

Quantitative Evaluation of Cable Protection Performance under Fire Scenarios in Safety Shutdown Cable Routing Areas Using Fire Dynamics Simulator (FDS)

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1. Introduction

Fire in a nuclear power plant can adversely affect multiple safety-related components and cables located within the same fire area. In particular, when redundant safe shutdown cable trains are routed in close proximity, a single fire may simultaneously affect multiple trains and challenge the capability to achieve and maintain safe shutdown. Therefore, adequate physical separation and fire protection measures are essential to limit fire-induced damage to redundant trains and to maintain safe shutdown capability [5]. Such a localized area, where redundant safe shutdown cable trains are routed in close proximity and may be affected by a single fire, is referred to as a pinch-point.

In this study, the thermal effects of a transient combustible fire on redundant safe shutdown cables were quantitatively evaluated using the Fire Dynamics Simulator (FDS). A virtual cable routing area representing a pinch-point configuration was developed, and four protection configurations were compared using heat release rate (HRR), cable temperature, and time to damage (TTD). The functional failure criterion for the monitored A-train cable was set to 205 °C, consistent with the criterion adopted in the original thesis based on previous studies and fire hazard analysis applications [1,2].

2. FDS Modeling and Analysis

2.1. FDS model and fire scenario

Fire simulations were performed using the Fire Dynamics Simulator (FDS) [3]. The computational domain was 40 m × 8 m × 6 m, representing a hypothetical safety shutdown cable routing area in a nuclear power plant. Redundant A- and B-train cable trays were arranged within the same fire compartment to represent a potential pinch-point condition. At the modeled pinch-point, the minimum clear separation distance between the A- and B-train cable trays was approximately 0.9 m. This configuration was selected to evaluate the potential for a single fire originating near the B-train cable trays to thermally affect the redundant A-train cables. The model included four levels of B-train cable trays and two levels of A-train cable trays, with the A-train cables serving as the primary target for evaluating thermal damage and safe shutdown capability. The overall FDS model configuration and cable-tray arrangement are shown in Fig. 1.

The fire modeling approach and interpretation of the simulation results were established considering the guidance and limitations for nuclear power plant fire modeling described in NUREG-1934 [4].

A transient combustible fire was located near the lower cable trays to simulate a fire that could expose the upper cable trays through flame and hot gas propagation. Propane was specified as the gas-phase fuel species for the prescribed FDS fire to represent the combustion reaction, rather than the actual composition of the transient combustible material. The initial fire was defined based on the transient combustible control location (TCCL) fire characteristics provided in NUREG-2233, which provides a 98th-percentile peak HRR of 143 kW for TCCL fires [6]. In the present FDS model, the fire source was represented by a 0.5 m × 0.5 m burner with a burning surface area of 0.25 m². Accordingly, the HRRPUA was calculated as 143 kW / 0.25 m² = 572 kW/m². In FDS, the prescribed fire size is determined by the product of HRRPUA and the burning surface area [3]. As the transient combustible fire developed, the adjacent B-train cables could become involved in the fire, resulting in increased thermal exposure to the redundant A-train cables. The same compartment geometry, cable arrangement, fire location, and initial fire conditions were maintained for all four cases, while only the applied fire protection measure was varied.

The maximum simulation time was set to 3,600 s. Case 1 and Case 4 were analyzed for the full duration to evaluate continued fire growth and thermal exposure. For Cases 2 and 3, which employed active water-based protection, the simulations were terminated after fire suppression and a sustained decrease in the A-train cable temperature were confirmed. The HRR and A-train cable temperature histories were used as the primary parameters for comparing fire protection performance, and a cable functional failure criterion of 205°C was applied to evaluate whether safe shutdown cable functionality was maintained.

Several assumptions were introduced to establish consistent boundary conditions among the four cases. The fire compartment was modeled as an enclosed space with the fire dampers assumed to be closed. In an actual plant, ventilation may continue to supply air until the fusible links are activated and the fire dampers are closed. However, the transient operation of the HVAC and fire dampers was not modeled because the primary objective of this study was to compare the relative effects of the four fire protection configurations under identical fire conditions.

In addition, for the functional damage assessment, a conservative threshold of 205 °C, corresponding to the thermoplastic cable damage criterion, was applied

instead of a higher damage threshold associated with thermoset cables. This assumption was adopted to provide a conservative assessment of cable functionality.

