

Verification of updated Two-layer Zone Model BRI2-CRIEPI Applicable to Fire PRA for Nuclear Power Plants

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Abstract: A practical fire model capable of reproducing realistic fire scenarios is essential for conducting a practical probabilistic risk assessment (PRA) for nuclear power plants. We have continuously improved the BRI2-CRIEPI fire simulation zone model to analyze compartment fires under mechanically ventilated conditions. This paper introduces the various characteristics of the fire model implemented in BRI2-CRIEPI under these conditions. These characteristics include: 1) the relationship between pressure and ventilation flow rate in ventilation fans, 2) the reduction in mass loss rate (MLR) due to oxygen depletion as the fire progresses, 3) representative oxygen concentrations corresponding to the height of the high-temperature gas layer, 4) a thermal radiation feedback model between the flame and the surrounding environment when the flame impinges on the ceiling, and 5) soot-induced filter clogging. We verified the BRI2-CRIEPI model using full-scale compartment fire test results from the OECD/NEA project (PRISME and PRISME3) and the Franco-Japanese joint fire research project (PRELUDE/PML), which was conducted by EDF and CRIEPI. Quantitative evaluation of representative assessment parameters (MLR, high-temperature gas temperature and smoke height) revealed no apparent bias or systematic trend in the model predictions.

1. INTRODUCTION

In implementing a probabilistic risk assessment (PRA) for fire in nuclear power plants (NPPs) [1], a practical fire model is necessary to create more realistic fire scenarios involving multi-compartment fires or multiple fire sources under mechanically ventilated conditions. According to NUREG-1934 [2], the capabilities of fire models are presented for the purpose of conducting fire modeling analyses, primarily for commercial NPP applications. This guide describes the features of various fire models, such as algebraic, zone, and computational fluid dynamics (CFD) models, focusing on their capabilities. The zone model, which divides the fire compartment into an upper layer of hot gas and a lower layer of cool, fresh air. It has been widely used as a cost-effective approach due to the advantages of the brevity of the calculation routine and the reliability of its calculation results. Figure 1 shows the concept image of the two-zone fire model.

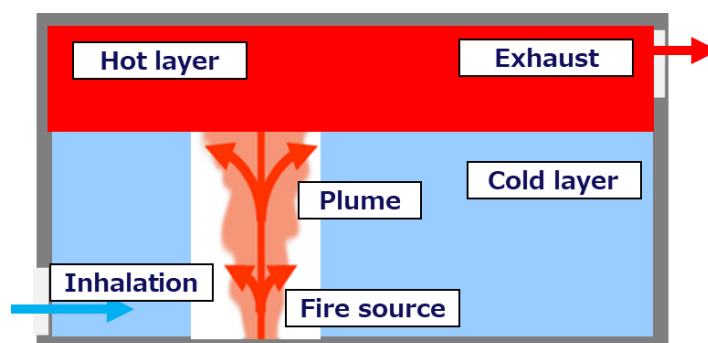


Figure 1: Concept of two-zone fire simulation model

In the event of a compartment fire in NPP under mechanically ventilated conditions, the fire characteristics may change from fuel-controlled to ventilation-controlled due to oxygen depletion resulting from fire growth. Changes in the mass loss rate caused by oxygen concentration degradation in a compartment have a clear limit and affect the HRR (heat release rate) from a fire source. Therefore, CRIEPI developed BRI2-CRIEPI, which allows for the analysis of NPP facility configurations under mechanically ventilated conditions as part of the design process and risk assessment [3]. This analysis considers the following key features, as shown in Figure 2.

- Fan curve model to consider the temperature dependence of the volume flow rate of exhaust gas passing through the exhaust vent in the compartment.
- The Peatross and Beyler model [4] to apply the burning rate reduction effect according to the decline in oxygen concentration in compartments, considering the elevation (height from the floor) of the fire source and the entrainment of a large amount of fresh air into the plume.
- A heat feedback model to consider the acceleration of the combustion of a fire source due to radiant heat transfer inside the compartment during a compartment fire.
- Heat transfer model to consider the bi-lateral flow [5] through the ceiling opening in the event of fire propagation in vertically connected fire compartments.
- Multiple Fire Source to apply for multiple fire compartments.

