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Review of Smoke Stratification and Spread Experimental Campaign of OECD/NEA PRISME-3 Project

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1. Introduction

The OECD Nuclear Energy Agency (NEA) has initiated and been implementing three international joint research projects to improve the fire safety of nuclear power plants (NPPs), and these projects include the following [1]:

1. The FIRE (Fire Incident Record Exchange) project, which aims to construct a database of fire events (sequence, cause, and effect) and establish an effective utilization system;
2. The HEAF (High Energy Arcing Fault) project, which aims to perform experimental identification and establish an effective assessment methodology for HEAF phenomena;
3. The PRISME (PRopagation d'un Incendie pour des Scénarios Multi-locaux Élémentaires) project, which aims to perform experimental identification and establish an effective assessment methodology for various real-scale fire spread and propagation phenomena in NPPs.

This study focuses specifically on Phase 3 of the PRISME project [2], conducted between 2017 and 2022.

The PRISME project was proposed by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in France, and the various fire experimental tests of the PRISME project are conducted using IRSN's two specially designed facilities in Cadarache: (1) SATURNE, a large enclosure equipped with a large-scale calorimeter in open atmosphere; and (2) DIVA, a large-scale multi-compartment facility including four (4) rooms and one (1) corridor connected with a mechanical ventilation system by means of inlet and outlet ducts and fans. The Korean Atomic Energy Research Institute (KAERI) and the Korea Institute of Nuclear Safety (KINS) participated in the PRISME-3 project as Korean representatives. The PRISME-3 project includes a total of three experimental campaigns: (1) Smoke Stratification and Spread (S3), (2) Electrical Cabinet Fire Spread (ECFS); (3) Cable Fire Propagation (CFP). The objective of this study is to review experimental conditions and results of S3 campaign, and derive meaningful insight to fire safety assessment of NPPs from the review results. Table I summarizes reports and data of the S3 campaign provided by the IRSN under the PRISME-3 project agreement.

Table I: Report and Data of the S3 Campaign

Type	Test	Date	Ref
Short Note	S3	2016-11-07	[3]
Short Note	S3	2017-04-07	[4]
Func. Spec.	S3	2017-06-06	[5]
QL Report	S3-B0	2017-11-17	[6]
QL Report	S3-B1	2017-11-17	[7]
QL Report	S3-B2	2017-12-07	[8]
QL Report	S3-C1	2017-12-07	[9]
QL Report	S3-A1	2018-04-04	[10]
QL Report	S3-A2	2018-03-26	[11]
Test Report	S3-B0	2018-05-24	[12]
Test Report	S3-B1	2018-05-24	[13]
Test Report	S3-B2	2018-05-24	[14]
Test Report	S3-C1	2018-05-24	[15]
Test Report	S3-A1	2018-06-21	[16]
Test Report	S3-A2	2018-06-21	[17]
Test Report	S3-S	2018-06-21	[18]
Analysis Report	S3-B, C, A	2019-04-12	[19]
Analysis Report	S3-S	2018-06-21	[20]
Analysis Report	S3-S	2019-02-13	[21]
Raw Data	S3-B, C, A	2018-07-02	
Raw Data	S3-S	2018-07-02	
Validated Data	S3-B, C, A	2019-05-02	
Validated Data	S3-S	2020-02-20	

2. Experimental Conditions

The S3 campaign aims to study new configurations of smoke propagation in a mechanically ventilated multi-room facility. The study is divided into three topics, namely multiple propagation modes (S3-A), multiple fire sources (S3-B), and elevated fire sources (S3-C). In total, six large-scale fire tests were performed in the DIVA facility, consisting of two tests for the first topic (S3-A1/2), two tests for the secon topic (S3-B1/2), one test for the third topic (S3-C1), and one reference test (S3-B0). The test parameters such as the ventilation configuration, fuel type, and its location were determined using numerical simulations with the zone fire model SYLVIA developed by the IRSN. The lubricant oil Mobil DTE Medium was chosen for the S3-A tests as it accurately represents realistic scenarios of smoke propagation within the facility. To ensure simultaneous pool ignition of both fire sources, dodecane fuel ($C_{12}H_{26}$) was used for the S3-B tests. Dodecane fuel was also utilized for the S3-C1 test to avoid safety constraints concerning preheating fuel at an elevated position. The test matrix of the S3 campaign is summarized in Table II.

