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, Emmanuel Porcheron, Yohan Leblois, Ioana Doyen, Christophe Journeau, Damien Roulet, Remi Delalez

Proceedings of FDR2022
International Topical Workshop on Fukushima Decommissioning Research
Oct 14-16, 2022. J-Village, Naraha, Fukushima, Japan

FDR2022-1037 (DRAFT)

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
Thomas.gelain@irsn.fr
Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
PSN-RES, SCA, LEMAC
Gif-sur-Yvette, 91192, France

Emmanuel PORCHERON, Yohan LEBLOIS
Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
PSN-RES, SCA, LPMA
Gif-sur-Yvette, 91192, France

Ioana DOYEN
Université Paris-Saclay, CEA, DEN, DM2S, SEMT
91191 Gif-sur-Yvette, France

Christophe JOURNEAU
CEA, DES, IRESNE, DTN, SMTA
St Paul lez Durance, 13108, France

Rémi DELALEZ, Damien ROULET
ONET Technologies
Engineering Business Unit
Pierrelatte, 26700, France

Keywords: CFD, aerosol, dispersion, fuel debris, laser cutting, Fukushima, pedestal.

ABSTRACT

IRSN has been involved with CEA for some years in projects led by ONET Technologies (OT) and funded by Japanese government (METI). These projects aim at evaluating a strategy for the retrieval of fuel debris fell over the floor of Fukushima Dai-Ichi (1F) reactor pedestal, by a laser cutting technology developed by CEA and adapted by OT for a potential use in the 1F site.

However, an important issue regarding aerosols dispersion and potential release into the environment is present around this well-proven technology and must be under control. To do that, IRSN has contributed in this project to provide quantitative information to assess the risk induced by aerosols generation and dispersion. Concomitant experimental and numerical simulations (CFD) studies were led in order to characterize the source term of aerosols from laser cutting of fuel debris simulants (Porcheron et al. 2020), to characterize their fate inside the reactor pedestal by the contribution of airflows coming from the laser cutting head (Gelain et al., 2019) (Gélain et al., 2018) and to propose solutions to help mitigating dispersed aerosols (Porcheron et al. 2019) (Sun et al., 2020) (Porcheron et al., 2021a) (Porcheron et al., 2021b).

The present article is dedicated to summarizing a global CFD study led to evaluate the impact of fuel debris laser cutting in a representative design of 1F2 reactor pedestal in terms of aerosols dispersion and mitigation means.

Given that laser cutting (as cutting in general) produces a large amount of aerosols, laser cutting head was first equipped with a local particle collection system close to the emission source. This system includes an extraction device (a flexible duct and filtration systems) allowing to catch a large part of emitted aerosols with a particle size distribution characterized by a mass median diameter of around 300 nm. However, even if this particle collection means is very efficient, a part of emitted aerosols is not collected and still dispersed in the pedestal. Hence, to collect them, IRSN proposed to implement a spray system, commonly used in French PWR to washout fission products in the event of a severe accident.

This article presents different results of CFD calculations showing the necessity of mitigation means to avoid high aerosols concentration in the pedestal which could lead to a release into the environment. These calculations give also quantitative information about the performance of intended collection systems (extraction and spray) implemented in a representative geometry of 1F2 reactor pedestal of Fukushima and their complementarity. Finally, they highlight the evolution of the aerosols emitted during a cutting scenario as well for the phases during which the laser cutting (cutting phase) is activated as the phases during it is stopped (non-cutting phase). This last part will allow to discuss about the options to help decreasing faster the aerosol concentration during the non-cutting phase.

