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Review of Cable Fire Propagation 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 CFP campaign, and derive meaningful insight to fire safety assessment of NPPs from the review results. Table I summarizes reports and data of the CFP campaign provided by the IRSN under the PRISME-3 project agreement.

Table I: Report and Data of the CFP Campaign

Type	Test	Date	Ref
Short Note	CFP	2019-11-08	[3]
Func. Spec.	CFP-S1/2,D1/2/3	2020-02-20	[4]
Func. Spec.	CFP-D4/5/6	2021-04-09	[5]
Func. Spec.	CFP-D4/5/6	2021-05-03	[6]
QL Report	CFP-D1	2020-11-06	[7]
QL Report	CFP-D2	2020-10-07	[8]
QL Report	CFP-D3	2020-10-07	[9]
QL Report	CFP-D4	2021-06-08	[10]
QL Report	CFP-D5	2021-06-08	[11]
Test Report	CFP-S0	2020-09-28	[12]
Test Report	CFP-S1	2020-09-28	[13]
Test Report	CFP-S2	2020-09-28	[14]
Test Report	CFP-D1	2020-12-16	[15]
Test Report	CFP-D2	2020-12-16	[16]
Test Report	CFP-D3	2020-12-16	[17]
Test Report	CFP-D4	2021-10-01	[18]
Test Report	CFP-D5	2021-10-01	[19]
Test Report	CFP-D6	2021-10-01	[20]
Analysis Report	CFP-S1/2	2020-12-14	[21]
Analysis Report	CFP-D1/2/3	2021-06-03	[22]
Analysis Report	CFP-D4/5/6	2022-03-22	[23]
Raw Data	CFP-S0/1/2	-	
Raw Data	CFP-D1/2/3	2020-12-16	
Raw Data	CFP-D4/5/6	-	
Validated Data	CFP-S0/1/2	2020-12-16	
Validated Data	CFP-D1/2/3	2021-05-28	
Validated Data	CFP-D4/5/6	2022-03-29	
Short Note	CFP-BCM	2020-04-09	[24]
Func. Spec.	CFP-BCM	2020-02-20	[25]
QL Report	CFP-BCM-S1	2020-07-17	[26]
QL Report	CFP-BCM-S2	2020-07-20	[27]
Test Report	CFP-BCM-S1	2020-09-28	[28]
Test Report	CFP-BCM-S2	2020-09-28	[29]
Analysis Report	CFP-BCM-S1/2	2020-12-14	[30]
Raw Data	CFP-BCM-S1/2	-	
Validated Data	CFP-BCM-S1/2	2020-12-10	

2. Experimental Conditions

The CFP campaign was conducted with 3 m long horizontal cable trays installed in the SATURNE and DIVA facilities for both open air and enclosed environments. The aim was to study the impact of various parameters such as cable type and installation configuration, and complete the analysis of prior tests conducted as part of the PRISME-2 project. The final stage of the campaign involved testing a new cable tray configuration with 6 m long cable trays in the DIVA facility.

2.1 Open Atmosphere Cable Fire Tests (CFP-S1/2)

The PRISME-2 project investigated fires in horizontal cable trays in open atmosphere and briefly examined parameters like the cable type, tray angle, and the presence of thermal protection. To complete the analysis and broaden the validation range of fire models, two additional parameters were investigated: the cable arrangement on trays (loose or tight) and the environment of the cable trays (with or without a sidewall). The arrangement of cables on trays can significantly affect fire propagation. For instance, a loose arrangement favors preheating of cables and promotes surface exchange with the gas phase and flames, whereas a tight arrangement blocks flames and shrinks the overall area of cable in contact with flames, increasing the overall inertia of fuel. The second parameter considered was the presence of a sidewall. Sidewalls can contribute to improving preheating of cables, resulting in higher flame spread and heat release rate.

The aim of the CFP-S1/2 tests was to study the effect of a single parameter, while maintaining the other setup of previous PRISME-2 CORE-1 test. A reference test, called CFP-S0, which was not part of the initial PRISME-3 agreement, was carried out to verify the reproducibility of the CORE-1 test scenario. Basically, five horizontal trays filled with 2.4 m long 21 cable samples made of poly vinyl chloride (PVC) were utilized for both CFP-S1/2 tests like the CORE-1 & CFP-S0 tests. A new dense arrangement using several cable bundles was proposed for the CFP-S1 test, while the sidewall was removed from the setup for the CFP-S2 test. The tray spacing and width were 0.3 meters and 0.45 meters, respectively, and all trays were ladder-type cable trays with a length of 3 meters. A 0.79 m × 2.1 m propane sand burner located at the center and 0.2 meters below the lowest tray was used to ignite the trays. The burner had a power of 80 kW and was turned off when the heat release rate exceeded approximately 400 kW.

