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

Table I: Report and Data of the ECFS Campaign

Type	Test	Date	Ref
Short Note	ECFS	2017-10-26	[3]
Func. Spec.	ECFS-S	2018-12-04	[4]
Func. Spec.	ECFS-S	2018-12-13	[5]
Func. Spec.	ECFS-D	2019-07-29	[6]
QL Report	ECFS-S1	2019-01-07	[7]
QL Report	ECFS-S2	2019-02-13	[8]
QL Report	ECFS-S3	2019-03-15	[9]
QL Report	ECFS-S4	2020-03-10	[10]
QL Report	ECFS-D1	2019-07-15	[11]
QL Report	ECFS-D2	2019-10-15	[12]
QL Report	ECFS-D3	2020-01-21	[13]
QL Report	ECFS-D4	2020-04-03	[14]
Test Report	ECFS-S1	2019-12-18	[15]
Test Report	ECFS-S2	2019-12-18	[16]
Test Report	ECFS-S3	2019-12-17	[17]
Test Report	ECFS-S4	2020-05-13	[18]
Test Report	ECFS-D1	2020-05-13	[19]
Test Report	ECFS-D2	2020-05-13	[20]
Test Report	ECFS-D3	2020-10-05	[21]
Test Report	ECFS-D4	2020-10-05	[22]
Analysis Report	ECFS-S1/2	2020-04-29	[23]
Analysis Report	ECFS-S3/4	2020-12-03	[24]
Analysis Report	ECFS-D1/2	2021-04-19	[25]
Analysis Report	ECFS-D3/4	2021-08-01	[26]
Raw Data	ECFS-S	2020-11-10	
Raw Data	ECFS-D	2020-11-10	
Validated Data	ECFS-S1/2	2020-12-15	
Validated Data	ECFS-S3/4	2020-12-15	
Validated Data	ECFS-D1/2	2021-09-28	
Validated Data	ECFS-D3/4	2021-09-28	
Short Note	ECFS-AFD	2018-09-28	[27]
Short Note	ECFS-AFD	2019-01-31	[28]
Func. Spec.	ECFS-AFD	2020-01-28	[29]
QL Report	ECFS-AFD	2020-02-27	[30]
Analysis Report	ECFS-AFD	2020-08-24	[31]

2. Experimental Conditions

The primary goal of the ECFS campaign was to examine the propagation of fire from an open-door electrical cabinet to closed-door cabinets placed next to or in front of the main cabinet (i.e., adjacent or opposite configuration) connected to each other via two overhead and two subfloor cable trays. To accomplish this, four tests (ECFS-S1/2, D1/2) were performed in the adjacent configuration, and four other tests (ECFS-S3/4, D3/4) were carried out for the opposite configuration. The study also investigated the impact of environmental conditions and cable types arranged in upper cable trays and subfloor cable trays on fire propagation. To investigate the impact of environmental conditions, four tests (ECFS-S1/2/3/4) were performed in the open atmosphere SATURNE facility, and four other tests (ECFS-D1/2/3/4) were carried out in the confined and mechanically ventilated DIVA facility. To take into account the impact of cable types, a low-qualified electric cable made of poly vinyl chloride (PVC) was used for four tests (ECFS-S1/3, D1/3), and a well-qualified electric cable containing a halogen-free flame retardant (HFFR) was used for four other tests (ECFS-S2/4, D2/4). These cables were identical to cable "G" and cable "A" used in the prior PRISME project. The cable trays were filled with tightly arranged cable samples of 3m length. It is worth noting that the central fire source cabinet had no doors to simulate an open-door cabinet fire. The fire source for all tests was ignited at the bottom of the open-doors cabinet using a propane burner, providing a heat release rate of around 10 kW for five minutes. Additionally, support tests were conducted in the SATURNE facility to measure the impact of specific parameters on fire spread. The test matrix of the ECFS campaign is summarized in Table II.

Table II: Test Matrix of the ECFS Campaign

Test	Ventilation	Configuration	Cable
S1	Open Atmosphere (SATURNE)	Adjacent	Low-qualified
S2			Well-qualified
S3		Opposite	Low-qualified
S4			Well-qualified
D1	Confined & Mechanically Ventilated (DIVA)	Adjacent	Low-qualified
D2			Well-qualified
D3		Opposite	Low-qualified
D4			Well-qualified

The confined and mechanically-ventilated DIVA facility was utilized to conduct four fire tests, with two for the adjacent configuration and two for the opposite configuration. Room 2 (R2) hosted the cabinet set-up, while the fire tests were conducted in R1, R2, and R3, which were connected by two open doorways. An inlet duct was positioned in the upper section of R1, while the upper parts of R2 and R3 housed the outlet ducts. Prior to ignition, the ventilation renewal rate for the R1 to R3 volume (i.e., 330 m^3) was approximately 11 h^{-1}, which resulted in an initial volume flow rate of approximately 3600 m^3/h at the inlet and 1800 m^3/h at each outlet. One of the aims of the confined fire tests was to describe the effects of the fire on the gas temperature, ventilation flow rate, pressure, gas concentration, and soot mass concentration for safety purposes and code validation. Furthermore, the study investigated the impact of the fire on the malfunction of digital converters positioned in the three opposite cabinets. Finally, one of the confined tests (ECFS-D3) was extended to additionally assess the performance of a network of 45 automatic fire detectors, which were installed in the ceiling of the three rooms of the DIVA facility, inside the target cabinets, and in the raised false floor.

2.1 Adjacent Configuration Tests (ECFS-S1/2 & D1/2)

The cabinet setup for the adjacent configuration included a central cabinet with an open door, two closed-door cabinet modules next to it, two overhead cable trays, and two subfloor cable trays. The primary aims of the tests were to examine the potential spread of fire from the central open-door cabinet to the closed-door cabinets next to it, using two types of cables, under both open atmosphere and confined conditions. The study investigated three possible paths for fire spread: through the double wall with a 1 cm air gap, via the overhead cable trays, and the subfloor cable trays.

