Numerical Analysis of One Liquid Pool Fire in Multiple Compartments Using FDS Model

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1. Introduction

A nuclear power plant consists of hundreds of compartments. To operate the reactor and generate electricity, each compartment consists of various mechanical and electrical equipment, and electrical and electronic components. To implement a fire protection program at a nuclear power plant, an area surrounded by a fireproof wall is defined as a fire area, which may comprise one or more compartments. In the case of a single fire area consisting of multiple compartments, there is a risk that a fire will spread from one compartment to an adjacent compartment. Therefore, various experiments and numerical analysis studies [1-4] on fire propagation in multiple compartments have been conducted.

This study was conducted as part of an international joint study of the PRISME (French acronym for “Fire Propagation in Elementary Multi-Room Scenarios”) project organized by the Organization for Economic Co-operation and Development (OECD)/ Nuclear Energy Agency (NEA). PRIMSE Project Phase-3 consisted of three campaigns: Smoke Stratification Spread (S3), Electrical Cabinet Fire Spread (ECFS), and Cable Fire Propagation (CFP) [1].

In this study, fire simulations were performed using a Fire Dynamics Simulator (FDS) model for the A1 and A2 experimental conditions of the S3 campaign of the PRISME Project Phase-3. The study numerically investigated thermal behaviors in each compartment caused by a single liquid pool fire with different fuel surface sizes when supply and exhaust vents were located in different compartments. The simulation results using the FDS model were compared with the experimental results conducted by the French Institute for Radiological Protection and Nuclear Safety.

2. Methodology

2.1 Fire Model

FDS is a three-dimensional computational fluid dynamics model that simulates the thermal fluid flow generated by a fire. It is suitable for subsonic, low-velocity flow fields. In this study, the FDS (version 6.7.5) model was used. The large eddy simulation (LES) scheme and the eddy dissipation combustion model were employed to calculate the turbulent flow generated by a liquid pool fire in multiple compartments.

2.2 Fire Simulation Inputs

Fig. 1 shows the computational domain of multiple fire compartments for the fire simulation. Lubricating oil ($C_{31}H_{64}$) as fuel was located in Room-3. The fuel pool surface area of Test-2 increased 2.5 times that of Test-1. The properties of the lubricant oil were as follows: the boiling point was 480 ℃, lower heating value was 42.7 MJ/kg, and density at 20 ℃ was 870 kg/m^3.

An open door of 0.8 m (width) x 2.1 m (height) exists between Room-1 and Room-2 and between Room-2 and Room-3. There is a 1 m (width) x 1 m (length) open door in the vertical direction between Room-3 and Room-4. In Test-1, the supply and exhaust vents were located in Room-4. In Test-2, they were located in Room-3. The airflow rate through the supply and exhaust vents was applied at 2,400 m^3/h. Five thermocouples were installed at a height of 3.05 m in each room. The average ceiling temperature was measured using the five thermocouples in each room.

