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STUDY OF VARIOUS AEROSOL MITIGATION MEANS FOR FUKUSHIMA DAIICHI FUEL DEBRIS REMOVAL OPERATIONS

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ABSTRACT

The general context of the article is to evaluate strategies that can be used to mitigate aerosol dispersion during the fuel debris or corium retrieval from Fukushima damaged reactors.

We propose to study various mitigation means, such as the spray scrubbing technology used to collect airborne particles, resin coating and local collection.

1. INTRODUCTION

One of the important challenges for the decommissioning of the damaged reactors at the Fukushima Daiichi Nuclear Power Plant is the retrieval of the fuel debris. In this regard, several R&D projects have been launched and subsidized by the Japanese government to study and arrange operations for the corium retrieval. In this framework, a French consortium (ONET Technologies, CEA and IRSN) has been selected among others to implement the R&D related to the laser cutting of Fukushima Daiichi (1F) fuel debris, focusing particularly on dust collection technology [1]. It follows that different fuel debris retrieval configurations must be studied to propose the best dismantling strategies that reduce the risk for workers and the environment. It is especially primordial to investigate cutting conditions in air or underwater, as well as various cutting tools such as thermal and mechanical ones, by considering their specificity, their capabilities regarding the implementation in the 1F Primary Containment Vessel (PCV) and their airborne particles generations. The characterization of the aerosol source term emitted during the cutting of the fuel debris is the key parameter to assess the aerosol dispersion that can lead to the release of radionuclides into the environment. The determination of the size and the morphology of particles emitted during the cutting is essential for predicting their transport and deposition by means of numerical simulations. In addition, these input data are mandatory to design and optimize technologies that ensure the containment, the collection and the filtration of particulate pollutants to avoid human contamination. Different strategies need to be considered to mitigate the dispersion of the airborne radioactive particles during dismantling operations. Among these, spray systems are commonly used in nuclear reactor containments to wash-out fission products emitted in the form of aerosol particles

during severe accidents. Understanding the aerosol size distribution is crucial for evaluating the efficiency of the spray system in scavenging aerosols and thereby reducing the Airborne Release Fraction (ARF). Other mitigation means could be implemented depending on the location inside the 1F PCV, the material to be cut and the cutting tool used. Among these means, a local collection system that allows to aspirate airborne particles as close as possible to the source and the coating of fuel debris and metallic structures with specific resins are potential solutions to mitigate aerosol issues.

2. AEROSOL SPRAY SCRUBBING TECHNOLOGY

Spray systems are a well-known technique for collecting airborne particles. Another advantage of this technique is the potential effectiveness in addressing fire issues. For the application in the current context, it is important to determine the relevant characteristics of the spraying system for reaching the best efficiency regarding 1F site implementation constraints, such as thermal-hydraulic conditions, water consumption and reactor pedestal geometry. Spray scrubbing tests were performed in the TOSQAN facility [2, 3, 4] to evaluate the scavenging coefficients for aerosols whose size distribution is representative of the one released during the cutting of fuel debris by various tools, such as mechanical and thermal ones. To simulate the particle generation during the fuel debris cutting, a specific pipe was implemented in the vessel to inject aerosols whose sizes are representative of the ones generated by the cutting tools. For laser cutting simulation, submicronic particles were injected with high velocity (100 m/s) to reproduce the cutting process. For mechanical cutting simulation, particles of few microns were injected by forming a plume with low flow velocity.

The spray system entitled as global spray is located at the top of enclosure dome on the vertical axis and is composed of multiple nozzles producing full cone water sprays. Various nozzles can be used to change the water spray mass flow and the spray droplets size distribution. The spray system entitled as local spray is located at 0.5 m above the aerosol source and consists of a single spray nozzle producing a hollow cone water spray. The general test scenario consists in seeding the vessel with particles whose number concentrations (C_n) are

