

Integrated Fire and Explosion Risk Assessment Using HIRAC and Dow F&EI in a Nickel Smelter Electric Furnace

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Article Information

Submitted: 19 September 2026

Accepted: 09 October 2026

Publish: 22 October 2026

Keyword: Dow Fire and Explosion Index; Electric Furnace; Fire And Explosion; HIRAC; Nickel Smelter; Process Safety;

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Year: 2026

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Abstract

Introduction: Nickel smelting using Rotary Kiln Electric Furnace technology involves substantial fire and explosion risks from high temperatures, coal, carbon monoxide, and molten metal. **Objective:** This study aimed to evaluate fire and explosion risks in the Electric Furnace area of a nickel smelter by integrating the Hazard Identification, Risk Assessment, and Control method with the Dow Fire and Explosion Index. **Method:** The Hazard Identification, Risk Assessment, and Control method identified hazards, assessed risks, and determined controls, while the Dow Fire and Explosion Index quantified fire and explosion potential. **Result and Discussion:** The Hazard Identification, Risk Assessment, and Control assessment identified several high and extreme occupational risks related to molten metal handling, oxygen-related tapping operations, hydraulic oil systems, combustible dust, refractory furnace failure, and other fire and explosion scenarios. The Dow Fire and Explosion Index produced a value of 229.06, showing that the Electric Furnace was classified as a severe hazard process unit with substantial potential for fire and explosion losses. **Conclusion:** Integrating both methods provides a practical basis for prioritizing fire and explosion controls and improving process safety in nickel smelting operations.

Introduction

The rapid expansion of electric vehicle and renewable energy industries has substantially increased the global demand for nickel (Crundwell, F. K., Moats, M. S., Ramachandran, V., Robinson, T. G., & Davenport, 2011; Shannak *et al.*, 2024; Warner, A. E. M., Díaz, C. M., Dalvi, A. D., Mackey, P. J., & Tarasov, 2006). Indonesia has become a major center of global nickel production and processing, particularly following the implementation of policies promoting domestic nickel downstreaming (Asyono *et al.*, 2026; Rivota & Wardhana, 2026). To increase the added value of nickel resources, substantial investments have been made in domestic nickel processing and smelting facilities (Asyono *et al.*, 2026). The Rotary Kiln Electric Furnace (RKEF) process is widely applied for ferronickel production from lateritic nickel ores and involves a sequence of high-temperature processing and smelting operations (Crundwell, F. K., Moats, M. S., Ramachandran, V., Robinson, T. G., & Davenport, 2011; Sudaryanto, S.; Sukanto, U.; Nugroho, 2024).

Nickel smelting operations employing Rotary Kiln Electric Furnace (RKEF) technology involve high operating temperatures, combustible reducing agents, molten metal handling, and hazardous gases (Crowl, D. A., & Louvar, 2019; Crundwell, F. K., Moats, M. S., Ramachandran, V., Robinson, T. G., & Davenport, 2011; Harvey *et al.*, 2022). Among the major process units, the Electric Furnace (EF) operates continuously at temperatures exceeding 1,500 °C and may involve molten metal splashing, refractory degradation, carbon monoxide (CO) leakage, combustible coal dust, and molten metal-water interactions, creating substantial fire and explosion hazards (Crowl, D. A., & Louvar, 2019; Crundwell, F. K., Moats, M. S., Ramachandran, V., Robinson, T. G., & Davenport, 2011). These conditions can lead to severe injuries, equipment damage, production interruptions, and other major consequences, making process safety a critical concern in nickel smelting operations (Mannan, 2012).

Systematic hazard identification and risk assessment are therefore required to evaluate operational hazards and establish appropriate controls (Center for Chemical Process Safety (CCPS), 2008; International Organization for Standardization, 2018; Iqbal *et al.*, 2021). HIRAC provides a qualitative framework for identifying hazards and evaluating likelihood and severity, whereas the Dow Fire and Explosion Index (Dow F&EI) provides a semi-quantitative assessment of fire and explosion hazard at the process-unit level based on the Material Factor (MF), General Process Hazard Factor (F1), and Special Process Hazard Factor (F2) (The Dow Chemical Company, 1994; Etowa, C. B., Amyotte, P. R., Pegg, M. J., & Khan, 2002). Thus, HIRAC and Dow F&EI address different but complementary dimensions of risk assessment, with HIRAC focusing on operational and occupational hazards and Dow F&EI characterizing process-level fire and explosion potential.