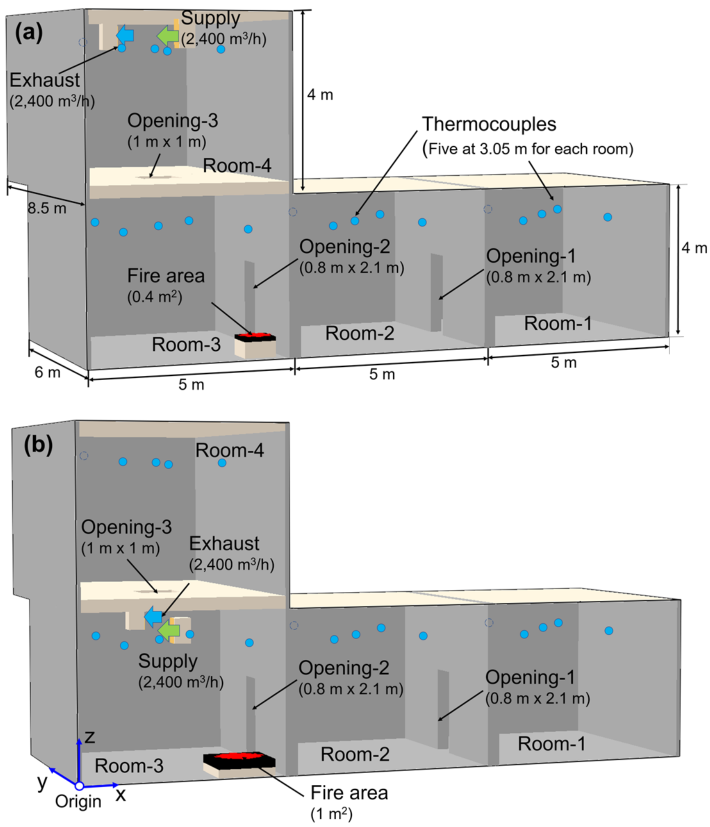

Fig. 1. Computational domains of (a) Test-1 and (b) Test-2

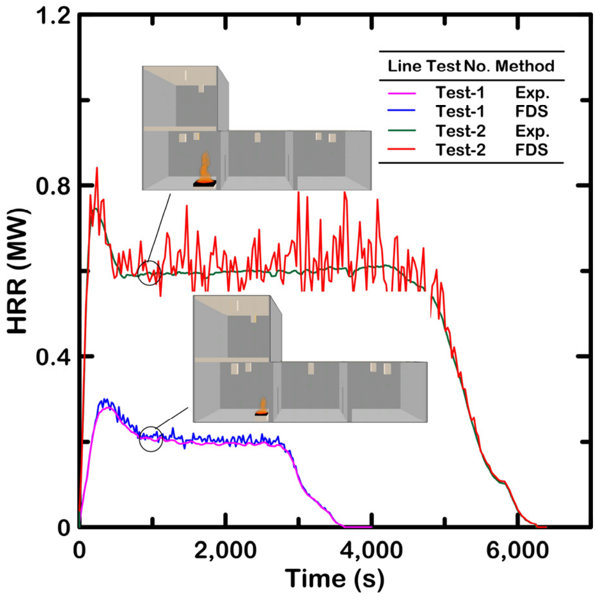

Fig. 2. Heat release rate time curve by experiments and FDS for Test-1 and Test-2

Fig. 2 shows the heat release rate (HRR) time curves for the lubricating oil pool fire. The HRR time curves measured in the PRISME experiments were used as input values for the FDS simulations. Notably, the HRR curves obtained experimentally agreed well with those predicted by the FDS model. As shown in Fig.2, the area enclosed by the HRR curve and x-axis indicates the total energy generated from the fuel. The total energy generated per unit area from the fuel in Test-1 was 1,538 MJ/m^2 and that in Test-2 was 3,166 MJ/m^2. When the surface area of the liquid fuel pool in Test-2 increased by 2.5 times that in Test-1, the energy generated from the fuel per unit area increased by 2.1 times.

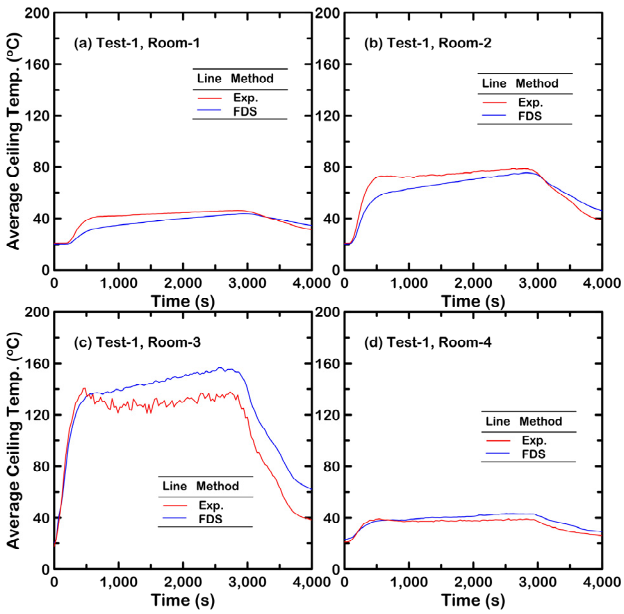

Fig. 3. Average ceiling temperature at 3.01 m at (a) Room-1, (b) Room-2, (c) Room-3, and (d) Room-4 for Test-1.