2.2 Opposite Configuration Tests (ECFS-S3/4 & D3/4)

The opposite cabinet setup comprised of a central cabinet with an open door, three modules of closed-door cabinets positioned on the opposite side, two overhead cable trays, and two subfloor cable trays. The main aim of these experiments was to investigate the potential fire spread from the open-door central cabinet to the three closed-door modules located on the opposite side, using two types of cables, under both open atmosphere and confined conditions. The study examined three possible paths for fire spread: through closed doors of the three opposite cabinets, via the overhead cable trays, and the subfloor cable trays. The distance between the cabinets was 1.2 m for the test carried out with the low-qualified cables (ECFS-S3, D3) and 0.8 m for the test conducted with the well-qualified cables (ECFS-S4, D4).

3. Experimental Results

The ECFS campaign aimed to explore the different paths of fire propagation from a burning electrical cabinet to its adjacent or opposite cabinets. The cabinets were connected through two overhead cable trays and two subfloor cable trays that were contained within a concrete raised false floor. The primary goal of this campaign was to investigate how the cable type and environment affect the propagation of fire.

3.1 Adjacent Configuration Tests (ECFS-S1/2 & D1/2)

Four tests were conducted with electrical cabinets in the adjacent configuration, in which the cabinets were connected to each other via two overhead and two subfloor cable trays, with an air gap of 1 cm between cabinets. The ECFS-S1/2 tests were conducted in open atmosphere, and they had identical conditions except for the type of electrical cables used along the cable trays, which was also the case for the ECFS-D1/2 tests, conducted in the confined DIVA facility. The ECFS-S1 & D1 tests utilized a low-qualified cables, while the ECFS-S2 & D2 tests used a well-qualified cables.

The tests conducted in the environment revealed that the fire spread from the central cabinet to the adjacent cabinets via the double steel panels separated by an air gap of 1 cm. As soon as the side wall temperature exceeded 500 ℃, several inflammations of the wall paintwork first occurred in the adjacent cabinets, which caused the inflammation of electrical components and resulted in a fire in the adjacent cabinets. These results contradict the recommendation in NUREG 6850, Appendix S, which assumes no fire propagation in case of separation of electrical cabinets by a double wall with an air gap. The tests also showed that the low-qualified cables propagated the fire through two overhead cable trays and two subfloor cable trays, while the well-qualified cables extinguished after ignition, even though the two central cabinet fires were similar for both tests (heat release rate peak of about 1900 kW).

Similarly, in the confined environment, the fire spread from the central cabinet to the adjacent cabinets via the double walls, and the wall paint and target ignited in the adjacent cabinets when their steel panels exceeded 500 and 600 ℃, respectively. Flame propagations were effective through the overhead cable trays and the subfloor cable trays, but only in the case of low-qualified cables. The heat release rates for the cabinet and cable fires in the confined environment were not significantly reduced compared to those obtained in the open atmosphere, despite the lower oxygen concentration in the DIVA facility. This is because the preheating of the overhead cable trays by the hot gas layer for the low-qualified cables counterbalanced the decrease in oxygen concentration and allowed complete burning.

3.2 Opposite Configuration Tests (ECFS-S3/4 & D3/4)

Four tests were conducted with electrical cabinets in the opposite configuration, in which the cabinets were connected to each other via two overhead and two subfloor cable trays, with a 1.2 m or 0.8 m distance from the fire source cabinets to the opposite cabinets. Two tests were performed in an open atmosphere (ECFS-S3/4), while the other two tests were carried out in the confined DIVA facility (ECFS-D3/4). The ECFS-S3 & D3 tests used low-qualified cables, while the ECFS-S4 & D4 tests used well-qualified cables, with the distance between cabinets reduced from 1.2 m to 0.8 m in the latter. The opposite right and left cabinets had metallic doors, while the opposite central cabinet had a 4 mm thick glass door. The right cabinet's metallic door was equipped with electrical monitoring devices such as voltmeters and ammeters in its upper half. Each of the three opposite cabinets contained electrical devices positioned close to the doors, such as PVC trunkings, HFFR electric cables, and terminal blocks.

The fire tests identified three paths for fire spread between the cabinets located opposite each other: through the overhead cable trays, through the subfloor cable trays, and directly by thermal radiation from the fire source cabinets to the opposite cabinets by igniting one of the door handles. In both open and confined environments, the fire propagation through the overhead cable trays was clearly observed, regardless of the type of cables, low or well-qualified. On the other hand, the fire propagation through the subfloor cable trays was observed only with the low-qualified cables. The last propagation path by thermal radiation was observed only for the shorter distance between cabinets (0.8 m) resulting in the ignition of some doors with handles and the melting of the electrical monitoring devices.

The analysis of the results showed that the peak heat release rates were roughly similar for both open and confined environments. For instance, the peak heat release rate for low-qualified cables was reduced by only about 400 kW (15%) between an open and a confined environment. The comparison of the results showed that confined conditions could be more severe than open conditions, as the propagation inside the opposite cabinets was favored by higher inner gas temperatures. The global heat release rates of the ECFS-D3/4 tests were higher than those of the ECFS-S3/4 tests. Thus, detailed fire tests and simulations by reflecting real conditions are necessary, as open environments are not necessarily more conservative in terms of fire spread along overhead cable trays or in closed-door cabinets than a confined environment, especially for complex fuels and configurations.

3. Conclusions

This study has yielded several tangible outcomes, including experimental data on electrical cabinet fire 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 electrical cabinet fire 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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