Previous studies have applied HIRAC or similar hazard identification approaches to industrial operations and Dow F&EI to fire and explosion assessment in process industries (Agarwalla *et al.*, 2025; Chau *et al.*, 2022; Etowa, C. B., Amyotte, P. R., Pegg, M. J., & Khan, 2002; Jensen, N., & Jørgensen, 2007; Khan, F. I., Husain, T., & Abbasi, 2001). However, evidence on the integrated application of these approaches to fire and explosion risk assessment in the Electric Furnace of an RKEF nickel smelter remains limited. This study addresses this gap by integrating HIRAC-based operational hazard identification with Dow F&EI-based process-level fire and explosion assessment to establish risk control priorities for Electric Furnace operations. Therefore, this study aims to evaluate fire and explosion risks in the Electric Furnace area of a nickel smelter by

integrating Hazard Identification, Risk Assessment, and Control (HIRAC) with the Dow Fire and Explosion Index. The resulting assessment is intended to link operational risk levels with process-level fire and explosion hazards and support the prioritization of appropriate engineering and administrative controls.

Method

This study was conducted in the Electric Furnace (EF) area of a nickel smelter in Indonesia employing the Rotary Kiln Electric Furnace (RKEF) process. The EF is a primary processing unit for smelting calcined nickel ore into ferronickel and operates continuously at temperatures exceeding 1,500 °C, involving molten metal, molten slag, reducing agents, and combustible gases. The assessment covered operational activities, processing equipment, hazardous materials, and working conditions, with data collected through field observations, direct inspections, company operational documents, standard operating procedures (SOPs), interviews with operational personnel, and hazard identification records. The research framework shows in Figure 1.

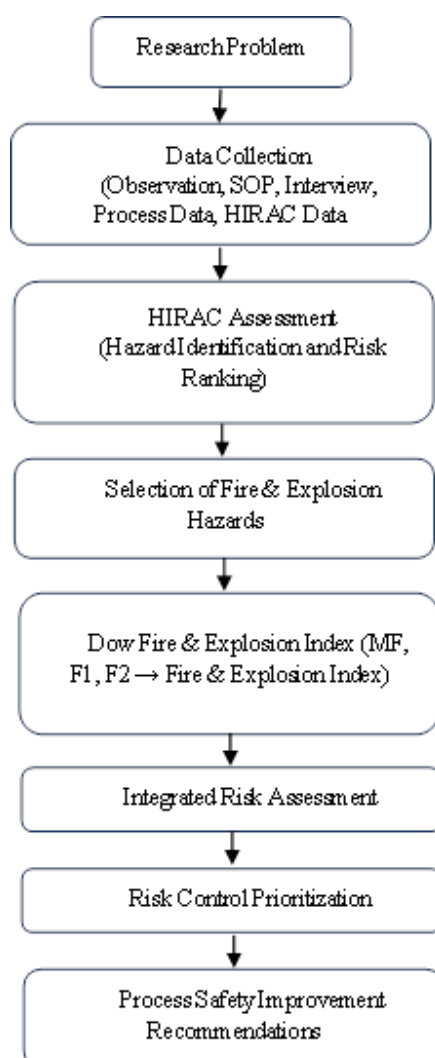


Figure 1. Integrated Research Framework for Fire and Explosion Risk Assessment Using HIRAC and the Dow Fire and Explosion Index

