Fire Risk Assessment and Evaluation of the Effectiveness of Fire Protection Actions in a Combined-Cycle Power Plant

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ABSTRACT

The increasing abundance of fires in industrial buildings has led to the growth of fire risk assessment and protection methods. However, few studies have been performed on the practical application of these risk assessment methods in industrial structures. This study aimed at assessing fire risk and determining the effectiveness of fire control measures to reduce fire-related injuries and fatalities to occupants at a combined-cycle power plant in the northeast of Iran.

In the present study, firstly, the fire risk level of the real condition for the occupants, building and contents, and activities were measured using the Fire Risk Assessment Method for Engineering (FRAME). Then, taking into account the fire control measures, the fire risk was recalculated and compared with the acceptable risk level.

The results indicated that the occupants' fire risk level was 1.26 that was above the acceptable level. Furthermore, in the case of a fire, the expected destruction of the control room will be approximately 20%. Assuming a constant fire load modulation via building construction by non-burning materials or up to 10% burning materials, the occupants' fire risk level will be decreased by 8% compared to the current situation. Also, in the state of designing standard emergency exit routes and using the fire alarm system, the fire risk level will be decreased by 50% and 52%, respectively, compared to the current condition.

This study indicated that applying quantitative engineering methods for fire risk assessment can help to find practical solutions to minimize losses and fire-related injuries to industrial building occupants.

Key words: Fire, Fire Risk Assessment, Power Plant, Building Occupants

INTRODUCTION

Among the various hazards, fire is recognized as one of the main threats to human life, health, and property [1, 2]. Therefore, fire risk assessment and prevention is considered as a critical part of system safety engineering [3, 4]. Some evidence showed that 60% of fire-related injuries and fatalities have been in industrial buildings and among workers and most of this catastrophic fire, occurred without any previous prognosis [5].

Among the major industries, power plants are rated as one of the most critical economic development infrastructures [6, 7]. Iran, as a developing country, is challenged with growing electricity demand. To respond to this demand and due to the presence of abundant resources of oil and gas, large power plant projects have been constructed or under construction in recent years [8-10]. Because of the complexity of the process, the incidence of fire in power plants is unavoidable. Consequently, the application of fire safety systems to keep occupants safe and continue the operation of power plants is essential [11].

In the recent decade, the increasing number of fires in industrial buildings has led to the growth of fire risk assessment and protection methods. Nevertheless, few investigations have been performed on the practical employment of fire risk assessment methods for reducing fire-related fatalities and injuries to industrial building occupants [12-14]. Furthermore, studies that include the effectiveness of these methods in fire protection in industrial buildings are minimal [15, 16]. Fire risk assessment method for engineering (FRAME) is one of the most practical and comprehensive methods used to determine the risk of fire in buildings. This method estimates the fire risk for three different modes including the building and its contents, occupants, and indoor activities. Compared to other fire risk assessment methods, this method has benefits such as semi-quantitative risk assessment, low cost, short-run ability, acceptable accuracy, and estimation of the extent of potential damage during a fire [17]. This method is the extended version of the Gretener method [18] that was introduced in 2008 by Erik De Smet. This method was validated by Mahdinia *et al.* in Iran [19]. Building regulations and codes are designed based on the safe escape of occupants. These regulations just provide a minimum amount of fire safety and are not sufficient for specific industrial buildings [20]. In contrast, the FRAME method is designed based on protecting structures, occupants, contents, and activities during a fire. This method covers issues such as building specifications, fire separation, fire loads, evacuation and escape facilities, ventilation, fire recognition, water supply, and fire extinguishing systems [17, 21, 22].

