

FUKUSHIMA DAIICHI FUEL DEBRIS RETRIEVAL: CFD CALCULATIONS OF AEROSOL DISPERSION AND MITIGATION BY SPRAY SYSTEMS IN REPRESENTATIVE CONDITIONS OF THE 1F2 REACTOR PEDESTAL

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Context

Fukushima subsidized projects of Decommissioning and Contaminated Water Management - Development of Technologies for Retrieval of Fuel Debris and Internal Structures



French consortium (ONET Technologies, CEA and IRSN) to implement R&D related to the laser cutting of fuel debris and to dust collection technology



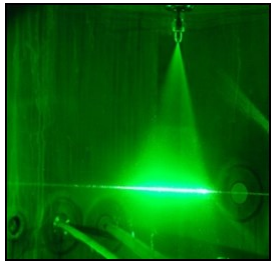
IRSN interests to aerosol issues during fuel debris removal by experimental and numerical means.

=> risk induced by aerosol dispersion and deposition into the reactor pedestal during the laser cutting operations

Issues & Objectives



Particle emission during the above-water cutting operations, involving a potential risk of dispersion into the reactor pedestal and further into the environment in case of containment failure.



Study by IRSN of the use of aerosol mitigation by spray during dismantling operations

Aerosol removal by spray considered as one of the best emergency system in nuclear reactors against several risks of dispersion of hazardous materials (hydrogen, radioactive aerosols)



Experiments and CFD simulations performed to evaluate the collection efficiency of the spray in conditions representative of the reactor pedestal of the unit 2 of Fukushima Daiichi (1F2).



Different scales used:

- to ensure the control of the environment and the associated measurement
- to get enough data for the CFD code validation



CFD calculations of aerosol emission by laser cutting and collection by sprays and local extraction in a geometry as close as possible to the 1F2 reactor pedestal.

CFD Modelling with ANSYS CFX

Eulerian modelling of aerosols

- Transport equation implemented in ANSYS CFX (Gelain, 2018)

$$\frac{\partial Y_n}{\partial t} + \frac{\partial}{\partial x_i} \left(\left(U_i + \tau_p(d_p) \left(g_i - \left(\frac{\partial U_i}{\partial t} - U_j \frac{\partial U_j}{\partial x_j} \right) \right) \right) Y_n \right) = \frac{\partial}{\partial x_i} \left((D_B + D_T) \frac{\partial Y_n}{\partial x_i} \right) + S_{Y,n}$$

With Y_n the aerosol mass fraction and d_p the particle diameter

Deposition model implementation (Nérisson, 2011)

- Deposition wall sink term set by: $\phi_{Y,dep} = -C_M u^* V_d^+$

$$V_d^+ = \frac{g^+ \cdot n}{1 - e^{-(g^+ \cdot n) I_p}}$$

Gravitational and centrifugal deposition

$$I_p = \frac{\sigma_t}{\kappa} \ln y^+ + \lambda(Sc_B, \tau_p^+)$$

$$\lambda(Sc_B, \tau_p^+) = \left[\frac{\tau_p^{+2n}}{\omega^n} + \left(\frac{Sc_B^{-\lambda_1}}{\lambda_0} \right)^n \right]^{-1/n}$$

Inertial deposition

Diffusional deposition

CFD Modelling with ANSYS CFX

Lagrangian description of droplets

- Blob' primary breakup model applied for the droplet injection
⇒ Only needs liquid mass flow rate and nozzle diameter which is the initial droplet diameter
- TAB (Taylor Analogy Breakup) secondary breakup model applied for the spray droplet evolution, depending on the typical breakup regimes defined by the Weber number and so-called:
 - Vibrational regime ($We < 12$)
 - Bag regime ($12 < We < 100$)
 - Sheet stripping regime ($100 < We < 350$)
 - Catastrophic regime ($We > 350$)