1. CONTEXT & OBJECTIVES

In the framework of the Fukushima subsidized projects of Decommissioning and Contaminated Water Management - Development of Fundamental Technologies for Retrieval of Fuel Debris and Internal Structures, IRSN carries out experimental tests and simulations for characterizing airflows, aerosols emitted during laser cutting operations, and their dispersion and deposition in the DELIA laser cutting facility developed and operated by the CEA (ALTEA Platform). Different R&D tasks were thus proposed by IRSN to study aerosol issues during fuel debris removal by experimental and numerical means. Among these tasks, one concerns the risk induced by the aerosol dispersion and deposition into the reactor during the laser cutting operations.

During cutting operations in air conditions, particles will be produced, involving a potential risk of dispersion into the reactor pedestal and further into the environment in the event of containment failure. To prevent and minimize this risk, different mitigation means were adapted and tested experimentally and numerically. Among them, the use of sprays for removing aerosols was studied by IRSN, knowing that this mitigation means is considered as the best protection in the nuclear reactors against several risks of dispersion of hazardous materials (hydrogen, radioactive aerosols) in the event of a severe accident.

This article presents the CFD simulations of aerosols dispersion and removal by spray and extraction close to the emission source during a scenario of fuel debris cutting in representative conditions of Fukushima Daiichi unit 2 (1F2) pedestal.

2. CFD MODELING

The CFD simulations of particle collection by a spray were performed with the CFD code ANSYS CFX v2020. In this context, the spray was simulated with a Lagrangian method whereas the particles, considered as polydispersed, were modelled using a Eulerian approach, with a simplified class method (no interaction between classes).

In order to take into account the particle scavenging by the spray, a collection efficiency model was implemented by following that described in (Marchand et al., 2006). The collection mass flux, depending on the characteristics of the spray droplets and the aerosol, was implemented as a sink term in the transport equations for each class of particle.

The equations to be solved in the general case of a multicomponent mixture in turbulent flow and weakly compressible are classically those of Navier-Stokes. Aerosol transport is modelled by a variable transport equation into which an aerosol slip velocity U_{sp} (Nerisson et al., 2011) is implemented to take into account the major forces acting on particles:

$$\frac{\partial \rho \bar{Y}_p}{\partial t} + \nabla.\left(\rho \bar{\bar{U}} \bar{Y}_p\right) = S_p \; avec \; \bar{\bar{U}} = \bar{U} + \overline{U_{s,p}} \quad (1)$$

$$\overline{U_{s,p}} = \tau_p \left(g_i - \left(\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} \right) - \frac{1}{C_p} \left(D_B \delta_{ij} + D^t_{p,ij} \right) \frac{\partial C_p}{\partial x_i} \right)$$

with ρ the density of the gaseous mixture, $\bar{U}$ the mean component of the velocity vector, Y_p the mean value of the particle mass fraction, S_p a potential mass source term, τ_p the particle relaxation time, D_B the Brownian diffusion coefficient of the particles, $D^t_{p,ij}$ the turbulent diffusion tensor, C_p the particle mass concentration ($C_p = \rho\, Y_p$).

2.1 Aerosol deposition model

The deposition model considered in these simulations was developed by Nerisson et al. (Nerisson et al., 2011) and implemented by IRSN in ANSYS CFX by the way of a wall surface flux term φ_d. This model takes into account the main phenomena of deposition such as turbulent diffusion, gravitational settling and turbulent impaction, and is detailed below:

$$\varphi_d = v_d^+ u^* C_p \quad \text{with} \quad v_d^+ = \frac{\boldsymbol{g}^+ . \boldsymbol{n}}{1 - e^{(\boldsymbol{g}^+ . \boldsymbol{n}) I_p}} \quad (2)$$

Where v_d^+ is the non-dimensional particle velocity, u^* is the friction velocity, C_p is the particle mass concentration, $\boldsymbol{g}^+$ is the non-dimensional gravity vector, $\boldsymbol{n}$ is the wall normal vector, I_p is an integration parameter which takes into account the main deposition phenomena (diffusion and inertia). The mass concentration C_p is defined at the first point of the mesh element the closest to the wall and u^* is defined by: $u^* = \sqrt{\tau_w / \rho}$, with τ_w the wall shear stress.

