RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

IRSN
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

ON THE ASSESSMENT OF THE RISK OF AEROSOL DISPERSION DURING LASER CUTTING OPERATIONS OF FUEL DEBRIS IN THE 1F2 REACTOR PEDESTAL AND THE INTENDED STRATEGIES IN TERMS OF MITIGATION MEANS

Thomas Gelain[1]*, Emmanuel Porcheron[1], Yohan Leblois[1], Ioana Doyen[2], Christophe Journeau[3], Damien Roulet[4]

[1]*Institut de Radioprotection et de Sûreté Nucléaire (IRSN), PSN-RES, SCA, Gif-Sur-Yvette, 91192, France*
[2]*CEA, DEN, Saclay, DM2S/SEMT/LTA, 91191, Gif-sur-Yvette, France*
[3]*CEA, DES, IRESNE, DTN, SMTA, 13108 Saint-Paul-lez-Durance, France*
[4]*ONET, Engineering Business Unit, 26700, Pierrelatte, France*

* Corresponding Author, E-mail: thomas.gelain@irsn.fr

➢ Dismanting operations of 1F2 damaged reactors

Reactor core meltdown

Corium accumulation in the reactor pedestal

➢ Fukushima reactors dismantling issue

IRSN – CEA collaboration in a project led by ONET and funded by METI

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

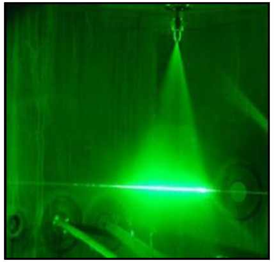
Development by CEA of a laser technique for the FD retrieval

IRSN interests to aerosol issues and mitigation means 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

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

TOSQAN (IRSN)



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 of the 1F2 reactor pedestal.

Eulerian modelling of aerosols

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

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

With $\mathrm{Y_n}$ the aerosol mass fraction and d_p the particle diameter

Deposition model implementation (Nérisson, 2011)

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

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

Gravitational and centrifugal deposition

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

Diffusionnal deposition

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

Inertial deposition

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:

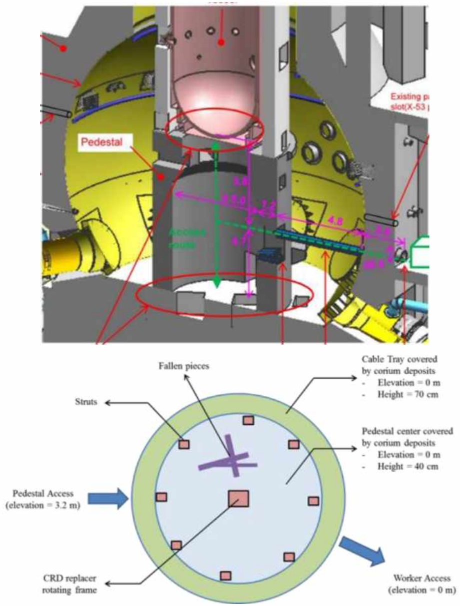
$$S_{capt} = E_m \pi r_p^2 U_d \frac{X_d}{V_d} C_p$$

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

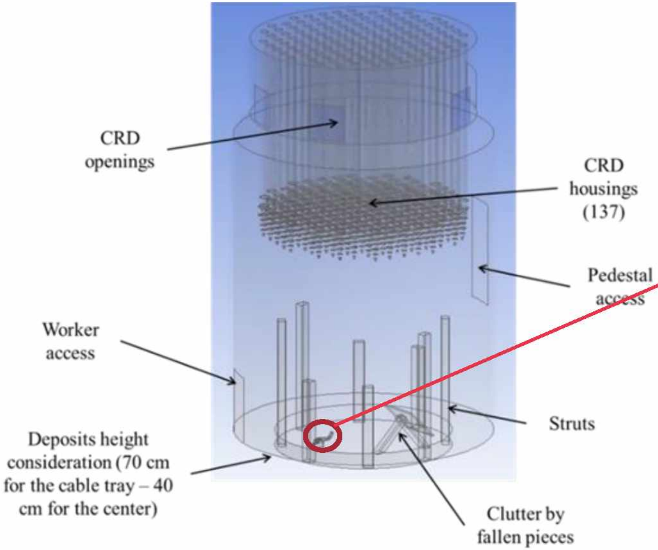
$$E_m = 1 - \left(1 - E_{diff}\right)\left(1 - E_{int}\right)\left(1 - E_{imp}\right)$$