Spray collection model

- Aerosol collection sink term added to the transport equations of aerosols:

$$S_{capt} = E_m \pi r_p^2 U_d \frac{X_d}{V_d} C_p$$

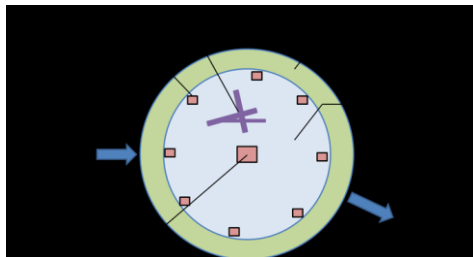
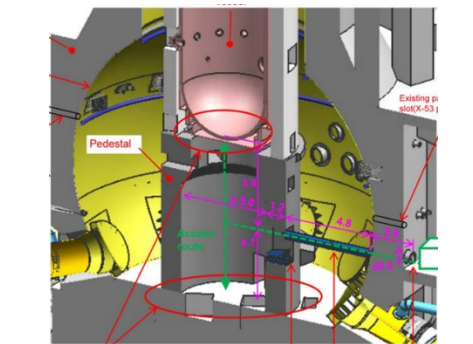
- Collection efficiency defined by (Marchand, 2006 – Plumecoq, 1997):

$$E_m = 1 - (1 - E_{diff})(1 - E_{int})(1 - E_{imp})$$

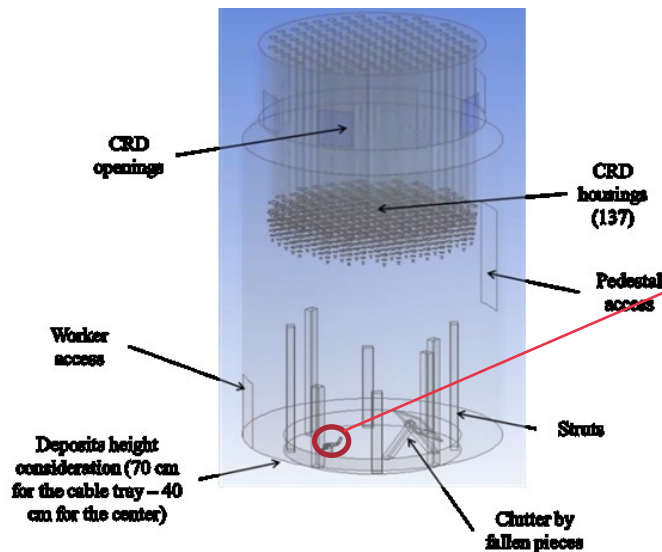
CFD Modelling with ANSYS CFX

➤ Geometry and calculation domain

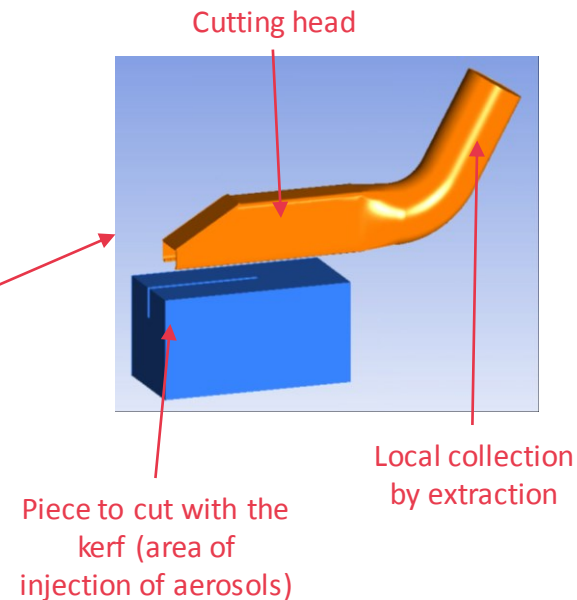
SKETCH OF THE 1F2 PEDESTAL



GEOMETRY OF THE PEDESTAL



LASER CUTTING HEAD DESIGN



CFD Modelling with ANSYS CFX

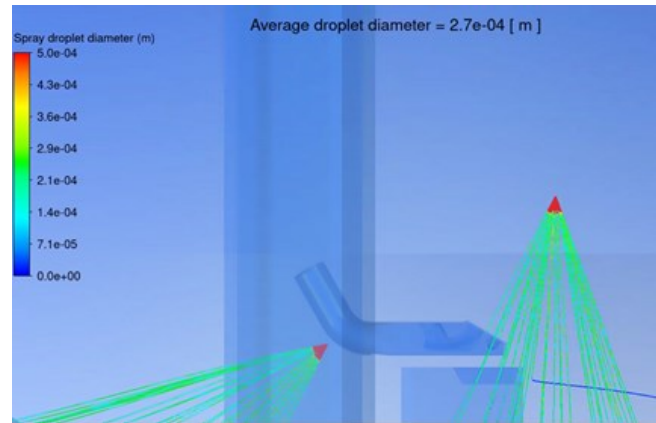
➤ Calculation setup

■ Local spray => two nozzles disposed on two sides of the cutting head.
-> spray angle = 60° - mass flow rate = 35 g/s.

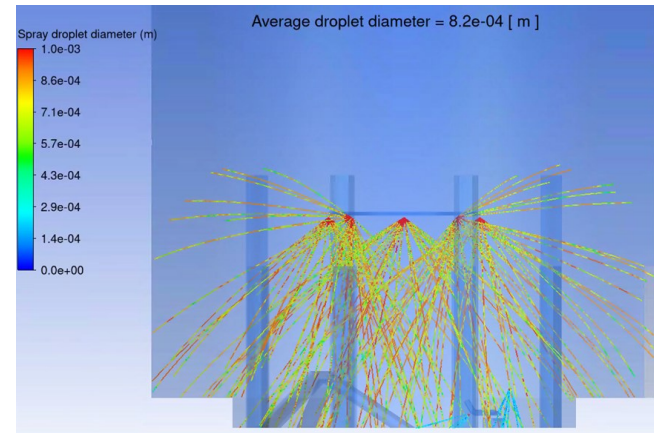
■ Global spray => spray bar with 8 spray nozzles located at 2.5 m above the floor and embedded on the robot arm -> spray angle = 120° - mass flow rate = 90 g/s.