A descriptive analytical approach was employed by integrating qualitative and quantitative risk assessment methods. The research consisted of hazard identification and risk assessment using HIRAC, quantitative fire and explosion assessment using the Dow Fire and Explosion Index, and integration of both results to establish fire and explosion risk control priorities. For HIRAC, hazards associated with Electric Furnace operations were identified and evaluated based on actual operating conditions, safety procedures, and company operational documents (PT Gunbuster Nickel Industry, 2024a, 2024b). The assessment covered molten slag and ferronickel tapping, cast iron machine operation, oil station activities, processing dust chamber operation, furnace inspection and maintenance, and refractory furnace conditions, with potential hazards including high-temperature exposure, molten metal splashing, oxygen-related hazards, combustible coal dust, refractory failure, electrical hazards, and confined working areas. Each hazard was assessed using Likelihood (L) and Severity (S) criteria according to the company's HIRAC risk assessment matrix, and the resulting risks were classified as Low, Moderate, High, or Extreme (Center for Chemical Process Safety (CCPS), 2008; International Organization for Standardization, 2018). The risk level was determined using the combination of likelihood and severity as expressed in Equation (1).

$$\text{Risk (R)} = \text{Likelihood (L)} \times \text{Severity (S)} \quad (1)$$

For the Dow Fire and Explosion Index (Dow F&EI), the Electric Furnace was assessed according to the Dow Fire and Explosion Index Guide by determining the Material Factor (MF), General Process Hazard Factor (F1), and Special Process Hazard Factor (F2) (Etowa, C. B., Amyotte, P. R., Pegg, M. J., & Khan, 2002; The Dow Chemical Company, 1994). The Fire and Explosion Index was calculated using Equation (2), where MF represents the Material Factor, F1 the General Process Hazard Factor, and F2 the Special Process Hazard Factor. The resulting F&EI value was classified according to the Dow Fire and Explosion Index hazard categories, ranging from Light Hazard to Severe Hazard (The Dow Chemical Company, 1994).

$$\text{F\&EI} = \text{MF} \times \text{F}_1 \times \text{F}_2 \quad (2)$$

The integrated assessment was performed sequentially by first identifying and classifying operational hazards using HIRAC, followed by selecting hazards with fire and explosion potential for Dow F&EI assessment. The HIRAC results were then combined with the Dow F&EI results to relate operational risk levels to process-level fire and explosion severity. The findings from both methods were interpreted collectively to establish risk control priorities and recommend engineering and administrative controls for improving process safety in Electric Furnace operations.

Result and Discussion

Hazard Identification and Risk Assessment Using HIRAC

The HIRAC method was applied to identify operational hazards associated with Electric Furnace activities and evaluate the corresponding occupational risk levels. Hazard identification covered the major operational activities represented in the Electric Furnace HIRAC assessment, including molten slag and ferronickel tapping, cast iron machine operation, oil station activities, processing dust chamber operation, furnace inspection and maintenance, and refractory furnace conditions. The assessment was based

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on the identified operational activities and hazardous conditions observed in the Electric Furnace area, with operational procedures and equipment requirements cross-checked against the company's internal operating documentation (PT Gunbuster Nickel Industry, 2024a, 2024b).

The identified hazards were evaluated using likelihood and severity criteria in accordance with the company's HIRAC risk matrix. The assessment indicated that several operational activities were classified as High and Extreme risk due to the presence of high-temperature processes, molten metal, combustible gases, electrical energy, and confined working conditions. Table 1 presents HIRAC results for all assessed activities.

Table 1
HIRAC Assessment Results

Operational Activity	Major Hazard	Consequence	Potential Fire/Explosion Scenario	Risk Level
Slag Taphole & Ferronickel Taphole Operation	Oxygen cylinder positioned too close to the ferronickel tap hole	Fire, Explosion	Oxygen-enhanced fire or explosion	Extreme
Slag Taphole & Ferronickel Taphole Operation	Splashing of molten slag or molten metal during tapping	Burns, Blisters	Molten metal fire and severe burn hazard	Extreme
Slag Taphole & Ferronickel Taphole Operation	Metal tools are not preheated before contacting molten metal	Fire, Explosion	Fire or steam explosion due to thermal shock	Extreme
Cast Iron Machine Operation	Insufficient cooling water circulation causing poor cooling of ferronickel molds	Molten metal falls to the ground and explodes	Steam explosion due to molten metal-water interaction	Extreme
Oil Station	Oil pipeline rupture due to excessive pressure	Fire, Explosion	Pool fire or flash fire	Extreme
Oil Station	Loose oil pipe connection	Fire, Explosion	Oil leakage leading to fire	Extreme
Oil Station	Oil station located too close to ignition sources without isolation	Fire, Explosion	Fire or explosion	Extreme
Processing Chamber	Dust Dust explosion	Burns, Blisters	Dust explosion	High