measured temporally with the Pegasor PPS sensor. The mass flow rate of injected particles is representative of a given cutting tool and cutting condition, such as laser or mechanical ones. For laser cutting, particles with single mode size distribution were used. For mechanical cutting such as a disk cutter, particles with bimodal size distribution were used (0.5 μm for the fine mode and 5 μm for the coarse one). Various scenarios of spray activation have been tested and we propose to present in this article only the most efficient one and the most challenges one in terms of mitigation issue. For this scenario which is representative of laser cutting secondary emission the local and the global sprays were activated with a various temporality during the particles injection phase, using various spray nozzles characteristics specific to the global spray system. Particle injection replicated the particle generation from the laser cutting in terms of particle size distribution and morphology [5]. The injection velocity of particles reproduces the laser cutting process for the emerging cutting configuration, where the piece to be cut is completely crossed by the laser beam. Particles of TiO_2 were used with a mass median diameter of 0.4 μm and a fractal morphology representative of laser cutting generation. The theoretical settling velocity of such particles is equal to $8.6 \cdot 10^{-5} \text{ cm} \cdot \text{s}^{-1}$, meaning that the sedimentation mechanism on horizontal wall of the vessel is negligible compared to the spray removal effect. The deposition rate of aerosols without spray activation was also characterized in order to assess the deposition on the vertical and horizontal walls of the TOSQAN vessel. Concerning the spray systems, the objective of this scenario is to reduce the water consumption while keeping a satisfactory efficiency of aerosol mitigation. To achieve that, nozzles producing spray droplets with small diameters have been implemented in the global spray system. This system is composed of 9 nozzles generating spray droplets size of 40 μm for a global water mass flow rate equal to 25 g/s (full cone spray with a 50° spray angle). The local spray, for its part, consists of a single nozzle generating spray droplets size of 200 μm for a water mass flow rate equal to 50 g/s (hollow cone spray). The total water consumption is therefore equal to 75 g/s. Larger droplets size are necessary for the local spray to interact efficiently with the high momentum jet gas used to simulate the laser cutting process and avoid droplets entrainment outside the aerosol source injection. The scenario is presented hereafter in Figure 1 with its different phases. In the first phase (with local spray), an increase of the airborne particle concentration is observed due to the particle injection in the vessel. During the phase (2), the local spray is stopped while the particle injection continues, leading to a more important increase in the particle concentration, underlining the capability of the local spray to mitigate aerosol dispersion towards the upper part of the vessel (particle concentration doubles in almost 500 s during the phase 2). The Efficiency Factor (EF) can also provide information regarding the capability of the spray systems to reduce the airborne particles concentration in the vessel for a given time (Eq. (1)).

$$EF = (C_0 - C_{t=1800s}) / C_0 \quad (1)$$

Where C_0 is the particle concentration just before the global

spray activation at the beginning of the phase 3 when the aerosol injection is stopped and, $C_{t=1800s}$ is the particle concentration after 1800 s of global spray activation. One should mention that the EF due to only particle deposition without spray activation was measured equal to be 0.06. For the phase (3), the efficiency of the global spray is quantified with the removal rate (equal to $1.96 \cdot 10^{-3} \text{ s}^{-1}$) which is obtained by the fitting of the exponential curve of particle concentration and the efficiency factor (EF at $t=1800 \text{ s}$ is equal to 0.91). This scenario demonstrates that it is possible to drastically reduce the water consumption of spray systems compared to other scenarios with higher water consumption and similar efficiency while keeping a given efficiency with the use of spray nozzles that produce smaller droplets. Indeed, spray scrubbing tests were also performed using larger droplets size for the global spray, i.e. 200 μm , with a mass flow rate of 50 g/s for each spray nozzle, leading to a total water consumption mass flow rate of 300 g/s for the spray systems [6]. The Efficiency Factor (EF) for these tests was equal to 0.93, which is very close to the results presented in Figure 1 despite the much higher water consumption, 300 g/s compared to 75 g/s. However, the use of smaller droplets is only suitable when airflow velocity is low, such as representative of natural convection flow. In the case of forced convection flows (phase (1) and phase (2) of the scenario during particles and gas jet injection), small droplets may be transported by airflow beyond the aerosol source, limiting the interaction between aerosols and droplets leading to reduce the spray scrubbing efficiency. That is why the local spray is necessary during the cutting phase with the use of larger droplets.