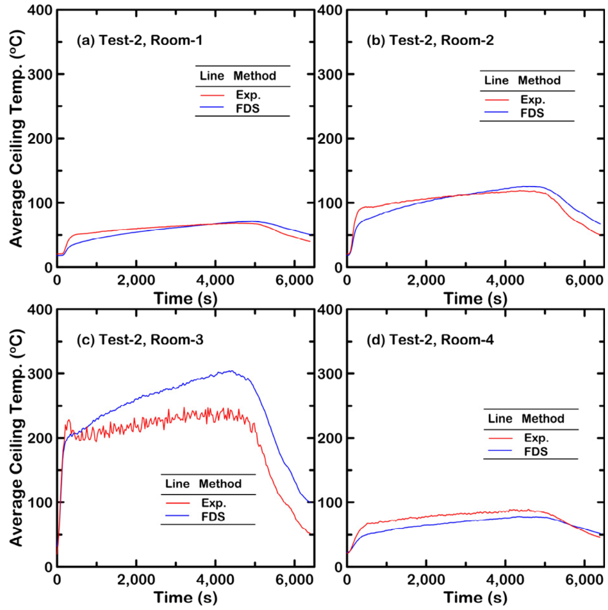

Fig. 4. Average ceiling temperature at 3.01 m at (a) Room-1, (b) Room-2, (c) Room-3, and (d) Room-4 for Test-2.

3. Results and Discussions

3.1 Average Ceiling Temperature

Fig. 3 shows the average ceiling temperature curve measured by five thermocouples located at 3.05 m in each room for Test-1. The average ceiling temperature curves by experiments and simulations were in good agreement. However, in Room-3 with an oil fire, the average ceiling temperature by the experiment and simulation exhibited a difference of up to approximately 20 °C. Previous studies have also found that the ceiling temperature in a fire compartment predicted by the FDS model overestimates that obtained experimentally [5]. Because the liquid pool fire is located in Room-3, the peak of the average ceiling temperature in Room-3 increased to approximately 160 °C. As shown in Fig. 3(c), when the fire is fully developed, the peak of the average ceiling temperature in Room-2 increases to 80 °C. However, the peak temperatures in Room-1 and Room-4 increase to approximately 40 °C. The average ceiling temperature in Room-2 was twice that in Room-4. This was because the supply and exhaust vents were located in Room-4; consequently, the hot gas from the liquid pool fire could flow horizontally better than vertically.

Fig. 4 shows the average ceiling temperature curves for Test-2. In the other rooms except for Room-3, the experimental and simulation results were in good agreement. However, as shown in Fig. 4(c), the average peak ceiling temperature predicted by simulation is 70 °C higher than that predicted experimentally. As shown in Fig. 3, the average ceiling temperature curves of Room-4 and Room-1 were almost identical. However, the peak average ceiling temperature of Room-2 was twice as high as those of Room-1 and Room-4. This implies that hot gases flow well to rooms that are horizontally adjacent to that wherein the fire occurred.