In the study of Setare *et al.*, three fire risk assessment methods were investigated. The results revealed that the fire risk assessment method for engineering is a proper tool for fire risk assessment and fire protection in new or existing buildings [23]. NG reported that the risk of fire for occupants in Hong Kong airport terminal was more than the risk of damage to equipment and building. Therefore, more consideration should be given to the safety of staff and passengers [24]. Abraham *et al.* reported that simultaneous use of active and passive fire protection methods is needed to have the risk level of fire in the acceptable range in buildings [25]. Furthermore, Mahdinia *et al.* assessed the fire risk for occupants, activities and buildings in a hospital in Qom, Iran, by Fire Risk Assessment Method for Engineering (FRAME) and showed that the fire risk levels were higher than acceptable level [26].

Despite the importance of preserving the safety of occupants and maintained regular operation and power generation, no study has been performed on fire risk assessment and evaluation of the effectiveness of fire control measures at combined-cycle power plants in Iran. This study aimed at assessing fire risk and determining the effectiveness of fire control measures to decrease fire-related fatalities and injuries to residents at a combined-cycle power plant in the northeast of Iran.

MATERIALS and METHODS

Primary Study and Data Collection

The present study was performed in a combined-cycle power plant in the northeast of Iran in 2017. In the present investigation, the risk level of fire for the occupants, activities, and building and its content was measured by applying the Fire Risk Assessment Method for Engineering (FRAME) [17].

At first, a complete inspection of the power plant was performed to gather the information required to perform the steps of the study. Considering that the FRAME method can be applied only in a closed area, the control room was determined after studying the different sections of the power plant. The FRAME has many parameters to calculate the fire risk level. Thus, to enhance accuracy and speed, the authors created a checklist based on all parameters in the FRAME guidelines. The data was collected through observations, interviews with workers and engineers, or by reference to the process documents. A wide range of calculations was employed in FRAME. Hence for enhancing precision and decreasing the probability of a calculation error, the computational package with EXCEL software was generated and used to measure the fire risk level at present study.

Fire Risk Level Calculation

After the previous steps, fire risk levels were determined independently for the occupants, building and their contents, and activities [17] step by step as follows:

The fire risk level for buildings and their contents

Regarding factors such as Potential Risk [P], Acceptable Risk Level [A] and the Protection Level [D], Fire Risk for building and content (R) was calculated according to the following equation:

$$\left(R = \frac{P}{A \times D}\right) \Rightarrow \begin{cases} D = W \times N \times S \times F \\ A = 1.6 - a - t - c \\ P = q \times i \times g \times e \times v \times z \end{cases}$$

Required parameters to calculate the fire risk level for the building and their contents are shown in detail in Fig. 1.

The fire risk level for occupants

Applying the factors including Potential Risk [P_1], Acceptable Risk Level [A_1] and the Protection Level [D_1], Fire Risk for building and content (R1) was determined according to the following equation:

$$\left(R_1 = \frac{P_1}{A_1 \times D_1}\right) = \begin{cases} D_1 = N \times U \\ A_1 = 1.6 - a - t - r \\ P_1 = q \times i \times e \times v \times z \end{cases}$$

Essential parameters to determine the fire risk level for the occupants are displayed in Fig 2.

The fire risk level for activities

Regarding the factors of Potential Risk [P_2], Acceptable Risk Level [A_2], and Protection Level [D_2], the Fire Risk for activities (R_2) was calculated as follows:

$$\left(R_2 = \frac{P_2}{A_2 \times D_2}\right) = \begin{cases} D_2 = W \times N \times S \times Y \\ A_2 = 1.6 - a - c - d \\ P_2 = g \times i \times e \times v \times z \end{cases}$$

Essential parameters to measure the activities fire risk level are shown in details in Fig. 3.

The estimated potential damage in the case of fire

According to the computed fire risk level, in the case of a fire, the assumed destruction to the building is estimated according to Table 1.

Control measures selection and fire management

The suggested fire control measures on the basis of the measured fire risk level for building and contents (R), occupants (R1), and activities (R2) were determined according to Table 2.