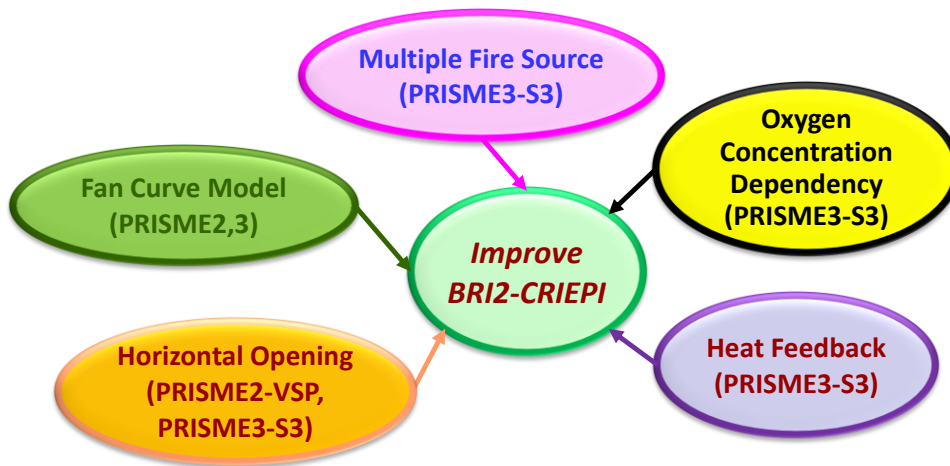


Figure 2: Improvement of BRI2-CRIEPI

2. EXISTING EXPERIMENTAL STUDY

2.1 PRISME Program

The PRISME [6] and PRISME3 [7] programs, an international joint research program by the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), had been completed to study fire characteristics in a complex, multi-compartment facility with forced mechanical ventilation, such as a NPP facility. The experiments were performed in the DIVA facility, a full-scale compartment fire facility owned by the IRSN.

Figure 3 shows a schematic diagram of the DIVA facility. The facility is a two-story structure. The first floor is divided into three rooms: Room1 (R1), Room2 (R2), and Room3 (R3). R3 is connected to Room4 (R4) on the second floor via a horizontal opening. The facility is mechanically ventilated. Each room has an inlet and outlet duct. The three rooms (R1, R2, R3) have the following dimensions: 6 m (length) x 5 m (width) x 4 m (height). R4 on the second floor has a larger area than the other rooms: 8.5m (length) x 5m (width) x 4m (height).

For the verification analysis, we selected specific sectional diagrams of the test compartment for the PRISIME source and PRISME3 programs, as shown in Figures 4 and 5, respectively.

As shown in Table 1, six types of fire test scenarios were selected for the PRISME source and three for the PRISME3.

For the PRISME source tests, a single fire source with a TPH pool area of either 0.20 m² or 0.40 m² was installed on the floor in the centre of R3, and the initial liquid surface level was set to 0.38 m.

For the PRISME3 test, a reference test (PR3-S3-B0) was conducted in which a single fire source with a 0.56 m² dodecane pool area was placed in the centre of R3, with an initial liquid surface level of 0.35 m.

- In the PR3-S3-A test series, two multiple smoke propagation mode tests were executed in four rooms (R1, R2, R3 and R4) to investigate the combined effect of vertical and horizontal smoke propagation. In these tests, a 0.40 m² or 1.0 m² lubricant oil pool area was set in the corner of R3.
- In the PR3-S3-B test series, two multiple fire source tests with three rooms (R1, R2, and R3) were performed to investigate smoke propagation from two separate fire sources with a 0.56 m² dodecane pool area.
- In the PR3-S3-C test series, one elevated fire source test with three rooms (R1, R2, and R3) was performed to investigate the impact of an elevated fire source on fire behaviour under ventilated conditions. A 0.56 m² dodecane pool area was set 2.1 m high in R3.

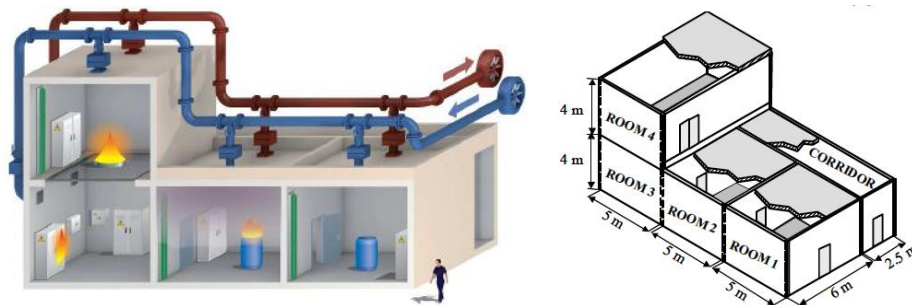


Figure 3: DIVA facility of IRSN [7]

Table 1: Test conditions for PRISIME source [6] and PRISME3 [7] programs

Program	Test No.	Case	Fuel	Pan area (m ²)	Pan height (m)	Note
PRISME SOURCE	PRS-Si-D1	D1	TPH	0.40	0.38	-
	PRS-Si-D2	D2		0.40	0.38	-
	PRS-Si-D3	D3		0.40	0.38	-
	PRS-Si-D4	D4		0.40	0.38	-
	PRS-Si-D5	D5		0.20	0.38	Small fire source
	PRS-Si-D5a	D5a		0.20	0.38	Small fire source
	PRS-Si-D6	D6		0.40	0.38	Lower air supply
	PRS-Si-D6a	D6a		0.40	0.38	Lower air supply
PRISME3	PR3-S3-A1	A1	Lubricant Oil	0.40	0.35	Horizontal opening
	PR3-S3-A2	A2		1.00	0.35	Horizontal opening
	PR3-S3-B0	B0	Dodecane	0.56	0.35	Reference case
	PR3-S3-B1	B1		0.56	0.35	Multiple fire source
	PR3-S3-B2	B2		0.56	0.35	Multiple fire source
	PR3-S3-C1	C1		0.56	2.1	Elevated fire source

