraulic disturbance on the repository system (in order to preserve the host rock).	Yes	The addition of coating in the waste could have an impact on voids in the waste package at a long time scale according to time of degradation between resin and other materials (will depend of the conditioning form of the waste)
To control dose rate according to overpack and/or repository design	Maximum dose rate at a given distance from the waste package should not impact repository components and be compliant with the overpack design (if any).	Yes	The addition of coating in the waste could lead to lower the maximum dose rate by shielding or by the limitation of the amount of radioactive material in the waste.
To control gas build-up according to overpack and/or repository design	Gases rate per waste package (corrosion, radiolysis, etc.) should be declared to verify its compliance with the repository design (including the overpack if any).	Yes	The coating could lead to a generation of gases (very low probablity) at long time scale.
To control overpack internal corrosion (chemical and radiolysis aggressiveness)	Substances favoring internal corrosion of the overpack (if any) should be declared at the waste package level and limited as much as possible.	Yes	Depending on composition and degradation products, some substances could have an impact

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.5 Methodology to study the impact of resin for each requirement identified

Main related functions	Criteria	Methodology
To limit dose rate in compliance with shielding design	Maximum dose rate at given distance of the waste package	The maximum dose rate will be lowered by the addition of coating in the waste. No further study requested for this point.
To maintain sub-critical conditions	Reference fissile medium and reflection conditions	Criticality studies for storage configuration
To dissipate heat from fuel debris	Heat power at reception	Determination of the coating effect on the fuel debris thermal power
To evacuate gases (radiolysis, corrosion, etc.)	Evacuation of gases generated within the waste package	Analysis of gas rate generated by coating under irradiation and high temperature
	Explosive gases rate	
Substances (To guarantee compliance with design and safety assessments)	Substances to be declared	Identification of the coating composition and degradation products and analysis based on the generic list determined for French storage and disposal facilities
	Special substances (ex. pyrophoric materials)	
	Prohibited substances	

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.5 Methodology to study the impact of resin for each requirement identified

Main related functions	Parameters /Requirements for disposal (post-closure) to be fulfilled considering constraint functions	Methodology
DISPOSAL PHASE		
To limit radionuclide release	In addition to the radiological inventory, a toxic inventory should be evaluated for the set of waste packages to be disposed of.	Determination of a generic list of substances studied for French storage and disposal. Identification of the coating composition and degradation products. Analysis based on the generic list previously determined.
To control degradation products	The quantity of organic materials and salts (forming potentially complexing species) present in fuel debris should be evaluated for the set of waste packages, and limited as much as possible.	
To dissipate heat from fuel debris with respect to the integrity of buffer material and near field host formation	The maximal thermal power at reception and the thermal power decay over time per waste package should be compliant with the disposal facility in order to preserve the integrity of buffer material and the host rock formation.	Determination of the coating effect on the fuel debris thermal power. Study to be performed to justify no hot spot creation due to resin above the maximal temperature of the model (used to evaluate radionuclide mobility in time)
To dissipate heat from fuel debris with respect to radionuclide mobility and migration	The disposal system evolution in time has to be modelled reliably. For this, the maximal thermal power at reception and the thermal power decay over time per waste package should be limited.	

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.5 Methodology to study the impact of resin for each requirement identified

Main related functions	Parameters /Requirements for disposal (post-closure) to be fulfilled considering constraint functions	Methodology
DISPOSAL PHASE		
To limit strains and hydraulic disturbance in the repository system	Voids within the set of waste packages should be limited as much as possible to limit strains and hydraulic disturbance on the repository system (in order to preserve the host rock).	The addition of coating in the waste could have an impact on voids in the waste package at a long time scale according to time of degradation between resin and other materials (will depend of the conditioning form of the waste). This point will have to be studied especially in case of waste blockage inside the waste package (cementation for instance => which is not the current senario)
To control gas build-up according to overpack and/or repository design	Gases rate per waste package (corrosion, radiolysis, etc.) should be declared to verify its compliance with the repository design (including the overpack if any).	Analysis of gas rate generated by coating under irradiation and high temperature Additional studies to be performed to evaluate risk of gas emission due to corrosion or chemical interaction with other waste inside the waste package or interaction with the waste package itself (very low probability as silicon resin are chemically inactive)
To control overpack internal corrosion (chemical and radiolysis aggressiveness)	Substances favoring internal corrosion of the overpack (if any) should be declared at the waste package level and limited as much as possible.	Determination of a generic list of substances studied for French storage and disposal. Identification of the coating composition and degradation products. Analysis based on the generic list previously determined.