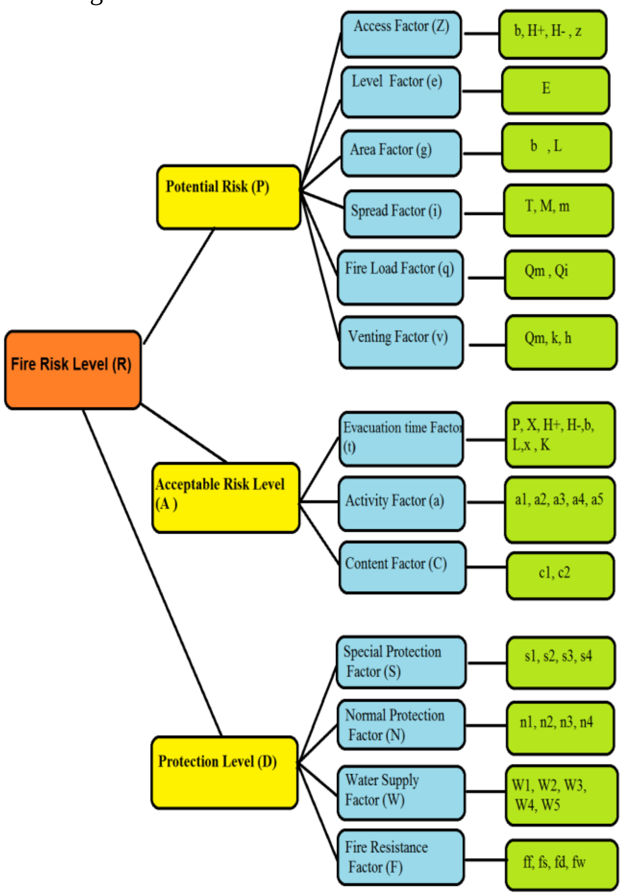

Fig. 1: Essential parameters to measure the fire risk level for the building and its contents

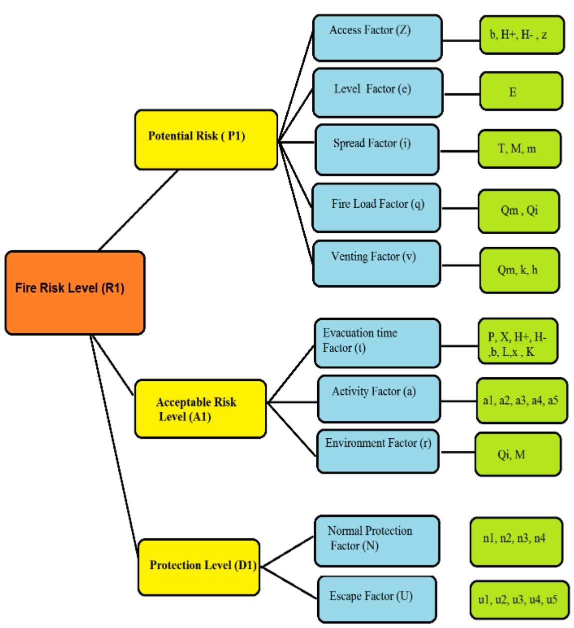

Fig. 2: Essential parameters to calculate the occupants' fire risk level

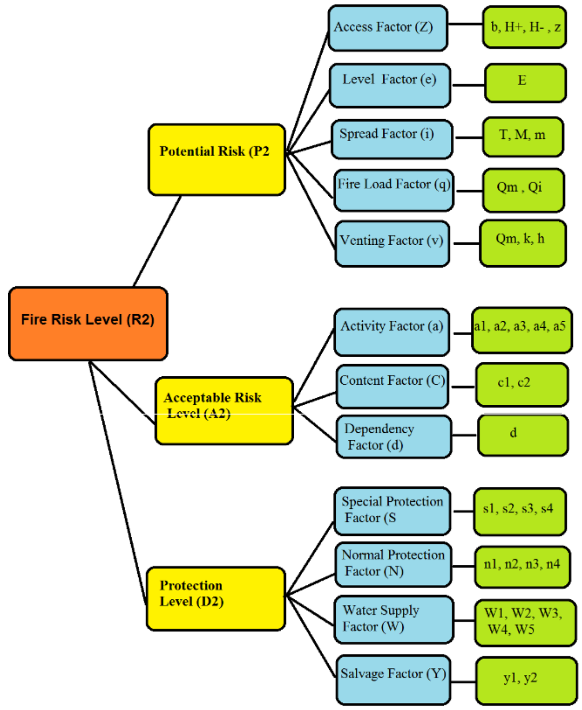

Fig 3: Essential parameters to estimate the activities fire risk level

Table 1: The expected destruction to the construction in the occurrence of a fire