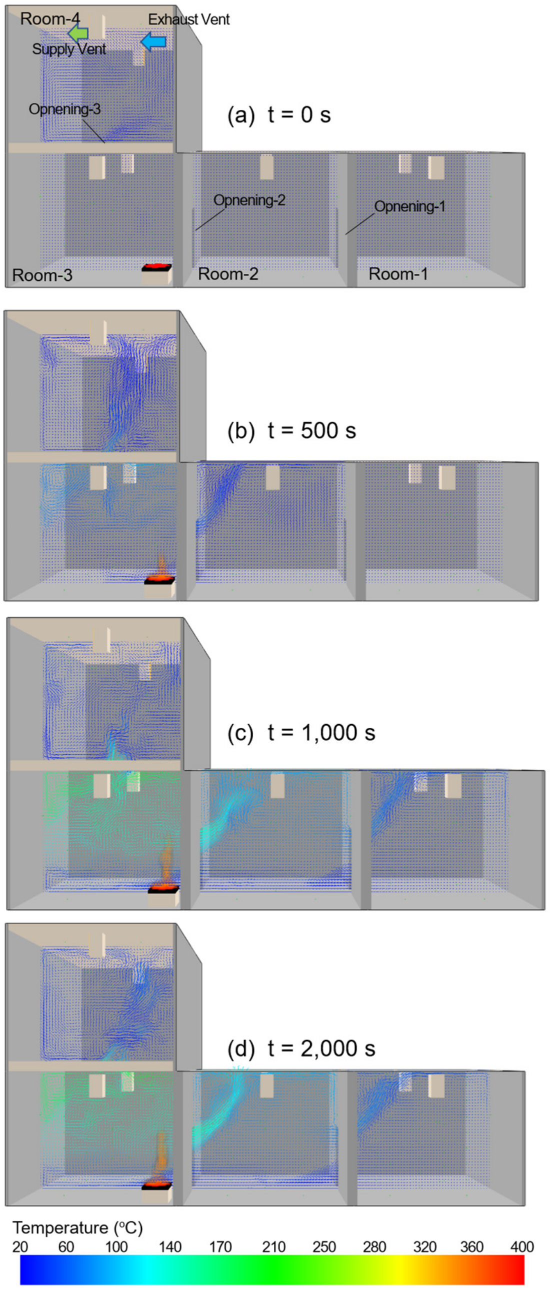

Fig. 5. Variation of gas flow and temperature in the multiple compartments for Test-1.

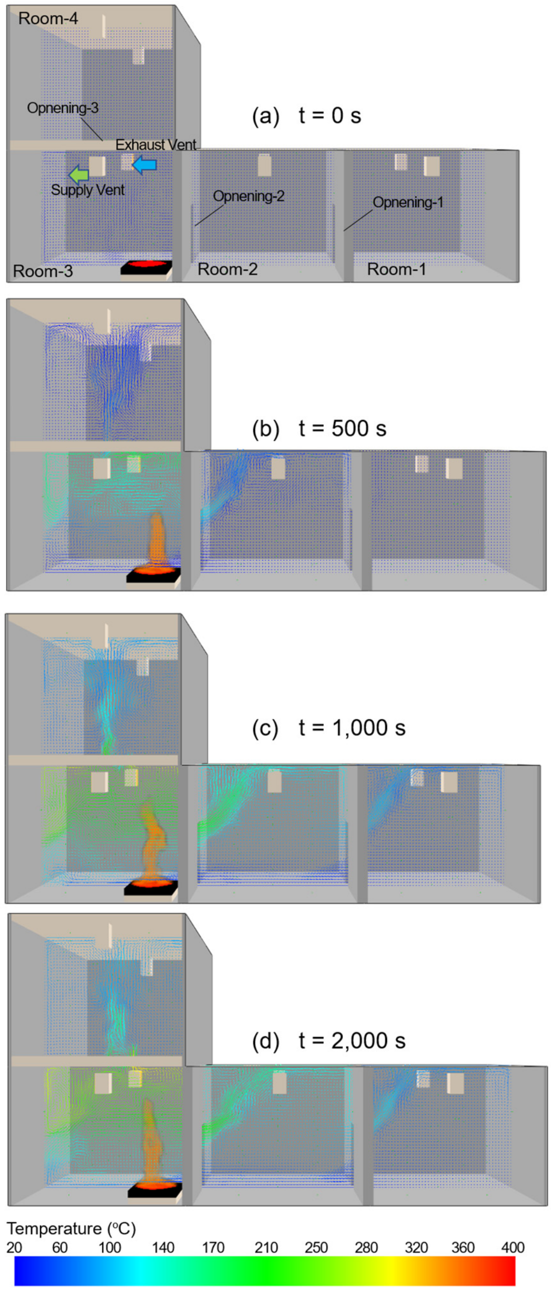

Fig. 6. Variation of gas flow and temperature in the multiple compartments for Test-2.

3.2 Room Temperature Distribution

Fig. 5 shows the gas flow and temperature distribution in multiple compartments as the fire grows in the cross-sectional area of y = 3 m for Test-1. At t = 0 s, air circulation flow is observed only in Room-4, where the supply and exhaust vents are located. At t = 500 s, the heat generated by the fire in Room-3 flows into Room-4 and Room-2. At t = 1,000 s, when the fire is fully developed, a hot gas of approximately 140 °C flows into Room-2, and that of approximately 80 °C flows into Room-1. Neutral planes are observed in Opening-1 and Opening-2.

Fig.6 shows the gas flow and temperature distribution in the compartments for Test-2. At t = 0 s, gas circulation flow is observed only in Room-3. As shown in Fig. 6(b), at t = 500 s, the hot gas generated in Room-3 flows into Room-2 and Room-4. However, as shown in Fig. 6(b), the temperature of the gas passing through Opening-2 and Opening-3 is higher than that shown in Fig. 5(b) because the energy from the liquid fuel pool increases. As shown in Figs. 6(c) and 6(d), the gas temperature flowing into Room-4 is significantly higher than that shown in Fig. 5. This is because the locations of the supply and exhaust vents affect the flow of the hot gas.