Sprays location



Local spray



Global spray

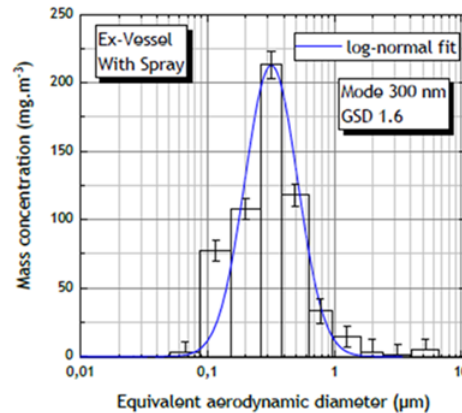
CFD Modelling with ANSYS CFX

➤ Input data and calculation parameters

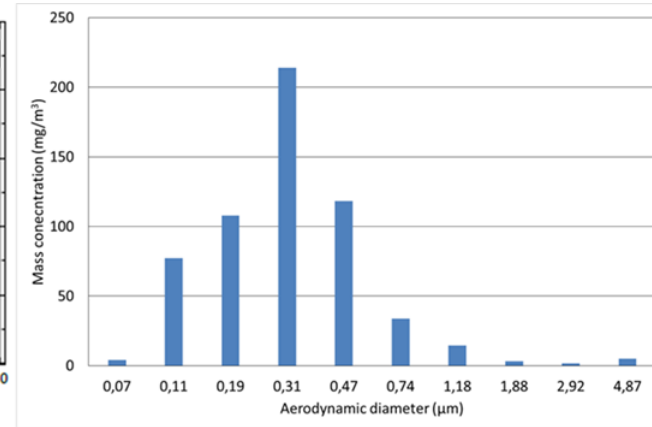
Parameter for calculation

Parameter	
Turbulence model	k- ω SST model (Shear Stress Transport)
Numerical scheme	Hybrid scheme (High Resolution)
Spray Model	Primary Breakup Model: Blob Secondary Breakup Model: TAB
Convergence	Steady state calculation
	Number of iterations = 15 000
	MAX residuals = 10^{-6}
Timescale	Between 0.01 s and 1 s

Experimental data (IRSN)



Input data for CFD code (IRSN)



- Steady state calculation of aerosol removal by spray and local collection
- Injection of aerosols in the kerf and dispersion by the airflows from the laser head
- Collection by local extraction and local and global sprays and analysis of aerosol dispersion in the pedestal