2.2 Spray model

For the collection of the aerosols dispersed in the vessel, spray technology was implemented. Indeed, this technology is already implemented in French Nuclear Powerplant to reduce the containment pressure and aerosol concentration (fission products) in the event of a severe accident. Its scavenging efficiency mainly depends on the aerosol size and on the droplet size, velocity and concentration.

The spray modelling was performed by using a Lagrangian method whose momentum equation for the droplets is presented below.

$$m_d \frac{dU_d}{dt} = \sum F_d \quad (2)$$

Where m_d is the droplet mass, U_d is the droplet velocity and F_d represents all the forces applied on the droplet; in our case, only drag and buoyancy forces were considered.

A ‘Blob’ primary breakup model was applied. This simple model, already present in ANSYS CFX, only needs to specify the liquid mass flow rate, the spray angle and the nozzle radius allowing to calculate the spray droplets velocities U_s. The initial droplet diameter is considered equal to the nozzle diameter before being subjected to aerodynamic induced secondary breakup.

TAB (Taylor Analogy Breakup) secondary breakup model was then applied, allowing to evolve the spray droplet depending on the Weber number defined by:

$$\mathrm{We} = \frac{\rho U_s^2 d_d}{\sigma} \quad (3)$$

Where d_d is the droplet diameter and σ the liquid surface tension.

2.3 Collection model

In order to allow the aerosol scavenging by the spray, a sink term was applied to the aerosol Eulerian phase by the way of a collection sink term added to the transport equation of each particle class (1) in place of S_p. This sink term (S_{capt}) considers a lot of variables depending on the spray, on the aerosol and also on the collection efficiency. It is defined hereafter:

$$S_{capt} = E_m \pi r_p^2 U_d \frac{X_d}{V_d} C_p \quad (4)$$

Where E_m is the captation mechanical efficiency, r_p is the particle radius, U_d is the droplet velocity, X_d is the droplet volume fraction, V_d is the droplet volume and C_p is the particle mass concentration. The mechanical efficiency is described in (Marchand et al., 2006).

3. CFD CALCULATION SETUP & RESULTS

3.1 Geometry and spray location

CFD calculations were led in a geometry the closest of the real 1F2 reactor pedestal design.

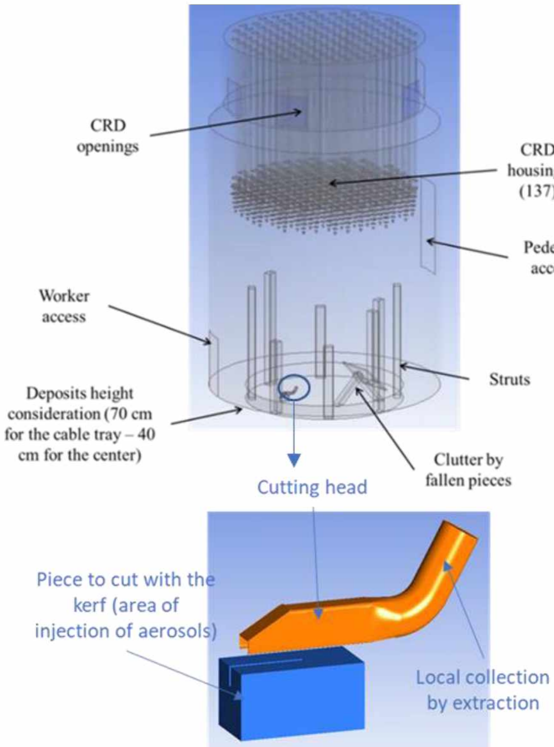


Fig. 1 Geometry of 1F2 reactor pedestal and principle of local collection head

Fig.1 shows a detailed geometry of the pedestal with CRD housings, struts, fuel debris deposit with a height of 40 cm, and some fallen pieces to represent the remaining clutter inside the pedestal. Laser cutting head is located on the ground where fuel debris are accumulated. A focus allows to visualize the external design of the system which includes different jets to clean the kerf, to protect the laser from aerosol entry and to force aerosol to go towards the extraction line.