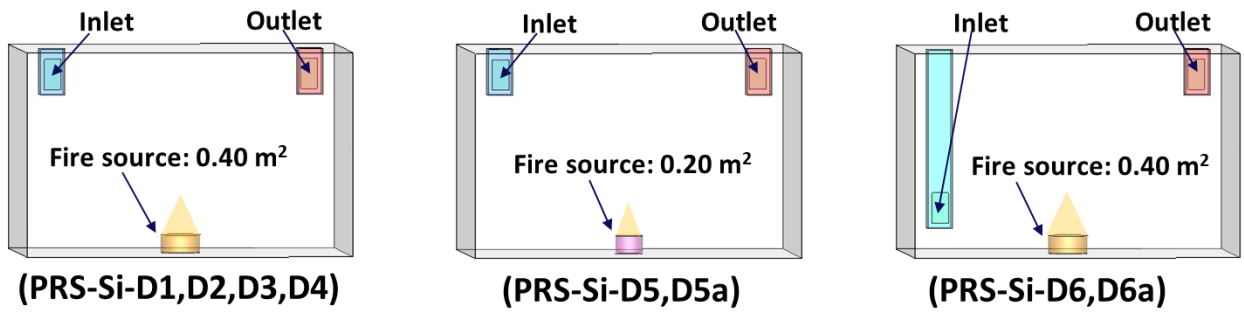


Figure 4: Sectional Diagrams of Test Compartment for the PRISIME source program

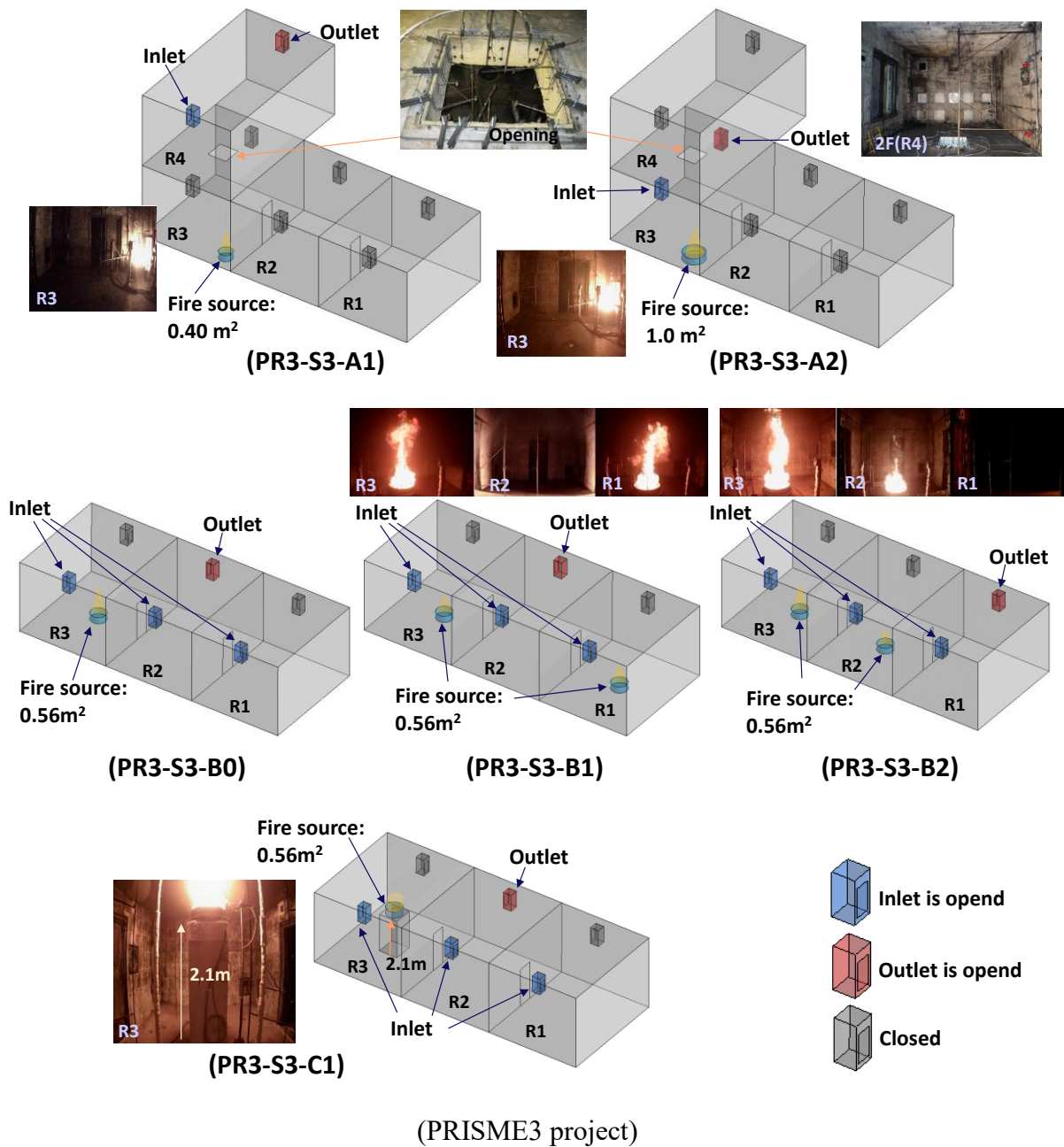


Figure 5: Sectional Diagrams of test compartment for the PRISME3 program

2.2 PRELUDE Program

The PRELUDE program was launched by Électricité de France (EDF) R&D on the IGNIS (French: Installation grandeur nature incendie sûreté) platform as shown in Figure 6. This platform is specifically designed for large-scale fire tests in confined environments [8]. One of this program's campaigns, the PML campaign, is being conducted as part of the joint EDF-CRIEPI test program from January 2024 to December 2026 [9], [10]. The PML campaign, the French acronym for multi-room propagation, aims to set up a realistic configuration for existing NPPs. The main objective of this campaign is to investigate the effects of both soot concentration and thermal feedback on an electrical target located in the fire room or the adjacent room. For this campaign, a 78.75 m³ gallery configuration with a mechanical ventilation system was implemented in the ME2 test facility.