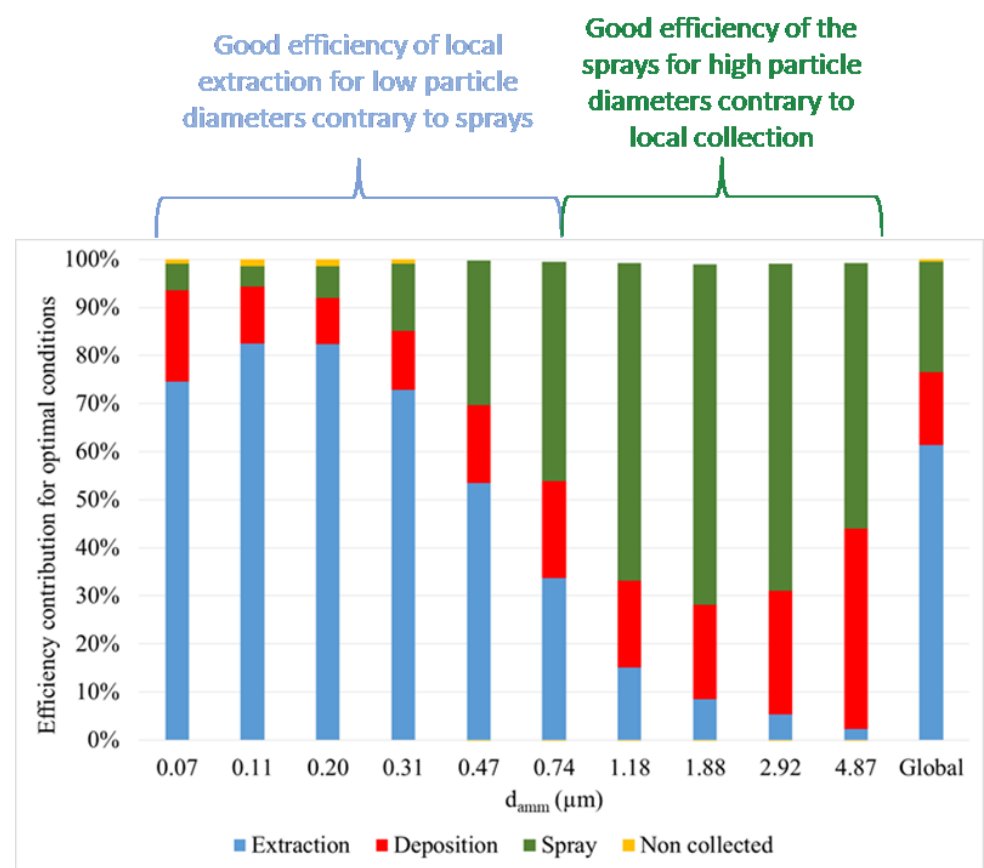
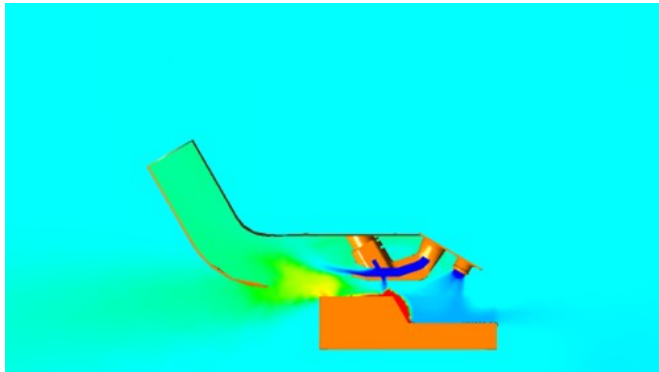
Results and comments

➤ Configuration with $d_p = 0,3 \mu\text{m}$ (Ex-vessel laser cutting)

■ Evaluation of the efficiency contributions of each collection means for stable conditions and of their robustness for different kinds of PSD