VII. ASSESSMENT OF IMPACTS

7. 5. WASTE MANAGEMENT

7.5.5 Analysis about "substances"

To identify the kind of substances that could have an impact in the waste package, the following list is based on prohibited or restricted substances in several French disposal facilities:

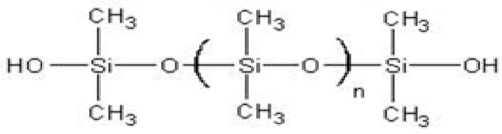
Kind of substances	Potential impact from coating
Products or mixtures presenting risks of ignition or explosion or presenting risks of sudden exothermic reaction with the various constituents of the package	No, there is no exothermic reaction between the resin and the stainless steel body of the cannister. More over, resin (especially silicone ones) are chemically inactive components
Waste presenting an infectious risk	No
Free aqueous liquids	Yes, Depending on composition and chemical reaction of degradation products, it could be possible to have some residual free liquid water in the waste
Organic liquids	No
Putrescible materials	No
Pyrophoric or very highly reactive metallic waste	No
Friable (loose) asbestos	No
Explosive substances	Yes, potential generation of explosive gases (H2 and CH4) under irradiation and high temperature or by degradation
Flammable substances if its flash point is inferior to 55°C (value from French regulation)	No, the coatings are considered as non-flammable. Tests of behavior under high temperature and flames
Toxic chemicals considered: uranium, lead, mercury, antimony, cadmium, selenium, arsenic, nickel, chromium, boron, beryllium, cyano radical, CMR and asbestos.	Yes. It is unlikely but an analysis of the detailed composition of coating is needed.
Complexant : - Inorganic substances: chloride, fluoride, nitrate, sulphate, carbonate - Organic substances, for instance: EDTA, NTA, DTPA, TTHA, oxalate, citrate, acetate, formate, ascorbate, gluconate, sulfamate, phthalate, picolinic acid, TBP and ethylene-diamine Others: sulfonate	Yes. The detailed composition and the analysis of degradation products are needed.
Aggressive substances : - Saline substances, including those inducing high ion strength, such as sodium salts or potassium salts (potassium sulfate for example), and especially sodium nitrates (and nitrites)	
Source of radiolysis	Yes, the radiolysis rate is determined by tests and compare to the radiolysis rate from substances in the Fuel Debris.

VII. ASSESSMENT OF IMPACTS

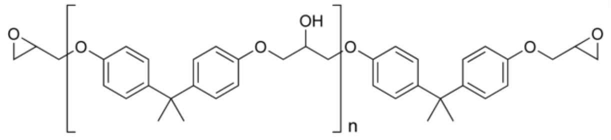
7. 5. WASTE MANAGEMENT

7.5.5 Analysis about "substances"

Two coating families are studied : a Silicon based coating (RTV FA 878) and an Epoxy base coating (EpoxyGuard)



Generic composition of silicone based coating



Generic composition of epoxy based coating

Laboratory analysis carried out during the project show that coating have the following component concentration:

		HALOGEN	SULFUR
FAMILY	COATINGS	$_{9}$F, $_{17}$Cl, $_{35}$Br	$_{16}$S
SILICONE	RTV FA 878	PMUC component (< 200 ppm) (French Regulation = means product usable in nuclear power plant)	
EPOXY	EPOXYGUARD	> 200 ppm (respectively around 100, 1600 and less than 20 mg/kg)	> 200 ppm (around 13300 mg/kg)

Some laboratory analysis showed that de propan-2-ol, triméthylsilanol and some Volatil Organic Component (VOC) are detected for both coating after heating at 80°C and 200°C. Furthermore, xylene for silicone coating and alkenes, alkanes and alcohol for epoxy coating are detected. So, the coating composition is more complex than the formula presented above.

A complete characterization of the two coatings has been made:
Differential Scanning Calorimetry (DSC) to characterize first and second order thermal first and second order thermal transitions (glass transition, melting degradation and associated enthalpies) for each sample.