Electric Furnace Inspection and Maintenance	Backdraft and hot material splash when opening furnace door	Burns, Blisters	Flash fire and thermal burn	Extreme
Refractory Furnace Failure	Molten material overflows from furnace	Fire, Explosion, Burns, Fatality	Fire and secondary explosion	Extreme

As showed in Table 1, the HIRAC assessment identified 10 High and Extreme operational fire and explosion hazards requiring priority control. The most critical hazards were associated with molten metal handling, oxygen-related tapping operations, unheated tools contacting molten material, cooling water and molten metal interaction, oil leakage and oil-related fire hazards, combustible dust, backdraft during furnace inspection, and refractory failure. These hazards were subsequently selected for quantitative evaluation using the Dow Fire and Explosion Index because they represent significant potential sources of fire and explosion incidents in the Electric Furnace.

Fire and Explosion Hazard Assessment Using Dow Fire and Explosion Index

The fire and explosion hazard associated with the Electric Furnace was quantitatively evaluated using the Dow Fire and Explosion Index (Dow F&EI). The assessment was based on the Material Factor (MF), General Process Hazard Factor (F1), and Special Process Hazard Factor (F2), which reflect the characteristics of combustible materials and hazardous operating conditions within the Electric Furnace. Carbon monoxide (CO) was selected as the reference material because it is continuously generated during the reduction process and represents the dominant flammable substance with the highest fire and explosion potential in the process unit.

Table 2
Dow Fire and Explosion Index Calculation Results

Parameter	Value	Description
Material Factor (MF)	21	Carbon monoxide
General Process Hazard Factor (F1)	2.94	General process Hazard
Special Process Hazard Factor (F2)	3.71	Special process Hazard
Process Unit Hazard Factor F3	10.91	F1 x F2
Fire & Explosion Index	229.06	Severe Hazard

As presented in Table 2, the Electric Furnace achieved a Dow Fire and Explosion Index of 229.06, which falls within the Severe Hazard category according to the Dow Fire and Explosion Index Hazard Classification Guide (The Dow Chemical Company, 1994). The high index value indicates that the Electric Furnace possesses a substantial potential for fire and explosion incidents due to the combined influence of combustible materials and hazardous operating conditions.

The General Process Hazard Factor (F1) of 2.94 was obtained by considering the combined effects of exothermic reactions, material handling activities, enclosed process configuration, limited firefighting accessibility, drainage conditions, high operating temperatures, and housekeeping practices (The Dow Chemical Company, 1994). These conditions were based on the actual operating characteristics and workplace conditions

observed in the Electric Furnace area and cross-checked against the company's internal operating documentation (PT Gunbuster Nickel Industry, 2024a, 2024b).

The Special Process Hazard Factor (F2) of 3.71 was primarily influenced by the continuous generation of carbon monoxide (CO), the presence of hydraulic oil systems, combustible coal dust, molten ferro-nickel and slag, pressure systems, rotating equipment, and other process-specific hazards (The Dow Chemical Company, 1994). Carbon monoxide represents a significant flammable gas hazard within the Electric Furnace process because it is continuously generated during the reduction process and conveyed through the furnace gas ducting and exhaust system (PT Gunbuster Nickel Industry, 2024a, 2024b). The assessment also considered the actual process configuration and equipment associated with the Electric Furnace, including hydraulic stations, piping, valves, gas ducting, exhaust systems, and associated process equipment (PT Gunbuster Nickel Industry, 2024a, 2024b). These conditions contributed to the elevated F2 value and, together with the general process hazards reflected in F1, resulted in the Severe Hazard classification of the Electric Furnace.