Figure 7 shows the test configuration for the PML campaign. Room(R1) is a enclosure that is 4.00 m long, 2.50 m wide and 3.00 m high. Various fire sources are lit inside the enclosure. A 2.00 m high, 0.80 m wide opening directly connects R1 to a target compartment. The target compartment is divided into two zones delimited by a smoke-retaining structure set on the ceiling. Each zone is 3.25 m long, 2.50 m wide and 3.00 m high. The fire source was placed in the centre of R1. The entire facility is ventilated at an air renewal rate of 10 h⁻¹ and the flow rate is divided equally among the three rooms in the configuration.

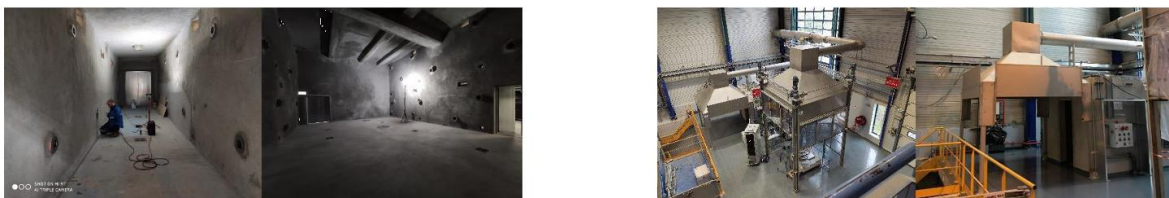
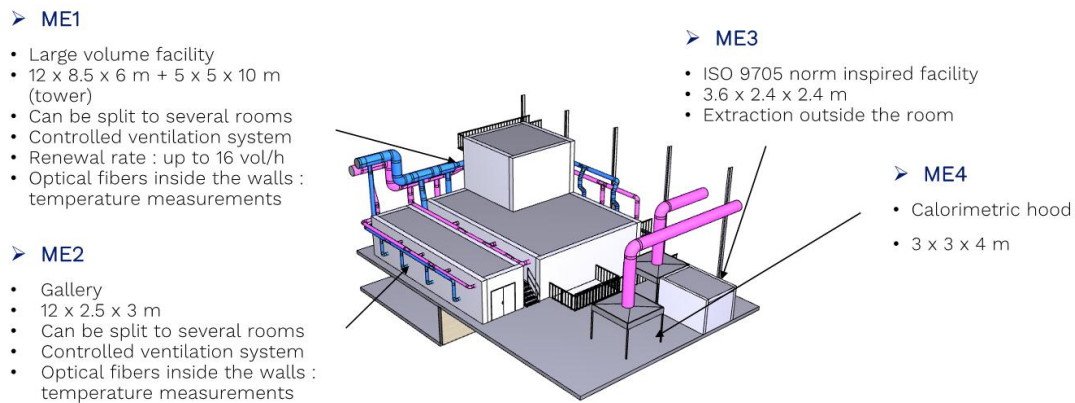


Figure 6: IGNIS fire safety experimental platform operated by EDF

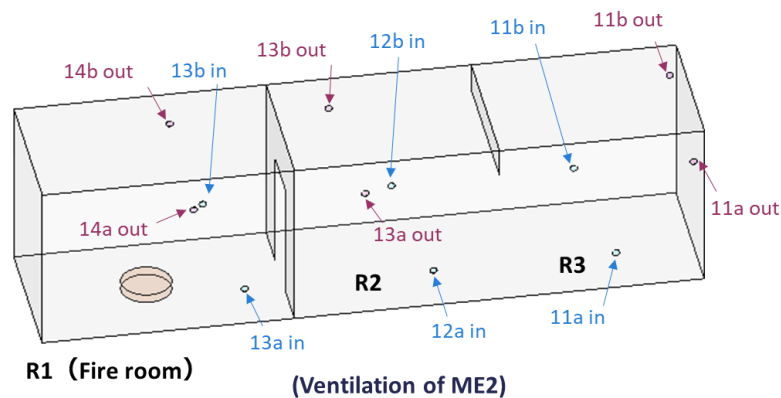


Figure 7: Test configuration for the PML campaign

As shown in Table 2, three test series were executed.

- Test 5 series: The target electrical cabinet was set in R2 to investigate the effect of smoke propagating from the fire source.
- Test 6 series: The target electrical cabinet with the radiation shielding panel was placed in R1, close to the fire source, to investigate the effects of smoke and high temperature gases originating from the fire source.
- Test 7 series: The target electrical cabinet without the radiation shielding panel was placed in R1, close to the fire source, to investigate the combined effects of smoke, high temperature gases and heat flux radiated from the flames of the fire.