- Thermo-Gravimetric Analysis coupled with IRTF (TGA-IRTF) to follow the evolution of the mass of a sample as a function of temperature and to identify the associated decomposition gases. Structural analysis by Pyrolysis/GCMS in order to identify the characteristic degradation compounds of the two resins.
- Liquid Phase Chromatography coupled to QToF Mass Spectrometry, in order to search for observable organic compounds using a screening method.
- Gas Chromatography coupled to Mass Spectrometry (GC-MS), in order to search for observable organic compounds using a screening method.
- Fourier Transform Infrared Spectroscopy (FT-IR) to determine the chemical nature of the sample and confirm its general structure.
- Field Emission Scanning Electron Microscopy coupled with an EDX microprobe (SEM/FEG-EDX) to perform semi-quantitative local chemical observations and analysis to identify chemical analysis to identify the composition of the residual inorganic charges after TGA (900°C).

VIII. APPLICATION ON SITE & SUGGESTED NEXT STEPS

8. 1. REAL CASE SCENARIO – APPLICATION ON SITE

The implementation of a coating system requires the use of several equipment and skids:

Located in the Pedestal

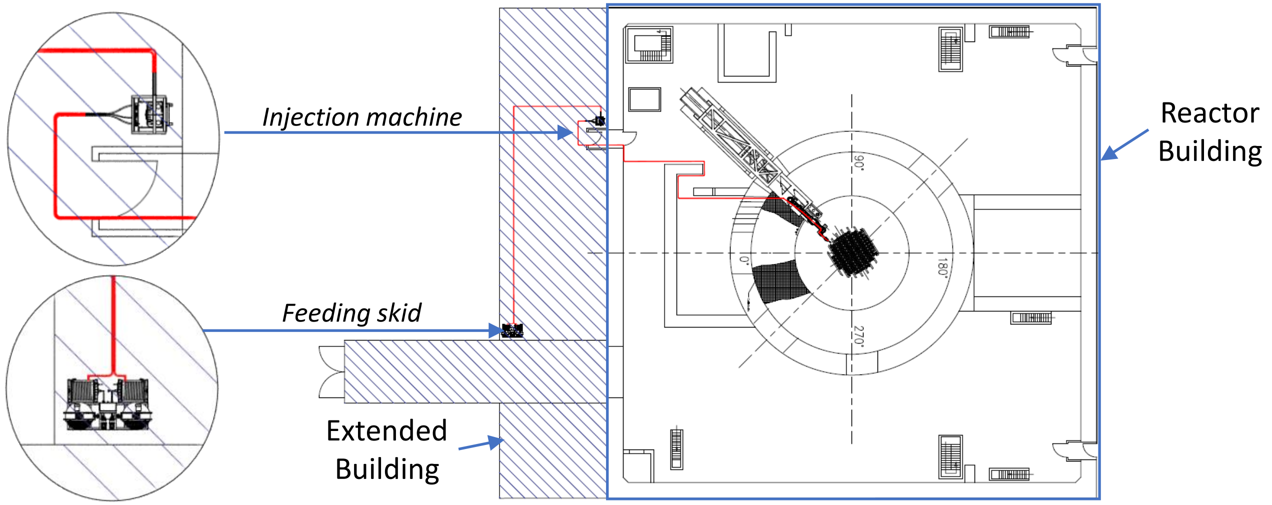
- Part 1: Spraying or spreading system implemented on the remote control arm
  - The spraying system is used to apply the coating to the top of the pedestal, the vertical walls and various elements (e.g. CRD, platform...)
  - The spreading system is used to cast the coating at the bottom of the pedestal on the fuel debris or waste above or under water