Table II: Test Matrix of the S3 Campaign

Test	Fuel	Ventilation
A1	Lube Oil (0.4 m^2) Off-centered	SUP 2400 m^3/h in R4 RET 2400 m^3/h in R4
A2	Lube Oil (1 m^2) Off-centered	SUP 2400 m^3/h in R3 RET 2400 m^3/h in R3
B1	Dodecane (0.56 m^2) Centered (R1 & R3)	SUP 3×1200 m^3/h in R1/2/3 RET 3600 m^3/h in R2
B2	Dodecane (0.56 m^2) Centered (R2 & R3)	SUP 3×1200 m^3/h in R1/2/3 RET 3600 m^3/h in R1
C1	Dodecane (0.56 m^2) Centered & Elevated	SUP 3×1200 m^3/h in R1/2/3 RET 3600 m^3/h in R2
B0 (Ref)	Dodecane (0.56 m^2) Centered	SUP 3×1200 m^3/h in R1/2/3 RET 3600 m^3/h in R2

2.1 Multiple Propagation Mode Tests (S3-A)

Two tests, S3-A1/2, have been conducted to investigate the first topic: multiple propagation modes. Each test involves four rooms and two modes of propagation: (1) horizontal doorway on the wall; and (2) vertical vent on the ceiling/floor. The fire source is located in room R3, enabling the study of both modes of propagation. The ventilation conditions are designed to maintain the vent flow close to the natural convection regime. Both tests utilize a 1 m^2 opening vent (between rooms R3 and R4), and 0.79 m × 2.1 m doorways (between rooms R1 and R2, and R2 and R3). The fire source is positioned off-center in one corner of room R3. Lubricant oil is utilized to enhance smoke production.

The S3-A1 test aims to examine a configuration without mechanical ventilation in the fire room (room R3). The flows entering the fire room through the doorway and vent are predominantly governed by natural convection. Adjacent rooms R1 and R2 are also not ventilated, while only the upper room, R4, is ventilated to provide oxygen to the fire room. This configuration replicates a realistic scenario where the ventilation breaks down for a three-room assembly connected to another zone (via a vent) where the ventilation remains operational. The S3-A2 test focuses on smoke propagation in confined and non-ventilated rooms known as “dead zones”. This low-speed propagation mode is challenging to simulate and crucial for fire model validation. The fire source is positioned at the center of room R3, which is the only mechanically ventilated room. The three other rooms are not ventilated, with the inlet and outlet branches closed.

2.2 Multiple Fire Source Tests (S3-B)

Two tests, S3-B1/2, have been carried out to investigate the second topic: multiple fire sources. Such an investigation is particularly relevant in simulating seismic-induced fire incidents. In the fire scenario, two fire sources were ignited simultaneously in adjacent two rooms (S3-B2) or two rooms separated by another one (S3-B1). The distance between the fires played a crucial role in determining different combustion regimes, with or without interaction. The tests were conducted in three rooms (R1, R2, and R3) with an open doorway serving as the propagation mode. Both tests used 0.56 m² dodecane liquid pools as the fire sources centered in the rooms.

The S3-B1 test did not account for any interaction between the two fire sources, which were located in rooms R1 and R3. The three rooms were ventilated with three admission lines, and one extraction line in room R2. In the S3-B2 test, the two fire sources were located in rooms R2 and R3, and the aim was to study their interaction and its impact on the doorway flow and gas stratification in room R1. The three rooms were ventilated with three admission lines, and one extraction line in room R1.

2.3 Elevated Fire Source Tests (S3-C)

The purpose of the S3-C1 test was to study the effects of an elevated fire source. The S3-C1 test involved three rooms (R1, R2, and R3), with open doorways for propagation. A 0.56 m^2 dodecane pool fire was ignited at the center of room R3, positioned at a height of 2 meters from the floor. The goal was to examine the fuel combustion regime, the potential for flame propagation through the doorway to the adjacent room, and the thermal stratification in the fire room. The ventilation setup was the same as that used in test B1 to enable a comparison between the two experiments. Additionally, a reference test (S3-B0) was carried out with the same configuration as the C1 test, except that the fire source was placed on the ground in room R3.

3. Experimental Results

The S3 campaign aims to assess smoke propagation within the facility to anticipate the impact of a fire, including gas stratification and smoke concentration. With an understanding of the changing environmental conditions, we can predict how electrical equipment will fail. Furthermore, the academic nature of these fire tests will broaden the validation domain of fire models.