Table II: Test Matrix of the CFP Campaign (S1/2)

Test	Cable Arrangement	Tray Environment
S1	Tight [New]	With Sidewall
S2	Loose	Without Sidewall [New]

2.2 Confined Cable Fire Tests (CFP-D1/2/3)

To study how ventilation affects the combustion regime of a cable tray fire with 5 ladders and a length of 3 meters, three fire tests were conducted. The ventilation layout used in the PRISME-2 project consisted of two interconnected rooms (R1 & R2) with an open doorway, with air entering from the fire room (R1) and being exhausted to the adjacent room (R2). A new configuration was proposed to improve the exhaust flow rates of combustion products in the fire room and to create an appropriate air vitiation configuration for validating fire models. Two tests (CFP-D1/2) were planned using this new configuration, with the same ventilation flow rates of 4 h^{-1} and 16 h^{-1}, and the same cable samples containing a halogen-free flame retardant (HFFR) used in the PRISME-2 CFS-3/4 tests. The third test (CFP-D3) aimed to replicate the configuration of the PRISME-2 CFS-3/4 test by increasing or decreasing the ventilation flow rate to 6 h^{-1}. One of the objectives of this test was to gain a better understanding of the oscillatory behavior observed in the CFS-3 test.

Table III: Test Matrix of the CFP Campaign (D1/2/3)

Test	Vent. Layout	Vent. Flow Rate [m^3/h] / Renewal Rate [h^{-1}]
D1	SUP R2 / RET R1 [New]	3660 / 16
D2	SUP R2 / RET R1 [New]	1010 / 4
D3	SUP R1 / RET R2	1440 / 6 [New]

2.3 Confined Long Cable Fire Tests (CFP-D41/51/61)

Long horizontal cable trays pose a complex and demanding challenge for testing. Most tests have been conducted for around 3 m long trays, and the results are only validated to the specific configuration that was tested. Consequently, modeling the quasi-steady flame propagation and the critical parameter, heat release rate, is a challenging task. There are only a limited number of numerical simulations available for this experimental setup, and the validation of numerical tools seems to be uncertain. To address this, three tests (CFP-D41/51/61) were conducted to investigate a long horizontal cable fire in a confined environment.

The primary objectives of the CFP-D41/51/61 tests were to characterize the quasi-steady flame propagation on cable trays and the maximum heat release rate of the fire. Since the fire community has not studied this configuration in a confined environment, the campaign focused on well-ventilated combustion regimes initially. This was done to prevent additional effects such as a vitiated environment or the production of unburned gases from interfering.

The fire source for the tests comprised three cable trays with a length of 6 meters installed in the DIVA facility's corridor (R4) adjacent to three rooms (R1/2/3). The admission flow rate in each room was set to 1,500 m^3/h, while the exhaust flow rate was set to 3,000 m^3/h in the corridor (R4) and room 3 (R3). This configuration was designed to ensure well-ventilated conditions. Each cable tray had 32 HFFR (well-qualified) cables for tests D41 and D61. Test D51 featured trays filled with 21 PVC (low-qualified) cables to study the impact of cable type. Tests D41 and D51 were conducted close to the ground, while test D61 was conducted near the ceiling at a distance of 1 meter.

Table IV: Test Matrix of the CFP Campaign (D41/51/61)

Test	Cable Type	Tray Installation
D41	Well-qualified	On Ground
D51	Low-qualified	On Ground
D61	Well-qualified	Near Ceiling

3. Experimental Results

The CFP campaign featured three sets of fire tests: (1) open atmosphere tests conducted in the SATURNE facility (CFP-S1/2), (2) confined tests conducted in two rooms of the DIVA facility (CFP-D1/2/3), and (3) confined tests conducted in the corridor of the DIVA facility (CFP-D41/51/61). The CFP-S1/2 tests consisted of examining the impact of cable arrangement and wall support on fire behavior. The objective of the CFP-D1/2/3 tests was to explore the effects of ventilation configuration on fire behavior and the emergence of an oscillatory combustion regime. Lastly, the CFP-D41/51/61 tests comprised three 6-meter-long cable trays positioned against a wall to investigate the impact of cable type and environment on fire propagation.