➢ Geometry and calculation domain

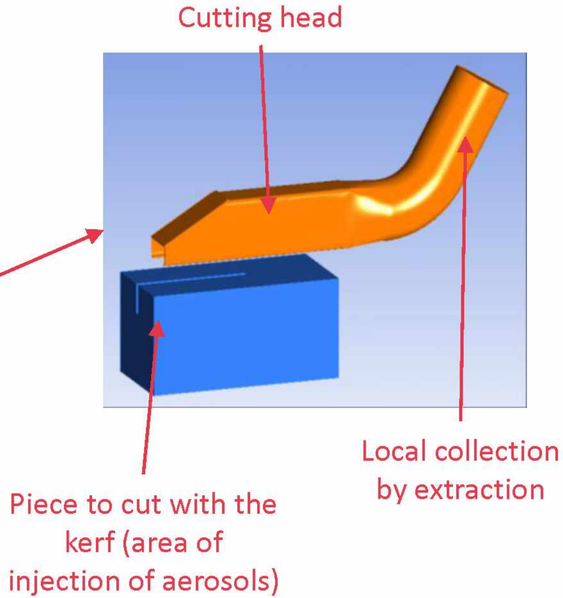
SKETCH OF THE 1F2 PEDESTAL



GEOMETRY OF THE PEDESTAL



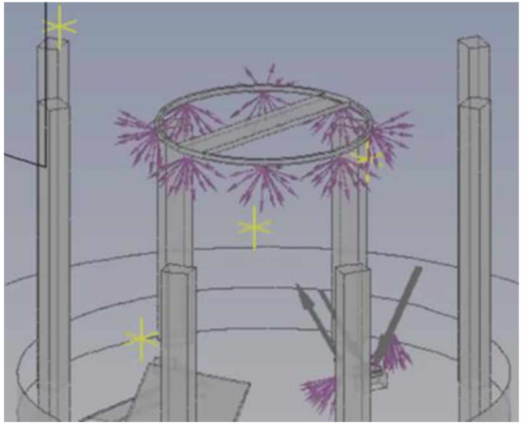
LASER CUTTING HEAD DESIGN



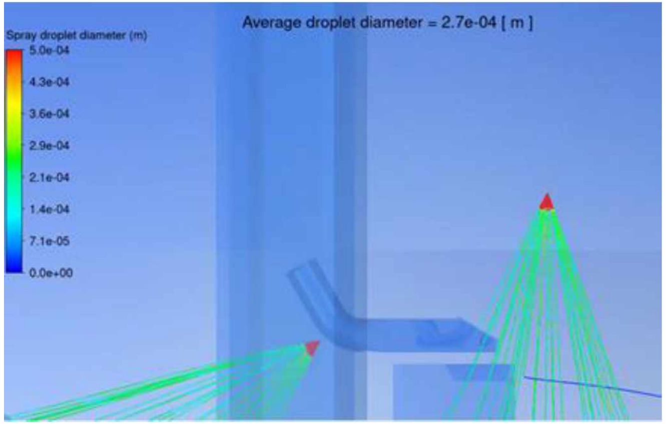
➢ Calculation setup

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

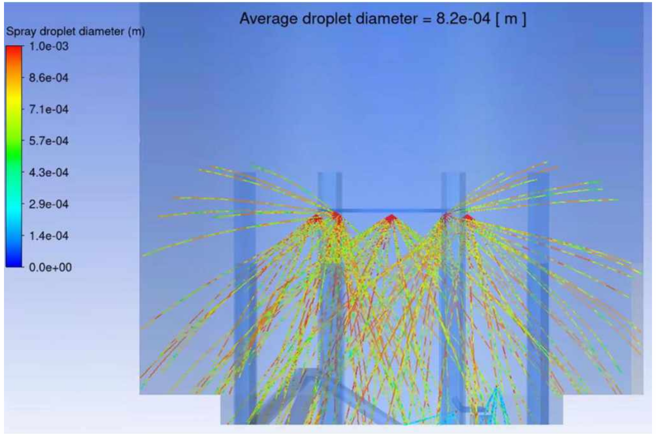
▌ Global spray => spray bar with 8 spray nozzles located at 2.5 m above the floor and embedded on the robot arm -> spray angle = 120° - mass flow rate = 90 g/s.