3.1 Multiple Propagation Mode Tests (S3-A)

The first experimental tests of the S3 campaign, S3-A1/2, aim to explore smoke propagation within a confined multi-compartment facility, including both horizontal and vertical propagation through openings. The experimental setup enables the identification of various mechanisms involved in smoke propagation during the fire scenario. One of the key outcomes of these tests is the time-dependent behavior of the heat release rate, which is compared to the analytical heat release rate obtained using Babrauska's correlation in an open environment. As the DIVA facility is confined, the heat release rate is reduced due to the depletion of oxygen during the fire scenario in contrast to that in an open atmosphere. For the 0.4 m^2 and 1 m^2 pool fire tests, the quasi-steady behavior of the heat release rate is around 200 kW and 600 kW, respectively. Understanding the flow rates through the openings, such as doors and vents, is crucial in assessing smoke propagation and fresh and vitiated air feeding in the fire room. The flow rates are determined by integrating the velocity and temperature over the opening area when the combustion regime is quasi-stationary inside the facility (t=2,000 s for S3-A1 and t=4,000 s for S3-A2). The distribution of flow rates through the various openings is observed for both tests S3-A1/2. In the first configuration, where the fire room is not ventilated (S3-A1), it is found that 60% of the fresh air passes through the open door, and 40% passes through the horizontal vent, emphasizing the importance of proper vent modeling in fire safety studies. Approximating fresh air feeding can result in inaccurate estimates of the heat release rate. When the fire room is connected directly to the ventilation network (S3-A2), the flow rate from the open doorway constitutes 66% of the total air feeding to the fire room. Although the upper room is typically considered a “dead zone”, vent modeling is critical to determine the flow distribution around the fire accurately. The flow at the vent is often complex and bidirectional, mainly governed by natural convection mechanisms. Smoke rises, and fresh or vitiated air descends, supplying the fire. In the S3-A2 test, the compartment above acts as a buffer tank, storing combustion products and providing fresh air, which poses a significant modeling challenge for standard fire models.

3.2 Multiple Fire Source Tests (S3-B)

When considering multiple fire configurations, the primary experimental findings indicate that the burning rate of each pool fire cannot be accurately determined by reference to a single pool fire that would burn alone in the same configuration. This is because smoke propagation and oxygen depletion throughout the facility have a global impact that affects the combustion process of each individual fire. To provide a comparison, the reference test (S3-B0) was conducted using a single centered pool fire with the same characteristics as each individual fire. During the quasi-steady state, the reference test produced a heat release rate of approximately 600 kW, while the S3-B1 test demonstrated a heat release rate of approximately 400 kW for each of the two pool fires. The same is true for the S3-B2 test with regard to the intensity of the two fires. Although the S3-B1 test showed that the two pool fires evolved similarly, the S3-B2 test revealed a quasi-steady combustion regime for the pool fire in room 2 and a more disturbed regime for the pool fire in room 3. The disturbance in combustion resulted from the strong interaction between the two pool fires since the fire in room 3 was not located near the room equipped with the inflow ventilation branch. The global heat release rates of both tests were also analyzed. The global power was about 800 kW in the case of weak interaction between the pool fires (S3-B1). In the case of strong interaction (S3-B2), on the other hand, the total heat release rate was approximately 400 kW, which was very close to the reference test using a single fire source. To enhance fire safety studies, it is recommended that all fire sources be modeled comprehensively instead of simply adding up reference fire sources.

3.3 Elevated Fire Source Tests (S3-C)

The third area of interest pertains to the propagation of smoke caused by fires that are elevated. This fire configuration creates complex fire dynamics due to the fire evolving in an environment that is both hot and vitiated. To better represent the situations that are encountered in NPPs, where many systems are placed high up and usually against a wall, a fire test was conducted. The reference test (S3-B0), which was previously described and composed of an identical pool fire located on the ground, was used for comparison. The results indicated that while the burning rate of the elevated fire was lower than that of the reference pool fire, the stratification for the elevated configuration was significantly more pronounced. Fire dynamics and smoke flows inside the compartment tended to increase the gas temperature near the ceiling and decrease it near the floor. The physical analysis of this test demonstrated a significant reduction in the heat release rate of about 25%. The difference between the two fire scenarios for this quantity was primarily due to the presence of a vitiated environment, which impacted the combustion process in the case of the elevated fire. The reduced oxygen concentration resulted in a less intense combustion process. However, despite the fire being less powerful, the ceiling gas temperature in the elevated configuration was a hundred degrees higher. This result was counter-intuitive and presented a challenge for fire modeling in safety studies. In fact, using this well-known correlation without modification for predictive fire simulations underestimated the heat release rate by approximately 30%. Therefore, the correlation was not conservative with its native formulation, and certain additional terms, such as the external radiative flux, needed to be taken into account for more precise calculations.

3. Conclusions

This study has yielded several tangible outcomes, including experimental data on smoke stratification and spread phenomena in NPPs at a real scale, as well as insightful interpretations of the experimental data for fire safety assessments of NPPs. Additionally, an international network has been established for joint research and development on NPP fire safety, with participation from 8 countries and 12 institutes.