Table 2: Test conditions for PRELUDE/PML Program

Program	Test No.	Case	Fuel	Pan area (m ²)	Pan height (m)	Note
PRELUDE PML	Test5a	Test5a	Diesel	0.38	0.3	Soot effect
	Test5b	Test5b		0.38	0.3	
	Test5c	Test5c		0.38	0.3	
	Test6a	Test6a		0.38	0.3	Soot and temperature effect
	Test6b	Test6a		0.38	0.3	
	Test7	Test7		0.38	0.3	Soot, temperature and radiation effect

3. VALIDATION OF THE BRI2-CRIEPI

3.1 Data Regression Method of Thermal Stratification due to Fire

To ensure confidence in the predictive capabilities of the two-zone fire simulation model, it is highly recommended that fire simulations be properly compared with experimental fire tests. H. Pretrel and L. Audouin proposed a data regression method to validate zone codes, determining the temperatures of the upper and lower zones and the interface height using experimental vertical temperature profiles from large-scale fire tests [11].

This method combines thermal stratifications showing a constant temperature in the upper layer, which is often encountered in well-ventilated fires, and thermal stratifications showing a constant gradient, which is often observed in fires in closed and forced-ventilated compartments. In principle, these data regression methods include three types of approaches, as follows:

- Type 1: Two homogeneous thermal layers approach, named "2ZH"
- Type 2: Two thermal layers approach with homogeneous for lower layer and constant gradient for upper layer, named "2ZG"
- Type 3: Three thermal layers approach, named "3ZG"

In this study, we selected the appropriate method at every time step that gave the smallest sum of the two parameters C_T and C_ρ , expressed as follows:

$$C_T = \left(\int_0^H |T^{exp}(z) - T^{type}(z)| dz \right) / \left(\int_0^H T^{exp}(z) dz \right) \quad (1)$$

$$C_\rho = \left(\int_0^H \left| \frac{1}{T^{exp}(z)} - \frac{1}{T^{type}(z)} \right| dz \right) / \left(\int_0^H \frac{1}{T^{exp}(z)} dz \right) \quad (2)$$

where H is the height of the compartment and, $T^{exp}(z)$ is the vertical experimental temperature profile, $T^{type}(z)$ is the vertical data regression profile in temperature.

Figure 8 shows examples of temperature profile of comparisons and the time history of the hot gas layer (HGL) height during fire tests (PRISME Source D1 and PRELUDE/PLM Test 5a). For reference, the N% rule ($N = 50$) [12] was also used to estimate the interface elevation. Among the vertical profile regression methods, “3ZG” appears to provide a better approximation, and the experimental temperature profiles indicate a lower interface height with a constant temperature gradient.

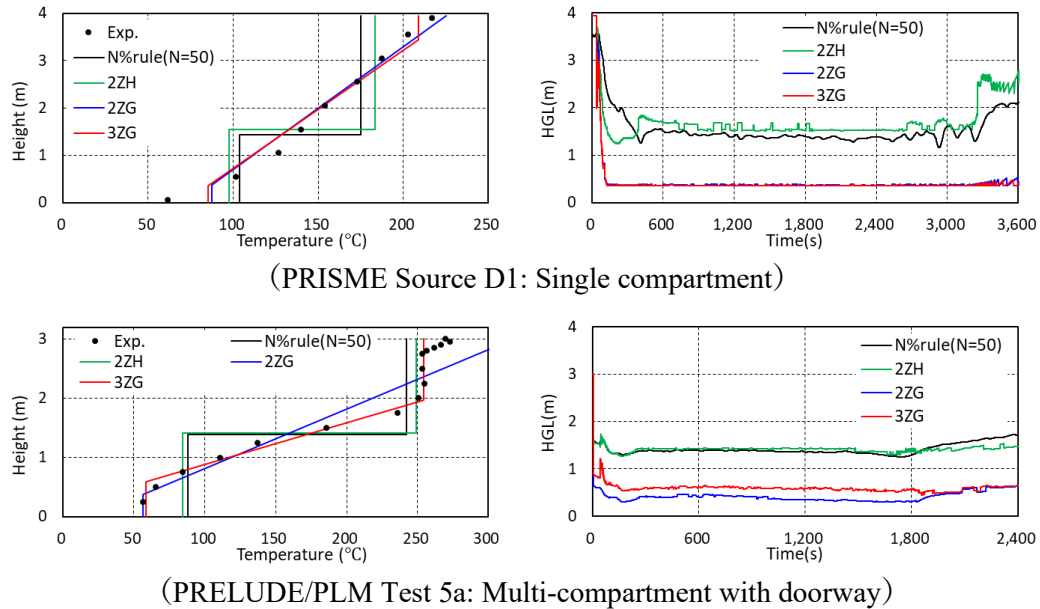


Figure 8: Examples of temperature profiles of comparisons and time history of the hot gas layer height during the fire tests