Value of R	% of compartment destroyed
Up to 1.0	10 % or less
1.0 to 1.3	10 to 20 %
1.3 to 1.5	20 to 30 %
1.5 to 1.7	30 to 50 %
1.7 to 1.9	50 to 80 %
More than 1.9	80 to 100 %

Determining the effectiveness of fire protection actions to reduce fire-related injuries and fatalities to occupants

In fire safety, both passive and active fire protection actions are applied in industrial buildings and structures. Active fire protection actions involve fire alarm and extinguishing systems while the passive measures include methods such as using non-burning materials in construction to contain fires or slower their spread and designing standard emergency exit routes for reducing fire risk level (27). In the present study, we investigated the effectiveness of reduction of fire load through building construction by non-burning materials or up to 10% burning materials, designing standard emergency exit routes (passive fire protection actions), and using fire alarm systems (active fire protection actions) to decrease the fire risk level for buildings and their contents, occupants, and activities. We obtained a value more than the acceptable level.

Table 2. The recommended fire control actions on the basis of the calculated fire risk level

Fire Risk Level	Control measures
The calculated risk level is ≤1	The use of manual fire protection systems and general methods, such as handheld fire extinguishers are recommended. It may sometimes be needed to apply extra actions to protect the occupant.
The calculated risk level is >1 to ≤1.6	The employment of the fire alarm system is suggested. It may sometimes be required to provide sufficient water supplies and the adoption of supplementary actions to preserve the occupants.
The calculated risk level is >1.6 to ≤4.5	The application of fire alarm and extinguishing systems, such as sprinklers, is necessary. If the risk level is ≥2.7, sufficient water supply should be ensured.
The calculated risk level is >4.5	Several approaches should be simultaneously implemented to decrease the fire risk level. The protection criteria as mentioned above are ineffective alone.

RESULTS

The results indicated that the occupants' fire risk level (1.26) was greater than the acceptable level. Consequently, fire protection measures should be applied to reduce fire-related injuries and fatalities. The findings of the study showed the fire risk levels for "activities" and "buildings and their contents" were 0.63 and 0.173, respectively, indicating that the fire risk level was within the acceptable range. The factors used for fire risk level calculation are shown in Table 3 and Table 4.

Table 3: Summary data applied for fire risk calculation

Subfactor	Value	Subfactor	Value
Geometry data		f_s	60
H	0	f_f	60
H^+	4	f_d	0
L	30	f_w	60
b	25	u_1	12
h	10	u_2	6
Fire - specific data		u_3	0
Q_i	1000	u_4	0
Q_m	600	u_5	4
M	2	w_1	0
T	100	w_2	0
a_1	0	w_3	0
a_2	0.2	w_4	0
a_3	0	w_5	0
a_4	0	**Method - specific data**	
a_5	0.1	Z	2
P	1	E	4
X	0.05	c_1	0.2
x	3.33	c_2	0
K	2	n_1	0
s_1	10	n_2	0
s_2	3	n_3	0
s_3	14	n_4	0
s_4	8	D	0.8
k	1.85		
Y_1	3		
Y_2	0		

Table 4: The results of the details of the fire risk level calculation

subfactors	Value	Calculated fire risk levels	Value
Potential Risk for building (P)	8.72	Building and their contents (R)	0.173
Acceptable Risk Level for Building (A)	8.43		
Protection Level for Building (D)	5.98		
Potential Risk for occupants(P1)	3.01	Occupants (R_1)	1.26*
Acceptable Risk Level for occupants (A_1)	1.04		
Protection Level for occupants (D1)	2.29		
Potential Risk for activities(P2)	1.28	Activities (R_2)	0.63
Acceptable Risk Level for activities (A2)	0.3		
Protection Level for activities (D2)	6.7		

* The occupants' fire risk level is higher than the acceptable level.