Fig.2 presents the location of local and global sprays.

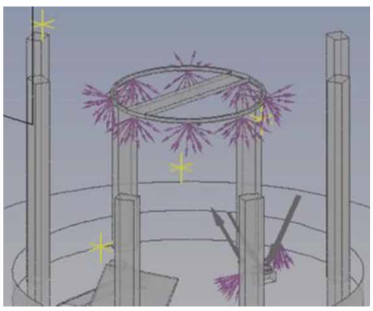


Fig. 2 Spray location in pedestal geometry

Sprays aims at collecting aerosols depending on aerosols and droplets size and aeraulic parameters. Local sprays allow to catch aerosols close to the emission source and to break jet velocities from the laser head. Global spray is dedicated to collect aerosols that are not trapped by extraction or local sprays and that are dispersed by airflows into the pedestal. It allows to create a collection volume at the pedestal bottom and to avoid aerosols to be entrained by global PCV (Primary Containment Vessel) extraction and to be potentially released into the environment.

Sprays parameters were optimized thanks to numerical parametric study and to experimental validation (Porcheron et al., 2021a), allowing to converge to an optimal droplet size of around 250 µm.

3.2 Input data and numerical parameters

Transient calculation of aerosol removal by spray and local collection were led for a real laser cutting scenario (with cutting and non-cutting phases) the most representative of the situation that could occur during dismantling operation. Aerosol emission was modeled by an injection of aerosols in the kerf during 10 min (cutting phase) and their dispersion by the airflows from the laser head during around 7 min (non-cutting phase) was then calculated by the CFD code. Finally, the collection of aerosols by local extraction and local and global sprays was evaluated, and their dispersion in the pedestal was analyzed.

Tab.1 summarizes numerical parameters implemented in the CFD code for calculations and Fig.3 shows the particle size distribution of Ex-vessel simulant acquired by experimental team (Porcheron et al., 2020) and discretized for use as input data.

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

Tab. 1 Numerical parameters for transient calculations

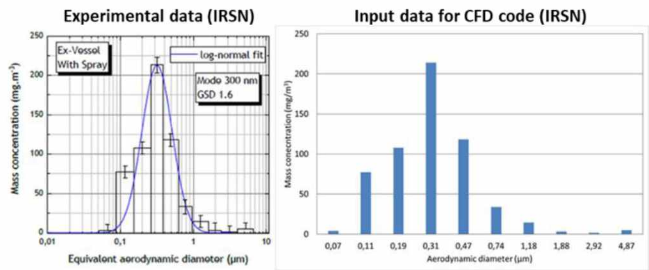


Fig. 3 Particle size distribution (PSD) of aerosols issued from cutting of ex-vessel fuel debris simulant

3.3 Calculation results

➢ *Collection means efficiency in stationary regime*

Calculations were first carried out to evaluate collection efficiencies of each mitigation means depending on aerosol size. Efficiency results are shown in Fig.4 which represents the contributions of extraction (in blue), spray (in red), deposition (in red) and the remaining part in suspension (in yellow).