Cable damage was evaluated using the calculated cable surface temperature rather than the internal conductor temperature. Therefore, the thermal delay associated with heat conduction from the cable surface to the internal components was not credited, providing a conservative basis for determining the time to damage.

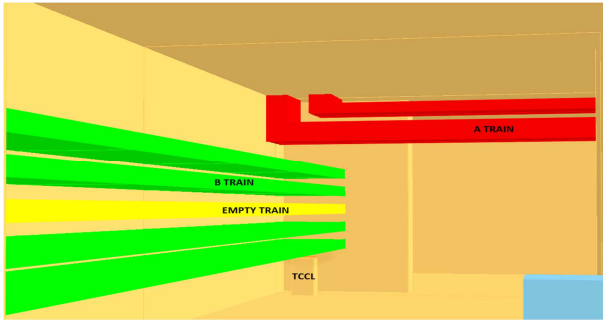


Fig. 1. FDS model of the safe shutdown cable routing area and transient combustible fire location.

2.2. Fire protection scenarios

Four fire protection scenarios were analyzed under the same basic compartment and fire conditions. Case 1 was the no-protection reference case. Case 2 used ceiling sprinklers, Case 3 used localized cable-tray water spray protection, and Case 4 used Fire Wrap as a passive thermal barrier.

The detailed conditions and protection mechanisms for the four cases are summarized in Table I.

Table I: Fire protection scenarios.

Case	Fire Protection	Simulation Time (s)	Peak HRR (kW)	Peak Time (s)	Protection Mechanism
1	No protection	3,600	6,061	2,278	None
2	Ceiling sprinkler	1,638	251	1,285	Fire suppression and cooling
3	Local cable tray water spray	1,393	252	1,182	Local suppression and direct cooling
4	Fire Wrap	3,600	1,582	3,585	Passive thermal shielding

Note: Cases 2 and 3 were terminated after suppression and decreasing thermal response were confirmed.

2.3. Modeling assumptions and limitations

Modeling the fire protection measures required several engineering simplifications. In particular, the discharge configuration of the localized cable-tray water spray system had to be represented by defining the nozzle locations and spray characteristics within the FDS

computational domain. The Fire Wrap configuration involved greater limitations because actual passive fire protection materials exhibit complex thermal and physicochemical behavior. Detailed representation of material properties, experimental thermal response, and transport phenomena associated with thermal decomposition was beyond the scope of the present model. Therefore, the Fire Wrap was represented as a simplified thermal barrier intended to reproduce its primary heat-shielding function rather than its detailed material behavior. Accordingly, the results of Case 4 should be interpreted primarily in terms of the relative effect of passive thermal protection.

3. Results and Discussion

3.1. Fire growth and suppression

As shown in Fig. 2, the HRR histories showed clear differences among the four fire protection scenarios. In Case 1, without additional fire protection, the transient combustible fire continued to grow and subsequently involved the adjacent cable trays, resulting in a peak HRR of approximately 6.06 MW. This indicates that cable involvement can significantly increase the overall fire intensity when no suppression system is provided.

In contrast, the peak HRRs of Cases 2 and 3 were approximately 0.25 MW, demonstrating substantial fire growth suppression by the active water-based protection systems. Both the ceiling sprinkler and localized cable tray protection effectively controlled the fire before significant cable involvement occurred. Case 4 exhibited a different response because Fire Wrap primarily provided passive thermal insulation to the protected cable tray rather than directly suppressing the fire. Consequently, the fire continued to develop, while heat transfer to the protected cables was delayed by the thermal shielding effect of the Fire Wrap.

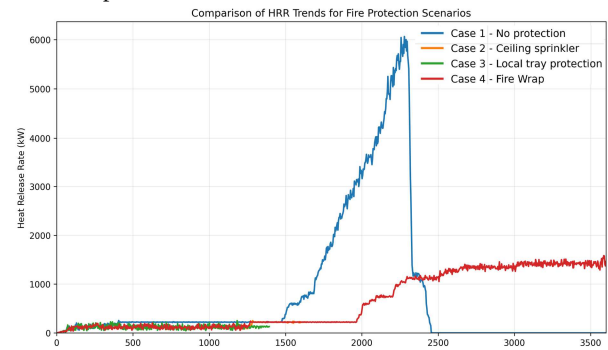


Fig. 2. Comparison of HRR trends for the four fire protection scenarios.