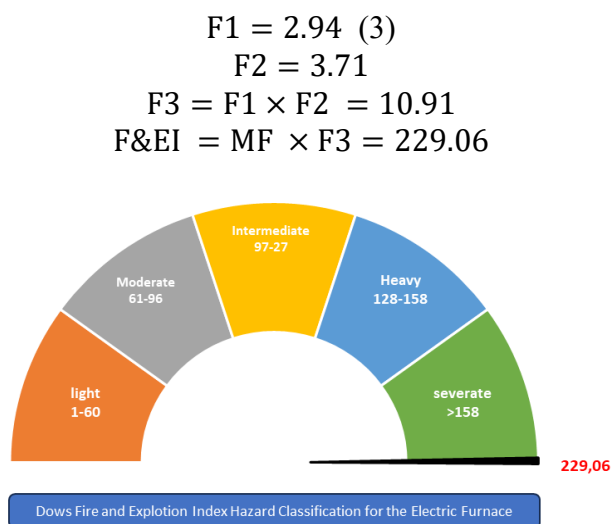


Figure 2. Dow Fire and Explosion Index Hazard Classification of the Electric Furnace

As shown in Figure 2, the Fire and Explosion Index indicates that the Electric Furnace falls within the Severe Hazard category. The high Fire and Explosion Index was primarily attributed to the continuous generation of carbon monoxide (CO) during the reduction process, the presence of combustible coal dust, hydraulic oil systems, molten ferro-nickel and slag at temperatures exceeding 1,500°C, and the enclosed process configuration involving gas ducting and associated equipment. These conditions significantly increased both the General Process Hazard Factor (F1) and the Special Process Hazard Factor (F2), emphasizing the need to prioritize engineering controls and process safety improvements to mitigate the potential consequences of fire and explosion incidents in the Electric Furnace.

Integrated Risk Assessment and Risk Control Prioritization

The integration of HIRAC and the Dow Fire and Explosion Index provides complementary information for interpreting fire and explosion risks in the Electric Furnace. HIRAC characterizes occupational risk according to likelihood and severity,

while the Dow Fire and Explosion Index provides a process-level indication of fire and explosion hazard potential. Therefore, the two methods can be interpreted together to determine whether operational hazards identified during routine activities also have broader implications for process safety and risk control.

The relationship between the two assessment approaches is particularly relevant for hazards involving molten materials, oxygen, combustible substances, and high-temperature process conditions. The Severe Hazard classification obtained from the Dow Fire and Explosion Index provides additional context for interpreting the High and Extreme risks identified through HIRAC, rather than representing a separate risk classification. This indicates that the operational hazards requiring attention may also contribute to wider fire and explosion scenarios within the process unit.

Table 3
 Integrated Risk Control Prioritization Based on HIRAC and Dow Fire & Explosion Index

Hazard Source		HIRAC Risk Level	Dow F&EI	Engineering Control	Priority
Molten metal handling		Extreme	Severe	Splash guard, and remote tapping	Very High
Oxygen-related tapping hazard		Extreme	Severe	Oxygen cylinder segregation, dedicated storage, separation from ignition/molten metal	Very High
Oil leakage and oil-related fire hazard		Extreme	Severe	Leak detection, piping inspection, isolation system, preventive maintenance	Very High
Combustible dust	coal	High	Severe	Dust collection, housekeeping, dust accumulation control	High
Backdraft and furnace opening		Extreme	Severe	Controlled furnace-opening procedure, gas monitoring, interlocks, remote monitoring	High
Refractory failure and molten material overflow		Extreme	Severe	Refractory condition monitoring, thermal monitoring, predictive maintenance	Very High