Located outside the reactor building

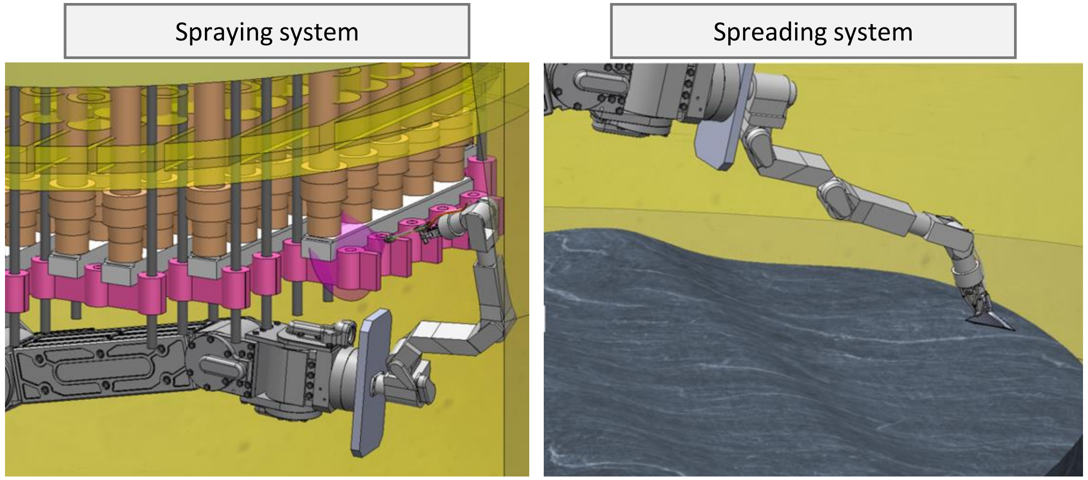
- Part 2: Specific machine for spraying and spreading coating
- Part 3: Skid for automatic feeding coating components

The locations of the feeding and injection skids in the extended building allow to facilitate the operations of intervention or maintenance. A possible implementation of the equipment is presented below:

- Placement of the specific injection machine near the access door to the reactor building (about 35m from the injection point)
- Placement of the feeding skid in an easily accessible area to allow manual charging of the coating components



Specific machine and Feeding skid implemented outside the reactor building.



Spraying and spreading system is implemented onto the robotic arm in order to carry out coating operations inside the pedestal

VIII. APPLICATION ON SITE & SUGGESTED NEXT STEPS

8. 1. REAL CASE SCENARIO – APPLICATION ON SITE

Part 1: Spraying or spreading system implemented on the remote control arm

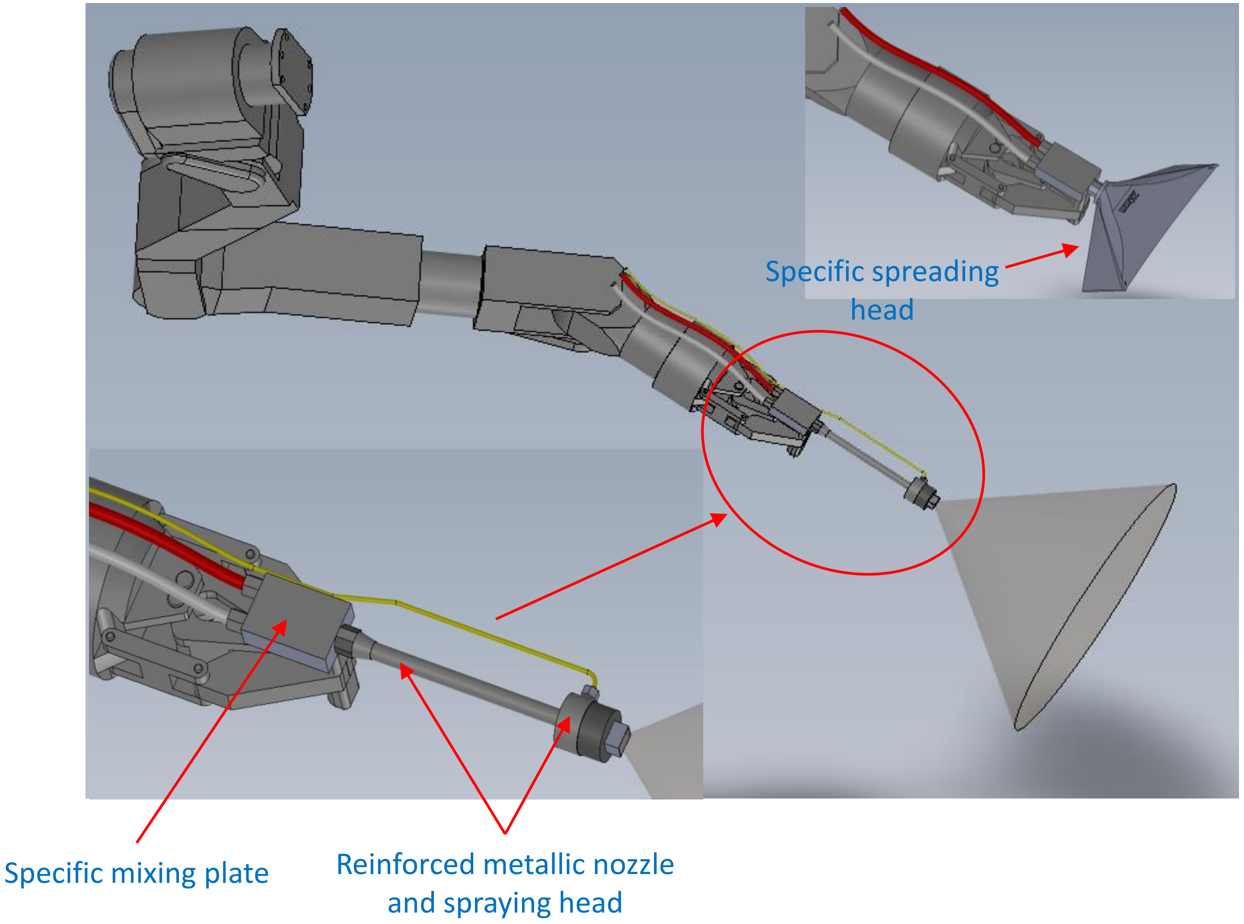
This is the system used where the resin must be sprayed/injected.