3.2. Thermal response of safe shutdown cables

In Case 1, A-train cable temperatures continuously increased with fire growth and reached maximum values of 361.3 °C and 393.7 °C. The 205 °C functional failure criterion was exceeded after approximately 30 min, indicating that continued fire growth and subsequent thermal exposure could result in functional failure of the redundant safe shutdown cables. This result demonstrates

that fire propagation from the B-train cable trays can thermally challenge the redundant A-train cables and potentially affect safe shutdown capability.

Under the ceiling sprinkler condition (Case 2), the maximum monitored A-train cable temperatures were limited to approximately 65.2 °C and 67.1 °C. Similarly, under the localized cable-tray protection condition (Case 3), the maximum temperatures were approximately 57.4 °C and 54.0 °C. In both active-protection cases, the cable temperatures remained significantly below the 205 °C functional failure criterion. In particular, the localized protection provided direct cooling to the cable-tray region, resulting in lower cable temperatures than those observed with the ceiling sprinkler configuration.

In Case 4, the maximum A-train cable temperatures reached 237.6 °C and 250.2 °C. Although the Fire Wrap reduced heat transfer to the protected cables and delayed the time to damage (TTD) by approximately 13–21 min, the 205 °C criterion was ultimately exceeded under prolonged fire exposure. These results demonstrate the different protection mechanisms of active and passive systems: passive Fire Wrap can delay cable thermal damage, whereas active water-based systems can simultaneously suppress fire growth, reduce thermal exposure, and cool the cable trays, thereby providing more effective protection of safe shutdown cable functionality.

The key results for the four fire protection scenarios, including peak HRR, maximum A-train cable temperature, and protection performance, are summarized in Table II.

Table II: Summary of result

Case	Fire Protection	Peak HRR (MW)	A-Train Cable Temp. (°C)	205°C Criterion	Protection Performance
1	No protection	6.060	361.3 / 393.7	Exceeded	Cable functional failure
2	Ceiling sprinkler	0.251	65.2 / 67.1	Not exceeded	Fire suppression and cooling
3	Local cable tray protection	0.252	57.4 / 54.0	Not exceeded	Local suppression and direct cooling
4	Fire Wrap	1.583	237.6 / 250.2	Exceeded	Functional failure delayed by 13–21 min

3.3. Comparison of protection performance

The simulations also demonstrated differences in fire propagation behavior depending on the location and configuration of the active protection systems. Both the ceiling sprinkler and localized cable-tray water spray systems rapidly controlled the developing fire; however, the localized system provided more direct water application to the protected cable-tray region and resulted in lower maximum cable temperatures. This indicates that the location of fire suppression equipment relative to the target component can influence the effectiveness of cable protection.

This finding is particularly relevant to nuclear power plants, where the primary objective of fire protection is not only to extinguish a fire but also to maintain the functions required for safe shutdown. Nuclear power plants employ preventive controls such as transient combustible management and fire-safe work controls to reduce fire occurrence. When additional suppression or protection is required, locating protection systems with consideration of safe shutdown equipment may therefore provide an effective means of limiting fire propagation and maintaining the required safety function.

4. Conclusions

FDS-based fire simulations confirmed that, without additional protection, a transient combustible fire can cause the monitored safe shutdown cable to exceed the 205 °C functional failure criterion. Ceiling sprinklers and localized cable-tray water spray substantially suppressed fire growth and maintained cable temperatures below the criterion. Their performance nevertheless differed according to installation configuration, with localized protection providing strong direct cooling of the cable-tray region. Fire Wrap delayed heat transfer but did not suppress the fire itself, so its protection capability depended on fire severity and duration. Finally, the results confirmed that the effectiveness of active fire protection varies with installation configuration. Because fire protection systems act after fire initiation, rigorous field fire-safety management, including control of transient combustibles and ignition sources, remains essential to prevent such fires from occurring.

These results suggest that cable routing through potential pinch-point areas should be carefully evaluated and that the arrangement of active fire protection systems in relation to redundant safe shutdown equipment should be considered when designing fire protection for nuclear power plants.

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