The experimental data and insights on various real-scale smoke stratification and spread phenomena in NPPs obtained through this study are expected to improve understanding and analytical technology on complex fire phenomena in NPPs, ultimately leading to a more realistic and effective evaluation of the fire-induced risk of NPPs.

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REFERENCES

[1] OECD NEA, "Nuclear Safety Research Joint Projects," Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Mar. 16, 2023. [Online]. Available: https://www.oecd-nea.org/jcms/pl_72332/nuclear-safety-research-joint-projects. [Accessed Mar. 16, 2023]

[2] OECD NEA, "AGREEMENT ON THE OECD PRISME 3 PROJECT," Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Paris, France, Agreement. (proprietary, for PRISME members only), Mar. 2018.

[3] H. Prétrel & W. Plumecocq, "IRSN proposal for PRISME-3 S3 campaign," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. (proprietary, for PRISME members only), Nov, 2016.

[4] H. Prétrel & W. Plumecocq, "Test matrix for PRISME-3 S3 campaign," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. (proprietary, for PRISME members only), Apr, 2017.

[5] H. Prétrel & W. Plumecocq, "PRISME-3 - S3 campaign - Functional specification," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. PSN-RES/SA2I/2017-00142 (proprietary, for PRISME members only), Jun, 2017.

[6] H. Prétrel, "PRISME-3 - PR3-S3_B0 Fire Test - Quick Look report," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. (proprietary, for PRISME members only), Nov, 2017.

[7] H. Prétrel, "PRISME-3 - PR3-S3_B1 Fire Test - Quick Look report," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. (proprietary, for PRISME members only), Nov, 2017.

[8] H. Prétrel, "PRISME-3 - PR3-S3_B2 Fire Test - Quick Look report," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. (proprietary, for PRISME members only), Dec, 2017.

[9] H. Prétrel, "PRISME-3 - PR3-S3_C1 Fire Test - Quick Look report," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. (proprietary, for PRISME members only), Dec, 2017.

[10] H. Prétrel, "PRISME-3 - PR3-S3_A1 Fire Test - Quick Look report," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. (proprietary, for PRISME members only), Apr, 2018.

[11] H. Prétrel, "PRISME-3 - PR3-S3_A2 Fire Test - Quick Look report," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. (proprietary, for PRISME members only), Mar, 2018.

[12] H. Prétrel, "PRISME-3 - S3 campaign - Test report - PR3_S3_B0," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. PSN-RES/SA2I/2018-00084 (proprietary, for PRISME members only), May, 2018.

[13] H. Prétrel, "PRISME-3 - S3 campaign - Test report - PR3_S3_B1," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. PSN-RES/SA2I/2018-00078 (proprietary, for PRISME members only), May, 2018.

[14] H. Prétrel, "PRISME-3 - S3 campaign - Test report - PR3_S3_B2," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. PSN-RES/SA2I/2018-00079 (proprietary, for PRISME members only), May, 2018.

[15] H. Prétrel, "PRISME-3 - S3 campaign - Test report - PR3_S3_C1," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. PSN-RES/SA2I/2018-00080 (proprietary, for PRISME members only), May, 2018.

[16] H. Prétrel, "PRISME-3 - S3 campaign - Test report - PR3_S3_A1," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. PSN-RES/SA2I/2018-00147 (proprietary, for PRISME members only), Jun, 2018.

[17] H. Prétrel, "PRISME-3 - S3 campaign - Test report - PR3_S3_A2," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. PSN-RES/SA2I/2018-00148 (proprietary, for PRISME members only), Jun, 2018.

[18] H. Prétrel, "PRISME-3 - S3 campaign - Test report - Support tests in open atmosphere," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. PSN-RES/SA2I/2018-00145 (proprietary, for PRISME members only), Jun, 2018.

[19] H. Prétrel, "PRISME-3 S3 fire test campaign - Analysis report," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. IRSN/2019-00117 (proprietary, for PRISME members only), Apr, 2019.

[20] H. Prétrel, "PRISME-3 S3 - Support tests - Analysis report of the open atmosphere dodecane pool fire tests," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. PSN-RES/SA2I/2018-00146 (proprietary, for PRISME members only), Jun, 2018.

[21] H. Prétrel, "PRISME-3 S3 - Support tests - Analysis report of the open atmosphere dodecane pool fire tests," Institut de Radioprotection et de Surete Nucleaire (IRSN), Cadarache, France, Tech. Report. IRSN/2019-00045 Indice 2 (proprietary, for PRISME members only), Feb, 2019.