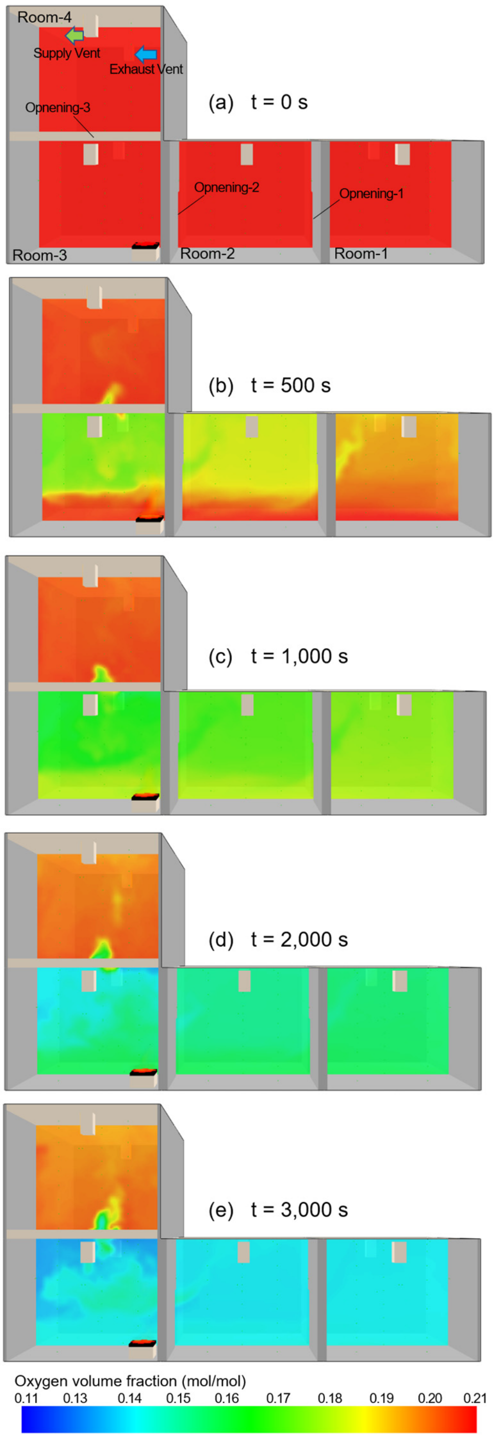

Fig. 7. Variation of oxygen volume fraction in the multiple compartments for Test-1.

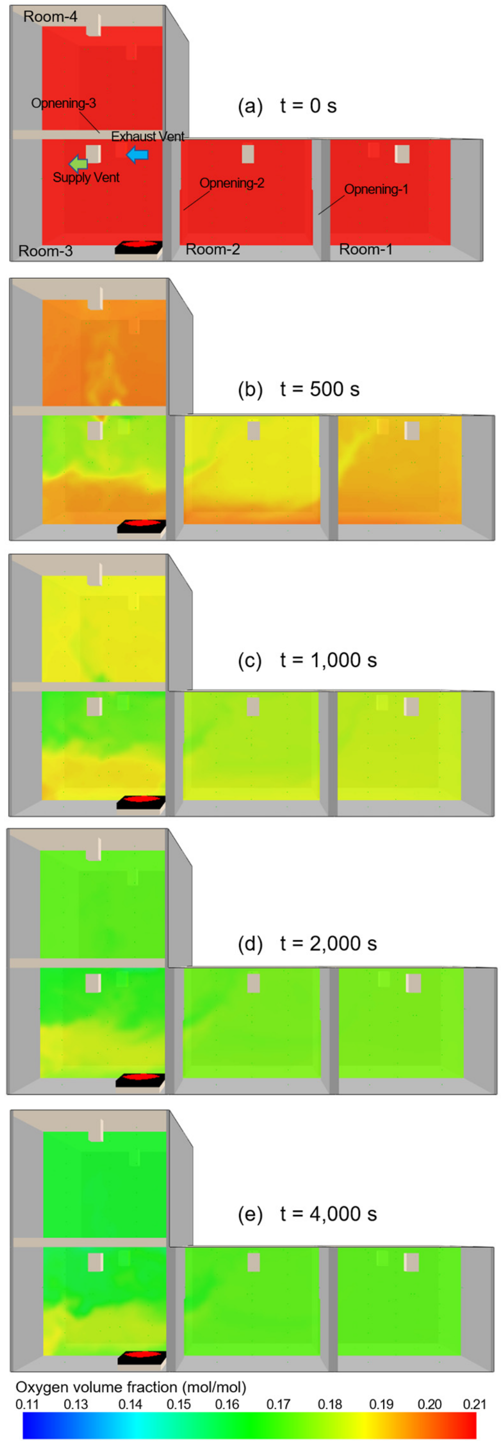

Fig. 8. Variation of oxygen volume fraction in the multiple compartments for Test-2.