A specific plate to mix part A and part B is mounted as close as possible to the injection zone, which limits the number of elements to be cleaned or changed.
Nota: Before mixing the components, there is no risk of reticulation and the circuit does not require specific cleaning. After mixing, the products has a pot life of a several minutes and must be injected continuously. If the injection is stopped, the section downstream of the flat mixing must be removed or cleaned.

Then the resin is injected on a reinforced metallic nozzle and the resin is sprayed with various specific metallic spraying heads adapted to the environmental accesses to the structures to be sprayed. Tests of coating application with a remotely operated arm carried out at CEA MARCOULE have shown that the injection head must be reinforced to be more resistant in case of collision.

For the areas where the resin must be spread (on the floor under water for example), the same system could be used with a specific head adapted to spread large quantity of resin on fuel debris.

A video network (mono or stereoscopic viewing with cameras + lighting) shall be installed on the robotic arm tip end and/or on the specific plate in order to help the operator for driving the manipulator's wrist and the embedded spraying head.



VIII. APPLICATION ON SITE & SUGGESTED NEXT STEPS

8. 1. REAL CASE SCENARIO – APPLICATION ON SITE

Part 2: Specific machine for spraying and spreading coating

This equipment is a compact specific injection and spraying machine placed in the Extended building at maximum 50m from the injection point.

The capacity of the skid is around 50 Kg of coating (2x 25 Kg).

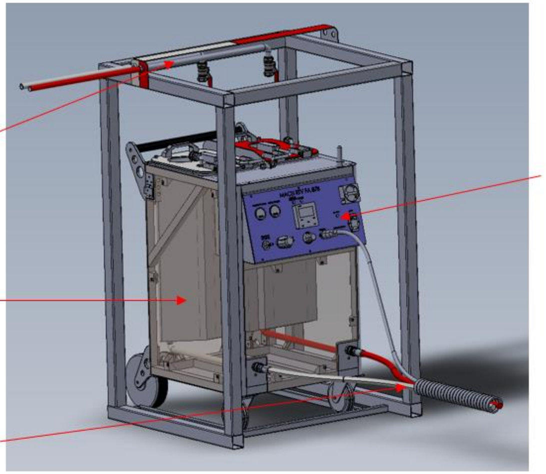
This machine inject part A and part B of coating inside 2 hoses running along the robotic arm inside the PCV.

This machine could be automatically reloaded in component by the skid detailed in third part.

An automatic system will control the ratio of part A and B injected in the hoses, together with the compressed air needed for spraying.