The results revealed that the potential destruction of the control room would be about 20% in the case of a fire because the occupants' fire risk level obtained was above the acceptable range. Thus, we investigated the performance of fire protection actions to decrease fire-related deaths and injuries in the occurrence of a fire. The results indicated that, by considering a constant fire load modulation through establishing buildings by non-burning materials or up to 10% burning materials, the occupants' fire risk level will be reduced by about 8% compared to the current condition. Furthermore, in the state of designing standard emergency exit paths and using fire alarm systems, the fire risk level will be reduced respectively by about 50% and 52 %, compared to the current situation. (Table 5). Also, if the mentioned fire protection measures are employed simultaneously, the occupants' fire risk level will be lowered by 63% compared to the existing situation (Table 6).

Table 5: Results of the fire risk level in the case of implementation the fire protection actions

Fire protection actions	Terms of the calculated risk level	Symbol	Risk level
An Existing situation	The calculated fire risk level for occupants of the existing condition	R_{1-1}	1.26*
Passive fire protection actions	The calculated fire risk level for occupants, considering a constant fire load modulation during building construction by non-burning materials or up to 10% burning materials	R_{1-2}	1.16*
	The calculated occupant's fire risk level, assuming designing standard emergency exit paths (internal and external fire escape staircases, emergency lighting escape paths, emergency exit signs, and complete evacuation plans)	R_{1-3}	0.63
Active fire protection actions	The estimated risk level, regarding the application of automatic fire alarm systems in the control room and exit paths	R_{1-4}	0.6

* The occupants' fire risk level is higher than the acceptable level

Table 6: Results of the fire risk level if all the studied fire protection actions are employed simultaneously

subfactors	Value	Symbol	The fire risk level of the existing situation	Fire risk level after used all fire protection actions
Potential Risk for occupants(P1)	3.01	Occupants (R_{1-5})	1.26	0.47
Acceptable Risk Level for occupants (A1)	1.15			
Protection Level for occupants (D1)	5.51			

DISCUSSION

This research revealed that the occupants' fire risk level (1.26) was greater than the acceptable (≤1) level. Thus, some fire protection actions must be employed to decrease the risk level. In line with these findings, Shirali *et al.* reported that the occupants' fire risk level of a thermal power plant was unacceptable. Important to note, the measured fire risk level in Shirali *et al.'s* study is very higher (20.6 vs 1.26) than the current study. The causes for the discrepancy in these results can be attributed to the old building of the power plant, differences in the structural status of buildings, differences in process, the setting of the control room on the fourth floor, and the lack of safety equipment compared to the power plant in this study [28]. It is necessary to note that the current study was performed in a combined-cycle power plant and the control room was located on the ground floor. Furthermore, Mahdinia indicated that radiology and clinical units of a hospital had the greatest occupants' fire level due to their location in the basement and problem of access and exit of occupants [29]. Moreover, Aslani and Habibi showed that the occupants' fire risk level in a hospital was unacceptable due to improper emergency exit paths and the lack of a fire alarm system [30].

The study results revealed that the level of fire risk for activities (0.63) and building and their contents (0.173) was within the satisfactory range. The reasons for this can be attributed to factors such as the newly-constructed buildings, appropriate dimensions of the control room proportional to the number of employees, and observation of the principles of fire safety during installation. These findings are consistent with those of NG who indicated that, in Hong Kong airport terminal, due to considering the fire safety policies during the designing and installation such as application of sprinkler and water supply system, the risk level for activities and building has been in a satisfactory level [24]. Furthermore, Sakenaite revealed that the building and contents fire risk level of an office building was within the acceptable range due to the low number of employees and suitable infrastructure of the building [31]. Also, Hokmabadi *et al.* found that the building and activities fire risk levels in a hospital were at an acceptable level [32]. In contrast, Shirali *et al.* reported that the building and their contents fire risk level of a thermal power plant was higher than the acceptable level [28]. The causes of these results can be attributed to the dimensions of the building, high density of people, lack of safe exit routes, and safety equipment compared to the power plant in the present study. Also, Sarsangi *et al.* found that the building fire risk level in a hospital was higher than the tolerable level due to the absence of a standard fire alarm and water supply system [33].