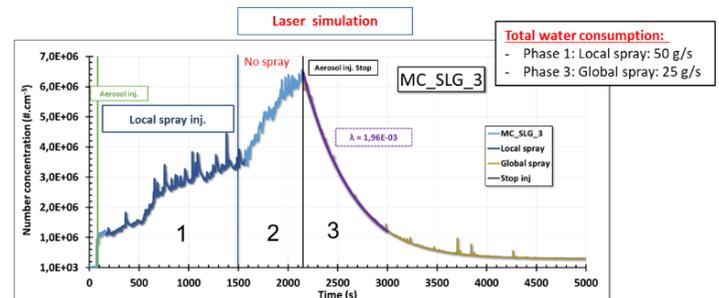


Fig. 1 Evolution of the airborne particle concentration in the vessel during spray scrubbing scenario representative of laser cutting conditions

According to the highlights of these trials, we propose the following strategy for the use of the spray scrubbing technology during fuel debris cutting:

- during particle generation associated with the laser cutting phase, local spray is efficient to mitigate aerosol dispersion and to confine particles in the lower part of the vessel due to recirculation effect of the hollow cone spray, reducing the airborne particle concentration far from the cutting area;
- the global spray activation in addition to the local spray during the cutting phase does not bring a significant improvement on the collection efficiency of aerosols;
- the mitigation strategy could be based on the activation of the local spray during the cutting phase

and on the activation of the global spray at the end of the cutting phase to clean the gas volume above the local spray area;

- the use of fine droplets for the global spray outside the cutting phase (no gas injection inducing strong airflows in the vessel) allows to drastically save water for mitigation systems by spray.

Even if sprays systems do not reach a total efficiency for airborne particles, in particular for submicronic particles, they strongly reduce the dispersion of aerosols compared to the case of simple sedimentation and deposition. The use of spray systems could also be considered as mitigation means against fire events, dust explosion issue and temperature increase of fuel debris.

3. ASSESSMENT OF EFFICIENCY BY COUPLING VARIOUS MITIGATION MEANS USING CFD SIMULATIONS

The assessment of various mitigation means contribution against aerosols dispersion was undertaken using numerical simulations by a CFD approach [7] using ANSYS CFX. We considered the collection of aerosols by spray scrubbing, local collection close to the source, and also deposition on the pedestal wall, considering the 1F geometry of the unit 2. Calculations were first carried out to evaluate collection efficiencies of each mitigation method depending on aerosol sizes. Efficiency results are shown in Figure 2 and Figure 3 representing the contributions of extraction (in blue), spray scrubbing (in green), deposition (in red) and the remaining particles in suspension (in yellow). Results presented in Figure 2 and Figure 3 highlight a very good global collection efficiency for all particle sizes when all mitigation means are implemented, both for mechanical cutting and laser cutting. For the mechanical cutting, as shown in Figure 2, according to the particle generation size (aerodynamic mass median diameter around 5 μm), the efficiency of the spray scrubbing is high due to impaction and interception collection mechanisms between droplets and aerosols. The efficiency of the local collection (extraction) is high for submicronic particles but becomes lower for larger particles. For laser cutting, as shown in Figure 3, according to the particle generation size (aerodynamic mass median diameter around 0.4 μm), the efficiency of the spray scrubbing is weak, while the efficiency of the local collection (extraction) is high. Finally, we can conclude that each mitigation means investigated in this work is efficient for a given range of particle size, and that all means are complementary. Combining these means ensures collection across all the ranges of size of airborne particles.

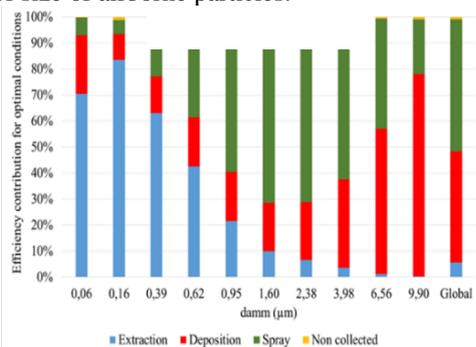


Fig. 2: Particle collection contributions for representative conditions of mechanical cutting

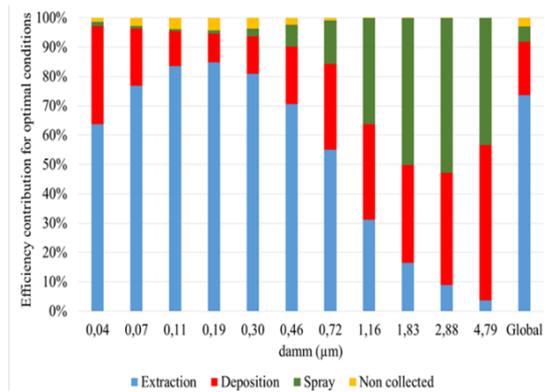


Fig. 3: Particle collection contributions for representative conditions of laser cutting