Overall dimensions (L x W x H) (tentative):

0.85 m x 0.85 m x 1.3 m



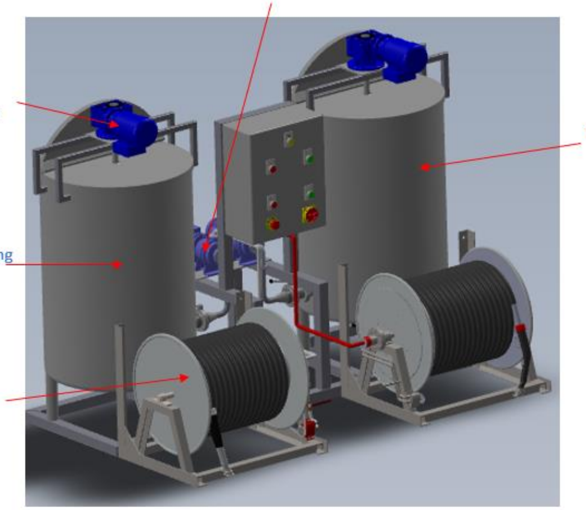
Part 3: Skid for automatic feeding coating components

This equipment is the main storage of coating components. The skid can be positioned in the Extended Building in an accessible area to allow for tank reloading.

The tank have a capacity of around 2 x 200 kg of component.

The connection lines between the feeding skid and the specific injection machine are made by two hose reel of 50m length capacity.

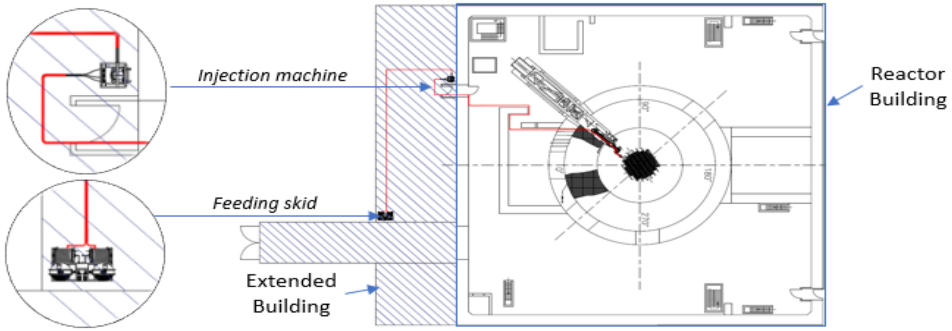
Overall dimensions (L x W x H) (tentative) : 1.9 m x 1.1 m x 1.3 m

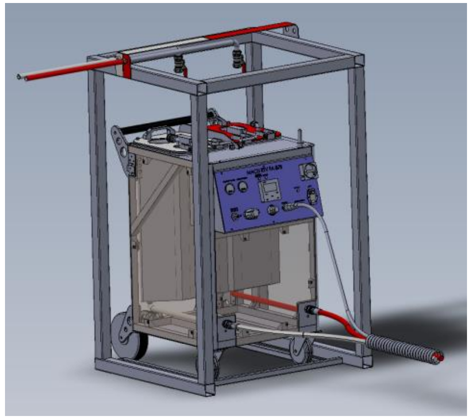


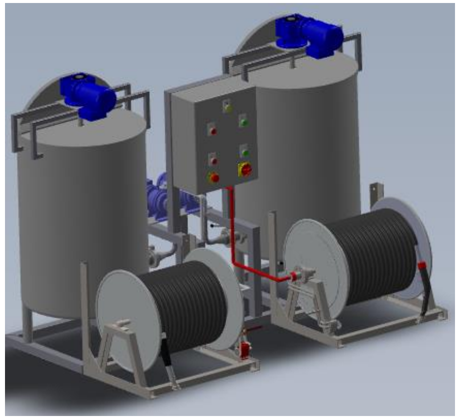
VIII. APPLICATION ON SITE & SUGGESTED NEXT STEPS

8. 2. SYNTHESIS FOR THE APPLICATION ON SITE – IMPORTANT PARAMETERS

8.2.1 *Implementation & Operation of injection/spraying system*







- Design of equipment must be carried out in order to facilitate the implementation on site
- Different skids must easily handlable. Because coating is transportable, tanks and pumps can be implemented in areas with lower dose rates
- Mounting of the injection/spraying head on the robotic arm must be carefully designed, good care must be also brought to the flexible hoses
- Even with the long distance between the tanks and the robotic arm inside the pedestal, diameters of flexible hoses can remain small. However, fluidity of coatings may impact the pressure loss and the design of the whole equipment
- It is important that all useful information is reported to the general post of command: air pressure, flow of coatings, level of coatings in the tank, etc. so the operators can easily remotely operate the system
- Especially, it is important for the operators to access to all injection/spraying parameters in real time so they can acknowledge if the operation is going accordingly to the expectations