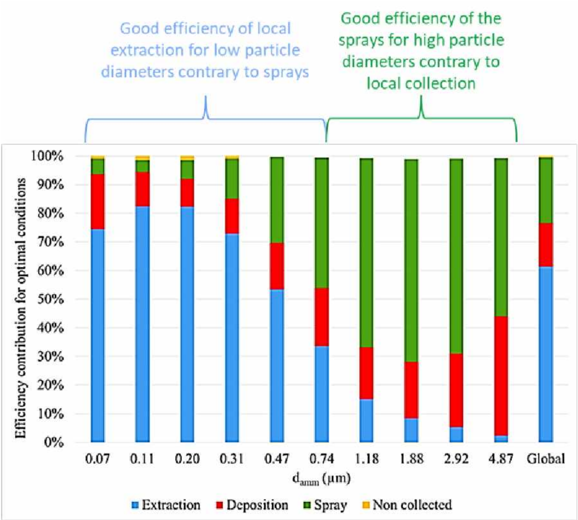


Fig. 4 Collection means efficiencies vs particle sizes

Fig.4 highlights a very good global collection efficiency for all particle sizes and all collection means activated, with an efficiency of 60 % for local extraction, 24 % for spray removal and in addition a deposition of 14 %. Hence only few percent of aerosols are in suspension and may be potentially released outside the pedestal. Results in Fig.4 highlight also the complementarity of the collection means whatever the particle size.

- *Aerosol dispersion for different configurations of collection*

Transient CFD calculations were done for three configurations of aerosol collection to study the impact of each mitigation means on aerosol collection and dispersion. The first configuration is without any collection means to get a reference configuration. Then the second configuration is with extraction activation without spray and the last configuration is with extraction and sprays activation.

Fig.5 shows aerosol mass fraction at the end of cutting phase.

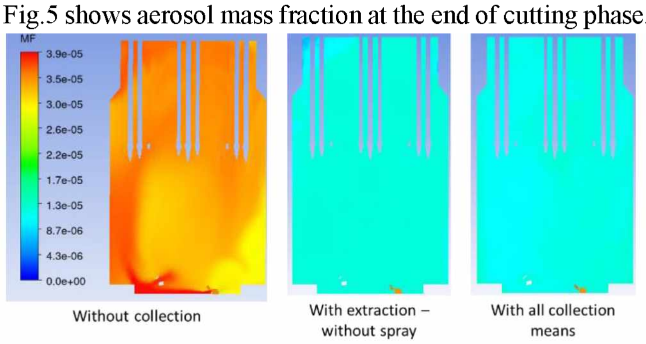


Fig. 5 Aerosol mass fraction at the end of cutting phase for each collection configuration

The comparison of aerosol mass fraction fields between each configuration highlights the strong positive impact of collection means on the aerosol dispersion into the pedestal during cutting phase.

The time evolution of non-dimensional concentration consolidates this observation and makes possible to evaluate the contribution of local extraction to around 60 %, which is close to that calculated for the stationary regime. The contribution of spray is slightly lower than in stationary regime because its efficiency is also due to the recirculation volume below the global spray and to the re-entrainment of aerosols which takes more time to operate.

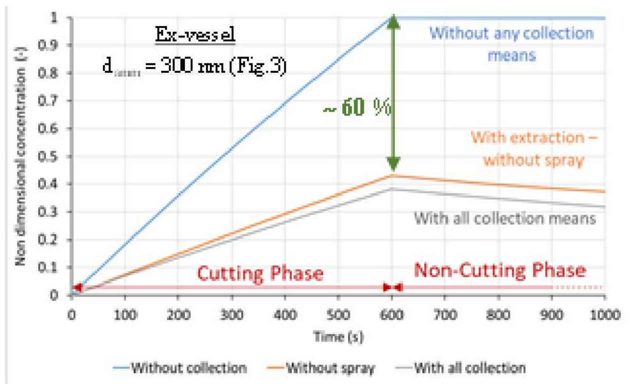


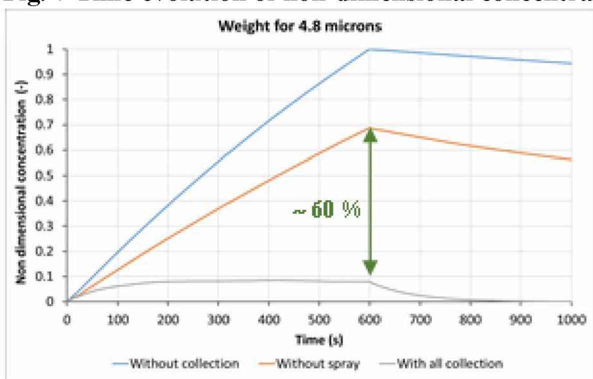
Fig. 6 Time evolution of non-dimensional concentration for each collection configuration (Ex-vessel – d_{amm} = 300 nm)