At the present study, the occupants' fire risk level obtained was over the satisfactory level. Hence, we examined the efficiency of fire protection actions to decrease the occupants' fire risk level in the state of fire. The findings of the present study showed that, by considering a permanent fire load modulation through installing building by non-burning materials or up to 10% burning materials, the occupants' fire risk level will be decreased by about 8% compared to the current situation. Moreover, in the case of designing standard emergency exit ways and applying fire alarm systems, the fire risk level will be respectively reduced by 50% and 52 %, compared to the current situation (Table 5). In other words, by using one of the fire protection actions (active or passive), the risk level of fire can be reduced to a satisfactory level. In contrast to the present study, Askaripoor *et al.* reported that active and passive fire protection actions, although having a significant effect on reducing the risk level of fire, cannot be able to separately provide a satisfactory level of risk in the control room of a thermal power plant [34]. Factors such as new power plant building, installation of the control room in the ground floor, and new equipment and facilities of the power plant in the present study can explain the disparities between the present study results and the study mentioned above. Ibrahim *et al.* reported that the active fire protection actions and fire management are the important principles in the modification of fire risk level in a heritage building [35]. Also, Ng suggested that the application of active fire protection action (water supply and sprinkler systems) and setup of fire safety regulations lead to a reduction in the fire risk of buildings and its content in the Hong Kong airport [24]. Charters have reported that the application of passive fire protection actions at the initial designing stage, in addition to minimizing the safety cost, could lead to enhanced redundancy and system reliability against the fire hazard in large industrial construction [36]. Furthermore, the results of another study conducted in a thermal power plant in the southwest of Iran showed that in the case of use of the 3rd chapter of Iranian National Building Regulations in a power plant, the fire risk level will be declined by about 11.7% compared to the existing situation [37]. Finally, it can be assumed that because of the high disaster caused by industrial fires, the identification of deficiencies and difficulties in fire safety systems is vital for fire prevention strategies. Furthermore, due to the characteristics of the industrial processes and structures, active or passive fire protection actions can be used to maintain the risk of fire at a pleasant level. However, to enhance the reliability and redundancy, with consideration of cost-benefit factors, the simultaneous application of both passive and active fire protection actions are recommended [38-40].

Limitations of the Study

One limitation of the present study was that FRAME cannot involve the cost factor in the determination of proper fire protection actions. Hence, it is suggested that authorities apply a different method besides this method for selecting the cost-benefit fire control measures.

CONCLUSION

Because of the complexity of the process, the occurrence of fires in industrial buildings such as combined-cycle power plants is inevitable. Thus, the use of fire protection actions to reduce fire-related injuries and fatalities is vital. The results showed that the occupants' fire risk level was greater than the satisfactory level. Also, by using one of the fire protection actions (passive or active), the fire risk level can be diminished to an acceptable level. Nonetheless, to improve the reliability and redundancy, the simultaneous application of both passive and active fire protection actions are suggested. Furthermore, it can be concluded that the Fire Risk Assessment Method for Engineering (FRAME) can help to find practical solutions to decrease fire risk level and minimize fire-related fatalities and injuries in industrial buildings.

ETHICAL ISSUES

Ethical issues such as plagiarism have been observed by the authors.

COMPETING INTEREST

The authors have declared that there are no conflicts of interest.

AUTHORS CONTRIBUTION

All authors equally participated in drafting, revising, and approving of the manuscript.

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