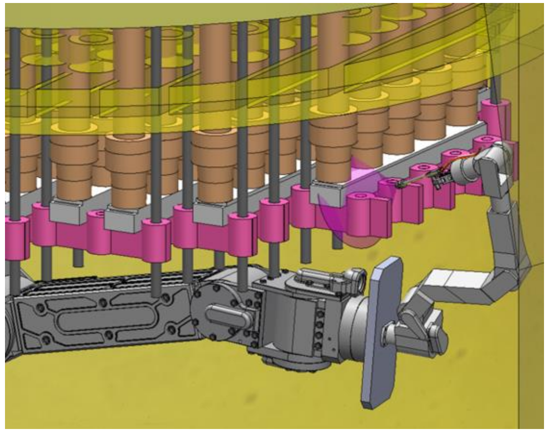
- ***It must be noted that this is an illustration of a possible implementation on site. Many other solutions may be studied. Especially, it is possible to use other penetrations and other systems to get inside the pedestal (robotic arm, telescopic pole, etc.)***
- ***Also, the spraying head presented in this report could be differently designed (number of spraying nozzles, spraying angles, spraying directions, etc.) depending on the need***

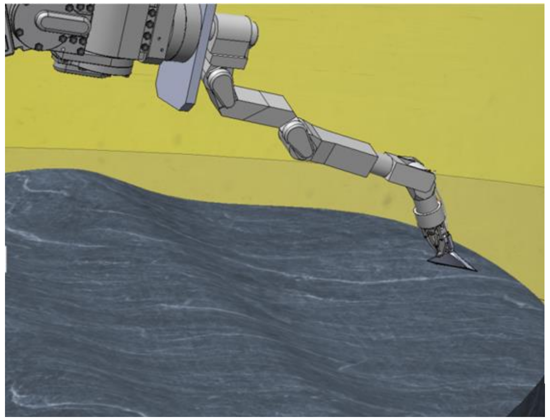
VIII. APPLICATION ON SITE & SUGGESTED NEXT STEPS

8. 2. SYNTHESIS FOR THE APPLICATION ON SITE – IMPORTANT PARAMETERS

8.2.2 *Coating parameters for the application inside the pedestal*

As the tests highlighted during the project, many parameters must be considered.





- For the spraying on the upper parts, it is important to consider coating easily sprayable (i.e. coating with adapted viscosity)
- Because of the gravity and in order to avoid that too much coating drips before crosslinking, it is important to use a coating with a short pot life
- Pot life of a coating will depend on several parameters, including its own properties and the temperature of use. Depending on the room conditions, retardants may be necessary or not

- In order to be effective, spraying operations must consider areas of application carefully: the robotic arm (movements) and the spraying nozzle specifications must comply with the objectives (coating thickness, percentage of coverage, … ?)
- Operational objectives must be clearly determined in order to design properly the final system/operation: different options must be considered whether the important parameters are the quantity of coating used, the operational time of coating, the percentage of coverage that must be reached, etc.

- One major point on which further developments are needed is the vision on site and more specifically the control of the coating thickness
- Indeed, tests have proven that cameras could be easily dirten. Therefore, solutions must be brought in order to protect them (air blowing, self cleaning, … ?). Movements of robotic arm and spraying nozzle must also be carefully considered in order to avoid that too much coating dirten the cameras
- As for the control of the coating thickness, properties of coating could be improved to ease this control: fluorescent properties could be added to the coating so with the correct lighting it could be easier to determine whether a coating operation has been effective or not

- For the bottom part, viscosity of coating shall also be consistent with the transportation from the skids. But coating pot life shall be longer because it will be necessary to let the coating to spread widely to ensure a good coverage of the surface
- Vision at the bottom of pedestal and control of thickness remain issues that shall be considered

VIII. APPLICATION ON SITE & SUGGESTED NEXT STEPS

8. 3. SUGGESTED NEXT STEPS

It could be interesting to continue the work on the use of coating inside the pedestal. Following items are suggested:

- Studies & tests to enhance global safety management:
    - Work on a test program for larger scale tests and carry out the tests. These tests could include fall of larger and heavier objects. Assessment of dust resuspension following a seism could be carried out
    - Numerical simulations in order to assess the dust resuspension rates in various situations and the gain that would bring the use of coatings
    - Demonstrations could be carried out for other areas of interest on site (from the top to the bottom of the RPV, in areas outside the PCV, etc.)