The prioritization presented in Table 3 suggests that control strategies should focus on hazards where high occupational risk coincides with conditions capable of producing severe fire or explosion events. Molten metal handling, oxygen-related tapping, oil leakage, and refractory failure receive Very High priority, showing that these hazards require controls directed at their sources and critical process conditions. Combustible dust and furnace-opening hazards receive High priority, reflecting their potential contribution

to fire and explosion development. The prioritization of engineering controls is consistent with the hierarchy of risk control, which recommends implementing engineering measures before administrative controls and personal protective equipment whenever technically feasible (International Organization for Standardization, 2018). This supports the use of measures such as splash protection, oxygen cylinder segregation, leak detection and isolation, dust collection, gas monitoring, refractory condition monitoring, and preventive maintenance because these controls directly address the hazardous conditions identified in the assessment. The value of the integrated approach therefore lies in connecting occupational risk information with process-level fire and explosion considerations. Rather than using the HIRAC and Dow F&EI outputs as separate assessments, the framework provides a basis for interpreting which operational hazards may require greater attention because of their potential process consequences. Figure 3 shows the integrated risk prioritization framework proposed in this study.

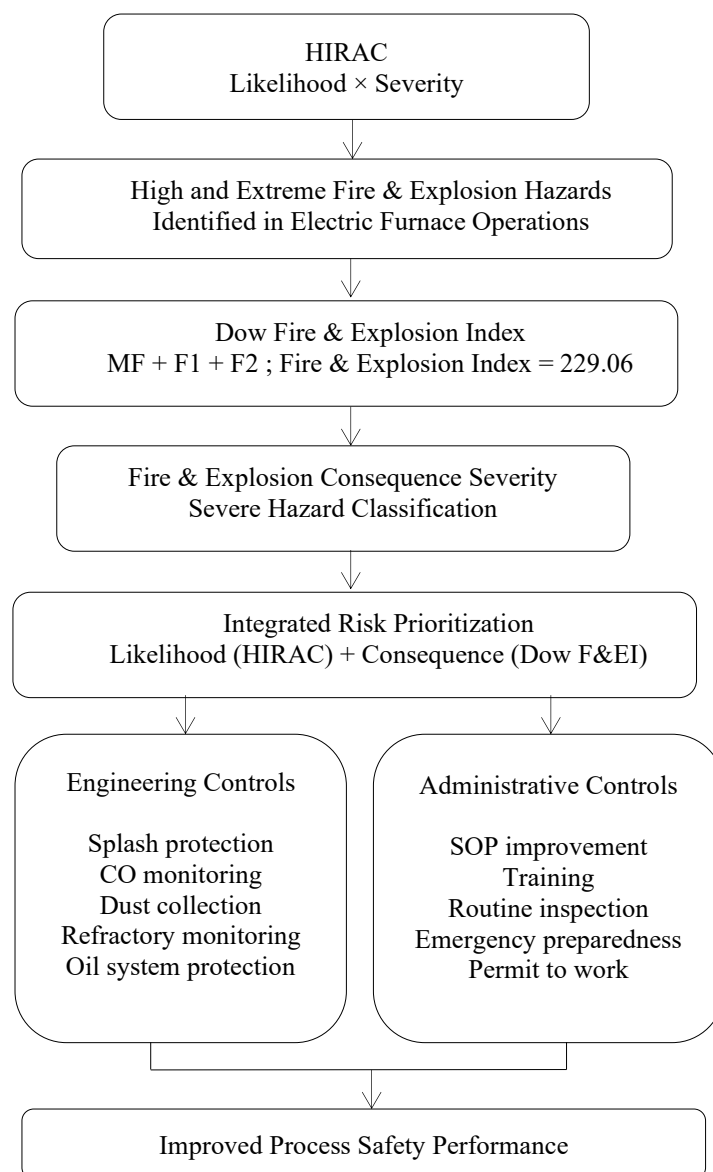


Figure 3. Integrated Risk Control Prioritization Framework Combining HIRAC and Dow Fire & Explosion Index