Fig. 7 shows the oxygen volume fraction in the multiple compartments for Test-1. As shown in Fig. 7(a), when t = 0 s, all the compartments are full of oxygen. Once the combustion starts, oxygen in each room should decrease, exhibiting the behavior of a typical under-ventilated fire. As shown in Fig. 7, because the supply and exhaust vents were located in Room-4, the concentration of oxygen in Room-4 is higher than those in other rooms. As shown in Fig. 7(b), because the gas generated from the fire in Room-3 flows to Room-1 via Room-2, the oxygen volume fraction of Room-2 is lower than that of Room-1. As shown in Fig. 7(c)–(e) representing the fully developed fire regime, the volume fraction of oxygen in each room gradually decreases as time increases from t = 1,000 s to t = 3,000 s.

Fig. 8 shows the oxygen volume fraction in the multiple compartments for Test-2. Fig. 8 also shows the under-ventilated fire behavior, as shown in Fig. 7. However, because the supply and exhaust vents are located in Room-3 for Test-2, the distribution of oxygen volume fractions in the multiple compartments of Fig. 8 is quite different from those shown in Fig.7. As shown in Fig. 8(b), the oxygen volume fraction is the lowest in Room-3 where the fire occurred. The oxygen volume fraction of Room-4 appears similar to that of Room-1. At the fully-developed fire regime of Figs. 8(d) and 8(e), the oxygen volume fractions in all rooms appeared almost the same regardless of the time change.

4. Conclusion

In this study, as part of international joint research with OECD/NEA, the fire modeling analysis of a liquid pool fire in multiple compartments was performed. When the surface area of a single liquid pool fire in a multi-compartment and the location of the supply and exhaust vents were changed, the effect on the average ceiling temperature and oxygen volume fraction in each room was investigated.

As the size of the fire increased and the location of the supply and exhaust vents changed into the lower room, the peak of the average ceiling temperature in Room-3 where the liquid pool fire started increased to approximately 150 °C. However, the peak of the average ceiling temperature in the other rooms adjacent to Room-3 increased only within the range of 10–20 °C. In addition, the oxygen volume fraction distribution in each room was affected by the location of the supply and exhaust vents.

ACKNOWLEDGMENTS

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REFERENCES

[1] S. Bascou, S. Suard, and L. Audouin, 2019, October. Benchmark Activity of the OECD/NEA PRISME 3 and FIRE Projects, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 25, 16th International Seminar on Fire Safety in Nuclear Power Plants and Installations, October 28-30, 2019, Ottawa, ONT, Canada, GRS-A-3963, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, (2019), https://www.grs.de/en/publication/grs-3963

[2] L. Audouin, L. Rigollet, H. Prétrel, W. Le Saux, M. Röwekamp, OECD PRISME project: Fires in confined and ventilated nuclear-type multi-compartments-Overview and main experimental results. Fire Safety Journal, Vol. 62, p. 80-101, 2013.

[3] OECD/NEA, Committee on the Safety of Nuclear Installations (CSNI): PRISME Project Application Report, NEA/CSNI/R(2012)14, Paris, France, (2012), https://www.oecd-nea.org/nsd/docs/2012/csni-r2012-14.pdf

[4] S. Suard, P. Zavaleta, H. Pretrel. Overview of the OECD PRISME 3 Project. Fire Safety and Emergency Preparedness for the Nuclear Industry, FSEP, (2019), OTTAWA, Canada. ⟨hal-02465442⟩, https://hal.archives-ouvertes.fr/hal-02465442

[5] K. Hill, J. Dreisbach, F. Joglar, B. Najafi, K. McGrattan, R. Peacock, A. Hamins, Verification & Validation of Selected Fire Models for Nuclear Power Plant Applications (NUREG-1824), U.S. Nuclear Regulatory Commission, 2007.