It may be also noticed that the time to decrease the concentration when cutting is off is very long and may last several hours. It is due to the renewal rate (Rn) of the pedestal that is very low depending on the flowrate of the cutting head extraction.

4. Analysis and potential optimization

The results presented before show a good efficiency of mitigation means during cutting phase with a contribution of sprays slightly lower than expected. As mentioned, the time of cutting phase is too short to state spray effect, but the particle sizes are also in the range of the less easy-to-collect particle size for the spray technique. Fig. 7 allows to highlight the impact of spray for bigger particle size (d_{amm} = 4.8 µm). For this particle size, the contribution for spray is widely higher and reach around 60 %.

Fig. 7 Time evolution of non-dimensional concentration



for each collection configuration (d_{amm} = 4.8 µm)

In Fig.6, it was observed that the time to decrease the concentration during the non-cutting phase is very low and need to be improved. The only way to reduce this time is to increase the extraction flowrate. It can be done by two ways, either by increasing the flowrate of the cutting head extraction, or by using the global PCV extraction. The first idea is not relevant because the capabilities to increase the flowrate of the cutting head extraction are limited and will be not sufficient to be efficient. In contrast, the use of PCV global extraction would allow to strongly increase the renewal rate and to really impact the time to decrease the particle concentration. As an example, Fig.8 shows the impact of the renewal rate on the decreasing time. Indeed, an increase by a factor 5 may allow to decrease the time almost by the same factor.

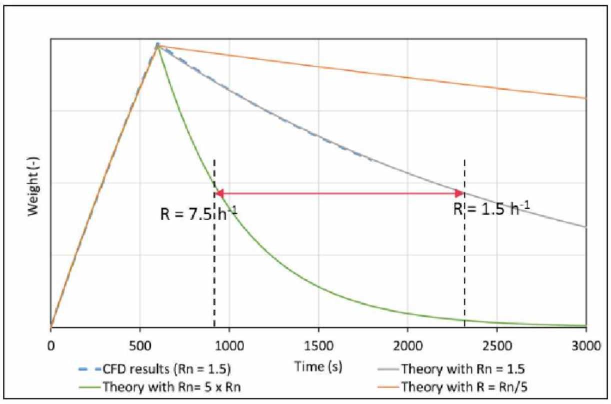


Fig. 8 Impact of the renewal rate on the decreasing time of particle concentration

5. Conclusion

The numerical study presented in this article aims at reproducing aerosol behavior in a geometry the most representative of the real pedestal during a scenario of laser cutting and at evaluating the impact of intended mitigation means.

The results of dispersion and mitigation for the calculated scenario allows to get following conclusions:

- collection by extraction close to emission source is very efficient during cutting phase for low particle diameter (such laser cutting generation) but much less for high particle diameter (such mechanical cutting generation);
- collection by spray is weakly efficient for low particle diameter, but very efficient for high particle diameter particle diameter.

Hence, gathering both mitigation means, extraction and sprays, allows to ensure a great complementarity whatever the PSD of emitted aerosols during aerosol emission.

However, it was highlighted that the purge of the pedestal during the non-cutting phase is poorly efficient due to low renewal rate and particle diameter of the PSD. Hence, a very long time is necessary to decrease particle concentration inside the pedestal.

A solution was proposed to improve the time to decrease particle concentration during the non-cutting phase. It consists in increasing the renewal rate, by using PCV global ventilation.