- Development of a first operational prototype:
    - Work with TEPCO in order to determine a realistic implementation scenario with accurate definition of objectives & requirements of operation
    - Design the operational prototype with determination of the interfaces with the future carrier
    - Work on the coating itself in order to improve properties that will ease the operation on site

- Related studies of the use of coatings:
    - Continue the studies about waste management and study system for an eventual sorting of wastes
    - Study different areas of application considering larger choices of coating candidates (beside the silicone and epoxy coatings)

VIII. APPLICATION ON SITE & SUGGESTED NEXT STEPS

8. 4. OTHER APPLICATIONS OF COATING FOR DISMANTLING WORK IN 1F

Other applications may be considered for the use of coatings on site and could be suggested. Indeed, preliminary results show the advantages of their use in order to avoid dust resuspension in the pedestal. But besides the pedestal, many items need to be dismantled, in the PCV and around, and dust resuspension may be a major issue for safety considerations.

Use of coatings shall be advantageous for the cutting and removal of any items, such as pipes for instance or for any opening operations (in the concrete, in metallic structures). It shall be particurlaly interesting for all the cutting operations using Abrasive Water Jet or laser cutting because these tools generate a lot of dust resuspension.

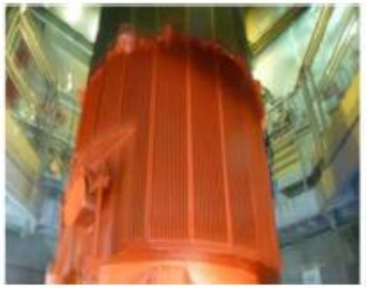
Furthermore, the study of the current project focused on the use of coatings inside the pedestal with the specific constraints of this specific application. If coatings were to be used elsewhere, criteria of selection shall be reviewed and some other families of products shall become interesting.

VIII. APPLICATION ON SITE & SUGGESTED NEXT STEPS

8. 4. OTHER APPLICATIONS OF COATING FOR DISMANTLING WORK IN 1F


Repair of the tightness of a sump

Coating used to remove contamination


Protection against contamination

Repair of the tightness of a ventilation duct

IX. CONCLUSION OF THE PROJECT

JUSTIFICATION OF THE CHOICE OF COATING	Benchmarking has been carried out to select potential coating candidates which characteristics are compliant with a use inside the pedestal at the very vicinity of Fuel Debris. Silicone coatings proved to be the most suited for the application. Other families of coatings can be used in other areas, but they have not been considered in the frame of this project.
JUSTIFICATION OF THE EFFICIENCY	Tests have been carried out in order to determine in which situations the use of coating is an asset. Conclusions is that the efficiency of coatings towards the dust resuspension phenomena is total when the coating is applied on the whole surface that is covered with dust. It has been proven for aeraulic and hydraulic stress and for the fall of objects. Tests proved also that even a partial covering is beneficial in all situations.
JUSTIFICATION OF APPLICABILITY	Applicability has been proven with the transportation of coating over 50 meters and the positive results of spraying and injection tests. Conclusive coating tests have been carried out with a remote controlled robotic arm. However these tests showed that improvements are needed before it is possible to use coating on site (improvement of spraying nozzles, of vision system, better definition of conditions on site, etc.)
JUSTIFICATION OF THE IMPACTS OF THE USE OF COATING	Among all the impacts that have been studied in the frame of the project, none has concluded that the use of coating shall lead to a prohibitive impact. Indeed, impacts on cutting operations are low (they barely lower the cutting performances of the tools, no unexpected particles is generated), safety risks (gases emissions, fire risk), heat transfer, criticality are manageable. However, these studies shall be continued, especially the study that concern the waste management.