Sprays location



Local spray



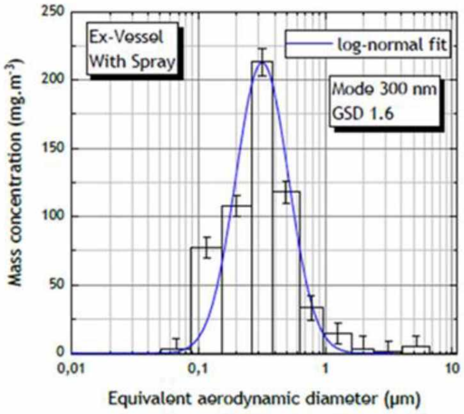
Global spray

➢ Input data and calculation parameters

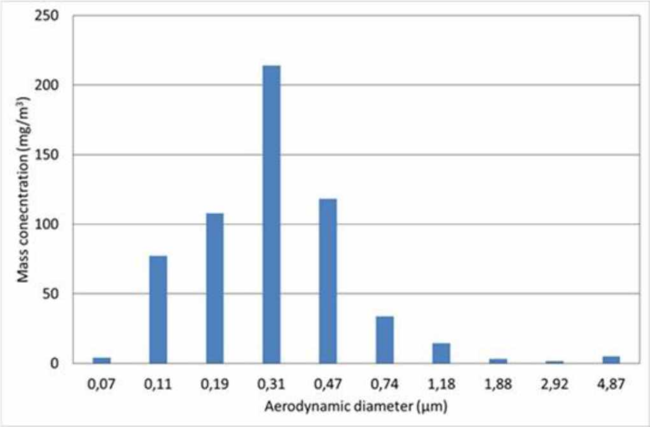
Parameter for calculation

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	Transient calculation Duration = 600 s for cutting phase + 400 s for non-cutting phase
Timescale	Between 0.1 s and 1 s

Experimental data (IRSN)

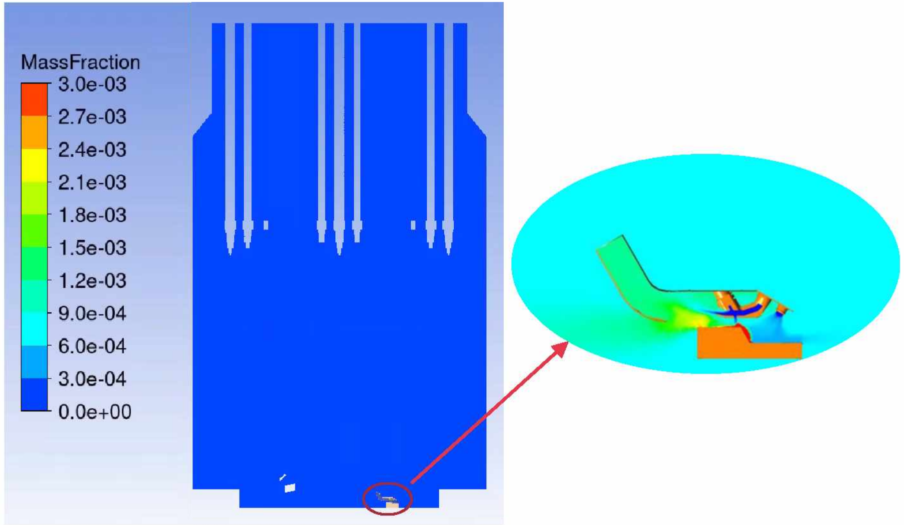


Input data for CFD code (IRSN)