4. INTRODUCTION TO OTHERS MITIGATION MEANS USING RESIN COATING

During dismantling operations, the risk of dust dispersion can be also induced by particles resuspension due to air flow generated by ventilation systems in the PCV, object displacement such as robots or gas injection in the event of the use of specific cutting techniques. Coatings have been used in the French nuclear industry for many years for various applications including contaminated dust resuspension prevention. Several polymer resins have been developed and seem to be suitable for such coatings on fuel debris or metallic structure inside the PCV of 1F. To evaluate the efficiency of the preselected coatings, a first set of tests have been performed to evaluate particle production suppression during mechanical cutting after coating application (Figure 4). Another set of tests was performed characterize particles resuspension mechanisms due to aeraulic stress after coating, by using a specific facility, called FAAMUS.

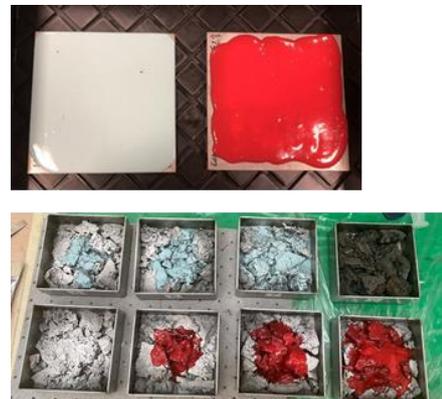


Fig. 4: View of resins coating of stainless-steel plate and simulants of fuel debris bed

Besides, during the dismantling operations of Fukushima Daiichi reactors, the occurrence of the objects falling is high, such as cut structures and cutting tools, and its consequence must be evaluated in terms of dust mobilization due to the impact against the ground covered of particle deposit. The efficiency of the resin used to mitigate particle resuspension during the fall of objects was evaluated in a specific facility named BERGAME. BERGAME is a fall hole connected at its basement to a vessel, in which the consequence of falling objects on particle resuspension are quantified. Various heights of fall can be reproduced up to 10 meters. The vessel located at the basement of the fall hole is instrumented with a Pegasor sensor used to measure the time evolution of number

and mass concentrations of airborne particles resulting of the object impact of the falling object on the ground.

Finally, during underwater operations such as fuel debris or structures cutting, or robot inspections, water agitation may lead to resuspension into water of dust and remaining sediments/mud. The consequences are both in terms of safety and operability with respectively the risk of aerosols transfer above the water level and the reduction of the visibility in highly turbid water. The efficiency of the resin coating for underwater conditions have been evaluated during trials undertaken in the TOSQAN facility where underwater stress produced by water jet and gas jet will be applied to the fuel debris with resin coating (Figure 5).



Fig. 5: View of the TOSQAN facility used to study the resin coating efficiency for underwater conditions due to various stresses – IRSN Saclay

5. CONCLUSION

This work focuses on the risk of the dismantling operations induced by the dispersion of radioactive aerosol particles emitted during the cutting of fuel debris. To enhance the safety of fuel debris retrieval operations, mitigation means against aerosol dispersion need to be developed with an evaluation of their efficiency. To reach this objective, specific tests of spray scrubbing have been carried out in the TOSQAN facility with the implementation of local and global spray systems allowing to assess the efficiency of airborne particles collection. These trials highlighted that a relevant scenario for mitigating aerosols dispersion with lower water consumption could be based on the activation of the local spray during cutting phase and on the activation of the global spray at the end of the cutting phase to clean the gas volume above the local spray area. The evaluation of other mitigation means is also investigated, such as using local collection systems to capture particles emitted during the cutting of fuel debris. By using CFD simulations, combining various mitigation means was achieved, showing that the complementarity of spray scrubbing technology and local collection technology allows to reach high efficiency to mitigate dust dispersion during cutting operations of fuel debris in 1F pedestal. Further research work is needed to investigate other strategies to increase the efficiency of spray scrubbing technology such as implementing electrostatic effects on spray droplets and the consideration of electrical charges of radioactive aerosols [8]. An introduction to another mitigation means is made, with the associated experimental facilities implemented in the efficiency trials: the coating of fuel debris with resins was studied to reduce particle

resuspension due to several stresses (cutting, aerodynamic, mechanical, vibrational) that can be encountered during decommissioning operations at 1F.

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