3.2 Experimental Analysis

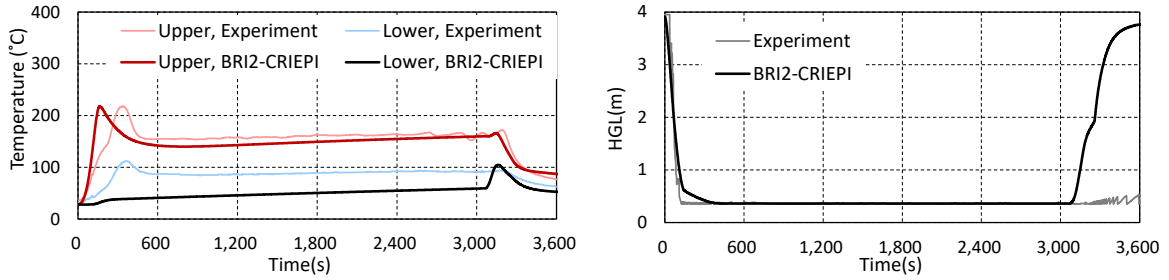
To verify the improvement to the BRI2-CRIEPI zone model described in the previous chapter, a series of experimental analyses were performed and compared with the experimental data in Tables 1 and 2. The test and predictive simulation results are presented to demonstrate the fundamental fire characteristics under mechanically ventilated conditions with a single fire source and a multi-room configuration. Figure 9 shows the examples of the calculated time history of the hot gas layer (HGL) temperature and height, along with the experimental values.

HGL Temperature

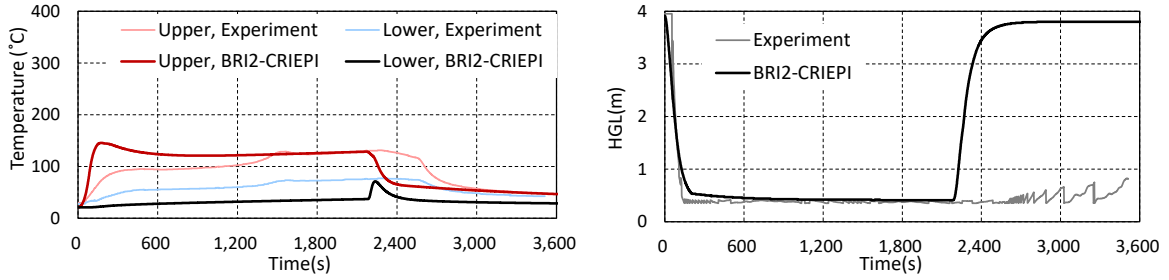
After ignition, the HGL temperature increased rapidly to the first peak and then reached a quasi-steady state due to a reduction in oxygen concentration. Despite the test conditions, the calculated values for this typical behavior of pool fires under ventilated conditions generally agreed with the experimental values.

HGL Height

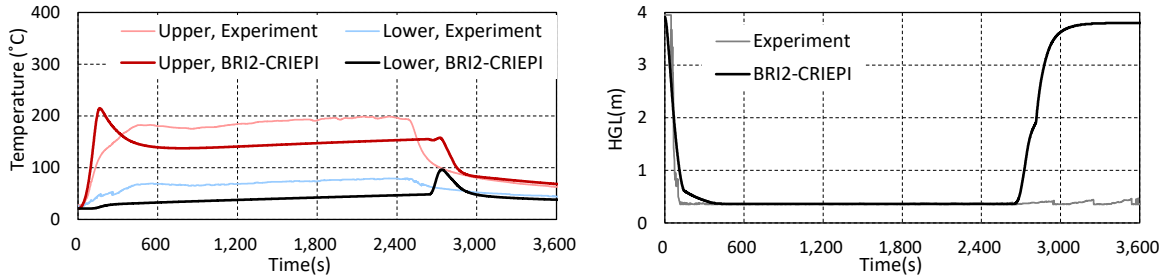
The HGL height is important in NPP fire scenarios because it indicates whether a target is immersed in high-temperature gases. For the multi-compartment configuration, the simulation results are higher than the experimental values. Figure 10 shows a schematic view of smoke propagation in a multi-compartment configuration. The PRISME Project has highlighted the combined effects of forced and natural convection on smoke propagation in confined and ventilated compartments [6].



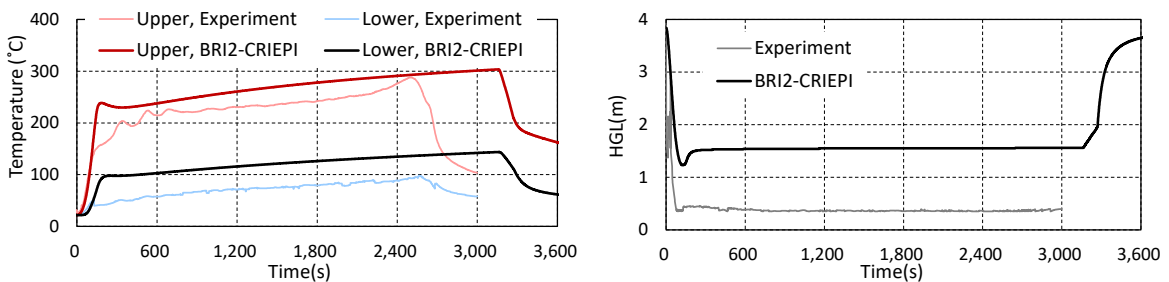
(PRISME Source D1: Single compartment: Reference case)