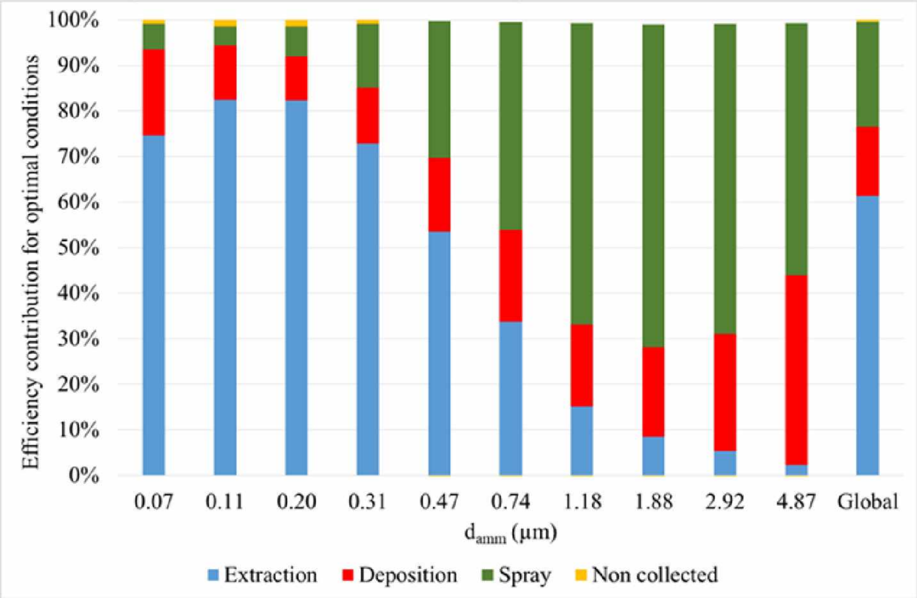
- Transient calculation of aerosol removal by spray and local collection during real cutting scenario (cutting and non-cutting phases)
- Injection of aerosols in the kerf and dispersion by the airflows from the laser head
- Collection by local extraction and local and global sprays and analysis of aerosol dispersion in the pedestal

- First calculations in steady-state conditions with aerosols of Ex-vessel laser cutting (d_p = 0,3 µm)



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



=> Very good global collection efficiency for all particle sizes
- 60 % for local extraction
- 24 % for spray removal
- 14 % of deposition

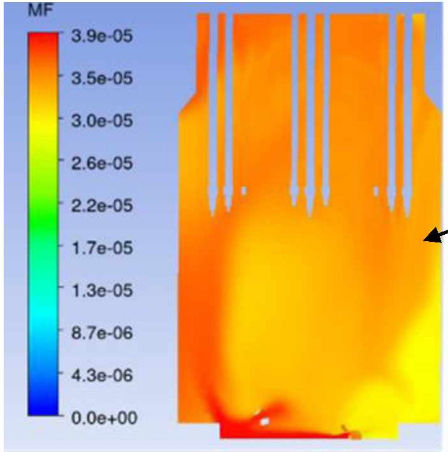
=> Highlighting of the complementarity of the collection meanings whatever the particle size