ACKNOWLEDGMENTS

This work has been carried out thanks to the subsidized projects of Decommissioning and Contaminated Water Management (Development / Advancement of Fundamental Technologies for Retrieval of Fuel Debris and Internal Structures) funded by the Japanese Ministry of Economy, Trade and Industry (METI) and managed by the Mitsubishi Research Institute (MRI).

REFERENCES

Gelain, T., Chagnot, C., Porcheron, E., Journeau, C., Paul, S., & Roulet, D. (2019). Development and validation of agglomeration model for CFD simulations of aerosol dispersion during Fukushima fuel debris retrieval. In *Proceedings of FDR2019 - International Topical Workshop on Fukushima Decommissioning Research*.

Gélain, T., Porcheron, E., Chagnot, C., & Roulet, D. (2018). Numerical evaluation of the fate of aerosols produced by the laser cutting of Fukushima fuel debris simulants. *Aerosol Technology*.

Marchand, D., Porcheron, E., Lemaitre, P., & Grehan, G. (2006). Characterization of the washout of aerosols by spraying water for thermal hydraulic conditions representative of a severe accident in nuclear reactor containment. *10th International Conference on Liquid Atomization and Spray Systems, ICLASS 2006*.

Nerisson, P., Simonin, O., Ricciardi, L., Douce, A., & Fazileabasse, J. (2011). Improved CFD transport and boundary conditions models for low-inertia particles. *Computers & Fluids*, *40*(1), 79–91. https://doi.org/10.1016/j.compfluid.2010.08.013

Porcheron, E., Chagnot, C., Leblois, Y., Journeau, C., Gelain, T., & Roulet, D. (2019). Study of spray scrubbing as mitigation means against aerosol dispersion during the Fukushima Dai-ichi fuel debris retrieval. *International Conference on Nuclear Engineering, Proceedings, ICONE*, *2019-May*.

Porcheron, E., Dazon, C., Gelain, T., Chagnot, C., Doyen, I., Journeau, C., Excoffier, E., & Roulet, D. (2020). Fukushima Daiichi fuel debris retrieval: results of aerosol characterization during non-radioactive simulants laser cutting. *Journal of Nuclear Science and Technology*, *00*(00), 1–13. https://doi.org/10.1080/00223131.2020.1806135

Porcheron, E., Dazon, C., Gelain, T., Chagnot, C., Doyen, I., Journeau, C., Excoffier, E., Roulet, D., Porcheron, E., Dazon, C., & Gelain, T. (2020). Fukushima Daiichi fuel debris retrieval : results of aerosol characterization during laser cutting of non-radioactive corium simulants. *Journal of Nuclear Science and Technology*, *00*(00), 1–13. https://doi.org/10.1080/00223131.2020.1806135

Porcheron, E., Leblois, Y., Gélain, T., Chagnot, C., Journeau, C., & Roulet, D. (2021a). Assessment of Spray and Pool Scrubbing Efficiencies for Means of Mitigation Against Aerosol Dispersion in the Context of Fuel Debris Retrieval at Fukushima Daiichi: Part 2. *Journal of Nuclear Engineering and Radiation Science*, *c*. https://doi.org/10.1115/1.4051538

Porcheron, E., Leblois, Y., Gélain, T., Chagnot, C., Journeau, C., & Roulet, D. (2021b). Assessment of Spray and Pool Scrubbing Efficiencies for Means of Mitigation Against Aerosol Dispersion in the Context of Fuel Debris Retrieval at Fukushima Daiichi: Part I. *Journal of Nuclear Engineering and Radiation Science*, *c*. https://doi.org/10.1115/1.4051611

Sun, H., Leblois, Y., Gelain, T., & Porcheron, E. (2020, August 4). Experimental Study on Aerosol Collection by Spray Droplets: Application to Fission Products Removal in Containment. *2020 International Conference on Nuclear Engineering Collocated with the ASME 2020 Power Conference*.