3.1 Open Atmosphere Cable Fire Tests (CFP-S1/2)

Two tests (CFP-S1/2) were conducted and compared to a reference test (CFP-S0). The CFP-S0 test was conducted in open atmosphere with a loosely arranged cable configuration and without a sidewall. In contrast, the CFP-S1 test utilized a tight cable arrangement positioned against a wall, while CFP-S2 had a loose cable layout without a sidewall. The experimental results indicated that the severest result arises with a sidewall and a loose cable layout. The sidewall had a small impact on the maximum heat release rate, increasing it by only around 13%. Meanwhile, the sidewall significantly increased the flame spread velocity on cables, even though only for the first two trays. Changing the cable layout from loose to tight contributed significantly to reducing the heat release rate by around 30%. This reduction was due to the considerable decrease in the cable area in contact with air, which participates in the combustion process. As a result, the mean horizontal flame spread velocity was reduced by over 20%.

These results are essential for validating both simple and complex fire models used in the fire safety community. They can also provide guidance for safety studies by identifying the most conservative configurations and the parameters that significantly impact fire consequences.

3.2 Confined Cable Fire Tests (CFP-D1/2/3)

The second phase of the CFP campaign (CFP-D1/2/3) focused on two compartments, Room 1 (R1) and Room 2 (R2), in the DIVA facility. The aim of the CFP-D1/2/3 test was to investigate the effect of different ventilation configurations on fire behavior, as well as to observe the emergence of an oscillatory combustion regime.

The CFP-D1/2 tests were conducted using a new ventilation configuration (referred to as configuration A), while the CFP-D3 test was conducted with a previous ventilation configuration (configuration B) but with a higher ventilation renewal rate of 6 h^{-1} compared to the PRISME-2 CFS-3 test, which had a renewal rate of 4 h-1. All tests utilized an assembly of five cable trays filled with 32 samples of HFFR cables of 2.4 m arranged loosely against a side wall. The CFP-D1 test was carried out with a ventilation flow rate of 3660 m^3/h, while the CFP-D2 test was conducted with a flow rate of 1010 m^3/h, corresponding to renewal rates of about 16 h^{-1} and 4 h^{-1}, respectively.

In configuration A, the intake was located in the adjacent room (R2), and the exhaust was positioned in the fire room (R1), which differs from configuration B. This setup could potentially promote fire growth because combustion products can escape directly from the exhaust ventilation branch (in the same room), whereas in configuration B, they may mix with fresh air. The results have also shown that placing the door in front of the fire allows for effective channeling of fresh air.

For the most ventilated case (3660 m^3/h), the heat release rate in configuration A is comparable to that of an open atmosphere, despite a renewal rate of 16 h^{-1}. However, there was a reduction of approximately 30% for configuration B, where fresh air is supplied to the fire room (R1). For the lower ventilation flow rate (1010 m^3/h), the reduction is even more pronounced, at about 40%, between configurations A and B. This trend of increasing heat release rate with configuration A can be explained by the concentration of the oxygen flow field near the fire source, which is much higher in configuration A than in configuration B. Additionally, gas stratification was more apparent in configuration A, with lower temperatures at the ground and higher temperatures near the ceiling, as compared to configuration B.

The third test focused on examining the impact of ventilation flow rate on the emergence of oscillatory combustion in configuration B. This was compared to earlier tests conducted during the PRISME-2 project, where ventilation flow rates of 3660 and 1010 m^3/h were used (CFS-4/3). The decrease in ventilation flow rate from 3660 to 1410 m^3/h led to a reduction in the amount of oxygen supplied to the compartment, resulting in a decrease in fire heat release rate. This, in turn, increased cable ignition time and reduced flame spread velocity in comparison to well-ventilated scenarios. However, under-oxygenated combustion processes increased the production of carbon monoxide and unburned gases due to incomplete combustion, raising the risk of a smoke explosion. The oscillatory behavior of the pyrolysis process produced oscillatory combustion regimes, as observed in the PRISME-2 CFS-3 test. The CFP-D3 test, which used a moderately increased ventilation flow rate of 1410 m^3/h, showed that the oscillatory combustion regime almost disappeared. However, instabilities were observed in configuration A with the same low ventilation flow rate, but they were quickly damped.