Results of transient calculations in real-scale geometry

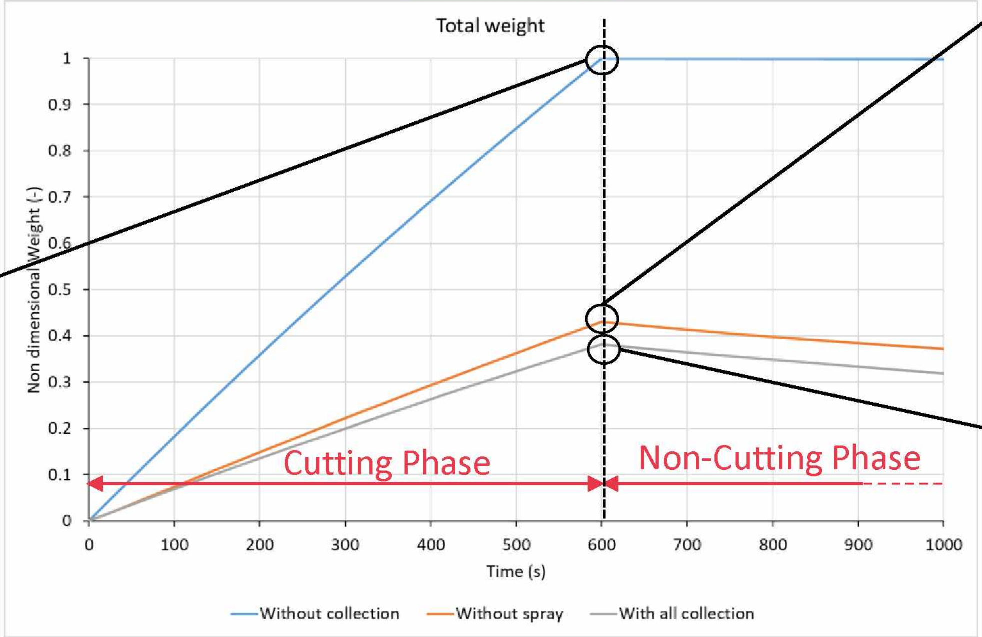
-> Evolution of particle total weight (non-dimensional) inside the pedestal for different cases:

- without collection
- with extraction, without spray
- with all collection systems