Figure 3 shows the proposed relationship between hazard identification, fire and explosion assessment, and risk control prioritization. The framework begins with the identification and classification of operational hazards through HIRAC, followed by consideration of their fire and explosion implications using the Dow F&EI. The resulting interpretation provides a basis for selecting control measures according to the nature and significance of the identified hazards. The interpretation of these findings is consistent with previous studies showing that high-temperature industrial and metallurgical operations involving combustible gases and molten materials can present substantial fire and explosion hazards (Crundwell, F. K., Moats, M. S., Ramachandran, V., Robinson, T. G., & Davenport, 2011; Etowa, C. B., Amyotte, P. R., Pegg, M. J., & Khan, 2002; Liu *et al.*, 2026). Previous studies have generally examined hazard identification or fire and explosion assessment through individual approaches (Agarwalla *et al.*, 2025; Chau *et al.*, 2022; Etowa, C. B., Amyotte, P. R., Pegg, M. J., & Khan, 2002; Jensen, N., & Jørgensen, 2007; Khan, F. I., Husain, T., & Abbasi, 2001). In contrast, the present study links operational hazard classification with process-level fire and explosion assessment, allowing the implications of identified hazards to be considered when establishing risk control priorities in Electric Furnace operations.

Implications for Process Safety Management

The findings show that process safety management in Electric Furnace operations should combine qualitative hazard identification with quantitative fire and explosion assessment to support risk control decisions (Center for Chemical Process Safety (CCPS), 2007; Mannan, 2012). Engineering controls should receive priority because they address hazards at or near their source (Center for Chemical Process Safety (CCPS), 2007; International Organization for Standardization, 2018). Relevant measures include CO monitoring, improved ventilation, splash protection, dust collection, refractory condition monitoring, hydraulic oil leak prevention, and predictive maintenance, while administrative controls such as inspections, SOP compliance, permit-to-work systems, competency development, and emergency training support their implementation.

The integrated HIRAC-Dow F&EI framework can therefore serve as a decision-support approach for prioritizing controls based on both occupational risk and process-level fire and explosion hazards. Although developed for an RKEF Electric Furnace, the framework may be adapted to other high-temperature metallurgical processes involving combustible gases, molten metals, and combustible dust, subject to differences in process configuration and operating conditions.

Limitations and Recommendations

This study was limited to the Electric Furnace of an RKEF nickel smelter, so the findings may not be directly generalizable to other facilities. HIRAC risk levels may also be influenced by the company's risk matrix and professional judgment, while Dow F&EI provides a semi-quantitative hazard indicator rather than accident probability or frequency. In addition, CO was used as the reference material for the Material Factor, although the process involves other hazardous materials and energy sources. Therefore, the resulting F&EI should not be interpreted as a complete quantitative risk assessment. Detailed consequence modelling, dispersion, radiation, overpressure, and frequency analysis were also outside the scope of this study. Future studies should extend the framework through quantitative consequence and risk analysis, including modelling of CO leakage, hydraulic-oil fires, combustible dust explosions, and molten material release.

Sensitivity analysis of Dow F&EI parameters, detailed assessment of dust characteristics and refractory failure, and validation across other process units or nickel smelters are also recommended. Integration with QRA, consequence modelling, reliability analysis, and process safety indicators could further strengthen the framework for engineering control prioritization.

Conclusion

This study integrated the Hazard Identification, Risk Assessment, and Control (HIRAC) method with the Dow Fire and Explosion Index (Dow F&EI) to assess fire and explosion hazards in Electric Furnace operations at a nickel smelter. HIRAC identified High and Extreme operational risks, while the Dow F&EI value of 229.06 classified the Electric Furnace as a Severe Hazard process unit. The integrated framework links operational risk identification with process-level fire and explosion hazard assessment, providing a basis for prioritizing engineering controls, including CO monitoring, splash protection, dust control, refractory monitoring, and hydraulic oil system protection. Its application can support process safety decision-making in high-temperature metallurgical operations. However, the study was limited to a single RKEF Electric Furnace and did not include detailed consequence modelling or quantitative risk analysis. Future research should incorporate consequence modelling, quantitative risk analysis, and sensitivity analysis to strengthen the assessment and evaluate its applicability to other pyrometallurgical processes.

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