=> Very good global collection efficiency for all particle sizes

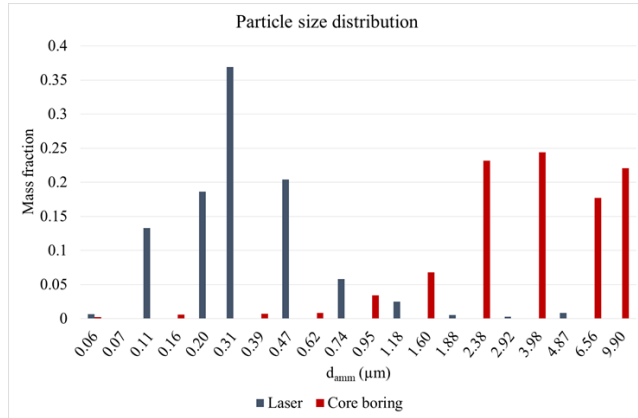
- 60 % for local extraction
- 24 % for spray removal
- 14 % of deposition



=> Highlighting of the complementarity of the collection meanings whatever the particle size

Results and comments

➤ Configuration with $d_p = 4 \mu\text{m}$ (Ex-vessel core boring cutting)

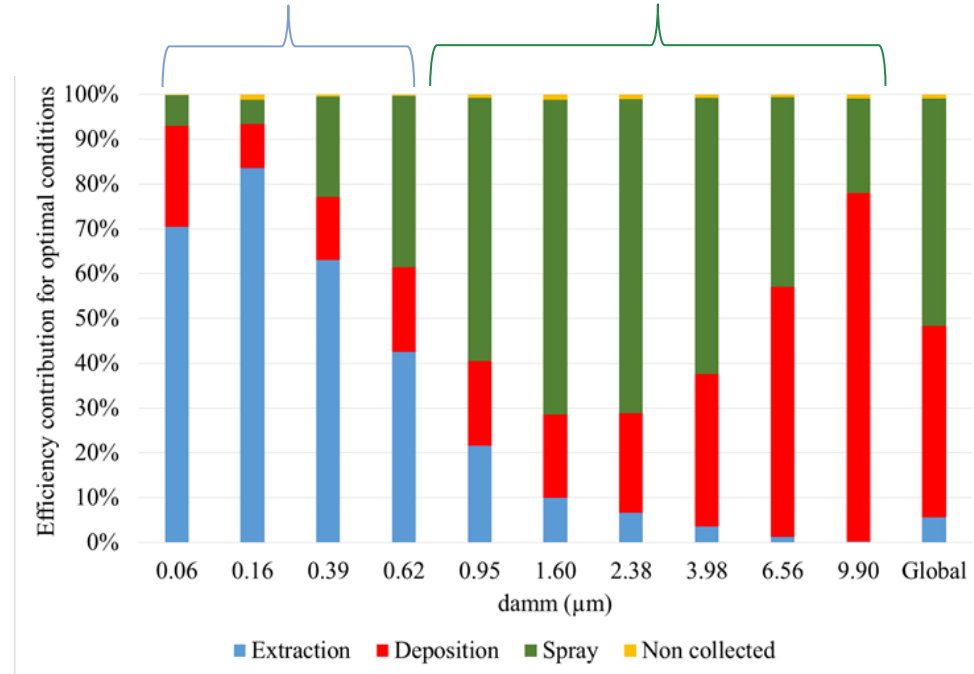


- => Very good global collection efficiency for all particle sizes
- > better efficiency of the spray collection due to higher particles sizes
- 6 % for local extraction
- 51 % for spray removal
- 40 % of deposition

=> Highlighting of the capability of these collection means to be adapted to different PSD

Good efficiency of local extraction for low particle diameters contrary to sprays

Good efficiency of the sprays for high particle diameters contrary to local collection



Conclusion

- Main issue of this study is to demonstrate the capabilities of the means developed and validated on small scale experiments to reach similar performance for the aerosol collection allowing to avoid their dispersion in the pedestal
 - Mitigation means (local extraction and sprays) are applied in a steady-state scenario of Ex-vessel aerosols emission
 - > it highlights that each of them is efficient for a specific aerosol diameter range and they are complementary
 - > it allows to cover a wide range of aerosol diameter with a global part of dispersed aerosols almost negligible
- => Capability of the mitigation means to be adapted to different cutting tools that produce different kinds of PSD in wide range of median diameters

Thank you for your attention