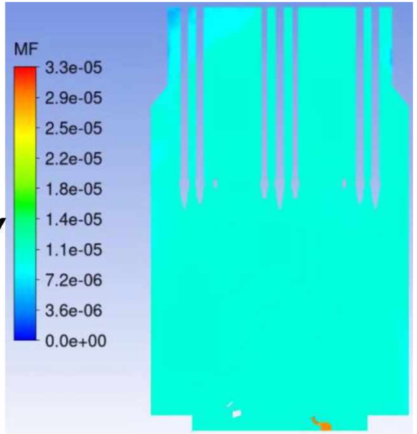
Ex-vessel : 0.3 µm

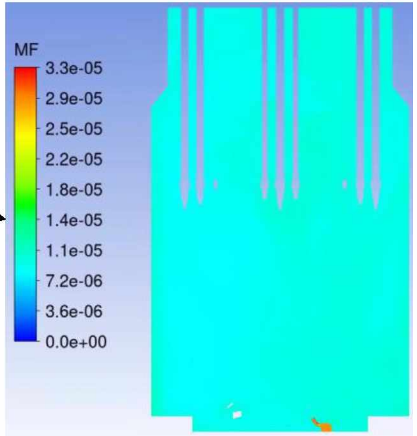


Without collection



With extraction – without spray



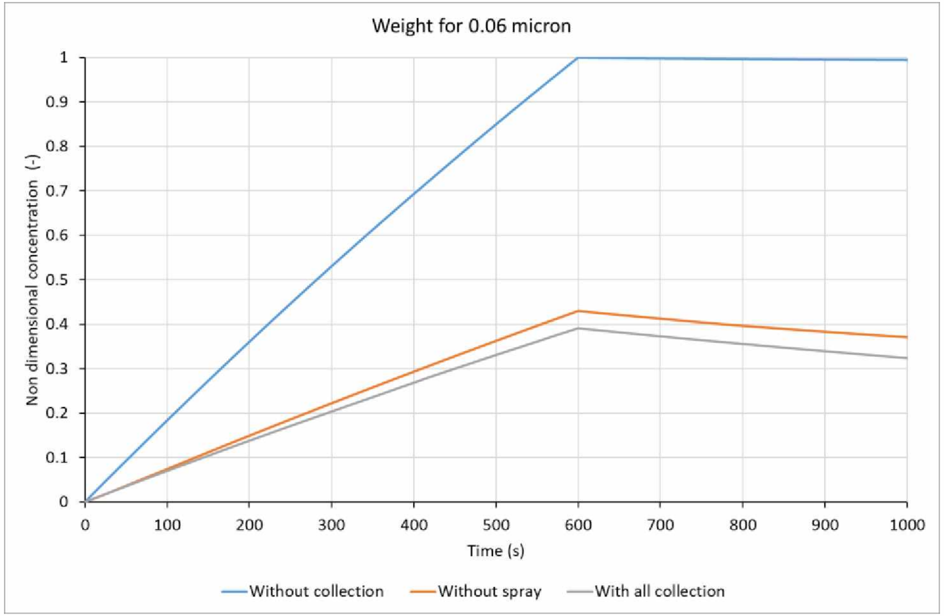


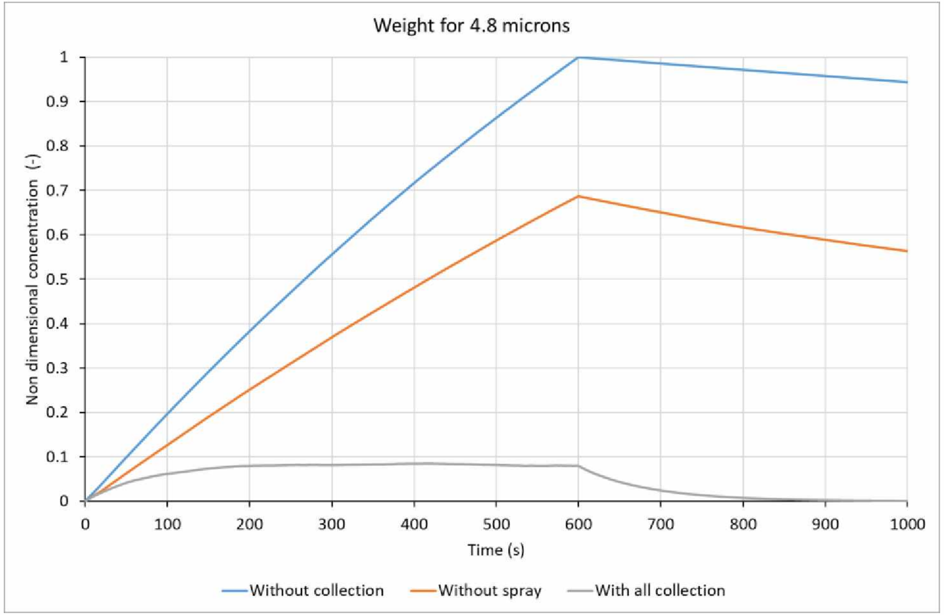
With all collection means

-> Good efficiency of collection by extraction for transient calculations (close to that in steady-state)

-> Low collection by spray due to low mean particle diameter

-> Impact of spray about the collection efficiency





-> For low particle diameters, very efficient collection by extraction (compared to spray) during the cutting phase, but low collection by spray

=> very slow decrease of particle concentration during the non-cutting phase due to low renewal rate

-> For high particle diameters (upper than 1 µm), poor collection by extraction, but very efficient collection by spray