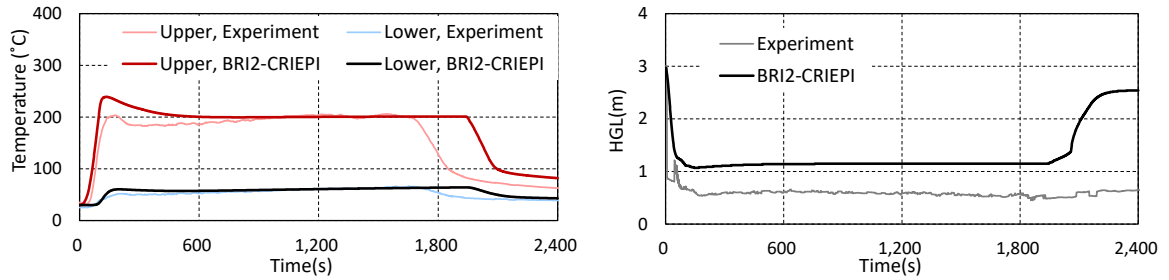
(PRISME Source D5: Single compartment with Small Fire Source)



(PRISME Source D6: Single compartment with Lower Air Supply)



(PRISME-S3-B0: Multi compartment: Reference case)



(PRELUDE/PML Test 5a: Multi compartment)

Figure 9: Examples of comparisons between experimental and analytical results

Natural convection is induced by high smoke temperature, while forced convection is induced by ventilation. Predicting smoke movement and its propagation requires understanding the coupling between these two physical mechanisms. As Figure 10 shows, the mechanical ventilation in a fire compartment can significantly modify the typical bidirectional flow along the doorway and contribute to a neutral position along the doorway plane. Figure 11 shows a visual observation of the flame and smoke. After 240 s of ignition, there is no visibility due to the smoke filling the entire compartment from floor to ceiling. Since the BRI2-CRIEPI model focuses on predicting the neutral position described above, the calculated results are inconsistent with the soot concentration profile. Therefore, calculated values of HGL height for confined multi-compartment fires using the zone model may not be useful for direct comparison to model results.

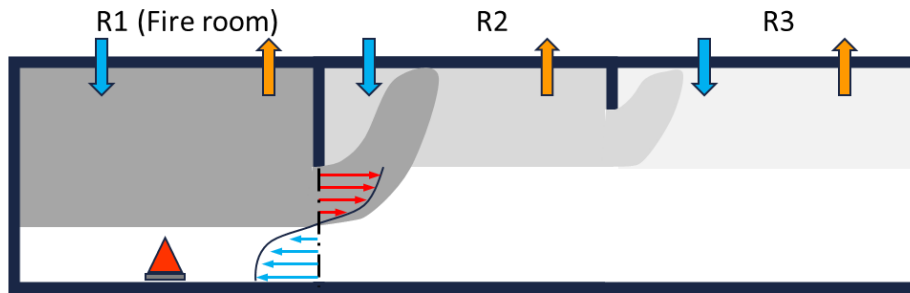


Figure 10: Schematic view of smoke propagation in the multi-compartment configuration

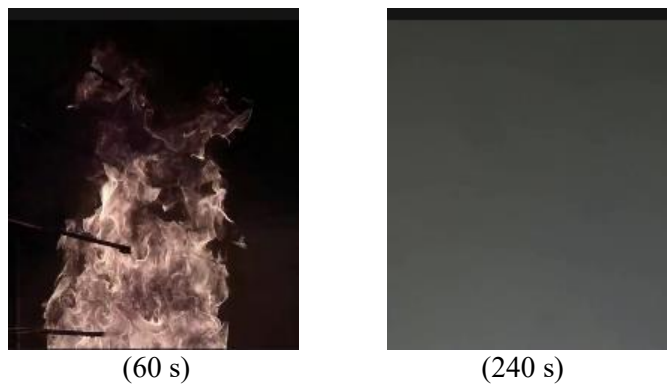


Figure 11: Visual observation of the flame and smoke (PRELUDE/PML Test 5a)

3.3 Discussion

To quantify prediction uncertainty of the improved BRI2-CRIEPI, we calculated two statistical parameters: the bias factor δ and the relative standard deviation of the model σ_M . Figure 12, shows the comparison between the experimental and calculated values for all analysis cases. The predicted MLR, HGL temperatures and heights are summarized at the maximum values, 600 s, 1200 s and 1800 s. This figure shows two sets of off-diagonal lines. The first set, shown as dashed black lines, indicates the experimental uncertainty in terms of the relative standard deviation, σ_E , assuming the experiments is unbiased (with a bias factor of 1.0 for the experimental measurement). The slopes of the dashed black lines are $1 \pm 2\sigma_E$, representing 95 % confidence intervals. The second set of lines, shown in red, indicates the model's relative standard deviation, σ_M . The slopes of these lines are $\delta \pm 2\sigma_M$.

Figure 12(a) shows the validation results for MLR. The uncertainty value used for MLR was 7.5 % [13]. It appears that there is no obvious bias in the model prediction (the model bias factor is 0.97), nor any particular systematic trend (the model relative standard deviation is 0.08).

Figure 12(b) shows the validation results for the HGL temperature. This parameter is very important metric in fire PRA because it indicates target damage away from fire source. The uncertainty value used for HGL temperature was 7.0 % [13]. It appears that the model has a bias factor of 1.11, and it slightly

overpredicts the HGL temperature, especially with a relatively small fire source (PRISME Source D5) and lower air supply (PRISME Source D6). This is likely due to the simplified assumption regarding the representative oxygen concentration for the proposed BRI2-CRIEPI zone code. Nevertheless, there is no particular systematic trend in the model prediction (the model's relative standard deviation is 0.14).