The results obtained from the CFP-D1/2/3 tests are significant for both safety concerns and modelers. The CFP-D1/2 tests have highlighted that the ventilation configuration plays a critical role in designing fire scenarios and prescribing heat release rates. Depending on the configuration, the heat release rate can be similar to the one obtained in open atmosphere or considerably reduced, up to 40%. Hence, these factors must be included in fire safety studies, regardless of the methodology used. Lastly, the CFP-D3 test has shown that predicting the emergence of unsteady or oscillatory combustion regimes requires a detailed description of all physical phenomena and coupling involved in any fire.

3.3 Confined Long Cable Fire Tests (CFP-D41/51/61)

The aim of the CFP-D41/51/61 tests was to establish the combustion length and maximum heat release rate of long cable fires and compare them with the values recommended by the fire safety community. The CFP-D41/51/61 tests utilized three cable trays that were 6 meters long and installed in the corridor of the DIVA facility. The CFP-D41/61 tests had 32 HFFR cables per tray, while the CFP-D51 test had 21 PVC cables per tray. The CFP-D41/51/61 tests studied the influence of cable type and environmental factors, such as tray height, on the burning length and heat release rate. The corridor was connected to three adjoining rooms in the DIVA facility, and the ventilation rates were set at 1,500 m^3/h for each room's air supply and 3,000 m^3/h for the corridor and room 3's exhaust. The well-ventilated conditions were necessary as these tests had the potential to damage the facility due to the extended cable lengths. The fire was ignited with a propane gas burner located beneath the lower tray at the start of the setup, away from the burner or cable edges, and maintained at 80 kW for 60 minutes for tests using well-qualified cables and 20 minutes for the test using low-qualified cables to attain self-propagation of the fire.

The burning length, fire spread velocities, and heat release rate were analyzed to investigate the impact of PVC cables (the CFP-D51) and the elevation of the fire source (the CFP-D61) in comparison to the CFP-D41 test (HFFR cables installed close to the ground). Temperature measurements along each cable tray were used to estimate the burning length and fire spread velocity. The quasi-steady combustion regime was identified by analyzing the variations in heat release rate and videos of the fire, characterized by a nearly constant heat release rate over a period after the burner was turned off (changes less than 10% of the mean value).

For the CFP-D61 test, the maximum heat release rate of about 727 kW was observed during the ignition phase just after the burner was turned off, which rapidly decreased afterwards. However, a quasi-steady combustion regime lasting around 26 minutes was observed after the extinction fronts reached the middle of the 6-meter-long cable trays. The average heat release rate during this period was approximately 157 kW, and the total burning length (sum of the three-burning lengths of each cable tray) was 7.5 m. The flame spread velocities for each cable tray were determined using thermocouple measurements. The fire was finally extinguished 3 hours and 40 minutes after ignition.

In the CFP-D51 test using low-quality cables, a more intense fire was achieved, with a maximum heat release rate of about 900 kW. Although a quasi-steady combustion regime with a nearly constant heat release rate was observed for only 20 minutes, the mean heat release rate during this period was very high (727 kW), and the maximum burning length was approximately 12.2 m. This was explained by a flame spread velocity that was 2.5 times higher than that observed during the first test (around 2 mm/s).

The maximum heat release rate for the CFP-D61 test was about 709 kW, and the quasi-steady combustion regime began 10 minutes after the burner was turned off (compared to 49 minutes for CFP-D41). The duration of the period (26 minutes) was similar to that of the CFP-D41 test (29 minutes), but the ceiling effect caused a higher mean heat release rate of 522 kW. The fire spread velocity was also higher, reaching about 50%, and the maximum burning length was 8.7 m. The fire was extinguished after 3 hours.

The unique aspect of the CFP-D41/51/61 tests was that it replicated a configuration in a large-scale experimental facility where cable fires could propagate freely. This enabled the results obtained to be extrapolated to real-scale safety studies, and the new experimental dataset could be utilized to improve the fire models' validation process. The flame spread velocity measurements revealed values that were twice as high as those recommended for certain configurations.

3. Conclusions

This study has yielded several tangible outcomes, including experimental data electrical cable fire propagation 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 electrical cable fire propagation 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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