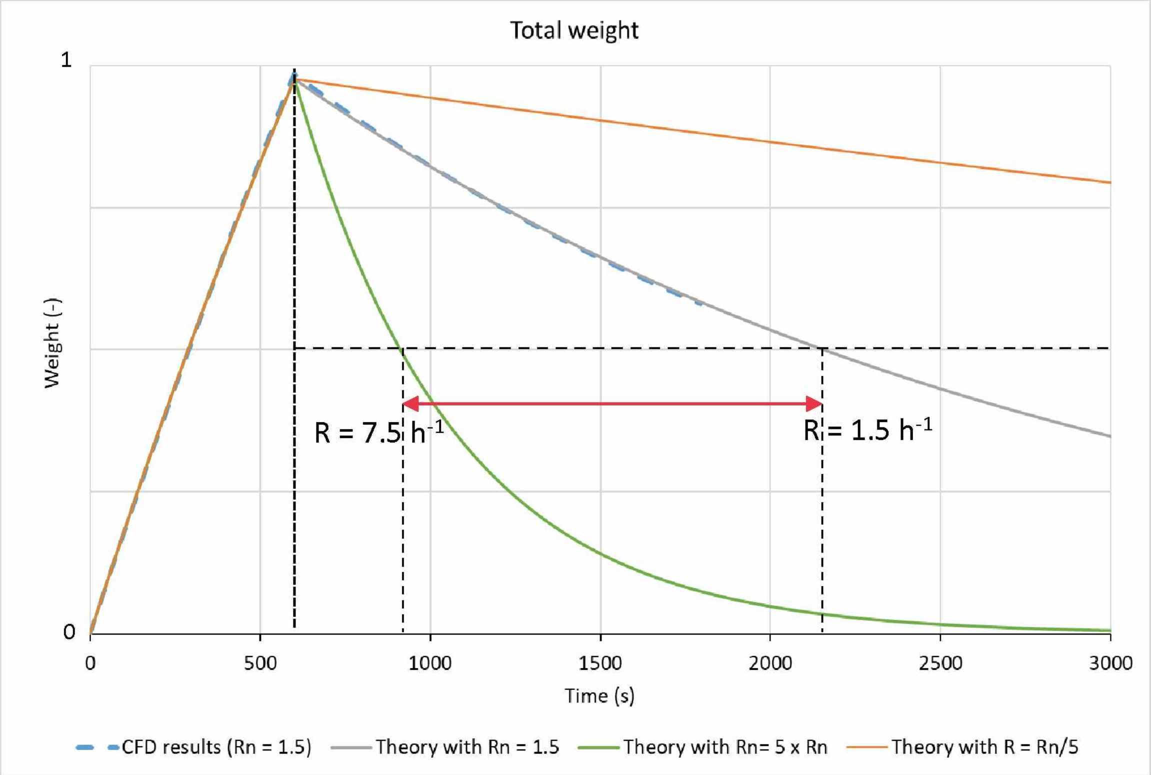
=> fast decrease of particle concentration (with help of deposition) inside pedestal due to spray efficiency

-> Optimization to improve particle concentration decrease during non-cutting phase

In order to improve the time to decrease particle concentration, the best way could be to increase the renewal rate:

- Either by increasing extraction flowrate => not sufficient !
- Either by using global PCV extraction network => more efficient

=> Increasing the renewal rate by a factor 5 may reduce the decreasing time by a factor around 5



- Main issue of this study is to evaluate the performance of mitigation means (extraction close to emission source and global sprays) during cutting phases in a geometry of 1F2 reactor pedestal of FD.
  -> Efficiency of these mitigation means was already proved experimentally and with steady-state calculations
  -> Application to a real cutting scenario

- Mitigation means (local extraction and sprays) are applied in a transient scenario of Ex-vessel fuel debris aerosols emission by cutting and of purge by extraction and spray sweeping
  -> Very efficient collection by extraction during cutting phase for low particle diameter but much less for high particle diameter.
  -> Poor collection by spray for low particle diameter, but very efficient for high particle diameter
  => complementarity with extraction whatever the PSD of emitted aerosols
  -> Purge of the pedestal during the non-cutting phase is poorly efficient due to low renewal rate and particle diameter of the PSD => great time to decrease particle concentration

- A solution to improve the time to decrease during the non-cutting phase is to increase the renewal rate
  => increase Rn by a factor 5 may improve the time by the same factor
  - Possibility to increase extraction flowrate, but probably not sufficient
  - Use the global ventilation of PCV may be very efficient

Thank you for your attention