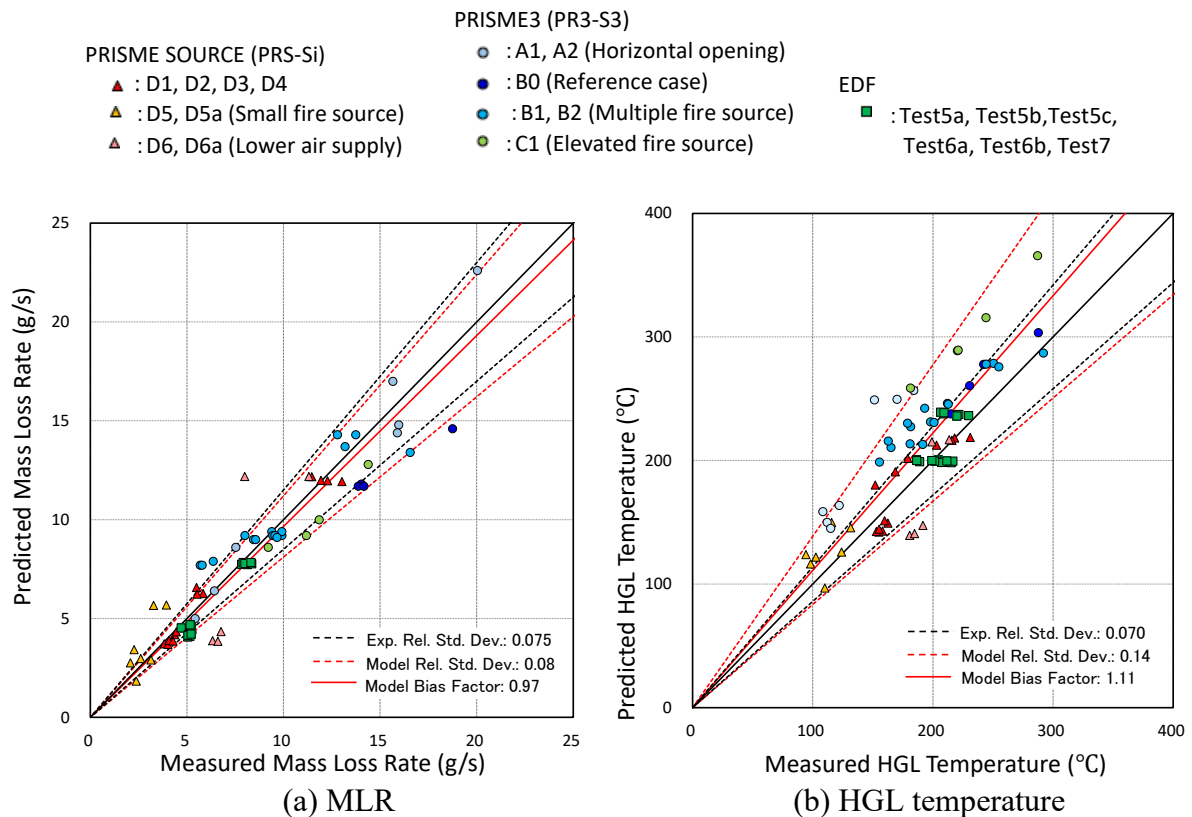


Figure 12: Validation of calculation results on MLR and HGL temperature

5. CONCLUSIONS

A numerical study was conducted to improve the two-zone model, BRI2-CRIEPI, and validate fire behavior in compartments under mechanical ventilation conditions that simulate the facilities in NPPs. This study used data obtained from the OECD/NEA Fire Program (PRISME Source and PRISME3) and the joint EDF-CRIEPI test program (PRELUDE/PML). These data sets include a total of twenty fire tests, focusing on smoke propagation in a mechanically ventilated multi-room facility with multiple fire sources, an elevated fire source, and multiple propagation modes through doorways and vents.

The main outcomes are as follows:

- Twenty fire test results were evaluated using the data regression method proposed by H. Pretrel and L. Audouin [11]. This method was used to validate the two-zone fire simulation model BRI2-CRIEPI, and to determine the temperatures of the upper and lower zones, as well as the interface height, using experimental vertical temperature profiles.
- The improved model was validated using the test results from the full-scale compartment test series obtained during the PRISME Source, PRISME3, and PRELUDE/PML campaigns. The validation results for the HGL temperature, an important metric in the fire PRA, show that there is no obvious bias (model bias factor of 1.11) or particular systematic trend (model relative standard deviation of 0.14) in the model predictions, except for small fire sources and cases with lower air supply. Consequently, the proposed BRI2-CRIEPI zone code was found to be a useful tool for estimating compartment temperatures in a practical manner for fire PRA.

- The experimental analysis revealed several physical phenomena that require further understanding to improve in the BRI2-CRIEPI in the future. These include soot predictions in multi-compartment cases, interactions between multiple fires, horizontal ceiling flow in vertically connected rooms, and more realistic mass loss rates, especially in complex compartments such as corridors or shafts.

Acknowledgements

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